

# 5th EUROMECH nonlinear dynamics conference, August 7-12, 2005 Eindhoven : book of abstracts

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Fifth EUROMECH Nonlinear Dynamics Conference

**Book of Abstracts** 

# Fifth EUROMECH Nonlinear Dynamics Conference August 7 -12, 2005

Chair Prof. Dick H. van Campen



Eindhoven University of Technology Auditorium Building, The Netherlands



# **Book of Abstracts**

Fifth EUROMECH Nonlinear Dynamics Conference August 7 – 12, 2005

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# Preface

The Fifth EUROMECH Nonlinear Dynamics Conference (ENOC-2005) was initiated by the EUROMECH Nonlinear Oscillations Conference Committee (ENOCC) and approved by the Council of the European Mechanics Society (EUROMECH).

Compared to the previous ENOC Conferences the structure of ENOC-2005 has been changed to a far-reaching extent. As usual, a limited number (i.e. seven) of General Lectures have been delivered by renowned scientists in different sub-fields of Nonlinear Dynamics. Besides, a substantial number (i.e. 22) of Mini-Symposia on major and challenging topics have been organized by recognized scientists, acting also as chairpersons of those Mini-Symposia. Contributions not falling within the specific topics of the Mini-Symposia have been combined in the miscellaneous sessions.

Most of the speakers at the ENOC-2005 conference did submit a full paper for the ENOC-2005 conference Proceedings on CD-Rom. Additionally, papers associated with the General Lectures are scheduled to be published in the September 2005 issue of the International Journal of Bifurcation and Chaos.

A successful organization of a conference like the ENOC-2005 is a considerable task. First, I would like to thank all the authors for submitting their valuable contributions and meeting the deadlines. The commendable job done by the ENOCC, by the Netherlands Steering Committee and by the co-organizers / co-chairs of the Mini-Symposia is greatly appreciated.

My sincere thanks go to the members of the Local Organizing Committee for all their efforts done. The editing of this book of Abstracts was done by Mrs. Ine van den Oever and Mr. Maciej Lazurko and I am greatly indebted to both of them.

Dick H. van Campen ENOC-2005 conference chair Eindhoven University of Technology The Netherlands August 2005

# **TABLE OF CONTENTS**

OPENING- AND KEYNOTE LECTURES	. 15
00-OPN:Holmes	. 17
00-KN1:Fossen	. 17
00-KN2:Laskar	. 18
00-KN3:Levi	. 18
<b>00-KN4</b> : Maas	. 19
00-KN5: Stépán	. 19
00-KN6:THOMSEN	20
MS 1: DYNAMICS AND BIFURCATIONS OF NON-SMOOTH SYSTEMS	23
01-021. Van de Woliw	25
01-076: BOURGEOT	
01-118: DANKOWICZ	
01-127 <sup>·</sup> Charfyron	28
01-149. PARKER	28
01-151 DE SCHUTTER	29
01-152 MARTINELLI	30
01-154 · LENCI	31
01-172: OLIVAR	32
<b>01-186: 7</b> HUSUBALIVEV	33
01-196 <sup>.</sup> Awrficfwicz	34
01-210. FOSSAS	35
01-213 Avritin	35
01-217. DORIS	36
01-219: DONIS	37
01-257: CHANG	38
01-258: CSFRNÁK	38
01-267. WILSON	39
01-26, HOGAN	40
01-290: OSORIO	40
01-290. USORIO	41
01-270. DEGER	42
01-302. DI BERNARDO	42
01-521, LOPEZ	
	. 45
MS 2: IMPACT SYSTEMS	. 45
02-018: Pfeiffer	. 47
02-030: Leine	47
02-040: Fidlin	48
02-090: Awrejcewicz	49
02-094: Seifried	50
<b>02-121</b> : LUO	51
<b>02-125</b> : TANAKA	51
02-204: Aeberhard	52
02-205: Ватако	52
02-228: ACARY	53
<b>02-234</b> : PAYR	54

02-280:	RYABOV	54
02-294:	NEUMANN	55
02-362:	DZONOU	55
02-392:	SAEKI	56
02-414:	DIMNET	56
<b>02-449</b> :	Frémond	57
MS 3: MI	JLTIBODY DYNAMICS	59
03-013:	KULVIETIENE	61
03-099:	Marjamäki	61
03-113:	KULESHOV	62
03-129:	SCHWAB	62
03-157:	MÄKINEN	63
03-158:	KANTH	64
03-176:	MEIJAARD	65
03-177:	POGORELOV	66
03-181:	Byrtus	66
03-188:	HENNINGER	67
03-246:	Kireenkov	68
03-295:	WACHAL	68
03-309:	JÄRVENPÄÄ	69
03-339:	KOVECSES	70
03-369:	ZAHARIEV	71
03-407:	NATSIAVAS	71
03-421:	AMBRÓSIO	72
MS 4: NO	ONLINEAR STOCHASTIC SYSTEMS	73
MS 4: NC 04-012	DNLINEAR STOCHASTIC SYSTEMS	. <b>73</b> .75
MS 4: NG 04-012 04-016	DNLINEAR STOCHASTIC SYSTEMS Foukzon Kuske	73 75 75
MS 4: NC 04-012 04-016 04-017	DNLINEAR STOCHASTIC SYSTEMS Foukzon Kuske Wihstutz	73 75 75 76
MS 4: NO 04-012 04-016 04-017 04-029	DNLINEAR STOCHASTIC SYSTEMS Foukzon Kuske Wihstutz Iourtchenko	73 75 75 76 76
MS 4: NC 04-012 04-016 04-017 04-029 04-033	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII	73 75 75 76 76 77
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN	73 75 75 76 76 77 77
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS	73 75 75 76 76 77 78 78
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV	73 75 75 76 76 77 78 78 78 79
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-081	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE	73 75 75 76 76 77 78 78 78 79 80
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-081 04-130	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU	73 75 75 76 76 76 77 78 78 78 79 80 80
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-060 04-066 04-081 04-130 04-236	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON	73 75 75 76 76 76 76 77 78 78 78 79 80 80 80
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-066 04-081 04-130 04-236 04-251	<b>NLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA	73 75 75 76 76 76 76 78 78 78 78 78 80 80 80 81 81
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-060 04-066 04-081 04-130 04-236 04-251 04-315	FOUKZON         FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA	73 75 75 76 76 76 77 78 78 79 80 80 80 81 81 81
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-066 04-081 04-130 04-236 04-251 04-315 04-323	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         SOFI	73 75 75 76 76 76 76 76 78 78 79 80 80 80 81 81 81 82 83
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         SOFI         NAMACHCHIVAYA	73 75 75 76 76 76 77 78 78 79 80 80 80 81 81 82 83 84
MS 4: NG 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-060 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         KOVALEVA	73 75 75 76 76 76 77 78 78 79 80 80 81 81 82 83 84 84
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-356	<b>DNLINEAR STOCHASTIC SYSTEMS</b> Foukzon         KUske         WIHSTUTZ         Iourtchenko         Simanovskii         Sichermann         Naess         Poloskov         Baxendale         Onu         HArrison         Namachchivaya         Keskinen         Sofi         Namachchivaya         Kovaleva	73 75 76 76 76 77 78 78 79 80 80 81 81 82 83 84 84 84 85
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-060 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-350	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         SOFI         NAMACHCHIVAYA         KOVALEVA         SOWERS         KLIEMANN	73 75 76 76 76 76 77 78 78 79 80 80 80 81 81 82 83 84 84 85 85
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-356 04-370 04-381	<b>DNLINEAR STOCHASTIC SYSTEMS</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII.         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         Keskinen         SOFI         NAMACHCHIVAYA         Kovaleva         Sowers         KLIEMANN	73 75 75 76 76 77 78 78 79 80 80 81 81 82 83 84 84 85 85 86
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-356 04-370 04-381 04-440	<b>DNLINEAR STOCHASTIC SYSTEMS.</b> FOUKZON         KUSKE         WIHSTUTZ         IOURTCHENKO         SIMANOVSKII         SICHERMANN         NAESS         POLOSKOV         BAXENDALE         ONU         HARRISON         NAMACHCHIVAYA         Keskinen         SOFI         NAMACHCHIVAYA         Kovaleva         SOWERS         KLIEMANN         TYLIKOWSKI	73 75 75 76 76 76 77 78 78 79 80 80 81 81 82 83 84 85 85 86 87
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-060 04-060 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-355 04-356 04-370 04-381 04-440 04-442	<b>DNLINEAR STOCHASTIC SYSTEMS</b>	73 75 75 76 76 76 77 78 78 78 78 78 80 80 81 81 82 83 84 85 85 86 87 88
MS 4: NO 04-012 04-016 04-017 04-029 04-033 04-055 04-060 04-066 04-081 04-130 04-236 04-251 04-315 04-323 04-347 04-355 04-355 04-355 04-356 04-370 04-381 04-440 04-442 MS 5: OI	DNLINEAR STOCHASTIC SYSTEMS	73 75 75 76 76 77 78 78 78 78 78 78 80 81 81 82 83 84 85 85 86 87 88 85 88 87 88 88 88 88 88 88

05 0(2) DARY	00
05-003: PARK	
<b>U5-184</b> : HOLOBUT	
<b>U5-185</b> : BŁACHOWSKI	
05-208: HALKJÆR	
<b>U5-200</b> : PETERA	
<b>05-320</b> : CHOI	
<b>05-334</b> : KOKALJ	
05-379: CHEBOUBA	
<b>US-419</b> : AMBROSIO	
MS 6: REDUCED-ORDER MODELING	
<b>06-007</b> : Touzé	
<b>06-052</b> : Gonçalves	
<b>06-061</b> : Avramov	
06-071: Awrejcewicz	
<b>06-072</b> : Moroz	
06-077: Martinez-Alvarado	
<b>06-098</b> : Markovic	
<b>06-173</b> : Gendelman	
06-191: Spiess	
<b>06-207</b> : DUMITRACHE	
<b>06-219</b> : Haller	
<b>06-260</b> : Glösmann	
<b>06-278</b> : TISO	
<b>06-301</b> : Chelidze	
<b>06-319</b> : Jansen	
<b>06-325</b> : Georgiou	
<b>06-326</b> : Kwasniok	
06-388: MEZIC	
<b>06-391</b> : Kossenko	
<b>06-406</b> : Natsiavas	
<b>06-410</b> : Worden	
<b>06-424</b> : Shaw	
06-443: Steindl	
<b>06-468</b> : ING	
06-469: Sinha	
MS 7: SYNCHRONIZATION OF OSCILLATORY SYST	'EMS
07-087: Gposs	123
07-002. UKUSS	
07-004. AU	
07-140. CHAVEZ	
07-203. INTER	
07-262. QUINN	
07-300. JINSA	
07-401. NOLTE	
07-403. DEEO WEN	
MS 8: SYSTEMS WITH TIME DELAY	
<b>08-010</b> : YANCHUK	
<b>U8-U28</b> : NAMACHCHIVAYA	

<b>08-059</b> : FUKUYAMA	
<b>08-080</b> : Ranković	
08-102: Sieber	
<b>08-108</b> : Orosz	
<b>08-109</b> : FAASSEN	
<b>08-171</b> : Pesquera	
<b>08-232</b> : Claussen	
08-237: Schöll	
<b>08-241</b> : Illing	
<b>08-242</b> : Benner	
08-273: Insperger	
<b>08-281</b> : YAPALI	
<b>08-297</b> : Germay	
<b>08-313</b> : YUAN	
<b>08-328</b> : Oguchi	
<b>08-375</b> : Frank	
<b>08-405</b> : Pyragas	
<b>08-430</b> : Bielawski	
MS 9. TIME SERIES AND RECONSTRUCTION	147
	140
09-194: KLEINHANS	
<b>09-224</b> : PARLITZ	
09-250: KWASNIOK	
09-274: SMITH	
<b>09-304</b> : CHELIDZE	
MS 10: CONTROL OF CHAOS	
MS 10: CONTROL OF CHAOS 10-048: Shi	<b>153</b>
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li	
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li	
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz	
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev	
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev 10-160: Alonso	153 155 156 156 156 157 158 158
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev 10-160: Alonso 10-229: Salas	153 155 156 156 156 157 158 158 158 158
MS 10: CONTROL OF CHAOS 10-048: Shi	153         155         156         156         156         157         158         158         159         160
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev 10-160: Alonso 10-229: Salas 10-231: Claussen 10-263: Ahlborn	153         155         156         156         157         158         158         159         160         160
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev 10-160: Alonso 10-29: Salas 10-231: Claussen 10-263: Ahlborn 10-283: Boukabou	153         155         156         156         156         157         158         158         159         160         161
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         159         160         161
MS 10: CONTROL OF CHAOS 10-048: SHI 10-053: LI 10-064: LI 10-074: AWREJCEWICZ 10-139: DZHANOEV 10-160: ALONSO 10-229: SALAS 10-231: CLAUSSEN 10-263: AHLBORN 10-263: BOUKABOU 10-288: DIMITRIU 10-303: DI BERNARDO	153         155         156         156         157         158         158         159         160         161         161
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         159         160         161         162
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         159         160         161         162         163
MS 10: CONTROL OF CHAOS 10-048: Shi 10-053: Li 10-064: Li 10-074: Awrejcewicz 10-139: Dzhanoev 10-160: Alonso 10-229: Salas 10-231: Claussen 10-263: Ahlborn 10-263: Ahlborn 10-288: Dimitriu 10-305: Di Bernardo 10-374: Magnitskii 10-412: Fradkov	153         155         156         156         157         158         158         159         160         161         162         163         164
MS 10: CONTROL OF CHAOS 10-048: SHI 10-053: LI 10-064: LI 10-074: AWREJCEWICZ 10-139: DZHANOEV 10-160: ALONSO 10-229: SALAS 10-229: SALAS 10-231: CLAUSSEN 10-263: AHLBORN 10-283: BOUKABOU 10-288: DIMITRIU 10-303: DI BERNARDO 10-305: DI BERNARDO 10-374: MAGNITSKII 10-412: FRADKOV MS 11: FRACTIONAL DERIVATIVES AND THEIR APPLICATIONICS	153 155 156 156 157 158 158 158 159 160 160 161 161 161 162 162 162 163 164 NS
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         159         160         161         161         162         163         164         NS         167
MS 10: CONTROL OF CHAOS 10-048: SHI 10-053: LI 10-064: LI 10-074: AWREJCEWICZ 10-139: DZHANOEV 10-160: ALONSO 10-229: SALAS 10-231: CLAUSSEN 10-263: AHLBORN 10-263: AHLBORN 10-288: DIMITRIU 10-288: DIMITRIU 10-303: DI BERNARDO 10-305: DI BERNARDO 10-374: MAGNITSKII 10-412: FRADKOV MS 11: FRACTIONAL DERIVATIVES AND THEIR APPLICATIO 11-022: BALEANU 11.041: MACHADO	153         155         156         156         157         158         158         158         159         160         161         162         162         163         164 <b>NS</b> 167         167
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         158         159         160         161         162         162         163         164 <b>NS</b> 167         168         160
MS 10: CONTROL OF CHAOS 10-048: SHI 10-053: LI 10-064: LI 10-074: AWREJCEWICZ 10-139: DZHANOEV 10-160: ALONSO 10-229: SALAS 10-229: SALAS 10-231: CLAUSSEN 10-263: AHLBORN 10-263: AHLBORN 10-288: DIMITRIU 10-288: DIMITRIU 10-303: DI BERNARDO 10-305: DI BERNARDO 10-374: MAGNITSKII 10-412: FRACTIONAL DERIVATIVES AND THEIR APPLICATIO 11-041: MACHADO 11-042: GALHANO 11-042: GALHANO 11.067: SCALAS	153         155         156         156         157         158         158         158         159         160         161         162         162         163         164 <b>NS</b> 167         168         169         160
MS 10: CONTROL OF CHAOS 10-048: SHI 10-053: L1 10-064: L1 10-074: AWREJCEWICZ 10-139: DZHANOEV 10-160: ALONSO 10-229: SALAS 10-231: CLAUSSEN 10-233: BOUKABOU 10-283: BOUKABOU 10-288: DIMITRIU 10-303: DI BERNARDO 10-305: DI BERNARDO 10-305: DI BERNARDO 10-374: MAGNITSKII 10-374: MAGNITSKII 10-412: FRADKOV MS 11: FRACTIONAL DERIVATIVES AND THEIR APPLICATIO 11-041: MACHADO 11-041: MACHADO 11-042: GALHANO 11-067: SCALAS 11 001: OPTICIMUD A	153         155         156         156         157         158         158         158         159         160         161         162         162         162         163         164 <b>NS</b> 167         168         169         170
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         156         157         158         158         159         160         160         161         162         162         163         164 <b>NS</b> 167         168         169         170         171
MS 10: CONTROL OF CHAOS 10-048: SHI	153         155         156         156         157         158         158         158         159         160         161         161         162         163         164 <b>NS</b> 167         168         169         170         171

11-138: Néel	
11-155: Valério	
11-230: VINAGRE	
11-270: Porto	
11-329: NIGMATULLIN	
11-338: SABATIER	
11-354: ZASLAVSKY	
11-363: KREMPL	
11-364: NIGMATULLIN	
11-365: KURODA	
11-393: NÉEL	
11-404: WESTERLUND	
11-417: Kalia	
11-426: MELCHIOR	
11-428: HEDRIH	
11-438: Chatteriee	
11-444· SHIMIZU	182
11-445 <sup>.</sup> Ortigueira	182
11-446 <sup>.</sup> AGRAWAL	183
	105
MS 12: OSCILLATORY MOTION IN HAMILTONIAN SYSTEMS	
<b>12-057</b> : Prants	
12-058: BROER	
12-069: Awrejcewicz	
12-110: NEISHTADT	
12-147: ZUBOVA	
12-200: RINK	
<b>12-216</b> : HALLER	
12-264: ZEVIN	
12-277: ICHTIAROGLOU	
12-311: YAGASAKI	
<b>12-330</b> : Hanßmann	
12-336: Romeo	
<b>12-360</b> : Tuwankotta	
	10.
MS 13: MECHANISMS FOR DIFFUSION IN THE PHASE SPACE	
13-078: Zaslavsky	
13-116: Kedar	
13-190: MARCO	
13-312: YAGASAKI	
13-471: TRESCHEV	
13-472: SAUZIN	
MS 14: COMPUTATIONAL METHODS FOR NON-SMOOTH SYSTEMS	201
$14.065 \cdot AWDERCEWICZ$	202
14-005, AWREJUEWICZ	
17-VOU. I UNI	
14-073, DIUDER	
14-131, AUAKY	
14-133, LAMIMEN	
14-137, DEMENKUV	
<b>14-1 / ð</b> : MIROINEN	

14-255:		
	DUMONT	208
14-256:	DUMONT	209
<b>14-262</b> :	MUTH	210
<b>14-376</b> :	BERNARDIN	210
<b>14-397</b> :	PELLICANO	211
<b>14-409</b> :	WORDEN	212
14-415:	DIMNET	212
<b>14-461</b> :	FOERG	212
MS 15: D	YNAMICAL CONCEPTS IN COMPUTATIONAL MODELING	215
15-032:	Ros	217
15-143:	TANRIÖVER	217
<b>15-287</b> :	HOMBURG	218
15-385:	BELOUETTAR	218
15-425:	SIMÓ	219
15-452:	DOEDEL	219
15-453:	JORBA	219
15-454:	Osinga	220
15-455:	MASDEMONT	220
15-457:	NOORT	221
15-458:	VEEN	221
15-459:	VIEIRO	222
15-460:	VITOLO	223
MS 16• N	UMERICAL BIFURCATION TECHNIOUES	225
16-031:	DOMOKOS	227
4 < 0.0 4		
16-034:	GOVAERTS	228
16-034: 16-097:	GOVAERTS	228 228
16-034: 16-097: 16-100:	GOVAERTS Ishida Schilder	228 228 229
16-034: 16-097: 16-100: 16-140:	GOVAERTS ISHIDA SCHILDER GREEN	228 228 229 230
16-034: 16-097: 16-100: 16-140: 16-141:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON	228 228 229 230 230
16-034: 16-097: 16-100: 16-140: 16-141: 16-142:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON LUST	228 228 229 230 230 231
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS	228 228 229 230 230 231 231
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-180:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS VIOQUE	228 228 229 230 230 231 231 232
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-199:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS VIOQUE KEVREKIDIS	228 229 230 230 231 231 232 232
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-199: 16-209:	GOVAERTS ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS VIOQUE KEVREKIDIS	228 228 229 230 231 231 232 232 232 233
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-180: 16-189: 16-209: 16-235:	GOVAERTS	228 229 230 230 231 231 232 232 232 233
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-199: 16-209: 16-235: 16-245:	GOVAERTS ISHIDA	228 229 230 230 231 231 232 232 233 233 233
16-034: 16-097: 16-100: 16-140: 16-141: 16-141: 16-161: 16-161: 16-180: 16-199: 16-209: 16-235: 16-245: 16-284:	GOVAERTS ISHIDA Schilder Green Henderson Lust Phipps Vioque Kevrekidis Wang Osinga. Samaey Rowley	228 228 229 230 230 231 231 232 232 233 233 233 234 235
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-209: 16-235: 16-235: 16-245: 16-284: 16-308:	GOVAERTS	228 229 230 231 231 232 232 233 233 233 233 234 235 236
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-209: 16-235: 16-245: 16-245: 16-284: 16-308: 16-314:	GOVAERTS	228 229 230 231 231 232 232 233 233 233 234 235 236 237
16-034: 16-097: 16-100: 16-140: 16-141: 16-141: 16-161: 16-161: 16-180: 16-209: 16-209: 16-235: 16-245: 16-284: 16-308: 16-314: 16-377:	GOVAERTS	228 229 230 231 231 232 232 233 233 233 234 235 236 237 237
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-142: 16-161: 16-180: 16-199: 16-209: 16-235: 16-245: 16-245: 16-284: 16-308: 16-314: 16-377: 16-382:	GOVAERTS	228 229 230 231 231 232 232 233 233 233 233 234 235 236 237 237 237
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-209: 16-209: 16-235: 16-245: 16-284: 16-308: 16-314: 16-377: 16-382: 16-399:	GOVAERTS. ISHIDA SCHILDER GREEN HENDERSON LUST. PHIPPS VIOQUE KEVREKIDIS WANG OSINGA. SAMAEY ROWLEY VLADIMIRSKY JORBA. VANDERBAUWHEDE PICK BEYN	228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 238
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-209: 16-209: 16-235: 16-245: 16-284: 16-308: 16-314: 16-377: 16-382: 16-399: MS 17: E	GOVAERTS	228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 237 238 <b>239</b>
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-142: 16-161: 16-180: 16-199: 16-209: 16-235: 16-245: 16-245: 16-245: 16-308: 16-314: 16-377: 16-382: 16-382: 16-399: MS 17: E 17-014:	GOVAERTS	228 228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 237 237 237 237 237 237 237
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-199: 16-209: 16-235: 16-245: 16-245: 16-245: 16-245: 16-308: 16-314: 16-377: 16-382: 16-399: MS 17: E 17-014: 17-025:	GOVAERTS. ISHIDA SCHILDER GREEN HENDERSON LUST UUST VIOQUE KEVREKIDIS WANG OSINGA SAMAEY ROWLEY VLADIMIRSKY JORBA VANDERBAUWHEDE PICK BEYN XPERIMENTS IN NONLINEAR DYNAMIC SYSTEMS ABDO. VAKAKIS	228 228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 237 238 <b>239</b> 241 241
16-034: 16-097: 16-100: 16-140: 16-141: 16-142: 16-161: 16-161: 16-180: 16-209: 16-209: 16-235: 16-245: 16-284: 16-308: 16-314: 16-377: 16-382: 16-399: MS 17: E 17-014: 17-025: 17-027:	GOVAERTS. ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS VIOQUE KEVREKIDIS WANG OSINGA SAMAEY ROWLEY VLADIMIRSKY JORBA VANDERBAUWHEDE PICK BEYN XPERIMENTS IN NONLINEAR DYNAMIC SYSTEMS ABDO. VAKAKIS HEERTJES	228 228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 237 237 237 237 237 237 237
16-034: 16-097: 16-100: 16-140: 16-141: 16-141: 16-142: 16-161: 16-180: 16-209: 16-209: 16-209: 16-235: 16-245: 16-284: 16-308: 16-314: 16-377: 16-382: 16-382: 16-399: MS 17: E 17-014: 17-025: 17-027: 17-026:	GOVAERTS. ISHIDA SCHILDER GREEN HENDERSON LUST PHIPPS VIOQUE KEVREKIDIS WANG OSINGA. SAMAEY ROWLEY VLADIMIRSKY JORBA. VANDERBAUWHEDE PICK BEYN XPERIMENTS IN NONLINEAR DYNAMIC SYSTEMS ABDO. VAKAKIS HEERTJES MACHETE	228 228 229 230 231 231 232 232 233 233 234 235 236 237 237 237 237 237 237 237 237 237 237

1/-000	: AWREJCEWICZ	245
17-095	: Pulngern	246
17-114	: Khayari	246
17-119	: Green	247
17-124	: YABUNO	247
17-145	Bender	248
17-156	: BALACHANDRAN	249
17-162	: Sartorelli	249
17-163	: Mann	250
17-193	: Pernot	251
17-202	: Nulj	251
17-215	: Mihajlović	252
17-221	: VAROTO	253
17-249	: VAROTO	254
17-261	: Ikeda	254
17-285	: TJAHJOWIDODO	255
17-292		256
17-351	: MAILYBAEV	257
17-352	Kuroda	257
17-367	: Welge-Lüssen	258
17-395	SPINOLA	259
17-396	: PELLICANO	260
17-408	: Worden	261
17-441	: Lacarbonara	261
17-448	: Ishida	262
NG 40 T		
MS 18: L	ASER DYNAMICS	263
MS 18: L 18-045	ASER DYNAMICS	263
MS 18: L 18-045 18-107	ASER DYNAMICS : Hek : Zhang	263 265 265
MS 18: 1 18-045 18-107 18-132	ASER DYNAMICS : Hek : Zhang · Mirasso	263 265 265 266
MS 18: L 18-045 18-107 18-132 18-148	ASER DYNAMICS : Hek : Zhang : Mirasso : García-Olal vo	263 265 265 266 266
MS 18: 1 18-045 18-107 18-132 18-148 18-167	ASER DYNAMICS : Hek : Zhang : Mirasso : García-Ojalvo : Sciamanna	263 265 265 266 266 267
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169	ASER DYNAMICS : Hek : Zhang : Mirasso : García-Ojalvo : Sciamanna : Erzgräber	263 265 265 266 266 266 267 268
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170	ASER DYNAMICS : Hek : Zhang : Mirasso : Mirasso : García-Ojalvo : Sciamanna : Erzgräber : Pesouera	263 265 265 266 266 266 267 268 269
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183	ASER DYNAMICS : Hek : Zhang : Mirasso : Mirasso : García-Ojalvo : Sciamanna : Erzgräber : Pesquera : Pesquera : Krauskopf	263 265 265 266 266 266 267 268 269 269
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197	ASER DYNAMICS : Hek : Zhang : Mirasso : Mirasso : García-Ojalvo : Sciamanna : Erzgräber : Pesquera : Pesquera : Krauskopf	263 265 265 266 266 266 267 268 269 269 269
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265	ASER DYNAMICS : Hek : Zhang : Zhang : Mirasso : García-Ojalvo : García-Ojalvo : Sciamanna : Erzgräber : Pesquera : Pesquera : Krauskopf : Lefranc : Wol frum	263 265 265 266 266 267 268 269 269 269 270 271
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269	ASER DYNAMICS	263 265 265 266 266 267 268 269 269 269 270 271 271
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-286	ASER DYNAMICS	263 265 265 266 266 267 268 269 269 269 270 271 271 271
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-286 18-349	ASER DYNAMICS Hek	263 265 265 266 266 267 268 269 269 270 271 271 271 272 273
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-265 18-269 18-286 18-349 18-427	ASER DYNAMICS Hek	263 265 265 266 266 267 268 269 269 269 270 271 271 271 272 273 274
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-269 18-286 18-349 18-427 18-429	ASER DYNAMICS Hek	263 265 265 266 266 267 268 269 269 270 271 271 271 272 273 274 274
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-269 18-269 18-286 18-349 18-427 18-429 18-431	ASER DYNAMICS Hek	263 265 265 266 266 267 268 269 269 270 271 271 271 272 273 274 274 275
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-265 18-269 18-286 18-349 18-427 18-429 18-431 18-447	ASER DYNAMICS Hek Zhang Mirasso García-Ojalvo Sciamanna Erzgräber Pesquera Krauskopf Lefranc Volfrum Peil Ackemann Erzgräber Peil Sciamanna	263 265 265 266 266 267 268 269 269 270 271 271 271 272 273 274 274 275 275
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-269 18-286 18-349 18-427 18-429 18-431 18-447 18-466	ASER DYNAMICS HEK ZHANG MIRASSO GARCÍA-OJALVO SCIAMANNA ERZGRÄBER PESQUERA KRAUSKOPF LEFRANC WOLFRUM PEIL ACKEMANN LIPPI BESNARD. FISCHER BARDELLA MANDEL	263 265 265 266 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-169 18-170 18-183 18-197 18-265 18-269 18-269 18-269 18-286 18-349 18-427 18-429 18-429 18-431 18-447 18-466 MS 19: N	ASER DYNAMICS Hek	263 265 265 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276 <b>279</b>
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-169 18-170 18-183 18-197 18-265 18-269 18-286 18-349 18-427 18-429 18-421 18-427 18-429 18-431 18-447 18-466 MS 19: N	ASER DYNAMICS Hek. Zhang Mirasso García-Ojalvo Sciamanna Erzgräßer Pesquera Krauskopf Lefranc Volfrum Peil Ackemann Lippi Besnard Lippi Besnard Fischer Bardella Mandel Yousefi Micro- AND NANO- ELECTRO-MECHANICAL SYSTEMS	263 265 265 266 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276 279
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-170 18-183 18-197 18-265 18-269 18-286 18-349 18-427 18-429 18-429 18-431 18-447 18-466 MS 19: N 19-015 10-101	ASER DYNAMICS. Hek Zhang Mirasso García-Ojalvo Sciamanna Erzgräber Pesquera Krauskopf Lefranc Volfrum Peil Ackemann Lippi Besnard Fischer Bardella Mandel Yousefi Micro- AND NANO- ELECTRO-MECHANICAL SYSTEMS.	263 265 265 266 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276 279 281 282
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-169 18-170 18-183 18-197 18-265 18-269 18-429 18-429 18-431 18-447 18-466 MS 19: N 19-015 19-101 10-220	ASER DYNAMICS. HEK. ZHANG MIRASSO GARCÍA-OJALVO SCIAMANNA ERZGRÄBER PESQUERA KRAUSKOPF. LEFRANC VOLFRUM PEIL ACKEMANN LIPPI BESNARD. FISCHER. BARDELLA MANDEL YOUSEFI MCRO- AND NANO- ELECTRO-MECHANICAL SYSTEMS. DANKOWICZ	263 265 265 266 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276 279 281 282 282
MS 18: 1 18-045 18-107 18-132 18-148 18-167 18-169 18-169 18-170 18-183 18-197 18-265 18-265 18-269 18-286 18-349 18-427 18-429 18-429 18-431 18-447 18-466 MS 19: N 19-015 19-101 19-239 10.240	ASER DYNAMICS	263 265 265 266 266 267 268 269 269 270 271 271 272 273 274 274 275 275 276 279 281 282 283

<b>19-293</b> : Krylov	
<b>19-307</b> : Yagasaki	
<b>19-318</b> : Вајај	
<b>19-346</b> : Lenci	
<b>19-400</b> : Faris	
<b>19-402</b> : WANG	
<b>19-423</b> : Shaw	
<b>19-464</b> : Gottlieb	
MS 20: NONLINEAR DYNAMICS AND CONTROL OF VEHICLE SYSTEMS	5 291
<b>20-036</b> : Polach	
<b>20-123</b> : YABUNO	
<b>20-144</b> : NEUBAUER	
<b>20-150</b> : Sharp	
<b>20-254</b> : Coleman	
<b>20-316</b> : Von Stryk	
<b>20-386</b> : NATSIAVAS	
20-420: Ambrósio	
MS 21: ASYMPTOTIC METHODS IN NONLINEAR DYNAMICS	299
<b>21-024</b> : Vakakis	
<b>21-037</b> : Mikhlin	
21-039: VERHULST	
21-047: MIKHLIN	
<b>21-070</b> : MANEVITCH	
21-075: Awrejcewicz	
<b>21-079</b> : Warminski	
21-085: MANEVICH	
<b>21-092</b> : MARINOVA	
<b>21-105</b> : Zeidis	
<b>21-166</b> : Gendelman	
21-174: Gendelman	
<b>21-179</b> : Bakri	
<b>21-189</b> : Valkhoff	
<b>21-212</b> : MUSIENKO	
21-214: SCHANZ	
<b>21-220</b> : WERONKO	
21-243: Kireenkov	
<b>21-268</b> : Andrianov	
<b>21-300</b> : DI BERNARDO	
21-327: KNOBLOCH	
<b>21-358</b> : VAN HORSSEN	
<b>21-389</b> : Hijmissen	
<b>21-411</b> : LEONOV	
<b>21-413</b> : FRADKOV	
<b>21-439</b> : Hedrih	
MS 22: NONLINEAR DYNAMICS OF DISTRIBUTED-PARAMETER SYSTE	ZMS 319
<b>22-002</b> : Kirillov	
<b>22-026</b> : VAKAKIS	
<b>22-044</b> : Ribeiro	

22-120: MALLON	
<b>22-128</b> : Fey	
22-195: Awrejcewicz	
22-244: Theodossiades	
<b>22-252</b> : Namachchivaya	
22-259: Lentzen	
<b>22-271</b> : Ecker	
22-299: Virgin	
22-310: LACARBONARA	
22-322: GEORGIOU	
22-324: Вајај	
22-331: PAVLOV	
<b>22-366</b> : Chirikov	
<b>22-378</b> : Manoach	
22-432: DI EGIDIO	
<b>22-467</b> : Karagiozis	
MS 23: MISCELLANEOUS	<b>337</b> 339 339 340 341
MS 23: MISCELLANEOUS	337 339 339 339 340 341 341
MS 23: MISCELLANEOUS	<b>337</b> 339 339 340 341 341 342
MS 23: MISCELLANEOUS	337 339 339 339 340 341 341 342 343
MS 23: MISCELLANEOUS	337 339 339 339 340 341 341 341 342 343 343
MS 23: MISCELLANEOUS	337 339 339 340 341 341 341 342 343 343 343 343
MS 23: MISCELLANEOUS	337 339 339 340 341 341 341 342 343 343 343 344 345
MS 23: MISCELLANEOUS	337 339 339 339 340 341 341 341 342 343 343 343 343 343 345 345
MS 23: MISCELLANEOUS	337 339 339 340 341 341 341 342 343 343 343 343 343 344 345 345 346
MS 23: MISCELLANEOUS	337 339 339 339 340 341 341 341 342 343 343 343 343 344 345 345 346 347
MS 23: MISCELLANEOUS	337 339 339 340 341 341 341 342 343 343 343 343 343 344 345 345 345 345

# **MINI-SYMPOSIA ORGANIZERS INDEX**

Abarbanel, Henry: MS 09: p.145 Agrawal, Om Prakesh: MS 11: p.163 Alleyne, Andrew: MS 20: p.289 Andrianov, Igor: MS 21: p.297 Awrejcewicz, Jan: MS 21: p.297 Balachandran, Balakumar: MS 22: p.317 Bestle, Dieter: MS 05: p.87 Breakspear, Michael: MS 07: p.119 Broer, Henk: MS 15: p.213 Brogliato, Bernard: MS 01: p.21 Chen ,Ron: MS 10: p.151 de la Llave, Rafael: MS 13: p.193 di Bernardo, Mario: MS 01: p.21 Doedel, Eusebius: MS 16: p.223 Eberhard, Peter: MS 03: p.57 Erneux, Thomas: MS 18: p.261 Fradkov, Alexander: MS 10: p.151 Glocker, Christoph: MS 02: p.43 Gottlieb, Oded: MS 19: p.277 Krauskopf, Bernd: MS 16: p.223 Lacarbonara, Walter: MS 17: p.237 Lamarque, Claude: MS 14: p.199 Leine, Remco: MS 14: p.199 Lenstra, Daan: MS 18: p.261

Lugner, Peter: MS 20: p.289 Machado, Tenreiro: MS 11: p.163 Manevitch, Leonid: MS 21: p.297 Maute, Kurt: MS 05: p.87 McPhee, John: MS 03: p.57 Namachchivaya, Sri: MS 04: p.71 Natsiavas, Sotirios: MS 22: p.317 Neishtadt, Anatoly: MS 12: p.183 Pyragas, Kestutis: MS 08: p.129 Sabatier, Jocelyn: MS 11: p.163 Shaw, Steve: MS 19: p.277 Simó, Carles: MS 15: p.213 Takens, Floris: MS 09: p.145 Treschev, Dmitry: MS 13: p.193 Troger, Hans: MS 06: p.97 Vakakis, Alexander: MS 06: p.97 van Campen, Dick: MS 23: p.335 van de Wouw, Nathan: MS 17: p.237 van Leeuwen, Cees: MS 07: p.119 Verduyn-Lunel, Sjoerd: MS 08: p.129 Verhulst, Ferdinand: MS 12: p.183 Vestroni, Fabrizio: MS 22: p.317 Wedig, Walter: MS 04: p.71 Yabuno, Hiroshi: MS 17: p.237

# **OPENING- AND KEYNOTE LECTURES**

# ENOC-2005 OPENING LECTURE: NINETY PLUS THIRTY YEARS OF NONLINEAR DYNAMICS: MORE IS DIFFERENT AND LESS IS MORE

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In the early 1970's dynamical systems theory was just reapproaching earth after a 70-year sojourn in the stratosphere of pure mathematics. Catastrophe theory was hot (if controversial), complexity was yet to come, and some prominent mechanicians and applied mathematicians told me that chaos didn't exist, or would be irrelevant if it did.

I will review some of the successes and failures of nonlinear dynamics since that time, traveling back to check its origins in the work of Poincaré, and forward to current frontiers involving infinite-dimensional evolution equations, hybrid and piecewise-smooth systems, and stochastic models. These will illustrate the first subtitle, drawn from an article by Philip Anderson (Science 177: 393, 1972). I will also emphasize the central ideas of dimension reduction via invariant manifolds, normal forms, and the role of simple canonical examples such as Smale's horseshoe, thus justifying the second subtitle (due to Mies van der Rohe). I will close by speculating on some future directions, and, in doing so, probably repeat the lack of foresight to which I alluded at the beginning.

ID of Contribution: 00 - KN1

# A NONLINEAR UNIFIED STATE-SPACE MODEL FOR SHIP MANEUVRING AND CONTROL IN SEAWAY

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This keynote lecture starts with the invention of the North-seeking gyroscope in 1908 by H. Anschutz, the ballistic gyroscope in 1911 by E. Sperry, and the analysis of the three-term PID-controller (Minorsky 1922). These developments were fundamental for the evolution of nonlinear ship control systems for station-keeping and maneuvering. More recently, the development of global satellite navigation systems and inertial measurements technology have further contributed to the design of highly sophisticated nonlinear ship control systems. From a historical point of view, the PID-controller was the dominating design technique until the invention of the Kalman filter in 1960. Kalman was instrumental in the development of the linear quadratic optimal controller (LQG) which is an attractive design technique in ship control. In 1976, J. G. Balchen proposed to model the wave-induced disturbances as 2nd-order oscillators in the Kalman estimator in order to filter out 1st-order wave-induced disturbances from the feedback loop. This technique is today known as wave filtering and it replaced the notch filter in dynamic positioning systems and autopilots. The concept of wave filtering has further been refined by using linear H-infinity controllers with frequency dependent weighting. This allows the designer to put penalties on the wave-induced disturbances in a limited frequency range. Nonlinear ship control systems became popular in the 1990s using Lyapunov methods for stability analyses (Fossen, 1994, 2002). This presentation will focus on these methods.

The kinematic and dynamic equations of motion for ships are presented in a historical setting starting with linear theory using state-of-the-art transfer function representations. The final model is a 6 DOF nonlinear model written in a compact matrix-vector setting exploiting structural properties like symmetry, skew-symmetry, positive definiteness, passivity etc.

The nonlinear equations of motion are used as basis for development of 3 DOF (surge, sway and yaw) nonlinear dynamic positioning systems for station-keeping and low-speed maneuvering of ships. Also weathervaning capabilities are demonstrated using adaptive design techniques. The main tool for doing this is Lyapunov methods including feedback linearization, backstepping and nonlinear PID-control. Experimental results using model ships are also reported.

More recently nonlinear trajectory tracking and maneuvering control theory have been developed and applied to ship control. Together with global positioning systems and inertial measurement systems these methods provides a tool for the design of nonlinear controllers for high-speed maneuvering exploiting the physical properties of the nonlinear maneuvering equations of motion. In addition, maneuvering control theory has been extended to formation control and synchronization of a fleet of ships. Experimental results are presented using scale models of ships in a model basin.

#### ID of Contribution: 00 - KN2

# LONG TERM EVOLUTION OF THE TERRESTRIAL PLANETS SPIN AXIS

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In a first order approximation, the planetary spin axis precess uniformly, with a constant obliquity (angle between the equator and orbital plane), under the torque exerted by the Sun (or the Moon) on its equatorial bulge.

In fact, the long term evolution of the spin axis of the planets strongly depends also on the gravitational perturbations from all the planets of the Solar System that create a large chaotic zone for their obliquity. Over the age of the Solar System, it is also necessary to take into account various dissipative effects that are usually not very well known (body and atmospheric tides, core-mantle friction), and that can change in a large amount the spin rate and orientation of the planet. In this talk, I will review the recent studies of the spin evolution of all Terrestrial planets (Mercury, Venus, Earth, and Mars), aimed to better understand their spin evolution over the age of the Solar System and to answer for to the following questions:

- Why is Mercury trapped into a 3/2 spin orbit resonance ?
- Why Venus is rotating in a retrograde way ?
- Is it possible that the Earth was tilted at more than 54 degrees 630 Myrs ago, in order to explain the observed equatorial glaciations of the Neoproterozoic ?
- The obliquity of Mars is chaotic, but can we still make predictions on its past obliquity ?

ID of Contribution: 00 – KN3

## GEOMETRY OF VIBRATION STABILIZATION AND SOME APPLICATIONS

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The gyroscope is the best known device that "defies gravity". I will briefly review some other less well known but no less fascinating phenomena, such as acoustic levitation, the Penning and the Paul traps - the devices used to suspend charged particles, the "levitron" - a magnetic top capable of hovering stably in the air above a permanent magnet, the upside-down pendulum (simple or multiple) stable due to vibration of its suspension.

I will then focus on one recently discovered geometro-mechanical connection which explains some of these phenomena; the explanation applies to the Paul trap, as well as to the multiple pendulum with vibrating suspension. To be more specific, it was recently observed that if periodic forcing is applied to a holonomic mechanical system, the latter starts to behave non-holonomically in the limit of high frequency forcing -- this is despite the fact that the system is actually holonomic. In a certain sense, the singular limit of a holonomic system is non-holonomic.

We thus discover a hidden constraint whose curvature enters averaged equations. This observation, first made for the pendulum with vibrating suspension, opens interesting connections with differential geometry. As an example, the multiple pendulum with the vibrating pivot leads to the problem of the geodesic flow on the oscillating (embedded) surface. The effective motion has to do with the curvature of the family of curves normal to the surface. Thus the averaged equations acquire a transparent geometrical meaning.

The appearance of a non-holonomic system leads us to expect the appearance of the geometric phase; we will show some examples where holonomy manifests itself, such as the motion of dust particles in acoustic waves and the propulsion of particles by the "Feynman ratchet".

ID of Contribution: 00 - KN4

# WAVE ATTRACTORS: LINEAR YET NONLINEAR

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The ocean is vertically stratified in density, due to a stratification of both its temperature as well as its salt contents. The coldest and saltiest water masses can be found near the bottom. At the surface, the water is heated by solar radiation, and is dilluted by rain, river outflow and ice melt, leading in general to warmer and less salty ('fresh') water masses. As a result, density profiles often exhibit a sharp jump (pycnocline) below the approximately 100 m thick surface mixed layer. Such interfaces support gravity waves, which are similar to those at the surface except for a reduction in scale and wave speed which are proportional to the relative density increment.

Below the pycnocline the density increases steadily, and a theoretical idealisation thereof assumes a constant rate of change, resulting in an everywhere constant gravitational restoring force (expressed in a constant stability frequency). The internal gravity waves that are supported by this continuous stratification, however, are quite different from their surface and interfacial counterparts (and also from e.g. acoustic waves). For almost all 2D container shapes, regardless the location of their source, these waves are focused onto a limit cycle, a so called 'wave attractor'. The self-similar, fractal patterns of both the wave's streamfunction field in physical space, as well as that of the attractor location in parameter space, represent features often associated with those from nonlinear dynamical systems. Nevertheless, these waves (energy perpendicular to phase propagation), which leads to monoclinic (fixed angle with respect to gravity) rather than specular (Snellian) reflection from a sloping wall. Mathematically, the reason lies in the hyperbolic nature of the partial differential equation describing the spatial structure of these waves. Solutions are constructed by means of characteristics, whose reflection points cast even the inviscid problem as a dissipative, nonlinear map of the boundary onto itself.

Interestingly, another dominant factor in ocean dynamics, the rotation of the earth, provides a second restoring mechanism, the Coriolis force, that leads to the same kind of transverse waves. Experiments in both stratified, non-rotating, as well as homogeneous, rotating fluids support the notion that wave attractors exist. This carries the suggestion that this might be relevant to the dynamics of ocean waves, where stratification and rotation usually occur together. One indication in favour of this interpretation is formed by the ubiquitous presence of a spectral peak at the so-called inertial frequency, which can be viewed as a manifestation of such a wave attractor.

These phenomena may also be relevant to magnetohydrodynamic (electron-cyclotron) waves, owing to an analogy of the Lorentz and Coriolis forces. 3D extensions and a complementarity to waves found in the case of quantumchaos will be discussed.

ID of Contribution: 00 - KN5

# DELAY, PARAMETRIC EXCITATION AND THE NONLINEAR DYNAMICS OF CUTTING PROCESSES

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It is a rule of thumb that time delay tends to destabilize any dynamical system. This is not true, however, in case of delayed oscillators, which serve as mechanical models for lots of surprising physical phenomena. Parametric excitation of oscillatory systems also leads to stability properties sometimes opposite to our physical sense. The combination of the two effects is a challenging task to predict nonlinear dynamic behaviour in these systems.

Machine tool vibrations have negative effects on the quality of machined surfaces. One of the most important causes of undesired vibrations in the cutting process is the so-called regenerative effect. Its physical basis is a time delay that arises naturally in the cutting process, where the delay is inversely proportional to the cutting speed. Referring to the infinite dimensional nature of the dynamics of cutting subjected to regenerative effect, its nonlinear vibrations are often compared to the problem of turbulence in fluid mechanics.

In case of turning, the linear stability analysis of stationary cutting provides complicated, sometimes fractal-like stability charts in the space of the technological parameters (cutting speed, depth of cut and feed rate). Some experiments predicted the existence of unstable periodic motions around the stable stationary cutting already in the early 80's, but the corresponding subcritical co- dimension 1 and 2 Hopf bifurcations in turning processes have been proven analytically only recently. The description of the global dynamics of the cutting process 'outside' the unstable limit cycles or unstable tori requires the analysis of the so-called self- interrupted cutting, when the time-intervals of the no-contacts between the tool and the workpiece are regulated by the system itself.

Milling is a kind of cutting where loss of contact between the teeth of the tool and the work-piece occurs typically in a periodic way. This leads to non-autonomous governing equations similar to the damped, delayed Mathieu equation. The parametric excitation in the delay-differential equation yields secondary Hopf (or Neimark- Sacker) bifurcations, and also period doubling (or flip) bifurcations, when the cutting speed is high enough. Low number of milling teeth and high speed together may often result highly interrupted cutting, when the Poincaré mapping of the governing equation can be constructed in approximate closed form. The subcritical nature of both bifurcations are shown, and the development of chaotic oscillations is also explained. The global nonlinear dynamics of turning and high-speed milling are compared as self-interrupted and parametrically interrupted cutting processes. The results show how nonlinear dynamics can contribute to the increase of efficiency in material processing.

ID of Contribution: 00 - KN6

# SLOW HIGH-FREQUENCY EFFECTS IN MECHANICS: PROBLEMS, SOLUTIONS, POTENTIALS

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What happens with mechanical systems exposed to high frequency excitation (HFE)? Vibration researchers and practitioners are typically trained to neglect possible HF components of excitations. This makes sense, since mechanical systems usually have strong low-pass filtering properties. But many knows what can happen when vibrating the support of a simple pendulum vertically at a frequency much higher than the fundamental natural frequency, even at small amplitude: The pendulum stabilizes in its upside-down position. This is a classical example of a 'slow' (in the sense 'average') effect of HFE. Other examples include changing dry friction into apparent viscous damping; transportation of mass (e.g. solid bodies, granular material, or fluids); and apparent changes in system properties such as stiffness, natural frequencies, equilibrium(s) and equilibrium stability, and various nonlinear characteristics. Thus, even a small-amplitude zero-mean symmetric HFE may feed off significant asymmetric effects having non-zero mean.

The presentation describes recent and current research in this general area, mentioning several studies of specific systems, and convenient techniques for analyzing them. Analytical, numerical, and experimental results are presented, along with results derived for quite general classes of lumped or distributed parameter mechanical systems. Three general effects of mechanical HFE are described: *Stiffening*, an apparent change in the stiffness associated with an equilibrium; *Biasing*, a tendency for a system to move towards a particular state which does not exist or is unstable without HFE; and *Smoothening*, a tendency for discontinuities to be apparently smeared out by HFE.

Topics under current investigation will be described, including the possible (mis)behaviors of feedback-controlled mechanical systems under HFE; analytical methods for predicting average movements of rigid objects on the surface of vibrating structures with consideration to impacts and friction; possible uses of HFE to position and orientate rigid objects; and the average dynamics of self-excited impact oscillators.

The HFE effects of concern may seem interesting, strange, useful, disturbing, dangerous, or disastrous, dependent on the circumstances. In many cases they are very small or unimportant. But to judge one needs to know about their existence and be able to analyze them. The results summarized in the presentation, though primarily scientific, may be useful also for certain technical applications, e.g., vibration damping and control, vibration-induced transportation and

positioning, structures with actively controlled properties (stiffness, stability, friction, modal), and general technical analysis and trouble shooting where HFE is at play.

# **MINI-SYMPOSIUM 1**

# Dynamics and Bifurcations of Non-Smooth Systems

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25

# STABILITY PROPERTIES OF EQUILIBRIUM SETS OF CONTROLLED LINEAR MECHANICAL SYSTEMS WITH DRY FRICTION

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The presence of dry friction can influence the behaviour and performance of mechanical systems as it can induce several phenomena, such as friction-induced limit-cycling and stiction. Dry friction in mechanical systems is often modelled using set-valued constitutive models, such as the set-valued Coulomb's law. Set-valued friction models have the advantage to properly model stiction, since the friction force is allowed to be non-zero at zero relative velocity. The dynamics of mechanical systems with set-valued friction laws are described by differential inclusions. We confine our study to set-valued friction laws which lead to Filippov-type systems. Filippov systems, describing systems with friction, can exhibit equilibrium sets, which correspond to the stiction behaviour of systems with friction.

The overall dynamics of mechanical systems is largely affected by the stability and attractivity properties of the equilibrium sets. Moreover, the stability and attractivity properties of the equilibrium set can also seriously affect the performance of control systems. Many publications deal with stability and attractivity properties of (sets of) equilibria in differential inclusions. For example, in [1] the attractivity of the equilibrium set of a one-degree-of-freedom friction oscillator with one dry friction element is discussed. Most papers are limited to either one-degree-of-freedom systems or to systems exhibiting only one switching boundary and often only discuss the Lyapunov stability of an equilibrium point in the equilibrium set.

We will provide conditions under which the equilibrium set is attractive for multi-degree-of-freedom mechanical systems with an arbitrary number of Coulomb friction elements using Lyapunov-type stability analysis and a generalisation of LaSalle's invariance principle for non-smooth systems [2]. Moreover, dissipative as well as non-dissipative systems will be considered. The non-dissipative systems that will be studied are linear mechanical systems with a non-positive definite damping matrix with additional dry friction elements. The non-positive-definiteness of the damping matrix of linearised systems can be caused by fluid, aeroelastic, control and gyroscopical forces, which can cause instabilities. It will be demonstrated in this paper that the presence of dry friction in such an unstable linear system can (conditionally) ensure the local attractivity of the equilibrium set of the resulting system with dry friction. Moreover, an estimate of the region of attraction for the equilibrium set will be given. A rigid multibody approach is used for the description of mechanical systems with friction, which allows for a natural physical interpretation of the conditions for attractivity. These conditions are that either the system (without dry friction) is dissipative or if it is not dissipative then the generalised force directions of the Coulomb friction elements should span the generalised force directions in which the linear damping forces are non-dissipative.

The effectiveness of the results is evaluated in MDOF examples by means of numerical simulation.

- [1] Shevitz, D. and Paden, B. Lyapunov stability of nonsmooth systems, IEEE Transactions on Automatic Control 39(9), pp. 1910-1914, 1994.
- [2] van de Wouw, N., Leine, R.I. Attractivity of Equilibrium Sets in Systems with Dry Friction, Nonlinear Dynamics, 35(1). pp. 19-39, 2004.

## ID of Contribution: 01 - 076

# ROBUSTNESS ANALYSIS OF PASSIVITY-BASED CONTROLLERS FOR COMPLEMENTARITY LAGRANGIAN SYSTEMS

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The focus of this paper is robustness analysis of passivity-based tracking controllers for a class of nonsmooth fully actuated Lagrangian systems subject to frictionless unilateral constraints on the position. Such systems may evolve in three different phases of motion:

- i) a free motion phase, where the mechanical system is not subject to any constraints,
- ii) a permanently constrained phase with a non-zero contact force,
- iii) a transition phase whose goal is to stabilize the system on some constraint surface. During this phase impact may occur.

The central issue of such controller is to design trajectories references for the transition phase which guarantees that the system is stabilized on the constraint surface.

A control strategy which consists of attaining the surface tangentially and without incorporating impacts in the stability analysis, cannot work in practice due to its lack of robustness. In view of this, the control law for the transition phase is defined in order:

- To make the system hit the constraint surface (and then dissipate energy during impacts) if the tracking error is not zero.
- To make the system approach the constraint surface tangentially (without rebound) if the tracking is perfect.

These two situations are conflicting, and controllers design for this work show how to cope with it [1]. The two controllers study here are the extension, for the nonsmooth dynamic, of two passivity-based controllers: the Paden-Panja PD+ controller and the Slotine-Li controller.

The robustness of these two hybrid controllers are studied in this paper. Analysis of robustness with respect to uncertainties in the dynamical model parameters give that the two schemes remain stable if the error is up to 30 percent on the mass. Then we analyse the robustness with respect to the uncertainty on the constraint position. Two situations may be considered.

- 1) The estimated position of the constraint is lower than the real position. In this case the closed loop system remains stable.
- 2) The estimated position of the constraint is above the real one. In this case, some configuration lead to the system never reaches the constraint. This situation is solved in this paper by adding an on-line estimation of the constraint position.

And finally robustness with respect to measurement noise is studied. White noise is added to position and velocity measure.

To conclude with robustness analysis, we note that by construction these controllers are robust with respect to the restitution coefficient because this coefficient is not used in the controller design.

Globally the hybrid Slotine-Li scheme is more robust than the hybrid Paden Panja scheme: this is due to the fact that stability conditions are easier to fulfill for Slotine-Li than Paden-Panja scheme, because the Slotine-Li control law is an exponentially stable law. These results are validated on numerical simulations.

## References:

[1] Bourgeot, J.M., Brogliato, B. : Tracking control of complementarity Lagrangian systems. The International Journal of Bifurcation and Chaos. 15(3) (2005)

27

# CONTINUOUS AND DISCONTINUOUS GRAZING BIFURCATIONS IN IMPACT OSCILLATORS

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Dynamical-systems bifurcations characterized by the disappearance of an attractor in the vicinity of an originally attracting motion under parameter variations occur frequently in physical systems and are naturally of concern to engineering-system designers. In smooth dynamical systems, examples of such bifurcations are the saddle-node or cyclic-fold bifurcations as well as subcritical pitchfork, period-doubling, and Hopf bifurcations. In nonsmooth dynamical systems, for example, those resulting from the presence of mechanical impacts, such discontinuous changes in system response have been found to be associated with transitions between nonimpacting and impacting motion, so-called grazing bifurcations. While the 'instability' associated with such loss of a local attractor is relatively weak in the smooth case (cf. the slow dynamics near a ghost solution in the saddle-node case or near the unstable limit cycle following a Neimark-Hopf bifurcation), in the impacting case, the dynamics are typically rapidly repelled from a neighborhood of the grazing motion.

The local dynamics in the vicinity of a grazing trajectory can be analyzed through the introduction of a discontinuity mapping as originally proposed by Nordmark [1]. The discontinuity-mapping approach was used by Fredriksson and Nordmark [2] to establish conditions for the persistence or disappearance of a local attractor in the vicinity of a grazing periodic trajectory in terms of properties of the vector field, impact surface, and impact map in the vicinity of the point of grazing contact. In a recent paper by Dankowicz and Jerrelind [3], these conditions formed the basis for a feedback control algorithm to guarantee the persistence of a local attractor near a grazing periodic trajectory.

The transition in parameter space between discontinuous and continuous grazing bifurcations of periodic trajectories can be traced to critical choices of values for the system parameters corresponding to degenerate, co-dimension-two bifurcation points. As in the case of smooth bifurcations, these degenerate bifurcation points serve as organizing centers for the local co-dimension-one bifurcation scenarios. In particular, normal-form analysis in the vicinity of such co-dimension-two bifurcation points may be employed to unfold the variety of co-dimension-one bifurcations associated with continuous and discontinuous grazing bifurcations.

In this paper, the discontinuity-mapping approach is used to formulate numerical normal-form descriptions near codimension-two grazing bifurcation points in a five-dimensional model of an impact microactuator. The analysis is used to predict the existence of bifurcation curves for the post-grazing impacting dynamics emanating from such codimension-two bifurcation points and to yield numerical approximations of their shape to be used for continuation purposes. Finally, the control strategy introduced by Dankowicz and Jerrelind is employed to break a degeneracy due to the low dimensionality of the actuator model and to establish universal numerical unfoldings valid for arbitrary statespace dimension.

- [1] A.B. Nordmark, "Universal limit mapping in grazing bifurcations," Phys. Rev. E 55(1), pp. 266–270, 1997.
- [2] M.H. Fredriksson, A.B. Nordmark, "Bifurcations caused by grazing incidence in many degrees of freedom impact oscillators", Proc. Roy. Soc. London A 453, pp. 1261–1276, 1997.
- [3] H. Dankowicz, J. Jerrelind, "Control of near-grazing dynamics in impact oscillators," (Submitted), 2004.

## ID of Contribution: 01 - 127

# A LASALLE'S INVARIANCE THEOREM FOR NONSMOOTH LAGRANGIAN DYNAMICAL SYSTEMS

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Originating in the analysis of the non-permanent contact between perfectly rigid bodies, the mathematical analysis of nonsmooth Lagrangian dynamical systems is very recent. It concerns Lagrangian dynamical systems with coordinates constrained to stay inside some closed sets, what leads to introduce mathematical tools which are unusual in control theory, velocities with locally bounded variations, measure accelerations, measure differential inclusions to name a few.

The control theory for such dynamical systems is just beginning to appear, and even the basic Lyapunov stability theory still needs to be stated. Indeed, it is usually presented for dynamical systems with states that vary continuously with time, what is not the case for nonsmooth

Lagrangian dynamical systems. Though we have been able to derive a Lyapunov stability analysis for nonsmooth dynamical systems very similar to what appear in the smooth case [1], the derivation of a theorem equivalent to the LaSalle's invariance theorem is far from being straighforward.

This paper is entirely devoted to the analysis and the developpement of a version of the LaSalle's invariance theorem for nonsmooth dynamical systems based on the framework of functions with bounded variation which leads easily to results that would be harder to obtain in the usual framework of hybrid systems (especially when having to go through accumulations of impacts).

A key condition for the statement of Lasalle's invariance theorem is the continuity of the trajectories of the systems with respect to initial conditions. Nonsmooth Lagrangian dynamical systems generally don't present such a continuity, but they do in many specific cases. So we must try to propose a version of LaSalle's invariance theorem for time-invariant flows that are countinuous with respect to initial conditions.

Note also that in the smooth case, Lasalle's invariance theorem is built on the analysis of the time-variation of a function, what is usually done with the help of its time derivative, but such a derivative may not exist for a flow with state discontinuities. We therefore propose a version of the LaSalle's invariant theorem without the use of time derivatives. Building on this theorem, we are then able to conclude on the attractivity of equilibrium points of nonsmooth Lagrangian dynamical systems and on the asymptotic stability of such points.

References:

[1] S. Chareyron and P.B. Wieber. Stabilization and regulation of nonsmooth Lagrangian systems. Technical report, INRIA Rhone-Alpes, 2004. submitted.

#### ID of Contribution: 01 - 149

## NONLINEAR DYNAMICS OF IDLER GEAR SYSTEMS

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Gear systems are widely used in numerous industries because of their mechanical efficiency and high power density. Gear vibration causes high dynamic loads that reduce the life cycles of mechanical parts and generate noise radiated through the bearings and housing. The primary source of vibration is parametric excitation introduced by the periodically-varying mesh stiffness of mating teeth as the number of tooth pairs in contact at each mesh fluctuates.

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Backlash between mating teeth, necessary for manufacturing tolerances, lubrication and thermal expansion, admits tooth contact loss nonlinearity that has been observed in practice and experiments [1]. This work examines the nonlinear, parametrically excited dynamics of idler gearsets that transmit power from input pinion to output gear via a middle idler gear. This multi-mesh system introduces two parametric excitation sources and two possible tooth separations. The excitations and nonlinearities from the individual meshes interact with each other. Two quantities of particular importance are the mesh phasing between the two periodic mesh stiffnesses and the contact ratios that control the shape of mesh stiffness variation.

This study identifies the periodic steady state solutions of idler gears using analytical and numerical approaches. Asymptotic perturbation analysis yields the solution branches and their stability near primary, secondary, and subharmonic resonances. The ratio of mesh stiffness variation to mean value is the small parameter. The time of tooth separation is assumed to be a small fraction of the mesh period. With these stipulations, the non-smooth separation function that determines contact loss and the variable mesh stiffness are reformulated to a form suitable for perturbation. Perturbation yields closed-form expressions that expose the impact of key parameters on the nonlinear response. The expressions in terms of fundamental design quantities have natural practical application. Despite the use of asymptotic analysis for this strongly nonlinear system, the results compare well to separate harmonic balance/arclength continuation and numerical integration solutions.

Several conclusions are:

- a) The peak amplitudes of the stable resonant solutions and the parameter boundaries for which nonlinear contact loss occurs are determined in terms of the known mesh stiffness, mesh phasing, contact ratio and vibration modes.
- b) The interactions between different meshes can change the dynamics drastically. Appropriate selection of mesh phasing and contact ratios can suppress the amplitudes of selected resonances.
- c) The period-2 subharmonic resonance solution branches show a dual-sided jump phenomenon where the response experiences sudden increase and then sudden decrease with increasing gear speed. This exposes the apparent source of practically observed but previously unexplained gear behavior.
- d) The applied torque changes the amplitude but not the shape of response in the absence of tooth modification, with higher response for higher torque. The nonlinear behavior remains even at high torque. This contradicts conventional wisdom that presumes gear teeth do not lose contact under heavy load.

References:

[1] Kahraman, A. and G.W. Blankenship, Experiments on Nonlinear Dynamic Behavior of an Oscillator with Clearance and Periodically Time-Varying Parameters. Journal of Applied Mechanics, 1997. 64: p. 217-226.

ID of Contribution: 01 - 151

## **MODEL PREDICTIVE CONTROL FOR PERTURBED PIECEWISE AFFINE SYSTEMS**

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In this presentation we give an overview of our recent results on model predictive control (MPC) for a class of nonsmooth hybrid systems subject to perturbations. More specifically, we consider continuous and non-continuous piecewise-affine (PWA) systems, which are characterized by an input/state space that is subdivided in several polyhedral region, in each of which the behavior of the system is described by an affine state space model.

MPC is a model-based, receding-horizon control approach that uses on-line or off-line optimization to determine appropriate control inputs. Several authors have already considered MPC for PWA systems (see, e.g., [1,2]). Furthermore, we have recently developed an MPC approach for continuous PWA systems [3] using the equivalence between continuous PWA systems and max-min-plus-scaling (MMPS) systems, i.e., systems the behavior of which can be described by the operations maximization, minimization, addition and scalar multiplication.

Most results on MPC for PWA systems involve non-perturbed systems. In this presentation we consider perturbed PWA systems with bounded disturbances, i.e., PWA systems whose system equations contain a disturbance term with a bounded support. This disturbance term could represent bounded modeling errors, noise and/or disturbances.

First, we consider perturbed continuous PWA systems (or MMPS systems) with PWA cost criteria. The proposed MPC method for this class of systems is based on minimizing the worst-case cost criterion, i.e. a min-max approach. We show that the resulting MPC optimization problem can be computed efficiently using a two-level optimization approach consisting of an off-line and an on-line step. In the off-line step we have to solve a multi-parametric linear programming problem and to compute a canonical expression of the cost criterion. On-line, we have to solve a set of linear programming problems, for which efficient optimization algorithms exist.

Next, we consider general PWA systems. Here we also use an MPC scheme consisting of an off-line step and an on-line step. In the first step, we compute off-line the set of states that can be steered to a certain convex target set using a semi-feedback controller. This local controller can be computed using linear matrix inequalities (LMIs). The second step consists in solving on-line, at each step a quadratic programming problem. This results in a min-max feedback MPC scheme based on a dual-mode approach that stabilizes the system.

For each class perturbed PWA systems we illustrate the proposed MPC approach with a worked example.

#### References:

- A. Bemporad and M. Morari, 'Control of systems integrating logic, dynamics, and constraints,' Automatica, vol. 35, no. 3, pp. 407-427, Mar. 1999.
- [2] M. Lazar, W.P.M.H. Heemels, S. Weiland, and A. Bemporad, 'Stabilization conditions for MPC of constrained PWA systems,' Proceedings of the 43rd IEEE Conference on Decision and Control, Paradise Island, Bahamas, Dec. 2004.
- [3] B. De Schutter and T.J.J. van den Boom, 'MPC for continuous piecewise-affine systems,' Systems & Control Letters, vol. 52, no. 3-4, pp. 179-192, July 2004.

ID of Contribution: 01 - 152

# OUTPUT REGULATION OF A CLASS OF MECHANICAL SYSTEMS WHICH ARE UNCONTROLLABLE AND UNOBSERVABLE IN ABSENCE OF IMPACTS

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The goal of this paper is the output regulation of a class of complementarity mechanical systems that would be uncontrollable and unobservable in absence of impacts. The systems are of the juggler type [1]: they are constituted by two independent bodies interacting only through impacts. The goal is to bring and maintain in a desired position the unactuated body by keeping bounded the trajectories of the overall system. The considered mechanical systems in absence of impacts would have linear dynamics and the constraints causing the impacts act as opposite impulsive inputs on the unactuated subsystem. It is assumed that the impacts are non-smooth and perfectly elastic and that the zero dynamics of the actuated subsystem is trivial. The main novelty of the paper is the possibility of obtaining the stabilization even if only one position variable of the actuated body is measured: this is achieved by using a dead-beat observer which extends the ones in [2]. The proposed control algorithm is multi-phase and hybrid in the following sense. It is multi-phase since the control interval is divided into a state estimation phase, a control phase and a steadystate phase. During the state estimation phase, by means of the impacts the only available measurement is used to estimate in finite time the whole state of the system. During the control phase, by using a technique similar to the one in [3], the impacts are used to bring the unactuated body in the desired rest position. During the steady-state phase, the unactuated body is maintained in the rest position by the actuated body, which slowly moves around it creating suitable degenerate impacts, which ensure a certain degree of robustness for the regulation task. The controller has the capability of automatically recognizing, based on the state estimate of the system, which is the control phase to apply. For example, if a disturbance temporarily acts on the system when the control is in the steady-state phase, the observer detects it and the controller automatically switches to the state estimation phase.

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The control phase is hybrid in the sense that it is partially discrete-time and partially continuous-time. As a matter of fact, the impacts are used as a discrete-time control input to control the unactuated body and the appropriate intensity of the impact is computed through a discrete-time model. On the other hand, the appropriate impacts are obtained by controlling the actuated body in continuous-time.

A non trivial example will be included in the final paper to illustrate all the interesting features of the proposed control scheme.

References:

- B. Brogliato and A. Zavala-Rio, 2000. On the control of complementary-slackness juggling mechanical systems. Trans. AC, 45(2).
- [2] F. Martinelli, L. Menini, A. Tornambè, 2003. Observability, reconstructability and observer design for linear mechanical systems unobservable in absence of impacts. J. of Mech. Syst., meas., and control (ASME).
- [3] L. Menini and A. Tornambè, 2003. Control of (otherwise) uncontrollable linear mechanical systems through nonsmooth impacts. Syst. & Contr. Lett., 49:311--322.

ID of Contribution: 01 - 154

# SOME ASPECTS OF THE NON-SMOOTH DYNAMICS OF AN IMPACTING INVERTED PENDULUM

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In this work a detailed analysis of the nonlinear dynamics of an impact damper constituted by an inverted pendulum bouncing on lateral walls is performed. Impact dampers are nowadays applied in several field of science and engineering, including mechanical and civil applications, due to their simplicity, reliability and to their other performances, which sometimes are better then those of classical viscous dampers. The main practical characteristics of the considered impact dampers are (i) that it has an activation threshold before starting to dissipate (below which the pendulum rest on the lateral barrier) and (ii) that it has no internal frequencies, so it can work well, at least in principle, on a broad range of frequencies.

The periodic attractors scenario is considered first. It is determined by studying the range of existence of the main stable cycles by the combined use of numerical basins of attraction and bifurcation diagrams. Attention is focused on local and global, classical and non-classical bifurcations that lead to the attractors-basins metamorphoses, and on the role played by invariant manifolds of appropriate saddles.

The attractors chart is discussed and illustrated in detail, and it is shown how in a certain region of the parameters space the multistability of several (up to seven) periodic attractors, of various period, is common, while in other regions only one cycle is observed. This provides a large flexibility in view of practical applications, permitting to choose different regions of behaviour according to required different performances.

Two specific phenomena are observed and considered in detail: the homoclinic bifurcation of the hilltop saddle, triggering cross-well scattered dynamics, and the disappearing of the rest position, through a route involving chattering on the lateral walls. All together, they constitute a threshold above which scattered and robust chaotic dynamics is likely to occur. This matter is investigated numerically, and some attempts are made in order to understand the underlying global bifurcation responsible for the crises causing sudden appearance/disappearance of the chaotic attractors.

The chattering appearing just at the end of the rest position, which is the main characteristic non-smooth phenomena of this class of non-resonant oscillators [1], is then investigated. Indeed, the classical grazing bifurcation, typical of other systems [2, 3], is observed only in some special cases. Some attempts are made in order to estimate the time length of chattering, which also provides information on the disappearing of chattering for increasing values of the excitation amplitude.

References:

- [1] Budd C., Dux F., 1994, "Chattering and related behaviour in impact oscillators," Phil. Trans. R. Soc. London A, 347, 365-389.
- [2] Peterka F., 1996, "Bifurcations and Transition Phenomena in an Impact Oscillator," Chaos, Solitons & Fractals, 7, 1635-1647.
- [3] Nordmark A., 1991, "Non-periodic motion caused by grazing incidence in an impact oscillator," J. Sond Vibr., 145, 279-297.

#### ID of Contribution: 01 - 172

# SMOOTH AND NON-SMOOTH BIFURCATIONS IN A DC-DC BUCK CONVERTER WITH ZAD STRATEGY

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DC-DC buck converters decrease a source voltage. They can be modelled as Variable Structure Systems due a discontinuous control action [1]. The error dynamics time constant appears as a bifurcation parameter. As it varies, a very rich dynamics is observed in the controlled system. From a circuit design viewpoint, it is well worth determining which regions of the parameter space should be avoided. From a mathematical viewpoint, it is interesting to note which kind of bifurcations appear, especially if they are non-smooth and to determine the specific route to chaos [2]. Careful computation with several methods of integration, and analytical piecewise solutions have been used to obtain the bifurcation results.

For T=0.1767, g=0.35, xref=0.8, and ks=4.5, simulations show that the stationary dynamics is an asymptotically stable T-periodic orbit. If we reduce the value of ks, and fix the remaining parameters, then a bifurcation occurs. A standard linear analysis allows the conclusion that the first bifurcation is of flip type because one of the Floquet multipliers of the T-periodic orbit passes through -1. This orbit will bifurcate into a stable 2T-periodic orbit and an unstable T-periodic orbit for ks=3.25 approximately [3].

By reducing ks slightly further the system shows 2T-periodic stable orbits with no saturation cycles. In the state space, as ks is varied, the stable 2T-periodic orbit approaches the switching boundary. And, for a specified parameter value, this discrete-time orbit collides with the boundary in a corner collision bifurcation (or transition). In this bifurcation, the number of equilibrium points does not change but the evolution of the orbits in the state space is different. Thus, another class of 2T-periodic orbits with one saturation cycle and one non-saturated cycle is obtained.

The third bifurcation is of flip type. This can be confirmed by computing the eigenvalues at the periodic orbit. After the bifurcation, the stability of the 2T-periodic orbits is changed and 4T-periodic stable orbits appear. For a certain bifurcation value of ks between 2.5 and 3, a small region in the switching manifold act as accumulation regions of points, and the chaotic period 4 bands appear. This is due to a corner collision bifurcation of the type  $2^n$ -periodic stable orbit - to - chaotic  $2^n$ -band.

In addition to these main bifurcations, several secondary bifurcations have been detected in very narrow ranges of the bifurcation parameter. They generally involve sudden creation and disappearence of different kinds of unstable periodic orbits, with different saturated and non-saturated cycles. They have been carefully continuated and show connections between corner-collision and saddle-node bifurcations.

Summarizing, several smooth and non-smooth bifurcations have been studied with detail in a PWM-controlled buck converter with ZAD strategy. A simplification due to the regulation characteristic of the converter allows some analytical work. Also numerical computations can be made faster. Flip bifurcations and corner collision bifurcations have been clearly detected. For a specific n, the 2<sup>n</sup>-periodic stable orbit bifurcates to a chaotic 2<sup>n</sup>-band. It finally leads to a one-band chaotic attractor after a merging band crises process.

- Study of Chaos in the Buck Converter, E. Fossas, G. Olivar, IEEE Transactions on Circuits and Systems, Part I: Fundamental Theory and Applications, Vol. 43, pp. 13-25, January, 1996.
- [2] Nonlinear Phenomena in Power Electronic Circuits, Verghese and S. Banerjee (editors), IEEE Press, Piscataway, NJ, USA, 2001.
- [3] Transition From Periodicity to Chaos in a PWM-Controlled Buck Converter with ZAD Strategy, F. Angulo, E. Fossas, G. Olivar, International Journal of Bifurcation and Chaos IJBC (accepted).

#### ID of Contribution: 01 - 186

## TORUS BREAKDOWN IN NON-SMOOTH SYSTEMS

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The transition from periodic to chaotic oscillations through torus destruction is a common phenomenon in nonlinear dynamical systems. Before breakdown, the resonance torus typically loses smoothness in discrete points through folding (or winding) of the involved manifolds, and this loss of smoothness then spreads to the entire torus surface through local (e.g., saddle-node) or global (i.e., homoclinic or heteroclinic) bifurcations. The basic theorem for the destruction of a two-dimensional torus in smooth dynamical systems was proved by Afraimovich and Shilnikov [1], and three possible routes for the appearance of chaotic dynamics were described. The generic character of these processes has since been confirmed numerically as well as experimentally for a wide class of both flow and discrete time systems [2].

Stimulated by applications in various fields of applied science and engineering (see, e. g., [3-5]), investigation of nonlinear dynamic phenomena in piecewise-smooth systems has recently attracted considerable interest [6, 7]. The results of a significant number of investigations [3 {8] show that such systems can exhibit a large variety of bifurcational phenomena that differ qualitatively from the transitions we know from smooth dynamical systems. This is connected with the fact that the nonlinear phenomena that one can observe in piecewise-smooth systems arise from an interplay between local and homoclinic bifurcations on one side and different forms of border-collision bifurcations on the other [9]. The transition to chaos through torus destruction in piecewise-smooth systems can also display essential differences from the Afraimovich-Shilnikov scenarios [1].

Considering a three-dimensional map describing the behavior of a DC/DC power converter as an example, in this paper we discuss a new type of border-collision bifurcation that leads to the birth of a 'bilayered torus'. This torus consists of the union of two saddle cycles, their unstable manifolds, and a stable focus cycle. When changing the parameters, the bilayered torus transforms through a border-collision bifurcation into a resonance torus containing the stable cycle and a saddle. We also present scenarios for torus destruction through homoclinic and heteroclinic bifurcations.

- V. S. Afraimovich and L. P. Shilnikov. Invariant two-dimensional tori, their breakdown and stochasticity. Amer. Math. Soc. Transl., 149(2):201 {212, 1991.
- [2] D. G. Aronson, M. A. Chori, G. R. Hall, and R. P. McGhee. Bifurcations from an invariant circle for two-parameter families of maps of the plane: A computer-assisted study. Comm. Math. Phys., 83:303 (354, 1982.
- [3] M. Gallegati, L. Gardini, T. Puu, and I. Sushko. Hicks' trade cycle revisited: Cycles and bifurcations. Math. Comp. Sim., 63:505 [527, 2003.
- [4] G. H. Yuan, S. Banerjee, E. Ott, and J. A. Yorke. Border-collision bifurcations in the buck converter. IEEE Trans. Circ. Syst. I: Fund. Theory and Appl., 45(7):707 {716, 1998.
- [5] Zh. T. Zhusubaliyev and E. Mosekilde. Bifurcations and Chaos in Piecewise-Smooth Dynamical Systems. World Scientific, Singapore, 2003.
- [6] P. Jain and S. Banerjee. Border-collision bifurcations in one-dimensional discontinuous maps. Int. J. Bifurcat. Chaos, 13(11):3341 (3351, 2003.
- [7] Zh. T. Zhusubaliyev, E. A. Soukhoterin, and E. Mosekilde. Quasi-periodicity and border-collision bifurcations in a DC/DC converter with pulsewidth modulation. IEEE Trans. Circ. Syst. I: Fund. Theory and Appl., 50(8): 1047 {1057, 2003.

[8] Zh. T. Zhusubaliyev, E. A. Soukhoterin, and E. Mosekilde. Border-collision bifurcations and chaotic oscillations in a piecewise-smooth dynamical system. Int. J. Bifurcat. Chaos, 11(12):2977 {3001, 2001.

[9] M. I. Feigin. Doubling of the oscillation period with C-bifurcations in piecewise continuous systems. Prikl. Mat. Mekh., 34(5):861 [869, 1970. in Russian.

ID of Contribution: 01 - 196

# SLIDING SOLUTIONS OF A SIMPLE TWO DEGREES-OF-FREEDOM DYNAMICAL SYSTEM WITH FRICTION

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The motivation for this work is the stick-slip motion termed sliding-standard solution as well) that occur in a piece-wise smooth dynamical system represented by a block-on-belt model. The block-on-belt model consists of the mass m attached to inertial space by the spring k. Mass m vibrates on the driving belt that is moving at the little perturbed velocity a. Between the mass and the belt, dry friction occurs with friction force F, which is dependent on the velocity v of mass m and on the variable control parameter b, that have a direct influence on shape of the static friction characteristics. Equations of motion of the considered four degree-of-freedom dynamical system are given in nondimensional form. Mass m and its association with driving belt provide the first two equations of our system. The next two, describing dynamic changes in a and b are introduced to have a little perturbation of the model parameters. Righthand sides of these equations are expressed by functions of displacement x, velocity v, and are multiplied by small perturbation parameters eps i miu, respectively. Analysis of sliding solutions and conditions of their appearance is then based on the form of generic Filippov system. Since a discontinuity boundary is introduced as a function of velocity of the belt, the investigated system can be divided into the two subsystems, which are continuously solved in the regions S1 and S2 separately. The analysis becomes more complicated when a precise sliding solution included in crossing set must be determined. In that case, to get an exact transition between solutions being defined in regions S1 and S2, a kind of numerical method with the exact crossing set detection (including detection of points lying exactly on crossing surface) has been implemented. With the use of this procedure, some special characteristic points like singular sliding points and tangent points (at which standard solution begins) have been determined and illustrated as well.

- [1] Awrejcewicz, J., Andrianov, I. & Manevitch, L.I. (1998) 'Asymptotic Approach in Nonlinear Dynamics: New Trends and Applications', Springer-Verlag, Berlin.
- [2] Awrejcewicz, J., Feckan, M. & Olejnik, P. 'On Continuous Approximation of Discontinuous Systems,' submitted to Nonlinear Analysis.

#### ID of Contribution: 01 - 210

# **APPLIED PERTURBATION THEORY: POWER CONVERTERS REGULATION**

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Switching sources are devices used in the implementation of power converters. As a consequence of the switching action, chattering, high order harmonic distortion and nonlinear phenomena appear. The latter can be dealt with control techniques, while chattering and harmonic distortion, inherent to switching, can be reduced, but not avoided, using fixed switching frequency. To achieve this reduction, some techniques have been reported in the literature: adaptive hysteresis band, signal injection with a selected frequency, zero average current in each iteration (ZACE) and, recently, zero average error dynamics in each iteration (ZAD). ZAD control schemes, recently proposed in [1], conjugates the advantages of fixed frequency implementations and the inherent robustness of sliding control modes. It is based on an appropriate design of the sliding surface that guarantees the fulfilment of the specifications and on a specific design of a duty cycle in such a way that the sliding surface average in each PWM-period is zero. A comparative study of this algorithm with respect to some of the previously reported can be found in [2], while in [3] this ZAD technique was applied to a linear converter showing good numeric and experimental results. However, the fundamentals explaining this behaviour are not yet reported.

The aim of this work is to put these basis in the frame of average theory (perturbation theory in mathematics). To be precise, Zero Average Dynamics - Pulse Width Modulation schemes will be supported, as well as steady-state maximum values for the error and the sliding surface in a sampling period. Results are generalised to single input second order systems of relative degree two.

#### References:

- [1] Fossas E., Grino R., and Biel D. 'Quasi-sliding control based on pulse width modulation, zero average and the L2 norm' in Advances in Variable Structure System, Analysis, Integration and Applications. Edited by Xinghuo Yu and Jian-Xin Xu. Ed. World Scientific. 2001. pp 335-344.
- [2] Biel D. and Fossas E. 'SMC applications in Power Electronics' in Variable Structure Systems: from principles to implementation. Edited by L. Fridman, A. Sabanovic and S. Spurgeon, IEE, 2004
- [3] Ramos R., Biel D., Fossas E. and Guinjoan F. 'A fixed-frequency quasi-sliding control algorithm: Application to power inverters design by means of FPGA implementation' IEEE Transcations on Power Electronics, vol. 18, No. 1, January 2003.

#### ID of Contribution: 01 - 213

# BORDER-COLLISION INDUCED BIFURCATION PHENOMENA AND MULTI-PARAMETRIC BIFURCATIONS IN A PIECEWISE-QUADRATIC MAP ON INTERVAL

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Behavior of piecewise-smooth dynamical systems is influenced by phenomena occurring at the border between partitions in the state space, whereby meanwhile the theory of border collisions in 1D discontinuous map is available (see [2] and references therein). In our work a 1D two-parametric map with a piecewise-smooth system function is investigated. In [1] it is shown, that this system represents a special kind of Poincare return map of the Lorenz system. It

is also shown in [3], that the investigated system shows the border collision period doubling scenario, formed by an infinite sequence of pairs of bifurcations. Each pair consists of a border collision bifurcation and a pitchfork bifurcation.

The aim of the current work is to explain the structure of the 2D parameter space of the investigated system. It is shown, that the behavior of the investigated system is determined by the interaction of local and global bifurcations. On the one hand, we detect an infinite number of cusp catastrophes, leading to saddle-node bifurcations. On the other hand, the behavior is strongly influenced by border-collision bifurcations.

The most important result of the presented work is a description of some singularities in the 2D parameter space, which we denote as big bang bifurcations. The characteristic property of these bifurcations is, that in an arbitrary small open neighborhood of the bifurcation point an infinite number of different periodic attractors exist. The periods of these attractors can be explained by an infinite adding scheme, related to the Farey-trees, applied in the space of symbolic sequences.

For all limit cycles, emerging at the big bang bifurcation point, the areas of stability are detected. All these areas have similar characteristic shapes, consisting of a main body and two longish bands, and are confined by the curves of bordercollision and saddle-node bifurcations. Within these areas at most three limit cycles with the same periods exist, caused by cusp catastrophes.

It turned out, that the intersection point of two border-collision bifurcation curves represents a point of a big bang bifurcation. Because at each point of a big bang bifurcation an infinite number of border-collision bifurcation curves begin, which intersect each other pairwise, we state, that a single big bang bifurcation causes in the investigated system an infinite number of further big bang bifurcations to occur. Each of these bifurcations causes a further infinite number of big bang bifurcations to occur as well. This nested process is continued ad infinitum and leads to the self-similarity of the 2D parameter space. A large number of numerical results can be easily explained taking this self-similarity into account.

As an outlook, the occurrence of big bang bifurcations in dynamical systems continuous in time is discussed. Additionally, the connection between the presented work and the phenomena occuring in piecewise-linear dynamical systems is demonstrated.

References:

[1] Gambaudo, Procaccia, Thomae, Tresser. Phys.Rev.Lett., 57(8):925--928, 1986.

[2] Jain, Banerjee. Int. J. Bif. & Chaos, 13(11), 2003.

[3] Schanz, Avrutin. Phys. Rev., E70, 2004.

ID of Contribution: 01 - 217

# DISTURBANCE ATTENUATION FOR A PERIODICALLY EXCITED PIECE-WISE LINEAR BEAM SYSTEM

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The motivation for this work originates from the need to analyse and control the dynamics of complicated engineering constructions, which exhibit structural elements with piece-wise linear (PWL) restoring characteristics, such as tower cranes, suspension bridges and solar panels on satellites.

More specifically, one would like to suppress the vibrations of such systems (PWL systems) caused by exogenous disturbances. As a benchmark example for such systems, we consider an experimental PWL beam system.

This system consists of a flexible steel beam that is clamped on two sides, a one-sided linear spring that supports the steel beam at a specific location, and an actuator that excites the beam harmonically. Due to the one-sided linear spring, the beam has two different dynamics regimes. Therefore, it behaves as a bi-modal PWL system. A 3DOF model of this

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system has been developed based on a finite element model of the beam which is reduced using a dynamic reduction method. The harmonically excited beam system exhibits multiple steady-state solutions (Heertjes, 1999).

The goal of this research is the disturbance attenuation of bi-modal PWL systems for a range of periodic excitations. Due to the fact that PWL systems are nonlinear, they often exhibit multiple steady-state solutions when excited by periodic disturbances, as is the case of the PWL beam system. In order to uniquely define the performance of the closed-loop system it should not have multiple steady-state solutions.

The present research focuses on attaining such property by making PWL systems convergent. Namely, a system is convergent if it exhibits a unique asymptotically stable steady-state solution. The controller design strategy developed in the present work uses: 1) A set of sufficient conditions for convergence (Pavlov, 2004) of PWL systems, in order to make the closed-loop system of the PWL beam globally exponentially convergent and, 2) a sensible performance measure in order to validate how the controller performs in terms of disturbance attenuation on the PWL beam. The control law that is used to render the closed-loop system convergent and to attain disturbance attenuation is static state-feedback.

Simulation results prove that the closed-loop system of the PWL beam is globally exponentially convergent and that the designed controller performs well, since it suppresses considerably all the (nonlinear) resonance peaks of the beam's transversal vibrations, in the presence of periodic disturbances.

References:

- [1] Heertjes, M.F. (1999). Controlled stabilization of long-term solutions in a piece-wise linear beam system. PhD thesis, Eindhoven University of Technology.
- [2] Pavlov, A. (2004). The output regulation problem: a convergent dynamics approach. PhD thesis, Eindhoven University of Technology.

ID of Contribution: 01 - 238

# **ON CONVERGENCE PROPERTIES OF PIECEWISE AFFINE SYSTEMS**

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One of the cornerstones of linear (control) systems theory is the so-called convergence property: an asymptotically stable linear system excited by a bounded input has a unique bounded globally asymptotically stable steady-state solution. This property forms the foundation of many results for linear systems including frequency domain identification and performance analysis. It also proves to be beneficial for performance analysis of nonlinear systems. Sufficient conditions for the convergence property for smooth nonlinear systems have been obtained in [1], see also [2]. In [3] sufficient conditions for the convergence property have been obtained for Lur'e systems.

In this paper we consider the convergence property for time varying systems with non-smooth and discontinuous dynamics. In the last case, solutions are understood in the sense of Filippov. Following B.P. Demidovich [1,2], we say that a system is convergent if the following conditions hold:

- 1) All solutions are defined for all positive times,
- 2) There is a unique globally asymptotically stable steady-state solution which is defined and bounded on the whole time axis.

If the steady state solution is uniformly globally asymptotically stable, then we say that the system is uniformly convergent; if it is globally exponentially stable, then the system is called exponentially convergent.

In this paper we consider a particular class of the time-dependent systems with non-smooth dynamics, namely, piecewise affine systems. The main result of the paper is an LMI-based condition that ensures the convergence property for piecewise affine systems. If the right-hand side of the system is continuous then the convergence property is guaranteed by the existence of a common quadratic Lyapunov function for the linear part of the system dynamics in every mode. At the same time the existence of a common quadratic Lyapunov function for each mode is not sufficient

to ensure the convergence in case of discontinuous right-hand side. In this case some additional passivity-like property is required.

References:

- [1] B.P. Demidovich. Lectures on stability theory. Nauka, Moscow, 1967 (in Russian).
- [2] A.Pavlov, A.Pogromsky, N. van de Wouw, H. Nijmeijer. Convergent dynamics, a tribute to Boris Pavlovich Demidovich. Systems and Control Letters, 52: 257-261, 2004.
- [3] V.A. Yakubovich. Matrix inequalities method in stability theory for nonlinear control systems: I. Absolute stability of forced vibrations. Automation and Remote Control, 7: 905-917, 1964.

ID of Contribution: 01 - 257

## IS BOUNCE JUGGLING EASIER IN A PARABOLIC BILLIARD THAN IN A WEDGE?

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In recent work [1], we analyzed a planar model of a bounce juggler. The model is a Hamiltonian system with elastic collisions. We analyzed the existence and stability properties of periodic orbits. We showed that some periodic orbits that are exponentially unstable in the fixed juggler become exponentially stable under harmonic forcing of the juggler arms.

In the present paper, we further investigate this stabilization mechanism for a class of Hamiltonian systems with collisions. We study these models in the vicinity of completely integrable configurations and explore ways to analyze stability without the explicit computation of the Poincare maps.

We are especially interested in applying these techniques to recently studied models of insect locomotion [2], in a situation where the stabilizing effect of a time-varying parameter is supported by biological evidence.

The paper will show the common features between the planar juggler model and the insect locomotion model.

References:

- [1] R. Ronsse, Ph. Lefevre, R. Sepulchre (2004). Open-loop stabilization of 2D impact juggling. Proc. 6th IFAC symposium on Nonlinear Control Systems, Stuttgart, 2004.
- [2] J.E. Seipel, P. Holmes and R.J. Full (2004) Dynamics and stability of insect locomotion: a hexapedal model for horizontal plane motions. Biological Cybernetics 91, 76-90.

ID of Contribution: 01 - 258

# SYMMETRIC AND ASYMMETRIC MOTIONS OF A HARMONICALLY DRIVEN DRY-FRICTION OSCILLATOR

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The possible solutions of a harmonically excited dry-friction oscillator are examined. The classical Coulomb model is used, i.e., the friction force is given by the signum function. As a consequence, the equation of motion is a multi-valued differential equation. The solution parts, that are valid for positive and negative velocities, respectively, cannot be

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matched analytically because of the appearance of transcendental equations. There is still a possibility to find solutions analytically: by searching for specific solutions. For this purpose, special assumptions must be intruduced.

Using the assumptions that the solutions are non-sticking, periodic with the period of the excitation, and that there are only two turnarounds per period, we found that two different cases may appear, depending on the duration t1 of the first phase of the motion.

- If sin(t1) is not zero, the durations of the two phases of the motion are equal and the greatest positive and negative amplitudes are also equal in magnitude. This symmetry of solutions was usually assumed to fulfil in the literature [1], but has not been proven yet. We examined the validity of the possible solutions and found that for small values of the friction coefficient S, a new, approximating sticking condition can be introduced: sticking solutions appear if the analytically determined amplitude is less than 1+S. - if sin(t1) = 0, the durations of the two phases of motion are still equal, but an infinity of asymmetric solutions appear at excitation frequencies 1/(2n), n = 1,2,... The possible maximal and minimal amplitudes of these solutions can be expressed using the condition of sticking and the condition of having only two turnarounds per cycle. A nonlinear stability calculation showed that these solutions are marginally stable in the third order approximation.

The analytical results were confirmed by numerical simulations.

 S.W. Shaw, J. of Sound and Vibration, On the Dynamic Response of a System with Dry Friction, Vol. 108, pp. 305-325, 1986

ID of Contribution: 01 - 267

## DYNAMICS OF GEAR RATTLE IN THE SMALL DAMPING LARGE STIFFNESS LIMIT

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We examine ODE models of the meshing of a simple pair of spur gears attached to a pair of stiff parallel shafts (X and Y say). The X-shaft is driven by an engine or a motor, whereas the Y-shaft is driven only by the X-shaft through the gear pair. Both shafts experience a small viscous drag loading, due to lubrication etc. This particular set-up can be used to model gear rattle in e.g. (i) roots blower vacuum pumps, or (ii) the loose gears in a manual automotive transmission. In each case there is an oscillatory forcing term: in (i) due to the (imperfect) eccentric mounting of the gears and in (ii) due to the engine cycle.

The models that we study are linear up to the inclusion of a backlash term that models the meshing force between gears in terms of their relative rotational displacement. In its simplest form, the backlash (or dead-zone) nonlinearity is a three-zone piecewise-linear function which is continuous but not differentiable at the zone boundaries. Consequently we may solve explicitly for segments of solution trajectories in each of the three linear regimes, and stitch segments together by the use of maps between the zone boundaries. In this way we may construct families of periodic solutions and derive (analytical, up to the use of expansions) conditions for existence. Further, since the backlash nonlinearity is continuous, classical Floquet theory may be used to obtain stability results.

Here our focus is to simplify the analysis by replacing the outer linear regimes of the backlash response with pure impacts with coefficient of restitution equal to one: i.e. we consider the infinite stiffness limit. In effect we analyse the dynamics of an impact oscillator with two boundaries which is driven by an oscillatory input whose mean is non-zero. The maps that must be solved for the construction of solutions now take a simpler form, although the stability analysis is more complicated since it requires the use of Nordmark's discontinuity mappings.

Thus we have derived analytical bifurcation diagrams by exploiting regular expansions in the small damping parameter. We have also developed and employed numerical continuation techniques to verify the analytical results and to unfold some of the novel codimension-two points that are predicted by the analytical theory. The solution structure is
surprisingly rich, with the possibility of coexisting rattle behaviours that are stable. We have thus worked out a new mathematical explanation for intermittent gear rattle phenomena.

#### ID of Contribution: 01 - 276

#### DYNAMICS OF STOCHASTIC NONSMOOTH SYSTEMS

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Many power electronics systems are nonsmooth (eg DC/DC boost and buck converters). These systems can undergo changes in behaviour under parameter variation that are not present in smooth systems called grazing bifurcations. We highlight the dramatic effect that noise can have on these bifurcations (including advance or smoothing of the bifurcation) and conclude by showing excellent agreement between experimental results and a stochastic model for the DC/DC boost converter.

ID of Contribution: 01 - 290

# **CHATTERING AND COMPLEX BEHAVIOR OF A CAM-FOLLOWER SYSTEM**

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Recently, a theory has been developed of nonsmooth bifurcations in discontinuous dynamical systems. This provides an analytical framework to characterise the complex behaviour exhibited by these systems. In this paper, we will discuss the analysis of complex behaviour in a class of impacting mechanical systems of relevance in Automotive Engineering. Specifically, the analysis will be detailed for a simplified model of an automotive camshaft system. The camshaft uses lobes (called cams) that push against the valves (follower) to open them as the camshaft rotates; springs on the valves return them to their closed position. We find that as the rotational speed of the cam varies, the valve dynamics can become increasingly complex with several bifurcations and chaos taking place. We will show that the unfolding of the complex dynamics exhibited by the system under parameter variations can only be accounted for by understanding the intricate relationship between so-called chattering motion and the occurrence of grazings and corner-collision bifurcations.

Even though this system can be modelled as a preloaded forced impact oscillator, it presents several peculiarities that makes worth the study of its dynamics. In particular, we will show that the system behaviour can be explained by appropriately adapting the theory of sawtooth bifurcations recently presented in the literature on impact oscillators (Budd, Piiroinen 2004). From a practical viewpoint, it turns out that there is a direct relationship between the shape of the cam lobes and the way the engine performs in different speed ranges. In particular, the shape of the lobes can present sudden changes in the velocity of the contact point producing the detachment of the follower with a resulting chattering sequence. This is an undesirable behaviour since the performance of the engine can be seriously affected as well as the wear of the components. Furthermore, a series of qualitatively different solutions can be found as a function of the velocity of the cam (given in rpm). The main bifurcations observed in the system and the transitions to chaos will be motivated analytically using so-called discontinuity maps (Dankowicz, Nordmark, 1999). Namely, we will construct analytical approximation of the system Poincarè maps close to the bifurcation points of interest, classifying the dynamical scenarios observed using the strategy recently presented in (Di Bernardo, Budd, Champneys, 2001). The analysis will be then validated through appropriate numerical simulations.

References:

- [1] (Budd, Piiroinen 2004) C.J. Budd, P. Piiroinen, "Sawtooth bifurcations in impact oscillators", in preparation. (2004)
- [2] (H. Dankowicz, A. B. Nordmark, 1999) On the Origin and Bifurcations of Stick-Slip Oscillations. Physica D 136 (2000) 280-302.
- [3] (Di Bernardo, Budd, Champneys, 2001) Normal From Maps for Grazing Bifurcations in n-Dimensional Piecewise-Smooth Dynamical Systems. Physica D 160 (2001) 222-254.

#### ID of Contribution: 01 - 296

# STABILITY OF DISCRETE SYSTEMS INVOLVING SHOCKS AND FRICTION

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The lecture aims at giving some recent results about the stability of equilibrium states of nonsmooth dynamical systems arising from the mechanics of contact and friction. For simplicity, we restrict our attention to a simple mass-springs system moving in the plane over an obstacle, as the one described by A. Klarbring in [3].

The contact with the obstacle is assumed to involve both nonpenetrability and friction conditions, that we take into account without any kind of regularization.

Due to possible shocks and to the positivity condition, the reaction of the obstacle is a measure, and the displacement is consequently a function the second derivative of which is a measure. Then the first step consists in writing the dynamical problem in a convenient form. Then:

- we first recall that the existence of a global solution is proved by the convergence of the solution of a discretized problem towards a solution of the continuous one;
- thanks to counter-examples of the same kind as those of previous works dealing with the frictionless case, it is then proved that uniqueness cannot be expected even with external forces which are infinitely continuously derivable functions;
- the last step of this well-posedness analysis recalls a recent result which establishes that uniqueness holds if the external forces are analytic [1].

Depending on the data (mass, friction coefficient, external force...), the set of equilibrium solutions is made either of a single point, which is either without contact or in grazing contact, or of two points, one without contact and one in contact with impending slip, or of infinitely many points, some of which being in impending slip, some others being strictly sticked [2].

Everything is then in place so that we are able to integrate the dynamics with initial data in any neighborhood of each of the equilibria, and to estimate the evolution of the distance between the trajectories and the equilibria. The results will be given in the lecture. In particular:

- if the data are such that there are infinitely many equilibria in impending slip different from the grazing contact state, they are all unstable,

- all the strictly sticked equilibria are Lyapunov stable,

- only the vertex of the Coulomb's cone, that is the equilibrium in grazing contact, may be asymptotically stable for some ranges of the data.

- [1] Ballard P., Basseville S., Existence and uniqueness for dynamical unilateral contact with Coulomb friction: a model problem, To appear, Math. Modelling and Numerical Analysis.
- [2] Basseville S., Leger A., Pratt E., Investigation of the equilibrium states and their stability for a simple model with unilateral contact and Coulomb friction, Archives Appl. Mech., 73, pp. 409-420, 2003.
- [3] Klarbring A., Examples of nonuniqueness and nonexistence of solutions to quasistatic contact problems with friction, Ing. Archiv, 60, pp. 529-541, 1990.

#### ID of Contribution: 01 - 302

# STRUCTURAL STABILITY OF BOUNDARY EQUILIBRIA IN PIECEWISE-SMOOTH DYNAMICAL SYSTEMS

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This paper is concerned with the structural stability of boundary equilibria in nonsmooth dynamical systems. Namely, we study the structural stability under parameter variations of equilibria lying on discontinuity boundaries in phase space dividing regions where the system under investigation is smooth. We show that it is possible to give a set of conditions to account for the possible dynamical scenarios that can be observed. In particular, we are interested in isolating the branches of solutions originating from a boundary equilibrium point under parameter variations. The analysis will be carried out for general n-dimensional systems.

ID of Contribution: 01 - 321

# HOW IMPORTANT IS THE FRICTION MODEL ON THE MODELING OF ENERGY DISSIPATION?

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Frictional forces arising from the relative motion of two contacting surfaces are a well-known source of energy dissipation. Sometimes this is an unwanted effect of the design, but it can also be intentionally used to increase the damping of a certain system in a simple and cost-effective way. In an earlier work [1] the energy dissipation of a 1-degree of freedom (DOF) system with Coulomb friction has been analytically studied for a friction law with equal dynamic en static friction forces en with a static friction force larger than the dynamic friction force. After establishing the existence and stability of a periodic solution, closed-form expressions for the maximum energy dissipation per cycle and the optimal friction force were obtained. A parametric study was also performed to determine the influence of system parameters such as stiffness or damping on the dissipated energy.

In the present work numerical simulations are performed with several different friction models currently used in the literature. For the stick phase smooth approximations like viscous damping or the arctan function are considered and the non-smooth switch friction model. For the slip phase several models of the Stribeck effect are used. The goal of this study is, for a given stable periodic solution, to determine the influence of the friction model on the predicted energy dissipation per cycle and especially on the maximum energy dissipation and the optimum friction force. This will help asses the validity of the conclusions derived from the Coulomb friction based analytical model.

References:

[1] Lopez I., Busturia J.M., Nijmeijer H., "Energy dissipation of a friction damper", Journal of Sound and Vibration 278, 539-561, 2004.

# CONTACT-MODEL-INDEPENDENT STABILITY CONDITIONS IN SYSTEMS WITH FRICTION

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The paper is devoted to the problem of determination of accelerations and reaction forces in multibody systems. As was shown by Painleve [1], in the presence of dry friction this problem may not have unique solution. Some approaches to the solution of such paradoxes have been developed in case of unique frictional contact. Here the cases of two or more frictional pairs are considered.

# Objective

Dynamics of constrained mechanical systems deals with two kinds of unknown quantities: accelerations and reaction forces. To determine these unknowns, general theorems of dynamics are used in combination with equations of constraints. In case of ideal constraints, the problem is well-posed: the accelerations can be expressed as single-valued functions of coordinates, velocities and applied forces. However, reaction-dependent friction (e.g. of Coulomb type) may cause paradoxical situations where the above mentioned functions are multi-valued or do not exist [1]. The situations may be treated by many authors, including P.Lötstedt (1982), M.T.Mason and Wang (1988), J.Trinkle et al. (1997), and others. The most popular approach is based on account of small contact deformations. In this paper, such approach is implemented to systems with multiple frictional contacts. Stability arguments were taken in account in [2,3].

#### Procedure

We introduce a small parameter, which is associated with deformation rate. The equations of motion are decomposed to "fast" and "slow" parts, corresponding to the "micro-" and "macro-" levels [2]. Standard asymptotical techniques allow to "freeze" slow sub-system and study "fast" motions separately. We look for stable equilibrium and limit circles. Moreover, we do not specify strain-stress functions.

#### Results

Some conditions of existence, uniqueness, and stability of equilibrium are obtained. It is worth noting that these conditions are invariant to the specific form of strain-stress functions. It is shown that even in the absence of Painleve paradoxes systems with friction may exhibit non-regular dynamics. An example is brake "squeal".

# Conclusions

Usual approach to the analysis of dynamics of systems with multiple frictional contacts is oversimplified. Though the mixed differential-algebraic system for determination of accelerations and reaction forces has unique solution, it may not correspond to a realistic motion due to instability. New results allow to avoid high-frequency oscillations in practice.

- [1] Painleve P., Lecons sur le frottement. Paris, 1895.
- [2] Dupont P..E., Yamajako S.P. Stability of Frictional Contact in Constrained Rigid-Body Dynamics. IEEE Trans. Robot. Autom., 1997. V. 13(2). P. 230-236.
- [3] Basseville S., Leger A., Pratt E. Investigation of the equilibrium states and their stability for a simple model with unilateral contact and Coulomb friction, Arch, Appl, Mech., 2003. V. 73. P.409-420.

# **MINI-SYMPOSIUM 2**

# **Impact Systems**

Chair / Organizer:

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# **EXPERIMENTS FOR IMPACTS WITH FRICTION**

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The test setup for measuring impacts with friction consists of a large rotating arm with a small rotating device at its end, which keeps a firm hold on a disc on the one and which releases this disc on the other side. The machine allows to realize translational and rotational velovities of the disc in the throwing plane. After being released the disc performs a ballistic trajectory, hits the ground and detaches from the ground again. This process depends on the initial conditions and on the material pairing as given by the disc and the ground surfaces. The whole experiment is filmed, which gives the data necessary to evalute the disc's trajectory and its velocities. The crucial point is the accuracy of these measurements, which depends heavily on the initial conditions when releasing the disc. Therefore the mechanical, the electronical and the control design of the throwing machine has been a real challenge.

Some of the requirements are the following: initial translational velocity 10 m/s maximum, initial rotational velocity 40 rps (2400 rpm) maximum, velocities continuously controllable, initial direction of the disc between 0 and 90, translational and rotational velocities not coupled, disc geometry with 50 mm diameter, 20 mm thickness and mass 300 grams, automatic test control with initial PC-mode, test processor mode and final evaluation PC-mode. The momentum generating and releasing unit operates electromagnetically and is processor controlled, the rotating arm generating the translational velocity is also processor controlled. The whole test-setup includes the throwing machine, a PC 486 computer with appropriate bus system, sensor and power electronics, a camera, a flash and a flash sensor, everything automatically controlled. Machine and control in soft- and hardware were the most difficult problems. The orginally realized release time of 156 ms could be reduced to 10 ms by optimization the release unit and the control concept.

More than 600 experiments [1] have been performed for various material pairings. In all cases the theory for impacts with friction [2,3] could be verified perfectly.

References:

- [1] Beitelschmidt, M., Reibstoesse in Mehrkoerper-systemen, Fortschrittberichte VDI, Reihe 11, Nr.275, Düsseldorf 1999
- [2] Glocker, Chr., Dynamik von Starrkörpersystemen mit Reibung und Stoessen, Fortschrittberichte VDI, Reihe 18, Nr. 182, Düsseldorf 1995
- [3] Pfeiffer, F., Glocker, Chr., Multibody Dynamics with Unilateral Contacts, John Wiley & Sons, New York 1996

ID of Contribution: 02 - 030

# FRICTION MODELS FOR THE ROLLING DISK

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How to stop moving bodies in finite time? Many answers different from classical solutions are provided by non-smooth dynamics, which deals with measure differential inclusions from time evolution problems in mechanics. The most familiar examples of such systems are collisions of rigid bodies and Coulomb's law of dry friction. Non-smooth dynamics, however, is much more than friction and impacts. It provides an extended concept of classical analytical mechanics with all its sub-disciplines and modern extensions, such as multi-body dynamics and robotics, by allowing for set-valued constitutive laws and discontinuities in the state variables as functions of time. Set-valued constitutive laws provide a sound basis for switching on and off various kinds of constraints in a most consistent way, where the switching rules are embedded in the constitutive laws themselves [1]. One important sub-class of such constitutive laws

are those expressed by normal cone inclusions from convex analysis as used in this paper (see also [2]), because they generalize the dynamics on manifolds to manifolds with boundary.

As one of the most demanding examples, the classical problem of a rolling disk is chosen with the main emphasis to study numerically the dissipation mechanisms generated by different kinds of set-valued constitutive laws at the contact point. In the course of the motion, both the inclination of the disk with respect to the support and its angular velocity decrease to zero, while the relative velocity of the contact point with respect to the disk tends to infinity in the final stage of the motion. We present a mechanical model of a rolling disk on a flat support in the framework of Non-smooth Dynamics and use Euler parameters for the description of the orientation of the disk. We model the disk with three unilateral contact constraints of the type point–surface in order to simulate a static equilibrium of the disk lying horizontally on the support as well as motion in the plane. The constitutive laws associated with the frictional unilateral contact constraints are set-valued force laws which account for resistance against sliding, pivoting and rolling. A numerical algorithm of the time-stepping type [3] is briefly presented, together with the numerical results, obtained with various combinations of frictional dissipation models. An analytical study of the rolling motion of a disk is given. Approximations are derived for the energy decay of the system during the final stage of the motion for various kinds of frictional dissipation models. Finally, the numerical and analytical results are discussed and compared with experimental results available in literature.

#### References:

- [1] Glocker, Ch. Set-Valued Force Laws, Dynamics of Non-Smooth Systems, vol. 1 of Lecture Notes in Applied Mechanics. Springer-Verlag, Berlin-Heidelberg-New York, 2001.
- [2] Le Saux, C., Leine, R.I. and Glocker, Ch. "Dynamics of a rolling disk in the presence of dry friction", submitted to Journal of Nonlinear Science, 2004.
- [3] Leine, R. I., and Nijmeijer, H. Dynamics and Bifurcations of Non-Smooth Mechanical Systems, vol. 18 of Lecture Notes in Applied and Computational Mechanics. Springer-Verlag, Berlin-Heidelberg-New York, 2004.

#### ID of Contribution: 02 - 040

# ON THE STRONGLY NONLINEAR BEHAVIOR OF AN OSCILLATOR IN A CLEARANCE

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Deliberate and unintended clearances are usual in mechanical engineering. Examples include all kinds of gears alongside with vibrating structures with stops and devices to crush or grind. Integrating of equations of motions between collisions and "stitching" of the solution intervals by means of kinematic impact conditions it the classical approach for solving dynamic problems in systems with collisions. It is simple and effective in numerical simulations but very elaborate for obtaining analytical predictions. General solution properties and qualitative parameters influence are usually mostly interesting for applications. Thus approximate analytic methods are both necessary and useful.

In this paper averaging combined with non-smooth unfolding transformations is used in order to investigate the basic properties of an oscillator in a clearance. The classical stereo-mechanical approach is used in order to describe collisions between the mass and the limits. Energy dissipation during collision events is taken into account.

Analysis is concentrated on the oscillation regimes with alternating collisions with both sides of the clearance. The appropriate non-smooth transformation unfolds the "saw tooth"-similar motion to a polygon-like curve with small brakes corresponding to the collisions. (The brakes disappear if the collisions are absolutely elastic.)

The self-excited friction oscillator in the clearance is considered as the first example. It is shown that using the unfolding transformation the oscillator can be converted to an almost conservative pendulum rotating in a limited, nonsmooth periodical potential field. Analytic predictions are obtained for the total energy of the pendulum which is the natural measure for the oscillations intensity. The oscillation amplitude is fixed for considered regime with alternating collisions at each side of the clearance. Thus only the oscillation frequency can increase with increasing energy input. Therefore the system can be interpreted as a frequency transformer. It is possible to control the oscillation frequency varying the negative slope of the friction characteristics, altering the normal force or changing the clearance length. The classical externally excited oscillator in the clearance is considered as the second example. Applying the same approach the problem of the resonant oscillations can be reduces to the analysis of the rotation of the harmonically excited pendulum in the same potential field as in the first example. The main attention is paid to the high-energy resonances corresponding to alternating collisions of the mass with each side of the clearance. The perturbation analysis in the vicinity of the resonant surfaces enables to dissociate slow, semi-slow and fast motions and to obtain very accurate analytic predictions for the energies of stationary resonant regimes. Bifurcations of the high-energy regimes are discussed alongside with the low-energy oscillations. The last case is typical for relative strong energy losses during collision events, so that the system needs several collision-free oscillations in order to increase the amplitude and reach the limits of the clearance.

All the analytic results are compared with numerical simulations and demonstrate the efficiency of the approach combining averaging with unfolding transformations for the dynamic analysis of discontinuous systems.

ID of Contribution: 02 - 090

# NUMERICAL BIFURCATION ANALYSIS IN THE TRIPLE PHYSICAL PENDULUM WITH RIGID LIMITERS OF MOTION

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The scope of the work includes modelling of the mechanical systems with rigid limiters of motion, their numerical simulation, stability analysis of the solution and bifurcation analysis using numerical tools.

In the present work the considered model is the plane three-degrees-of-freedom triple physical pendulum with rigid obstacles, the first body is harmonically excited and the contact between the bodies of the pendulum and the arbitrarily situated obstacles is assumed to be frictionless.

The system is modelled as a hybrid one since its dynamics is treated as a composition of the continuous dynamics and discreet events. The continuous dynamics between each two successive events is governed by the differential-algebraic equations (DAEs), where algebraic equations results from the permanently active constraints (on the given time interval) and the normal reactions from the active obstacles are introduced to the differential equations in the form of Lagrange multipliers. At each event, the continuous dynamics description for the next time interval is altered (the set of permanently active constraints changes) and the impulsive change in the system state may take place due to the impact phenomenon.

The frictionless single impact is modelled by the use of generalized Newton's law based on the restitution coefficient rule [1], where we assume the force impulse vector perpendicular to the impact surface and apply restitution rule to the relative velocity of the system along the normal direction to the impact surface. As mentioned, that model describes the single impact against only one smooth surface in a time instant. But it is shown, that in some cases, the multi-impact phenomenon can be treated also as a sequence of single impacts.

Then the linear stability is numerically investigated using the classical approach based on integration of the variational equations and special modifications while handling with perturbed solution in points of discontinuity ('saltation matrices') based on the theory of Aizerman and Gantmakher [2].

Owing to the developed algorithms for obtaining the perturbed solution we develop numerical methods for firstly seeking, and then following branches and bifurcation analysis of periodic solution and the Lyapunov exponents variation of attractors in the investigated piece-wise smooth (PWS) system.

In the analysed system the classical bifurcations appear (though we need modified classical methods for finding them) as well as non-classical ones, like grazing bifurcation (where we need special numerical methods).

For the special case of the investigated system, i.e. the three identical rods with the horizontal barrier, we show some examples of dynamical phenomena and its analysis. Among others we present examples of Lyapunov exponents'

spectra, where for attractors with some parts of trajectory having permanent contact between the system and the obstacle, the pairs of exponents in minus infinity appear. We focus on grazing bifurcations and show examples of complex system behavior near grazing incidence and compare results with the grazing bifurcations in a simple mechanical oscillator.

#### **References:**

- [1] B. Brogliato, Nonsmooth Mechanics, Springer, London, 1999.
- [2] P.C. Muller, Calculation of Lyapunov exponents for dynamic systems with discontinuities, Chaos, Solitons and Fractals, 5, 1671-1691, 1995.

ID of Contribution: 02 - 094

#### **COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS FOR IMPACTS**

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Impact processes have a significant engineering relevance. However, they are still not fully understood due to their complexity. During impact kinetic energy is lost by plastic deformation of the contact region, viscoelastic effects and wave propagation in the bodies. Due to the short impact duration these wave phenomena are characterized by high frequencies. Especially for the impact involving slender bodies, such as rods, beams or plates, a significant amount of the initial kinetic energy is transformed into wave propagation. These waves then propagate in the bodies until they vanish after separation due to material damping.

For a detailed investigation of impact processes, numerical and experimental methods must be able to catch these high frequency phenomena. In this paper four models are presented for numerical impact investigation on a fast time scale. The first model consists of a modal model of the bodies, describing their elasto-dynamic behavior, combined with the elastostatic Hertzian contact law. In the second model the Hertzian contact law is replaced by a pre-computed contact model based on quasi-static FE-contact, including the effects of plasticity. In the third model the modal model is simulated in parallel with a dynamic FE-model of the contact region resulting in a co-simulation. The fourth model is a complete FE-model of the impacting bodies. A comparison of the four models shows the good consistency. However compared to the complete FE-model, the models based on a modal description of the bodies show a significant efficiency advantage. The modal models with quasi-static FE-contact and dynamic FE-contact can be modified to simulate successive impacts of the same bodies including the deformation history of the contact region due to plastic deformation.

The accuracy of the proposed models is verified by extensive experimental investigations of impacts of a sphere on a short cylinder, a rod, a half-circular plate and a beam [1,2]. The impacting bodies are suspended in a frame with kevlar wires like a pendulum. At the beginning the steel sphere is released by a magnet from a predefined height and strikes the second body which is initially at rest [3]. For the measurement of out-of-plane displacements and velocities 1D-Laser-Doppler-Vibrometers (LDV) are used, while a 3D-LDV is used for in-plane velocity measurements. As second measurement technique strain gauges are used for strain measurements at selected points of the bodies. A comparison of the two techniques shows a good consistency, however, the LDVs show much less noise than the strain gauges.

While the impacts on the short cylinder produce hardly any wave phenomena and all energy loss is due to plasticity, the impacts on the rod and beam shows substantial energy transformation into waves. It is shown that in a series of successive impacts the contact region gets plastically deformed by the first impacts until a configuration is reached where no additional plastic deformation occurs. In this stationary phase the energy loss is purely due to wave propagation.

- [1] Seifried, R.; Hu, B.; Eberhard, P.: Numerical and Experimental Investigation of Radial Impacts on a Half-Circular Plate. Multibody System Dynamics, Vol. 9, No. 3, 265-281, 2003.
- [2] Schiehlen, W.; Seifried, R.: Three Approaches for Elastodynamic Contact in Multibody Systems. Multibody System Dynamics, Vol. 12, No.1, 1-16, 2004.

[3] Hu, B., Schiehlen, W., Eberhard, W.: Comparison of Analytical and Experimental Results for Longitudinal Impacts on Elastic Rods. Journal of Vibration and Control, Vol. 9, 157-174, 2003.

ID of Contribution: 02 - 121

# FRAGMENTIZED STRANGE ATTRACTORS IN A PERIODICALLY FORCED, PIECEWISE OSCILLATOR WITH IMPACTS

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In this paper, the grazing bifurcations and flows of an idealized, piecewise linear system are investigated from the nonsmooth dynamical system theory of Luo (2005). The necessary and sufficient conditions for such grazing bifurcations of all the generic mappings are obtained. The initial and final grazing, switching manifolds for all the generic mappings are introduced for the grazing motion. The fragmentation of strange attractors in non-smooth dynamical systems is described mathematically. The fragmentation mechanism of the strange attractors for such a non-smooth dynamical system is qualitatively discussed. Such a fragmentation of strange attractors is illustrated numerically through the switching sets. This investigation will provide a better understanding of the mathematical structures and characteristics of strange attractors in non-smooth dynamical systems.

ID of Contribution: 02 - 125

#### **IMPACTS OF EXTREMELY SOFT ELASTIC SPHERES**

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Although the impact of soft materials such as rubbers and gels is important and interesting from the viewpoint of industrial application or biomechanics, few investigations have been done on it. In this study, to obtain a physical picture for the impact in the elastic large deformation regime where the usual Hertz theory breaks down, we study the impact of soft gel balls experimentally and theoretically.

In our experiment, the impact processes of spherical gel balls were recorded with a high-speed CCD video camera; the contact time and the deformation time, defined as the time between the onset of the impact and the moment of maximal deformation, were measured on the recorded images as a function of the impact velocity. For large impact velocities, comparable to the speed of sound (shear wave) in the gels ( $\sim 1$  m/s), the gel balls deforms into thin pancake like shapes at the maximal deformation. In the large deformation (pancake) regime, the deformation time and the impact time show plateau behavior, i.e., they are independent of the impact velocity. We also measured the coefficient of restitution; similar plateau behavior was observed for the coefficient.

To explain the plateau behavior of the contact time and the deformation time, we propose a scaling argument [1] based on the following assumptions: (i) the deformation time is proportional to the time scale given by impact velocity and lateral dimension of the "pancake" at the maximal deformation; (ii) the deformation is uniform; (iii) the deformation energy is given by the ideal rubber-type one. We also propose a simple analytical model based on the assumptions of (ii) and (iii). It can qualitatively explain the plateau value of the deformation time.

Important points of this study can be summarized following. The plateau behavior of the deformation time and the contact time is a characteristic of the impact in the elastically large deformation regime. To understand the behavior we should take account of the lateral (i.e., perpendicular to the impact velocity) expansion as the principal deformation mode (the above assumption (i)). Employing the ideal rubber-type deformation energy (and the approximation of uniform deformation), we can qualitatively explain the plateau value of the deformation time.

References: [1] Y. Tanaka, Y. Yamazaki and K. Okumura, Bouncing Gel Balls, Europhysics Letters, 63, 149-155(2003)

ID of Contribution: 02 - 204

# **ENERGY CONSIDERATIONS FOR EXCITED PERFECT COLLISIONS**

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The energetic consistency of collision problems is considered. Regarding collisions in perfectly constrained mechanical systems with finite degrees of freedom, it is known that the restriction of the kinetic energy [2,3] with respect to a reference state [1] to the pre-impact value can be seen as third independent class of conditional inequalities for possible post-impact velocities, if the system is kinetically not excited. A reference state has the same displacements as the one being considered, but vanishing contact velocities of all closed contacts. Therefore, for each closed contact, a reference velocity has to satisfy an affine equation. While scleronomic systems and some rheonomic systems, e. g. systems with only one closed unilateral contact always have a reference velocity, rheonomic multicontact systems with so called "non-uniform" closed contacts have no such reference velocity. This fact leads to the necessity of a reformulation of the energy concept. A possible way out is to embed it into the concept of the contact work postulating the collective work of all contacts to be non-positive only. As a consequence, it will be shown, that the set of the energetically possible post-impact velocities is the intersection of all balls around extremal points of some convex set in tangent space, which includes the pre-impact velocity. If the number of closed unilateral contacts is finite, the intersection is also and its geometrical shape is some sort of a lense. The intersection reduces to one single ball, if all contacts are uniform; hence the embedding is perfect.

References:

- Glocker, Ch., The Geometry of Newtonian Impacts with Global Dissipation Index for Moving Sets. Proc. of the Int. Conf. on Nonsmooth/Nonconvex Mechanics, Thessaloniki, Greece, July 2002, pp. 283 - 290, Editions Ziti, Thessaloniki, 2002.
- [2] Glocker, Ch., Concepts for modeling impacts without friction, Acta Mechanica 168, 1–19 (2004)
- [3] Glocker, Ch., Aeberhard U., The Geometry of Newton's Cradle. Proceedings of the International Colloquium in Honour of the 80th Birthday of Jean Jacques Moreau, Montpellier, France, November 17--19, 2003, to appear.

ID of Contribution: 02 - 205

# FRICTION DRIVEN VIBRO-IMPACT SYSTEM WITH ENGINEERING APPLICATION

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The dynamics of a friction driven vibro-impact system is presented. This is a self-exciting system that introduces a new principle of percussive-rotary drilling as a practical industrial application. The system has two degrees-of-freedom with strong nonlinearity in each co-ordinate i.e. dry friction and impact. Friction-induced vibration is used as the source of excitation of impacts, which influence the parameters of stick-slip motion. In this model, the friction force is a function of sliding velocity, which allows for the self-excitation of coupled vibration of both co-ordinates. The dynamic coupling of vibro-impact action with the stick-slip process provides entirely new adaptive features with practical industrial application.

The dynamic response of the system is studied firstly without impact and secondly with superimposed impact; as the system is non-smooth, the equations of motion are solved numerically. The analysis focuses on the relationship between the sticking and impacting phase of the process in order to provide engineering applicability of the mechanism. An area of practical application of the model is presented, i.e. percussive-rotary drilling and provides an understanding of the mechanics of the drilling process that allows the design of new drilling tools with advanced characteristics. The issue of

ENOC-2005, Eindhoven, the Netherlands

synchronisation problem is addressed with the use of a single drive in contrast to conventional rotary-percussive with two actuators and synchronisation devices.

References:

- Batako A.D., Babitsky V.I. and Halliwell N.A., Self-Oscillatory System of Percussive-Rotary Drilling; Journal of Sound and Vibration, 2003,259, 1, 97-118.
- [2] Batako A.D., Babitsky V.I. and Halliwell N.A., Modelling of Vibro-Impact Penetration of Self-Exciting Drill Bit, Journal of Sound and Vibration, 2004, 271, 209-225.
- [3] Jansen J. D., Van Den Steen L., Active damping of self-excited torsional vibration in oil well drillstrings. Journal of Sound and Vibration, 1995 174(4), 647-668.

#### ID of Contribution: 02 - 228

# CONCURRENT MULTIPLE IMPACTS IN RIGID BODIES: FORMULATION AND SIMULATION

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Concurrent multiple impacts in rigid bodies can be defined as the occurrence of many impacts at different points of the system at the same time. Chain of balls or Newton's cradle are academic examples where concurrent multiple impacts occur.

Heuristic algorithms have been developed to solve this problem. For instance, a sequential approach or an introduction of some initial artificial gaps have been tested but their validities and physical meanings are doubtful. On the other hand, theoretical works have been made in order to define an enhanced framework for rigid body including new internal constraints and a matrix of coefficients of restitution [Fremond 2002]. The work of [Aeberhard & Glocker 2003] defines a set of kinematic, kinetic and energetic constraints, which must be fulfilled for a relevant impact law, respecting the fundamental principles of Dynamics. These rigorous frameworks are consistent with thermodynamic principles but a precise definition of the parameters and their physical interpretation somewhat lack. The aim of this work is to exhibit an impact law build on physically motivated parameters which complies with the rigorous framework cited above.

To have a clear idea of what an impact law is, we suggest to study a chain of 3 hard balls with same mass \$m\$. There are many convenient reasons to consider such kind of example. Firstly, a chain of balls allows analytical solution thanks to the simple kinematics and kinetics. Secondly, Hertz's theory of contact is very well correlated with the experiments at low velocity range [Falcon et. al . 1998]. This remark justifies physically the use of a regularized model based on Hertzian springs. Two major results are found : a) the percussion ratio between the two contacts depends only on the ratio of stiffnesses and masses of the ball. b) The same property holds for the times of beginning and end of the multiple impact. Thanks to these results, we conclude that the percussion ratio is an effective parameter that allows one to compute in a unique way the post impact velocity.

The case study of a 3-ball chain is extended to finite dimensional systems subjected to perfect unilateral constraints. We formulate more generally an impact law for rigid bodies in the case of Lagrangian systems. More general results on the qualitative properties will be given. Particularly, we will consider the behaviour of percussion ratio when we converge to the limiting case of rigid bodies.

Finally we propose a suitable algorithm in the framework of mathematical programming techniques. This section is aimed at adapting our general formulation to this kind of algorithms in order to reach numerical efficiency.

- [1] [Fremond 2002] Fremond, M., Non Smooth Thermodynamics, Springer Verlag
- [2] [Aeberhard & Glocker 2003] General Impact Theory, Deliverable D3.1, Siconos Project IST2001-37172
- [3] [Falcon et. al . 1998] Collision of a 1D column of beads with a wall. The European Physical Journal B, vol. 5: 111-131.

# **EXPERIMENTAL TREATMENT OF MULTIPLE-CONTACT-COLLISIONS**

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Single contact collisions of rigid bodies are treated by smooth as well as non-smooth theories in a, more or less, sufficient way, see e.g. [1]. If the complexity of the system, namely the number of contacts, increases, non-smooth approaches show up considerable advantages opposite to smooth ones: The treatment of the impacts as singleton downsizes the problem, since no compression and/or restitution periods are resolved. In exchange a general impact law, based on energetic and kinematical considerations, is introduced [2]. The cone of feasible post-impact-states given by the impact law is represented e.g. by a matrix allowing each contact i to directly interact with all other contacts j, which is the main idea of Frémond [3].

To validate this general impact law experiments on multi body collisions are necessary. Interesting impact configurations are chains of balls (Newton's Cradle) as well as longitudinal bars of different length and forked bars. With increasing longitudinal dimension the influence of wave effects on the topology of the multi contact collision increases (Lagrange diagram) whereas for short bodies (balls) the measured contact time correlates to the theory of Hertz.

The test setup consist of the impacting bodies (balls or longitudinal bars) hanging on threads. They are equipped with an affixed steel scale tape for an exposed linear encoder. The velocities of the bodies are obtained applying a finite difference scheme on the positios sampled by the exposed linear encoder. Based on this data the Frémond Matrix of the tested impact configuration is determined. A test circuit applying binary coding of the index set H of closed contacts is used to measure the contact time of each single contact of the configuration. These results are compared with the theoretical results of Hertz theory and the Lagrange diagram. References:

- [1] Payr, M., Glocker, Ch., Oblique Frictional Impact of a Bar: Analysis and Comparison of Different Impact Laws, To appear in Nonlinear Dynamics
- [2] Glocker, Ch., Aeberhard U., The Geometry of Newton's Cradle. Proceedings of the International Colloquium in Honour of the 80th Birthday of Jean Jacques Moreau, Montpellier, France, November 17--19, 2003, to appear.
- [3] Frémond, M. 1995 Rigid bodies collisions. Phys. Lett. A 204, 33-41.

ID of Contribution: 02 - 280

#### **TIME-DEPENDENT BILLIARDS**

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Properties of billiards with time-dependent boundaries are investigated. Planar billiards in the form of stadium and in the form of circle are studied.

It is shown that small oscillations of boundaries of dispersing and semi-dispersing billiards cannot qualitatively change their chaotic dynamics. Besides, it is found that, in general, for billiards the boundaries of which consist of neutral and focusing components (e.g. circle arcs) such oscillations do not give new aspects in the behaviour. At the same time, there is a specific class of billiards for which small oscillations of the boundary (under certain conditions) lead to stabilization of the dynamics and regularization of the billiard ball. This is expressed as vanishing the Lyapunov exponent.

ENOC-2005, Eindhoven, the Netherlands

The problem of a particle acceleration (so called Fermi acceleration) in the described d billiards is studied. Two cases of time-dependence are investigated: stochastic perturbations of the boundary and its periodic oscillations. Average velocities of the particle ensemble as functions of time and the number of collisions are obtained.

References:

- A.Loskutov, A.B.Ryabov and L.G.Akinshin. Mechanism of Fermi acceleration in dispersing billiards with perturbed boundaries. - J. Exp. and Theor. Physics, 1999, v.116, No5(11), p.1781--1797.
- [2] A.Loskutov, A.B.Ryabov and L.G.Akinshin. Properties of some chaotic billiards with time-dependent boundaries, J. Phys. A, 2000, v.33, No44, p.7973-7986.
- [3] A.Loskutov, A.Ryabov. Particle dynamics in time-dependent stadium-like billiards. J. Stat. Phys., 2002, v.108, No5-6, p.995-1014.

ID of Contribution: 02 - 294

# ON THE MODELING AND MODEL ANALYSIS OF A PIEZOELECTRIC IMPACT DRILLING DEVICE

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The modeling focus on a new technique for drilling of brittle materials is based on the mechanism of an impacting mass. This impacting mass transmits vibrational energy of a piezoelectric transducer as shock waves into a drill stem. This device is designed for planetary in situ rock sampling. The presented investigations are motivated by the question whether such a technique may be an alternative to classic actuator technologies in hand-held drilling devices, as for example in electropneumatic drilling devices. This requires a detailed understanding of the dynamics of the device which is missing to the present day. Therefore, a model is proposed which describes the transition of the mechanical vibrations of the transducer via the impacting mass as shock waves into the drill stem. Experimental results of a simple prototype device show for example irregular motion of the impacting mass. In the model analysis part the type of motion of the impacting mass is examined and discussed with respect to various design parameters. Bifurcation techniques for the non-smooth system will be investigated and a set oriented numerical approach will be proposed in order to derive a map of absorption probabilities for the model of repeated impacts of the impacting mass.

ID of Contribution: 02 - 362

# A NUMERICAL SCHEME FOR FINITE DIMENSIONAL FRICTIONLESS DYNAMICS WITH INELASTIC CONTACT AND A GENERAL INERTIA OPERATOR

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We consider a mechanical system with a finite degree of freedom, submitted to a perfect unilateral constraint: it must stay in a closed set L, defined by a single inequality. We consider the case of inelastic contact without friction and use Moreau's formulation of the dynamic as a measure differential inclusion. As we now assume that the inertia operator is state-dependent (in a Lipschitz-continuous way), this work generalizes results obtained by J. J. Moreau and M.M. Marques where the inertia operator reduced to identity. A numerical scheme is presented which enables us to approximate the solution of the Cauchy problem. As we are dealing with state-dependence we have to consider different kinetic energy norms in the estimates of the total variation of the numerical solution. By using the sweeping process technique, "variational formulation" and local kinetic metric we are able to show the convergence of the numerical scheme to a solution of the contact dynamic problem, which yields an existence result.

This work was performed under the supervision of Profs L. Paoli (Saint-Etienne) and M. M. Marques (Lisboa)

# DYNAMICS OF REPEATED IMPACTS IN PLASTIC VIBRATORY SEPARATOR

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The high quantity of plastic waste produced has resulted in a lack of suitable sites for landfilling. In view of the environmental problems, it is desirable that the performance of plastic recycling systems is improved so as to reduce disposal.

Plastic products usually consist of different types of plastics. Therefore, the separation of mixed plastics is one of the most important processes in a plastics recycling system.

This paper presents the results of experimental and analytical studies of the performance of a novel plastic separator. The separator consists of a vibratory conveyor equipped with two plate electrodes. The principle behind the separation technique is based on the difference in Coulomb force acting on the plastic particles after triboelectric charging. The motion of the plastic particles to be separated can be either of the sliding type, of the hopping type, or a combination of both. Therefore, the separator can be considered as a non-linear dynamic system experiencing repeated impacts between the plastic particles and the electrode. This paper presents a simplified model and analysis for the dynamic behavior of the plastic particles. An analytical solution is provided to estimate the recovery of plastics. The dynamic effects from the variation of several physical parameters are examined and important features for the effective design of the vibratory separator are presented.

#### References:

- Higashiyama, Y. and Asano, K. 1998. Recent process in electrostatic separation technology. Particulate Science and Technology. 16. pp. 77-90.
- [2] Inculet, I. I., Castle, G. S. P. and Brown, J. D. 1998. Electrostatic separation of plastics for recycling. Particulate Science and Technology. 16. pp. 101-106.

# ID of Contribution: 02 - 414

# NON-REGULAR EVOLUTION OF AN INCOMPRESSIBLE FLUID: THE EXAMPLE OF A COLLISION

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When a collision occurs between deformable solids and/or fluids, in a first step, very large forces and stresses are active during a very short time, in order to make the different velocities compatible. After this, the collision may still last (the colliding bodies keep in contact) but the evolution is smoother and can be modelised by regular equations.

The first step, called instantaneous collision, is described by an instantaneous discontinuity of the velocities, and the efforts are concentrated in time and modelised by percussions.

# STHENIC INCOMPATIBILITIES IN RIGID BODIES MOTION

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When a rigid body collides with a rigid plane, it is no longer possible to solve the smooth equations of motion because it is impossible to compute the acceleration. This is a cinematic incompatibility. Collision theory, assumes a time discontinuity of the velocity. This assumption associated with the basic laws of mechanics, i.e., equations of motions and constitutive laws satisfying the laws of thermodynamics, gives a solution to this problem by producing a predictive theory which takes into account the cinematic incompatibilities.

The motion of rigid bodies may involve friction which introduces reaction forces. These forces depend on exterior forces and velocities through algebraic or differential equations. It may happen that these equations have no solution whereas there is no cinematic incompatibility. Again it is no longer possible to solve the equations of motion. What occurs? May the predictive theory cope with this unexpected situation? Is it too schematic and has more sophistication to be added? In this case, one may think that the rigidity assumption has to be removed. We show that the above mentioned collision theory is rich enough to provide a solution and that there is no necessity to get rid of the rigidity assumption. We call this kind of incompatibility, a sthenic incompatibility (sthenic means relative to the forces). We describe an example depending on only one degree of freedom, the Klein sthenic incompatibility.

# MINI-SYMPOSIUM 3 Multibody Dynamics

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# SYMBOLIC-NUMERIC VIBRATIONS ANALYSIS OF THE SYSTEMS WITH MANY DEGREES-OF-FREEDOM

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Computer algebra techniques were applied to analyze vibrations of the systems with many degrees-of-freedom. For this purpose, two solution methods were compared from computer algebra point of view and harmonic balance method was chosen. System is divided into the linear and nonlinear parts. The linear part of the system can be formalized as usual and symbolic computations were applied to perform closed-form solution of the nonlinear part. The symbolic-numeric approach chosen, specially dedicated to systems with many degrees-of-freedom, affords various advantages: it leads to a simplification of the theoretical formulation of models, a considerable reduction in the size of generated equations and hence in resulting computing time, and also enhanced portability of the multibody models towards other specific environments.

ID of Contribution: 03 - 099

#### **MODELLING TELESCOPIC BOOM**

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In this paper, we shall extend an idea for the modelling flexible telescopic boom using a non-linear finite element method to the three dimensional case. The boom is assembled by Reissner's geometrically exact beam elements. The sliding boom parts are coupled together by the element, where a slide-spring is coupled to beam with the aid of a master-slave technique. This technique yields system equations without algebraic constraints. Telescopic movement is achieved by the rod element with varying length and the connector element expressing the chains.

Telescopic booms with flexibility are often used in machinery. A telescopic boom is a combination structure with two or more beam parts sliding between each other. The second part is usually translated via a hydraulic cylinder, whereas the other parts are extended by extraction chains and shortened by retraction chains. The flexible telescopic boom is a particular case of a flexible multibody system.

Modelling such a boom system by using commercial FE-software is cumbersome in plane case. The modelling in the three dimensional case is far more difficult due to joints and large rotations that model has to undergo. The modelling requires constraint equations for the telescopic members sliding between each other as well for rotational joints needed to revolve boom system members. Also the modelling the kinematics of the hydraulic cylinder movements may be difficult.

In this paper we introduce a method for modelling the boom system that is based on a non-linear finite element method where dependent variables are measured by means of an inertial frame. We choose the geometric exact approach over the fundamental beam hypothesis. The placement field of the beam element is measured with respect to an inertial frame and no co-rotational frames are involved. This yields a more complicated stiffness matrix but a very simple mass matrix and the constraint equations. Especially, flexible translational joint where the joint follows the beam central line has a rather simple form.

For the modelling of the constraint equations we use the embedding constraint equation method. The modelling constraint equation with an embedded technique can be completed either implicitly or explicitly. In rigid multibody dynamics, the implicit methods for numerically embedding constraints are usually realised. We note that these methods

are approximate and do not pay regard to the variability of a kinematic matrix, keeping the kinematic matrix fixed for certain moment. Methods involving an explicit embedding usually take into consideration this variability. In finite element literature, the explicit constraint embedding procedure is traditionally called a master-slave technique.

In flexible multibody dynamics, the embedding of constraint equations using the master-slave technique is not so complicated as is in the rigid multibody systems. Hence, it is possible to effectively utilise a master-slave technique that gives parametrization of the underlying constraint manifold. The resulting governing equations are a type of ordinary differential equations without constraint equations.

#### ID of Contribution: 03 - 113

# DYNAMICS OF ROTATIONAL MOTION OF THE SATELLITE IN SUNLIGHT FLUX

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We consider the motion of an axisymmetric satellite about its centre of mass under the solar radiation torques. The satellite has an axially symmetric solar stabilizer and a set of paddles arranged like a windmill. The total moment of forces may be represented as superposition of a conservative moment and a propelling torque.

The equations in evolutionary variables are used to study the attitude dynamics. The averaged system of equations is obtained. This averaged system admite first integral and an invariant measure, but in general case it is not integrable: for integrability we need another first integral. The phase space structure is investigated. The results of numerical simulations are presented as 2D-graphs.

ID of Contribution: 03 - 129

# A MULTIBODY DYNAMICS BENCHMARK ON THE EQUATIONS OF MOTION OF AN UNCONTROLLED BICYCLE

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In this paper we present the linearized equations of motion for a bicycle as a multibody dynamics benchmark. The results obtained by pencil-and- paper and two multibody dynamics software programs are compared.

The first publication of the correct linearized equations of motion for an upright uncontrolled bicycle was by F. J. W. Whipple [2] in 1899. Subsequently equations were derived by scores of people, some of these agree, others do not. The Master thesis by R. S. Hand [1] gives a detailed review and presents the equations that were derived by J. M. Papadopoulos.

The bicycle model we consider here consists of four rigid bodies, viz. a rear frame, a front fork and handlebar assembly, a rear wheel and a front wheel, which are connected by revolute joints. The contact between the knife edge wheels and the flat level surface is modelled by holonomic constraints in the normal direction and by nonholonomic constraints in the longitudinal and lateral directions. The rider is rigidly attached to the rear frame with hands free from the handlebar.

For the benchmark we consider the linearized equations for small perturbations of the upright steady forward motion. The entries of the matrices of these equations form the basis for comparison. Three different kinds of methods to obtain the results are compared: pencil-and-paper, the numeric multibody dynamics program SPACAR, and the symbolic software system AutoSim.

Because the results of the three methods on a exemplary bicycle are the same within the floating-point round-off error, we assume that the results are correct and can be used as a bicycle dynamics benchmark.

Finally, the world of bicycle dynamics is filled with folklore. For instance, some publications persist in the necessity of positive trail or gyroscopic effect of the wheels for the existence of a forward speed range with uncontrolled stable operation. It will be shown, by means of a counter example, that this is not necessarily the case.

#### References:

- Hand, R. S., 'Comparisons and Stability Analysis of Linearized Equations of Motion for a Basic Bicycle Model,' MSc Thesis, Cornell University, May 1988.
- [2] Whipple, F. J. W., 'The Stability of the Motion of a Bicycle,' The Quarterly Journal of Pure and Applied Mathematics, Vol. 30, 1899, pp. 312-348.

ID of Contribution: 03 - 157

# TOTAL LAGRANGIAN PARAMETRIZATION OF ROTATION MANIFOLD

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A finite rotation is a vector quantity, or more precisely, the finite rotation belongs to a tangential vector space on a manifold. This manifold is a Lie group of the special orthogonal tensors SO(3), also called the manifold of finite rotations or shortly the rotation manifold. In general, Lie-groups are noncommutative groups which are also differentiable manifolds such that their differentiable structure are compatible with their group structure for the definitions of general Lie-groups. As it is shown in [1] that material incremental rotation vectors, material angular velocity vectors, and material angular acceleration vectors belong to the different tangent spaces of the rotation manifold SO(3). Hence, the direct application of the material incremental rotation vector with standard time integration methods yields serious problems: adding quantities which belong to the different tangent spaces.

There are two main approaches in engineering science for the time-integration of finite rotation with a three-parametric presentation [2]. One approach, which we call Eulerian formulation, directly applies a spin rotation vector, angular velocity vector and angular acceleration vector in their formulation. However, this approach suffers problems described above.

Another approach, which we call updated Lagrangian formulation, applies a current reference placement, which are updated an incremental way. In this approach, updated rotation vectors and their time derivatives belong to the same tangential space of rotation and do not suffer problems like in Eulerian formulation.

Moreover, we could present the third approach, called total Lagrangian formulation, where a reference placement is permanently the initial placement and a total rotation vector and its time derivatives are used as unknown variables. Well-known singularity problems at full-angle and its multiples can be bypassed with introducing a complement rotation vector. A rotation vector and its complement rotation vector are the parametrization charts of the rotation manifold SO(3). We could represent the rotation manifold globally with these two parametrization charts. When a rotation angle exceeds straight-angle, we accomplish the change of parametrization, giving a new rotation angle smaller than straight-angle. Thus, we get out of the singularity problems at full-angle.

We introduce the total Lagrangian parametrization for a rigid body motion including fully consistent tangential tensors; in addition, a numerical example is given. We note that the total Lagrangian parametrization can be also applied in beam and shell theory.

References:

- [1] Mäkinen, J., (2001), "Critical Study of Newmark-Scheme on Manifold of Finite Rotations", Computer Methods in Applied Mechanics and Engineering, 191(8-10), pp. 817-828.
- [2] Géradin, M., Cardona, A., (2001), Flexible Multibody Dynamics: A Finite Element Approach, John Wiley & Sons, Chichester.

ID of Contribution: 03 - 158

# COUPLING OF MODULAR SUBSYSTEMS IN A MECHATRONIC SIMULATION ENVIRONMENT

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For the simulation of coupled mechatronic systems the interdependencies of components of multibody systems (MBS), control engineering and hydraulic systems, have to be taken into account. This way it is possible to analyze the dynamic behavior of the whole system at once. Large dynamic systems with components from different physical domains often show significant differences in eigenvalues. Due to stiff springs, mass differences, high frequency controllers, or hydraulic components with small control volumes, the system behavior is characterized by a subset of eigenmodes that lie far beyond the interesting frequencies. For the numerical solution the integrator is forced to reduce the step size radically to meet accuracy requirements, see [Kübler00]. In order to avoid this problem, the system can be subdivided and specialized integration methods can be used for the solution of subsystem equations. This approach is called partitioned integration, see [Rentrop85]. For the usage of partitioned integration it is necessary to exchange coupling data during the integration. Though, especially for systems with a homogenous structure, partitioned integration may be inefficient. Additional effort in data exchange and limitations of the integrator step size, regarding the communication step size, may slow down the overall integration process enormously. Furthermore rounding errors and other inaccuracies have a negative influence on stability properties.

For the simulation of mechatronic systems, an approach was implemented which is capable to integrate the whole system at once or use partitioned integration. It has to be taken into consideration that the stability of the integration process depends on the tightness of coupling of the subsystems. With the help of a stiffness ratio it is possible to evaluate if, and in how many subsystems the system has to be separated to guarantee a stable and efficient integration. The subsystems can be evaluated independently in separate processes that communicate with each other, controlled by a superior entity.

If the system is divided into subsystems characterized by heavy changes in their dynamic behavior during the integration, the efficiency can be increased enormously by an automatic control of the communication step size. Controlling the relative error by Richard extrapolation [HairerNorsettWanner93] has the advantage, that the control is not only based on coupling information and the order of local convergence of the methods, but on the system dynamics related to the coupling frequency.

For the realization of separated processes a shared data management was implemented, which implies a defined direction of data flow, for all processes. Furthermore the estimation of the coupling variables was improved by cubic-spline interpolation for input data, and polynomial extrapolation for output data.

Typical elements of mechatronic systems are described by discontinues functions. By discontinuities the so called Lipschitz condition is violated and the uniqueness and general existence of the solution can not be guaranteed, see [HairerNorsettWanner93]. For this reason the separated processes are able to temporarily stop the integration, search for a zero crossing and restart the integration with adjusted states.

- [1] [HairerNorsettWanner93] Hairer, E.; Norsett, S.P.; Wanner, G.: Solving Ordinary Differential Equations I -Nonstiff Problems, Berlin, 1993
- [2] [Kübler00] Kübler, R.: Modulare Modellierung und Simulation mechatronischer Systeme, Fortschritt-Berichte VDI, VDI Verlag GmbH, Düsseldorf, 2000

[3] [Rentrop85] Rentrop, P.: Partitioned Runge-Kutta Methods with Stiffness Detection and Step Size Control, Numerical Mathematics, 47:545-564, 1985

ID of Contribution: 03 - 176

# PRACTICAL STABILITY ANALYSIS OF MULTIBODY SYSTEMS WITH APPLICATION TO THE BRAKING OF A MOTORCYCLE

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The stability of vehicles has been the subject of several experimental and theoretical studies in the past. Because of the transient character of the braking procedure over a finite time, traditional stability concepts are of little use, because they cannot predict instability. This was already remarked in the first thorough theoretical investigation on braking of vehicles [1]. Often, the condition on the real parts of the eigenvalues of the time-varying linearized system is used, which can only yield reliable results if the linearized equations change slowly. In order to have a precise and useful stability criterion, we propose the application of the concept of practical stability [2]. This takes into account the size of finite perturbations that can occur in the real system and only demands that the deviations from the unperturbed solution remain within some specific bounds.

A rigorous analysis of practical stability requires a large number of simulations. The work can be reduced to a manageable amount by only considering the linearized equations and assuming that the set of actually occurring perturbations as well as the set of allowable perturbations can be approximated by the interior of a hyperellipsoid. Then a practical stability index can be defined, which measures the growth of perturbations and can be used as a quantitative measure for the margin of stability.

The calculation procedure consists of the following steps. The equations of motion for the multibody system are derived with the aid of the symbolic multibody code AutoSim. From these, the linearized equations can be derived with symbolic differentiation. The non-linear equations together with a full set of linearized equations are integrated over the desired finite time interval, from which the practical stability index can be derived. The results from the linearized analysis are finally checked by giving some finite initial perturbations in the most critical directions and observing the resulting behaviour of the system in a non-linear simulation.

The procedure is applied to the analysis of the stability of a motorcycle during braking. The results show that for moderate levels of deceleration, rear wheel braking has a destabilizing effect and front wheel braking has a stabilizing effect. For high levels of deceleration, however, locking of the front wheel leads to a more severe instability than locking of the rear wheel.

It can be concluded that the proposed procedure for the analysis of the practical stability of transient phenomena in multibody systems can provide insight in the growth of perturbations with a limited computational effort.

- W.T. Koiter and H.B. Pacejka, 'On the skidding of vehicles with one or more locked wheels', Proceedings of the Institution of Mechanical Engineers 183 (3H) (1968/9), pp. 3-18.
- [2] J. La Salle and S. Lefschetz, Stability by Liapunov's Direct Method, With Applications, Academic Press, New York, 1961.

#### ID of Contribution: 03 - 177

# **MODELING CONSTRAINTS BY COMPLIANT JOINTS**

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Use of compliant joints (CJ) gives an alternative to constraint equations in modeling multibody systems (MBS) with redundant coordinates due to closed kinematic loops. Cutting some joints to open loops leads to DAE, and requires special solvers for numeric integration of equations. CJ replace the corresponding algebraic equations by applied forces and torques, which depend on the constraint discrepancy, its time derivative etc. [1].

In this paper some properties of solution of equations of motion in presence of the CJ are studied with the help of the singular perturbation theory. In particular, it was shown that the known Baumgarte stabilization is a particular case of the CJ.

Explicit mathematical models of CJ are given both for lower and higher kinematic pairs. To reduce the computational expenses due to high stiffness of equations for MBS with CJ, analytic expressions for approximate Jacobians corresponding to stiff forces are derived. The Jacobians are necessary for implicit solvers.

It is shown that combination of CJ with the block-diagonal local Jacobians for stiff forces [2] allows an effective adaptation of the articulated body algorithm to simulation of MBS with closed loops. CJ are also useful for simulation of systems with unilateral constraints and friction.

Some other features of use the CJ, such as initial value problem, reduction of communication data size in parallel simulation of large MBS with the subsystem technique [3] are discussed.

Applications of CJ to simulation of some technical systems, in particular to analysis of dynamics of a high-speed track carrier, are considered.

References:

- [1] Schiehlen W., Rukgauer A., Schirle Th. Force Coupling Versus Differential Algebraic Description of Constrained Multibody Systems, Multibody System Dynamics 4 (4), 2000, 317-340.
- [2] Pogorelov D. On Calculation of Jacobian Matrices in Simulation of Multibody Systems, Preprints of the NATO Advanced Study Institute on Virtual Nonlinear Multibody Systems. V.1. Edited by W. Schiehlen and M. Valasek.-Czech Technical University in Prague, Prague, June 23 - July 3, 2002, 159-164.
- [3] Pogorelov D. Yu. On numerical methods of modeling large multibody systems, Mech. and Mash. Theory 34, 1999, 791-800.

#### ID of Contribution: 03 - 181

# MODELLING AND ANALYSIS OF GEAR DRIVE NONLINEAR VIBRATION

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The presented modal synthesis method used for the modelling of gear drive nonlinear vibrations is based on the system decomposition into subsystems, modelling of linearized uncoupled subsystems by FEM, discretization of nonlinear couplings between subsystems, modelling of gyroscopic effects of the rotating subsystems and on an assembling of the condensed mathematical model of the system. The condensed mathematical model of the coupled system is created by means of spectral and modal submatrices corresponding to the lower vibration mode shapes of the mutually uncoupled and undamped subsystems [1]. This methodology allows to model very complex systems with complicated structure and nonlinear couplings.

ENOC-2005, Eindhoven, the Netherlands

In this paper is the emphasis laid on modelling of nonlinear discrete couplings between subsystems, thus on modelling of rolling-element bearing and gear couplings. The model of gear couplings allows to respect the gear mesh interruption and impact motions of gears if the tooth backlash is considered. In papers [1], [3] were considered linear models of roller-element bearings characterized by in-line stiffness in a static force direction and by the lateral stiffness. In this contribution is considered real number of roller contact forces acting between the journals and the outer housing, that is modelled as 3D continuum by FEM. This model of bearings is nonlinear, because the contact forces are expressed as nonlinear functions of radial deflections for every roller-element.

Further this work deals with the analysis of operation modes of gear drives, when in consequence of low static load and of internal excitation generated in gear meshing, comes to the gear mesh interruption. In phases of gear mesh interruption the system vibration is characterized by impact gear motions, bifurcations and chaotic motions [2]. The gear drive motions are explained by direct time integration method. The presented approach to the nonlinear vibration analysis of the large multibody gear drives is applied to the test gearbox, that consist of the driving and driven shaft and a housing. The shafts with gears are joined together by gear couplings and with housing by roller-element bearings.

References:

- Zeman V., Byrtus M., Hajzman M.: Nonlinear vibration of gear drives. CD-ROM Proceedings of XXI International Congress of Theoretical and Applied Mechanics, ISBN 83-89687-01-1
- [2] Thompson J. M. T., Stewart H. B.: Nonlinear Dynamics and Chaos. John Wiley & Sons, Chichester 2002, ISBN 0-471-87684-4.
- [3] Zeman V., Hlavac Z.: Mathematical modelling of vibration of gear transmissions by modal synthesis method. Proceedings of the Ninth World Congres on the Theory of Machines and Mechanisms, Vol. 1, pp. 397-400, Politechnico di Milano, Italy 1995.

ID of Contribution: 03 - 188

# AVOIDING CHATTER BY TUNING THE DYNAMICS OF THE MACHINE STRUCTURE WITH A DAMPED VIBRATION ABSORBER

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In the field of machining technology, productivity in the sense of high material removal rates at acceptable accuracy and surface finish is restricted mainly by the occurance of machine tool chatter. For both turning and milling lots of effort is spent in investigating and influencing machine tool chatter since the late 1950s. One of the most important chatter mechanisms in machining is the so-called regenerative chatter. In order to investigate the regenerative effect, the dynamics of the cutting process must be modelled as a time-delayed feedback system. The transfer function of the machine structure can be obtained from measurements of the real system or from a finite element or flexible multibody system model of the machine. Beneath the transfer functions of the machine tool and the workpiece, dynamic stability depends on the process parameters width of cut and cutting frequency. Assuming linear system behavior, the border of stability, the so-called stability lobes, can be achieved applying Nyquist's theorem.

In order to enlarge the regions of stability, various approaches have been investigated. On the one hand, the dynamics of the process is influenced by varying the cutting frequency using variable pitch cutters or varying the turning speed during the process. On the other hand, the system dynamics of the machine tool is modified by changing the design of the tool or applying additional devices. In recent years, the application of active vibration control methods for suppressing chatter has been object of a couple of research projects, while the potentials of passive vibration control is nearly not investigated. Here, the effect of increasing the threshold of stability, i.e. the minimum value of critical width of cut over the regarded range of cutting frequency, has been shown theoretically.

In this contribution, the authors want to discuss the influence of passive vibration control on the shape of the stability lobes of cutting processes. In order to understand the basic mechanisms, we investigate the simplest case consisting of an orthogonal turning process with a simplified 1-DOF lumped mass machine model. An additional damped oscillator (absorber) is attached to the machine model to tune the system with the aim of maximizing the stable regions. In contrary to previous work found in literature, it is not the aim to increase the threshold of stability only, but to expand both the width and height of the stability peaks between the lobes in order to increase the maximum material removal rate with stable cut and to facilitate the exploitation of the peaks. The design variables for the optimization are the mass, the spring constant and the damping coefficient of the absorber. It is shown that not only the threshold of stability, but also the width and height of the stable peaks can be strongly influenced by tuning the machine system with a damped vibration absorber.

ID of Contribution: 03 - 246

# THREE-DIMENSIONAL MODEL OF COMBINED DRY FRICTION AND ITS APPLICATION IN NON-HOLONOMIC MECHANICS

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An essentially new three-dimensional model of combined dry friction is presented. The model is a logical generalization of Zhuravlev's two-dimensional model to the case of an arbitrary shape of the contact area and an arbitrary distribution of contact stresses. By a model of dry friction we understand the relationships between forces, torques, and velocities, the physical nature of the phenomena occurring within the contact area being not considered. The dimension of the model is defined as the number of kinematical parameters determining the force interaction. The model involves the replacement of exact integral expressions for the force and torque components, formed with the assumption that Coulomb's friction law is valid at each point of the contact area, by appropriate Pade approximations. This substantially simplifies the combined dry friction model, making the calculation of double integrals over the contact area unnecessary. Unlike available models, the model based on the Pade approximations enables one to account adequately for the relationship between force and kinematical characteristics over the entire range of angular and linear velocities. The approximate model preserves all properties of the model based on the exact integral expressions and correctly describes the behavior of force and torque components and their first derivatives at zero and infinity. When using this model to solve a problem of rigid body dynamics, one does not have to calculate the integrals to determine the coefficients of the Pade approximation. The desired coefficients can be identified from experiments. The threedimensional model under consideration can be regarded as a rheological model of combined dry friction. Using this model, we have solved anew a classical problem of non-holonomic mechanics of the motion of a skate along a horizontal plane. The skate was modeled as a thin rod. The normal pressure distribution along the length of the skate was assumed to be uniform. For this problem, one can obtain an analytical solution both for the dry friction model based on the Pade approximations and the model based on the exact integral expressions and compare the results.

#### ID of Contribution: 03 - 295

# **USE OF AIR SPRING ELEMENTS FOR VIBRATION INSULATION**

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Steadily increasing requirements on accuracy and rapidness of micromechanical production processes enforce the improvement of working conditions inevitably. Especially vibration insulation plays a significant role, intensified even more by the development of nano-technology. As experience shows, an effective solution of vibroinsulation problems is the application of special membrane air springs as supporting elements of heavy platforms. However, the radial damping of such an insulator type lags behind its axial behaviour. Therefore, we balance this drawback for horizontal platform motion by additional air springs in horizontal direction. Such a concept can be driven as a pure passive system or better by active control of the horizontal air springs in order to achieve a higher insulation effect. However, by all control concepts the right choice of the control parameters has to be achieved requiring a model of the whole system consisting of platform, passive vertical air springs, horizontal pneumatic actuators and control.

An air spring insulator consists of two connected chambers and a roller membrane with a plunger, which can move relative to the insulator body. Through this movement the pressure is changing resulting in an air flow between the

ENOC-2005, Eindhoven, the Netherlands

chambers where damping is caused by air viscosity. The governing equation of such a system can be found from force balance, thermodynamic state equations and a description of the air flow. It turns out, that the air spring behaves like a linear spring in parallel with a series connection of a second spring with a linear viscous damper. Such a model describes both radial and axial dynamics of the insulator and serves for further analyses of the platform dynamics.

The same air spring is used for active insulation where it acts as executive part of an actuator chain consisting of air source, active pressure regulator and air spring. The active pressure regulator is realized by a controlled 3/2-way valve.

Models for air spring and the pressure regulator are developed from physics and validated by an experimental setup which also serves for parameter identification. Identification is accomplished by means of a comparison between simulation and measurement utilizing parameter optimization algorithms.

Based on the resulting model, the horizontal vibration control of the platform can be analyzed and optimized in order to find appropriate control parameters. Suitable criteria have to be defined taking into account insulation requirements, damping behaviour and decay time after excitation of the platform by internal forces.

#### ID of Contribution: 03 - 309

# DYNAMICAL MODELING AND SIMULATION OF CALENDERING ROLL CONTACT

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The rolling contact of two rolls in a paper calendering machine is studied. The calendering units are used at the end phase of the paper manufacturing process to produce paper with constant thickness. In the unit the rolls are compressed together by hydraulic actuators to create optimal line loading. Then during calendering the paper web enters to this nip of rolls and undergoes deformations and surface polish to achieve equal thickness. It has been experienced that the dynamics of this system is sensitive to the operational and constructional parameter selections and this can create undesired vibrations during calendering with an unfavorable setup. The problem is that it is difficult to predict accurately enough the dynamics of the system by using current design methods.

The aim in this paper is to determine some of the dynamical behavior of calendaring by creating a numerical time domain simulation model. The model is based on the test calendering unit in university's laboratory environment. This test unit is about half scale of the real size machine with 4 meter length cast iron rolls and it includes build-in wireless strain and acceleration measurement and data transfer system. However, the paper web has not been included in the test unit, but this still is very beneficial environment to verify the results of numerical models.

The simulation model is based on multibody dynamics. The equations of motions for each roll are expressed inside a rotating coordinate frame and by using modal decoupling with sets of lowest semi-definite eigenvectors. The rolls are modeled like simply supported beams but by using 3D continuum finite element meshes. The contact of the rolls is described by contact force coupling in the right hand side of the equations. One of the rolls is coated by soft polymer layer and another has hard surface without coating. The contact stiffness between the rolls is calculated according to the polymer layer stiffness. Because solid element meshes are used and the rolls are making rigid body spin rotation, the contact line load needs to smoothly move on the surfaces within each element and across element boundaries. This has been modeled by describing equivalent element nodal forces to the surface elements as a function of the rigid body rotation angle.

The solution of these system equations requires a non-linear time integration procedure and the time domain simulation is implemented in MATLAB environment. The numerical circumferential strain responses have been compared to the measured data and very good correlation in steady-state periodicity has been achieved (ie. the shape of the responses are similar as measured). The strain amplitudes also match, but strongly depend on the contact stiffness and especially on the amount of the contact line load.

References:

[1] M.A. Crisfiled: Non-linear Finite Element Analysis of Solid and Structures, John Wiley & Sons 1997

- [2] M. Gérandin, D. Rixen: Mechanical Vibrations, John Wiley & Sons 1997
- [3] A.A. Shabana: Dynamics of Multibody Systems, Cambridge University Press 1998

ID of Contribution: 03 - 339

#### STABILITY OF MULTIBODY SYSTEMS WITH DIGITAL FORCE FEEDBACK

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Multibody systems are often used to perform operations where force feedback information can be useful to control interaction forces developed in the system. As an example, we can mention polishing or other manufacturing operations performed by robots where the forces and moments developed between the end effector and the environment need to be controlled to achieve good product quality. In such cases, the robot performs a so-called constrained operation, and force feedback can be used to control the constraint forces and moments developed during the operation.

Most studies regarding force feedback based control have been performed in the area of robotics considering multibody models. The methods developed for the analysis and design of force control algorithms are mainly based on continuous-time models of multibody systems and their controllers. However, the force feedback received from force/torque sensors is usually a digital signal, and the implementation of force control algorithms is also normally done using digital controllers. Techniques are available to transfer the whole system to the discrete time domain and do numerical analysis. However, such formulations do not give analytical insight into the dynamics behaviour induced by the interaction of digital force feedback and a continuous-time multibody system. In this paper, we propose a novel formulation to gain such an insight.

We will use a continuous/discrete-time model for multibody systems with digital force feedback based control. This makes it possible to establish a detailed analytical investigation to provide insight into the complex physical phenomena governing the dynamic behaviour of such systems. We will present a detailed analysis regarding this intricate dynamics. We will particularly address the stability characteristics of multibody systems.

The analysis relies on a formulation that enables the user to connect the complex, nonlinear models of multibody systems to a set of abstract oscillator models to capture the important effects of digital force feedback. This formulation employs a unique decomposition technique developed for admissible and constrained motions of mechanical systems. It results in a model representing the dynamics of the constrained motion of the system. This model can be further modified using modal decomposition. After this operation, the constrained motion of the system is represented with a set of uncoupled, abstract oscillators. These oscillator models make it possible to perform a detailed, closed-form mathematical analysis of the stability behaviour. These results can then be transformed back to characterize the behaviour of the multibody model that represents the actual physical system. Detailed stability charts can be established for representative ranges of parameter values characterizing the mechanical system, the force feedback, and the control algorithm. These stability charts show very interesting features regarding the dynamics of the system. The stable and unstable domains and their boundaries reveal that quite non-trivial behaviours exist under digital force feedback. For example, unexpected, low frequency vibrations can be developed even at very high sampling frequencies. We will illustrate the results using examples taken from robotics and virtual reality applications.

# DEPLOYMENT BIFURCATION AND MOTION SIMULATION OF TETHERED SATELLITE

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The tethered satellites are the longest structures ever flown in space and its dynamic behavior involve oscillations over a wide range of frequencies. Moreover, higher frequency oscillations, called 'dynamic noise,' which are essentially random, are more difficult to predict. Both the satellite and tether move through the ionosphere. They 'cut' through magnetic field lines generating electromotive force. By exploring the dynamics of tethered systems, we may develop a variety of possible applications, such as extremely long antenna, generating electrical power or propulsion for future spacecrafts and space stations [1].

Future applications of long tethers (till 240 kilometers) demand development and verification of reliable theoretical and computational models. The tethered systems (satellites, mutually connected stations or spaceships, tethered astronauts working outside in space and etc.) are extremely flexible structures. The tether behavior could not be treated as motion of structures connected by simple ropes. In most cases the tether plays the role of an umbilical connection along which information, electricity, fuel and etc. is transferred. The tether internal bending stiffness, as well as, the force relation between bending and transversal motion cannot be neglected in the dynamics simulation.

Shabana [2] discussed large flexible deflections developing generalized Newton – Euler dynamic equations for rigid and flexible multibody systems. He used the position of the reference frames and relative displacements of the deformable bodies as coordinates in the equations. In the paper a general recursive algorithm for computer code generation of dynamic equations of rigid and flexible multibody systems is applied for simulation of the nonlinear motion of Short Electro-Dynamic Tether. Novel Generalized Newton – Euler equations [3] are applied for effective modeling of the inertia terms in the dynamic equations. The equations proposed here are invariant to the coordinates, and the dynamic equations, just as for the classical Newton – Euler equations, are derived with respect to the quasivelocities and accelerations. The method enables both absolute and relative nodal coordinates to be used to simulate the flexible deflections. The advantages of the algorithm are demonstrated modeling the deployment and vibrations of a tethered satellite with two branches. Different initial deviations of the endpoint branches (satellites) and the influence over the basic station deviation are analyzed. Loss of stability of the tether during the deployment is simulated.

#### References:

- [1] NASA MSFC Program Development: http://liftoff.msfc.nasa.gov/academy/tether/tethers.html.
- [2] Shabana A.A., Dynamics of Multibody Systems (second edition), John Wiley & Sons, New York, 1998.
- [3] Zahariev E.V., Generalized Newton Euler Dynamic Equations, Proc. 21st International Congress of Theoretical and Applied Mechanics (CD-ROM), August 15 21, 2004, Warsaw, Poland, pp. 1-2.

ID of Contribution: 03 - 407

# DYNAMICS AND IDENTIFICATION OF VEHICLE MODELS WITH PIECEWISE LINEAR SUSPENSIONS

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In the first part of this study, a systematic methodology is applied for obtaining the dynamic response of complicated vehicle models with nonlinear suspensions. Namely, the vehicle nonlinearities arise due to the function of the suspension dampers, which assume a different damping coefficient in tension than in compression. The suspension

springs may also possess piecewise linear characteristics. These lead to models with parameter discontinuities. The equations of motion of these models are first derived by applying the method of finite elements. Since the resulting number of degrees of freedom is quite large (in the order of a million), appropriate component mode synthesis techniques are first applied. This reduces drastically the dimension of the original system without affecting the accuracy of the calculations within a preselected forcing frequency range. On the other hand, this allows the application of several methods which are effective for scale dynamical systems. First, techniques leading to direct determination of steady state response to periodic forcing are applied. Then, a statistical system identification methodology is applied for performing parametric identification and fault detection studies in nonlinear vehicle systems. Emphasis is put on investigating unidentifiability issues arising in the system identification of nonlinear systems and the importance of sensor configuration and excitation characteristics in the reliable estimation of the model parameters. A methodology is proposed for designing the optimal sensor configuration (number and location of sensors) so that the corresponding measured data are most informative about the condition of the vehicle. The effects of excitation characteristics on the quality of the measured data is systematically explored. The effectiveness of the system identification and the optimal sensor configuration design methodologies is confirmed using simulated test data from a classical two-degree of freedom quarter-car model as well as from more involved and complete vehicle models, including four-wheel vehicles with flexible body.

#### ID of Contribution: 03 - 421

# A CONTROL STRATEGY FOR THE DYNAMICS OF A MOTORCYCLE, INCLUDING RIDER

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The stable motion of a motorcycle requires that its banking is kept under control by the rider motion, who leans to the left and right, and by the steering actions of the rider over the handlebar. Depending on the size and characteristics of the motorcycle, the anthropometry of the rider, the velocity of the ride, the road where it runs and on the rider' style the vehicle steering may require more or less preponderance of the rider banking over the handlebar steering. Certainly, among all road vehicles, motorcycles are those that not only have a more complex dynamics but also have a less obvious steering control. Therefore, it is not surprising that few works address the development of computational models for the control of the stability and maneuverability of motorcycles. This work proposes a control model for the stability of a motorcycle for prescribed maneuvers. A simplified model for the motorcycle, based on a close form of the dynamic equations of the motorcycle, provides the basis for the controller, which is based on an optimal control paradigm, the linear quadratic method. This model uses the angles between the rider and the motorcycle and of the handlebar as control variables and the banking angle of the motorcycle as the objective of the control. This controller, implemented in MATLAB, acts upon a detailed multibody model of a motorcycle, implemented in the general purpose multibody code DAP3D. The motorcycle model includes all the mechanical components of the vehicle, with a detailed representation of its suspension systems, and uses a tire model with comprehensive slip, based on a torus geometry, to represent the interaction between the vehicle and the ground. Moreover, a detailed biomechanical model of the rider, where a realistic anthropometry and all relevant anatomical segments are represented, is included with the vehicle model. The methodology proposed here is applied to the control of the motion of a motorcycle for a prescribed trajectory. The targeted banking angle of the motorcycle, required as reference by the controller, is calculated in each instant as a function of the instantaneous radius of the prescribed trajectory and the velocity of the motorcycle. The results of the application allow discussing what the preferred strategies to steer a motorcycle are and allow devising the characteristics required for the development of virtual drivers for motorcycles.

# **MINI-SYMPOSIUM 4**

# **Nonlinear Stochastic Systems**

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# **NEW SCENARIO FOR TRANSITION TO SLOW 3-D TURBULENCE**

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Numerical-analytical study of the three- dimensional nonlinear stochastic partial differential equations, analogous to that proposed by V. N. Nikolaevskii [Recent Advances in Engineering Science (Springer - Verlag, Berlin. 1989)] to describe longitudinal seismic waves, is presented. The equation has a threshold of short-wave instability and symmetry, providing long-wave dynamics. The results of computation are in a sharp contradiction with Tribelsky M.I and K. Tsuboi's work (Phys. Rev. Lett. 76 1631 (1996)), in which the influence of the thermal fluctuations was not taken into account and a principally erroneous scheme of numerical modeling of chaos on the lattice was used. Proposed new mechanism for quantum chaos generating in nonlinear dynamical systems. The hypothesis is said, that physical turbulence could be identified with quantum chaos of considered type.

#### ID of Contribution: 04 - 016

# **COHERENCE RESONANCE IN NOISY MACHINE TOOL VIBRATIONS**

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In this talk we analyze the amplification of noise in a model of machine tool chatter. The system is developed to consider sources of noise due to variations in the material properties of the material being cut. It is based on a simple model of machine tool chatter, which has been studied in the deterministic case [1]. The structure of the stability region for the deterministic problem has implications for the operation of the system. Due to the increased range in a material parameter for certain narrow regions of stability, it is often beneficial to operate the system in a range which is near the deterministic stability boundary predicted by theory.

In our analysis we show that the sources of both additive and multiplicative noise can have a significant effect on the dynamics, even when the noise is small. The result is due to the fact that by operating near the stability boundary, one operates near a subcritical bifurcation. Through resonances with the additive noise, small oscillations can be amplified, which then lead to large stochastic effects through the multiplicative noise. We verify this through simulations and a multi-scale analysis [2], which allows one to isolate the resonance effects from the fast oscillations related to the natural modes of the system.

There are several valuable aspects of the multi-scale analysis. It relates the proximity of the bifurcation to the amplitude of the noise, which translates into important scaling relationships for the dynamics. Projections onto the resonant modes yield a reduced system which provides an efficient means of simulation as well as a quantitative description of the variability in the machine tool vibrations. This approach has been used to study other systems with oscillations. For example, for oscillators near bifurcations in systems without delay, such as the van der Pol-Duffing oscillator with multiplicative noise, we obtain results which are equivalent to other averaging methods. The method has been applied to linear and logistic models with delays and additive and multiplicative noise [3], where resonances also play an important role.

- [1] G. Stepan, Modelling nonlinear regenerative effects in metal cutting, Phil. Trans. R. Soc. Lond. A (2001) 359, pp. 739-757.
- [2] R. Kuske, B. L'Esperance, and T. Soo, Resonance effects with noise in metal cutting, in preparation.

[3] M. M. Klosek and R. Kuske, Multi-scale analysis of stochastic delay-differential equations, in review.

#### ID of Contribution: 04 - 017

# LYAPUNOV EXPONENTS ASSOCIATED TO CRITICAL EIGENVALUES OF THE SCHROEDINGER OPERATOR WITH RANDOMLY PERTURBED PERIODIC POTENTIAL

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Investigating the optical effects of periodic media with impurities (e.g. light traveling through air glass air glass etc.) leads, in the simplest situation, to a scalar Schroedinger operator with periodic potential that is perturbed by a stationary noise process of small intensity. Our interest is in the behavior of the eigenfunctions of the Schroedinger operator, given an eigenvalue that is the square of the frequency of the traveling wave.

The eigenvalue problem for the unperturbed operator yields the classical band-gap structure for the intervals of the eigenvalues (propagation of waves if the eigenvalue is in a band, and localization if the eigenvalue is in a gap). The asymptotics of the Lyapunov exponents of the eigen functions (as the noise intensity tends to zero) gives insight into the effect of the random perturbation of this band-gap structure, especially for eigenvalues at the boundary of a band or gap.

References:

- [1] R. Carmona and J. Lacroix, Spectral Theory of Random Schroedinger Operators, Birkhaeuser 1990
- [2] M. Pinsky and V. Wihstutz, Lyapunov exponents of real-noise driven nilpotent systems and harmonic oscillators, Stochastics and Stochastic Reports 35 (1991), 93-110

ID of Contribution: 04 - 029

# **RESPONSE PDF OF A STIFFNESS-CONTROLLED SYSTEM BY THE PATH INTEGRATION METHOD**

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Finding a response probability density function (PDF) of a stochastic, nonlinear system is a desirable and yet extremely challenging task. Exact expressions for the response PDF are known only for certain types of nonlinear systems [1]. For systems with small nonlinearities various approximate techniques have been developed for estimating their response PDF [1]. Nevertheless, when a system possesses non-small nonlinearities, most of the methods fail to predict a response PDF accurately and therefore one has to use one of the numerical techniques available today to obtain the desired result. Direct numerical solution of different types of Fokker-Planck-Kolmogorov (FPK) equations have been performed by finite difference as well as finite element methods. However, some problems with special types of strong nonlinearities such as the "signum" function are not easy to deal with by the FPK equation approach due to the fact that it leads to the occurrence of a delta function in the corresponding FPK equation.

Another approach is the path integration (PI) method [3,4]. The main idea of the approach is to iteratively improve an estimate of the PDF until some sense of convergence is reached, rather than looking at realizations of the process. The PDF at time t can be expressed from the PDF at t' = t - D t by the total probability law. The (incremental) transition probability density function (TPD) in this formula is expressed by the noise term and the trajectories of the deterministic part of the system. The numerical integration is performed using an interpolation method over the previous PDF, and a Runge-Kutta scheme is used for the time stepping method.

The primary goal of this paper is finding the response PDF for a certain, strongly nonlinear system by the PI method. The authors consider a system with strong, "signum" type nonlinearity, a so-called stiffness-controlled system. This is an undamped SDOF system, excited by Gaussian, zero mean white noise. The stiffness term in the governing equation of motion contain regular linear stiffness as well as an additional term proportional to a parameter R, which is not necessarily small, multiplied by a signum of displacement and velocity. Therefore, energy losses in the system happen due to proper switches, which increase and decrease the system's apparent stiffness. Thus, it is of interest to find the response PDF of such a system for the whole range of values for the parameter R varying from 0.1 up to 0.99. The former provides the case of small nonlinearity, which can be treated approximately, whereas the latest corresponds to the case of strong nonlinearity.

#### References:

- [1] Lin Y.K., Cai G.Q. Probabilistic Structural Dynamics. New York, McGraw-Hill, 1995.
- [2] Naess, A. and Johnsen, J.M.: "Response statistics of nonlinear, compliant offshore structures by the path integral solution method'. Probabilistic Engineering Mechanics, Vol. 8, No. 2, 1993.
- [3] Naess, A. and Moe, V.: "Efficient Path Integration Methods for Nonlinear Dynamic Systems". Probabilistic Engineering Mechanics, Vol. 15, No. 2, pp. 221-231, 2000.

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# NONLINEAR OSCILLATIONS IN MULTILAYER SYSTEMS

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It is well known, that the stability problem for the mechanical equilibrium state in a two-layer system is not self-adjoint, thus an oscillatory instability is possible. The oscillations produced by the hydrodynamic and thermal interaction between convective motions on both sides of the interface have been found in the case of the transformer oil - formic acid system (see [1]). However, the minimum value of the Rayleigh number for the oscillatory instability was higher than that for the monotonic instability.

In order to decrease the oscillatory threshold below the monotonic one, some "artificial" systems have been suggested. Nevertheless, the oscillatory instability for any real system of fluids was not predicted. Oscillations just above the instability threshold have been observed in the experiments of Degen et.al. (see [2]), though the linear stability theory for the onset of the buoyancy convection has predicted a monotonic instability. In [3] it was suggested that the appearance of the oscillations might be caused by the influence of the thermocapillary effect.

In the present work nonlinear regimes of the oscillatory convection for the real system of fluids, 47v2 silicone oil - water, are investigated. It is shown that under the combined action of buoyancy and the thermocapillary effect, the oscillatory instability may become the most "dangerous". In the case of periodic boundary conditions, regimes of traveling waves have been predicted. In the case of rigid heat-insulated lateral walls, symmetric and asymmetric standing waves are observed.

During the last decades, a new scientific direction of investigation, convection in multilayer systems, was developed. Some new phenomena which arose as a result of the interaction between different interfaces, were discovered. In the present work some peculiarities of the instabilities in three-layer systems are investigated. It is shown that the oscillatory instability in multilayer systems is much more widespread than in twolayer systems. Transitions between different types of oscillatory motions are studied.

- [1] Gershuni G. Z.and Zhukhovitsky E. M. 1982 Sov. Phys. Dokl. 27, 531.
- [2] Degen M. M., Colovas P. W., and Andereck C. D. 1998 Phys. Rev. E57, 6647.
- [3] Nepomnyashchy A. A. & Simanovskii I. B. 2004 Phys. Fluids, 16, 1127.

# PREDICTION OF EXTREME SHIP MOTIONS IN IRREGULAR WAVES

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Large amplitude roll motions and capsizing of ships are reported to occur most likely in head and following seas. Although no or little direct roll excitation is present under these circumstances, significant roll motions can be induced by internal resonance or by temporal loss of the roll restoring capacity in waves. These mechanisms are qualitatively well understood and can be explained by the nonlinear kinematic couplings between heave, pitch, and roll motion as well as by the interaction of the ship hull with the free water surface.

The parametric excitation of large amplitude roll motions in regular waves can be assessed by classical techniques like averaging or the method of multiple time scales. It is known that the presence of noise destabilizes parametrically induced steady state large amplitude motions [1]. However, for a narrow-banded, wave-like excitation numerical simulations indicate that parametrically excited large amplitude roll motions also occur in irregular waves. Stochastic averaging of the envelope of the roll motion yields a measure for the relative frequency of such large amplitude responses in relation to ship, sea state, and operation parameters.

Capsizing of a ship in following seas has a mechanical counterpart in escaping from a potential well characterized by a time-dependent potential function. For this scenario, we apply the theory of Melnikov processes [2] to calculate upper bounds for the probability of capsizing within finite periods of time. It is further shown that the capsizing event is primarily triggered by a small amount of direct excitation due to diagonal waves which are always present in ocean waves.

This paper aims at a rational assessment and a deeper understanding of the mechanics of extreme ship motions on a probabilistic basis. The model equations describing the nonlinear roll motion are obtained form a full six degrees of freedom ship motion model after rigorous order of magnitude analysis where the leading nonlinear effects have been identified. The approximate results presented here have been validated with respect to direct numerical simulations.

#### References:

- [1] M. F. Dimentberg: Statistical Dynamics of Nonlinear and Time-Varying Systems. Research Studies Press, Taunton, England, 1988.
- [2] E. Simiu: Chaotic Transitions in Deterministic and Stochastic Dynamical Systems. Princeton University Press, Princeton, N.J., 2002.

ID of Contribution: 04 - 060

# STOCHASTIC GEAR DYNAMICS BY PATH INTEGRATION

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Whilst a variety of extremely complicated phenomena are involved in gear dynamics, one well-known effect is studied in the proposed paper. Namely, at very low loads (torques), noise and vibration in many gears increase with decreasing load. This is clearly explained by a so-called backlash nonlinearity. The static equilibrium point at high loads may be far to the right from the gap range with zero restoring moment so that this nonlinearity would not be active during vibration. However, if the equilibrium point is moved closer to the gap, the system would occasionally enter the backlash range generating higher harmonics that would lead to increased noise.

ENOC-2005, Eindhoven, the Netherlands

A gear pair with rigid shafts and backlash is considered. A certain amount of eccentricity in the gears is also assumed, which produce sinusoidal-in-time forcing for angular vibrations. Thus a second-order equation of motion is derived, and its solutions result in a quantitative description of the above effect.

The main contribution of the proposed paper is to adapt and explore the use of a numerical path integration (PI) method to study the dynamics of the gear system. The PI method consists of adding small Gaussian white noise to the sinusoidal forcing in the equations of motion of the gears. By this, the gear dynamics become characterized by the joint probability density function (PDF) of the relative rotation of the gears and its time derivative. The numerical PI calculates this joint PDF.

It will be demonstrated how PI gives a unique way of exploring and analyzing the dynamics of gear systems.

ID of Contribution: 04 - 066

# ON ANALYSIS OF NONLINEAR STOCHASTIC REGIMES IN DIFFERENT MEDIA

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An analysis of random processes in nonlinear dynamic systems is a very important topic for theory and practice. A necessity of such analysis is urgent for study of various phenomena.

Usually dynamics of random nonlinear systems with distributed and lumped parameters are described by stochastic differential equations (SDEs) with or without delay, stochastic partial differential equations (SPDEs), and integrodifferential equations. Nowadays there is a significant number of exact and approximate methods intended to analyze stochastic events [1,2]. But many problems, that can't be solved with the help of existing algorithms, arise in researches. Several ways to overpass some of such problems are marked below.

A presence of aftereffect is an essential element of different objects functioning. To take into account multiple constant delays in random dynamics, we consider a system of stochastic differential-difference equations, expand the phase space of the system and reduce a non-Markovian source random vector process to a Markovian one. Then we construct a chain of Fokker-Planck-Kolmogorov equations satisfied by probability density functions for phase vectors of an arising length and show a technique for calculation of the first moments for the source phase vector in different cases. The technique is applied to study a number of linear and nonlinear simple models, linear equations of car motion effected by front-to-rear delay and a rough road, dynamics of pollutions discharged into a cascade of natural water bodies. The package Mathematica [3] is a tool of such studies.

It's well known that distributed delays occur during examinations of random elastic vibrations. Several cases of such problems studies, including theoretical and practical aspects, are presented. Here we mark different forms of stochastic integro-differential equations, which can be transformed to SDEs, and describe a new technique to find the first moments of the phase vector on the base of a Green matrix-function etc. A number of examples demonstrates our approaches.

Further we consider a system with distributed parameters, which is modeled by SPDEs in the Stratonovich sense, and present a technique to derive equations for the first moments of random fields fulfiling these differential equations. The technique is based on a transfer from continuous model to a finite-difference approximation and back. Moreover, stationary functionals of probability can be found along this way, for example with the help of the detailed balance principle. Among examples considered there is the Ginzburg-Landau equation, the Burgers equation, and a model of random oscillations of an elastic column. The Christov's and trigonometric functions are used as basic functions for approximations of the first moments with the aid of Mathematica, Maple and Fortran code programs.

- [1] Gardiner, C.W. (1985) Handbook of Stochastic Methods for Phisics, Chemistry and the Natural Sciences. Springer-Verlag, Berlin.
- [2] Malanin, V.V. and Poloskov, I.E. (2001) Random Processes in Nonlinear Dynamic Systems. Analytical and Numerical Methods of Analysis. Regular and Chaotic Dynamics, Ijevsk (in Russian).
- [3] Wolfram, S. (1999) The Mathematica Book, 4th edn. University Press, Cambridge.

#### ID of Contribution: 04 - 081

# RANDOM SOURCES AND SINKS FOR STOCHASTIC DYNAMICAL SYSTEMS

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Phase portraits have proved to be an effective tool for the description of the long term behavior of deterministic dynamical systems. In this talk we will describe some early results from an ongoing program to develop similar techniques for stochastic dynamical systems. We will illustrate some of the essential differences between the deterministic and stochastic theories by presenting examples of stochastic dynamical systems (generated by stochastic differential equations) on the circle and the two-dimensional torus.

References:

L. Arnold (1998). Random dynamical systems. Springer, Berlin Heidelberg New York.
H. Crauel (2002). Invariant measures for random dynamical systems on the circle. Arch. Math. 78, 145--154.

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# STOCHASTICALLY FORCED SURFACE-GRAVITY WAVES

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Surface gravity waves have captured the interest of many scientists. Though not the first, Michael Faraday was one of the most accomplished ones in this group. In 1831, he reported to the Royal Society on experiments he did in which a thin layer of water was placed on a vibrating membrane. Though his initial motivation may have come simply from the aesthetic beauty of the problem, he delved deeper and established that the standing waves that form on the plate have an oscillation frequency equal to one-half the vertical forcing frequency used to produce them. It is due to this discovery that nowadays, many investigations in wave excitation are known under the rubric of the "Faraday problem."

In certain applications, for example in experiments carried out on spacecraft where 'g-jitter' is hard to eliminate, there is a need to describe the surface gravity wave patterns that form under the influence of 'noisy' forcing (H. U. Walter, Fluid sciences and materials science in space, Springer-Verlag, 1987). Thus, in the present development we focus on stochastic forcing. Specifically, we examine the long-term evolution of a Faraday system when two wave-modes are near 1:1 resonance and show that in this case, rather than studying the fast timescale evolution of two individual wave modes (i.e. a four-dimensional system), one can focus on the long timescale evolution of two conserved quantities (the Hamiltonian and the angular momentum.)

The governing equations for this problem are based on conservation of mass and momentum; we follow John Miles's work (Journal of Fluid Mechanics 75: 419, 1976), who, using a variational formulation, shows how to write the Hamiltonian of this system when forcing and viscous dissipation are ignored. We then apply a series of canonical transformations in order to obtain the phase-space orbits along which stochastic averaging is to be performed. The averaged system, with forcing and dissipation re-introduced is shown to evolve on a three-branched graph. In order to jump from one branch of this graph to another, gluing conditions (N. Sri Namachchivaya and R. B. Sowers, Random Vibration of a Nonlinear Autoparametric System, in preparation) will be required. Both the original and the averaged systems will be simulated numerically to demonstrate the validity of stochastic averaging when applied to the Faraday problem.
# SYSTEM IDENTIFICATION WITH STOCHASTIC NEURONAL MODELS

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Cortical activity is the product of electrodynamic interactions among neuronal populations. Macroscopic electrophysiological phenomena are generated by these interactions, which afford constraints on biologically plausible models of their causes. Macroscopic features of cortical activity can be modeled in terms of the microscopic behavior of neurons in the same way that pressure, volume and temperature can be formulated from the microscopic properties of atoms that comprise a gas.

An evoked response potential (ERP) is the mean electrical potential measured from an electrode on the scalp, in response to some event. The purpose of this paper is to outline a population density approach (Knight, 2000) to modeling ERPs. The model encompasses four basic characteristics of neuronal activity and organization; (i) neurons with similar biophysical and response profiles form sub-populations, which in turn (ii) form networks whose electrical response to (iii) stochastic input, from other neurons, is (iv) dynamic. This leads to a formulation of population neurodynamics in terms of the Fokker-Planck equation. The solution of this equation is the temporal evolution of a probability density over state-space, representing the distribution of an ensemble of trajectories. Each trajectory corresponds to the changing state of a neuron. Measurements can be modeled by the expectations over this density e.g. mean membrane potential, firing rate or energy consumption per neuron, within the population.

Here we formulate a population model, based on model neurons with spike-rate adaptation and synaptic dynamics. Neuronal sub-populations are coupled to form an observation model, with the aim of estimating and making inferences about coupling among subpopulations using real data. We approximate the time-dependent solution of the system using a bi-orthogonal set and first-order perturbation expansion. The model is first developed in the context of deterministic input before extension to stochastic effects. The approach is demonstrated using synthetic data, where model parameters are identified using a Bayesian estimation scheme.

#### References:

[1] Knight, B.W. (2000). Dynamics of encoding in neuron populations: some general mathematical features. Neural Comput. 12, 473-518.

#### ID of Contribution: 04 - 251

# STABILITY OF NOISY AUTO-PARAMETRIC SYSTEMS

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The purpose of this paper is to formulate and develop methods to analyze certain behaviors of noisy auto-parametric systems. Random excitations affect these systems in a profound way, and the presence of random vibrations can lead to a host of undesirable effects. An understanding of their dynamics necessitates a study of the complex interactions between noise, resonances, and nonlinearities. We state the mathematical structure of the problem and formulate it as a perturbed four dimensional Hamiltonian system.

The primary concern in this paper is the analysis of the single mode solutions of nonlinear auto-parametric systems; the determination and prediction of steady-state or stationary motions and their corresponding stability. We shall use analytical techniques to extend the existing results to examine such multi-dimensional nonlinear systems with noise,

ENOC-2005, Eindhoven, the Netherlands

and in particular additive white noise. We obtain an approximation for all four Lyapunov exponents, the exponential growth rate, of the response of the so-called single-mode stationary motion. We show analytically that the top Lyapunov exponent is positive, and for small values of noise intensity and dissipation.

There are recent results for the top Lyapunov exponent of weakly perturbed single oscillators with single-well potentials by Arnold et al.[1] and Baxendale and Goukasian[2]. Contrary to the single oscillators, there are no results pertaining to stationary measures and their stability for coupled nonlinear oscillators. The challenge is to develop an effective, systematic approach to determine the stability of single mode solutions. It is this need and challenge that we shall address in this paper.

#### References:

- [1] Arnold, L., Imkeller, P., and Namachchivaya, N. Sri. The Asymptotic Almost-Sure Stability of a Noisy Nonlinear Oscillator. Journal of Sound and Vibration, 269(3-5), 1003-1029, 2003.
- [2] Baxendale, P., and Goukasian, L. Lyapunov exponents for small perturbations of Hamiltonian systems. Annals of Probability 30(1), 101-134, 2002.

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# STOCHASTIC ANALYSIS OF ROLLING CONTACT

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A commonly used arrangement in paper finishing is to compress the paper web between two rolls for dewatering, coating or polishing purposes. In order to give enough time for the manipulation process, the other roll is covered by a soft polymer-layer, the purpose of which is to extend the machine-directional width of the contact zone. Polymers, as visco-elastic materials, have the property of maintaining information from their deformation history, which property in this application means that the contact oscillations are not only marking the roll cover but also re-entering the contact zone after a delay corresponding to the roll revolution time. This self-excited vibration is present beyond a threshold speed, whose value depends on the recovery dynamics of the layer material. Above this speed, one can identify resonance states, in which the eigenfrequency of the roll-against-roll mode is equal to product (roll rotation frequency) x (number of penetration waves in the layer over the roll perimeter). Although this complex, but purely deterministic, phenomenon is quite well known, another question which is not yet fully understood is the role of statistical imperfections in the paper web and in the roll itself. These anomalies can be categorized as internal and external excitations. The former are related to initial out-of-roundness errors of the layer and deviations in the layer compression elasticity. The latter are related to the thickness profile variation of the web entering the nip. All these statistical imperfections are modifying the contact force randomly, thus generating a stochastic bottom source to the self-excited vibration mechanism. Characteristic for these sources is that their frequency spectrum is controlled by the rotation speed. On the other hand, the external web-fixed source is purely stationary, while the internal layer-based source is cyclo-stationary. The purpose of this investigation is to analyse the effect of the stochastic excitation on the delay resonance. The analysis is done by means of a theoretical model, in which the rolls, as long elastic rotors, execute bending motions and the roll contact is described using a nonlinear Hertzian-like elastic foundation model. Model derivation proceeds by splitting the quasi-static part of the contact force distribution from the dynamic one representing the parametric sources, which have a stochastic nature in this application. The running speed is then slide for different line load levels, and the contact force and roll motion responses are computed using complex frequency response functions. A comparison between deterministic (harmonic) and stochastic (white noise) excitation cases is then made with respect to the existence, location and magnitudes of classical and delay-type resonance peaks. Special attention is given to the different nature of the external excitations to generate additional satellite resonance peaks, a phenomenon not present in the internal parametric excitation case.

# A METHOD FOR DETERMINING RANDOM RESPONSE ENVELOPE STATISTICS OF A CLASS OF NONLINEAR OSCILLATORS

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A method for determining the non-stationary random response statistics of a class of lightly damped nonlinear oscillators subjected to Gaussian broad-band stationary stochastic excitations is presented. Within the framework of stochastic averaging [1], the procedure relies on Markovian modelling of the response envelope process through the definition of an equivalent linear system with envelope-dependent stiffness and damping coefficients [1]. An approximate solution of the associated Fokker-Planck equation is derived by resorting to a Galerkin scheme. Specifically, the non-stationary probability density function of the response envelope is expressed as the sum of a timedependent Rayleigh distribution and of a series expansion in terms of a set of properly selected basis functions with time-dependent coefficients. These functions are the eigenfunctions of the boundary-value problem associated with the solution of the Fokker-Planck equation governing the evolution of the probability density function of the response envelope of a linear oscillator. The selected basis functions lend themselves to an expeditious mathematical treatment as a consequence of the orthonormality condition that they satisfy [2]. Further, they can be readily evaluated using an efficient recursive scheme relating eigenfunctions of consecutive order. To determine the unknown time-dependent series coefficients, the projection of the residual error on the select set of basis functions is set equal to zero. In this manner, a set of linear first-order ordinary differential equations, governing the evolution of the time-dependent series coefficients, is obtained. The computational effort required by the derivation of these equations is substantially reduced by exploiting some notable properties of the basis functions. Specifically, recursive formulae for evaluating integrals involving the eigenfunctions and powers of the response envelope are available [2]. These formulae are also useful for the computation of the statistical moments of the envelope process. The coupled linear differential equations for the series coefficients can be solved either analytically or numerically.

Applications of the proposed method are presented regarding oscillators with either nonlinear damping or stiffness. Appropriate comparisons with the data obtained by related Monte Carlo studies show that the method, being nonperturbative in nature, provides accurate results even for large values of the nonlinearity parameter; this applies to both the stationary and non-stationary regions of the probability density function. This feature attests to the versatility of the method which is applicable to a broad class of oscillators with analytical nonlinearity. Potentially, the method can also be modified to treat systems with hysteretic nonlinearity [3].

- [1] Roberts, J. B., Spanos, P. D. (1986). Stochastic averaging: an approximate method of solving random vibration problems. International Journal of Non-Linear Mechanics, 21, pp. 111-134.
- [2] Spanos, P.-T. D., Iwan, W. D. (1978). Computational aspects of random vibration analysis, Journal of Engineering Mechanics Division, ASCE, Vol. 104, No. EM6, Proc. Paper 14226, pp. 1043-1415.
- [3] Spanos, P. D., Cacciola, P., Muscolino, G. (2004). Stochastic averaging of Preisach hysteretic systems, Journal of Engineering Mechanics Division, ASCE, Vol. 130, No. 11, pp. 1257-1267.

#### ID of Contribution: 04 - 347

# **PROBABILISTIC STABILITY OF A DELAY OSCILLATOR IN WIENER PROCESS**

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The study is aimed at examining the stability in the probabilistic sense of a single degree of freedom machining oscillator with regenerative chatter, whose spindle speeds are modulated parametrically by a Wiener process. By constructing a generalized centre manifold, together with the use of the theorem of Hopf bifurcation, which describes the crossing of a complex conjugate pair of eigenvalues of linearized stability along the imaginary axis transversely, and the stochastic integral averaging method for the determination of Markovian equations, we shall derive explicit conditions for the stability of the machining oscillator. The signs of the Lyapunov exponents of the resulting Markovian equations will determine the stability of the oscillator in the probabilistic sense. Regenerative chatter is an instability vibration problem. It is manifested as a result of time delay mechanisms, which are generated when a tool is cutting a surface profile that is already modulated from a pre-machined surface profile. The time delays are inversely proportional to spindle speed modulations, and at low and high spindle speed modulations, they are continuously altered for every tool cut. It is anticipated that the overall response amplitudes will grow and subsequently stabilize or finite levels. The amplitude stabilization by reducing the rate of energy dissipation and destabilize at some destabilization by increasing the rate of energy dissipation in the machining operation are influenced by the nonlinear regenerative cutting forces and the phase undulations of the undeformed chip thickness. It is then to be expected that machining oscillators are deterministic and stochastic in nature.

ID of Contribution: 04 - 355

# LOGARITHMIC ESTIMATION OF ESCAPE TIME FOR A LAGRANGIAN SYSTEM WITH SMALL NOISE EFFECTS

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In a number of applications, a reference domain of the system motion is associated with the domain of attraction of a fixed point. If noise is small, escape from this domain is interpreted as a rare event with a very long time until escape. Escape time, or other statistical properties of a system with small noise effect, can be asymptotically estimated by means of large deviation theory (Freidlin and Wentzell, 1984, Dupuis and Ellis, 1997). Though the theory has been developed for systems of a general structure, analytical results for systems with a dimension more than one are few in number.

The general approach is restricted to the system in the Cauchy form with the uniformly non-degenerate noise. However, the non-degeneracy condition is not natural for the mechanical systems in the Lagrangian form. Kushner (1987) has demonstrated that the non-degeneracy condition is not necessary, and the large deviation approach can be applied to systems with partition of the noise intensity matrix. This allows formal extension of the theory to the Lagrangian systems.

This issue considers an n-dimensional Lagrangian system with small additive noise and linear dissipation. The unperturbed system has an asymptotically stable equilibrium O with the domain of attraction D, and an admissible domain of motion G is within D. Small noise results in escape from G with a non-zero probability. Let T be mean escape time from the domain G. The task is to find logT in a small noise limit as the solution of a corresponding equation of large deviation theory.

Routh transform converts the Lagrangian function of the system to the Hamiltonian function, with an associated transformation of the equation of motion. The conservative part of the transformed system has the Hamiltonian form.

# ENOC-2005, Eindhoven, the Netherlands

The Hamiltonian properties allow simplification of the equation for the requisite quantity logT. It is shown that, under certain relations between the dissipation and noise matrices, the solution can be found explicitly and expressed through the components of kinetic and potential energy of the system.

References:

- Freidlin, M.I. and Wentzell, A.D. (1984). Random Perturbations of Dynamical Systems. Springer-Verlag, New York. Dupuis, P. and Ellis, R.S. (1997). A Weak Convergence Approach to the Theory of Large Deviations. J. Wiley, New York.
- [2] Kushner H.J. (1987). Approximation and Weak Convergence Methods for Random Processes, with Applications to Stochastic System Theory. The MIT Press. Cambridge, MA.

#### ID of Contribution: 04 - 356

# **NEW RESULTS ON RANDOM PERTURBATIONS OF PSEUDOPERIODIC FLOWS**

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Arnol'd in 1991 characterized "pseudoperiodic" flows on the 2-dimensional torus. We consider small random perturbations of such flows. Under appropriate scaling of time, we search for an averaged picture which describes the evolution of local "energies". Under certain circumstances, we identify a certain limiting Markov process with glueing conditions (as suggested by Freidlin in 1996) which characterizes energy evolution.

ID of Contribution: 04 - 370

# ALMOST INVARIANCE FOR STOCHASTIC DYNAMICAL SYSTEMS

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Almost invariance is an often used concept for stochastic dynamical systems that intends to describe sets such that the system

- stays with a set in the state space for a 'long' time,
- exits from the set only under 'large' noise perturbations,
- and may return to this set at a later, much 'longer' time.

Like transient chaos, bistability or multi-stability, almost invariance tries to describe a transient phenomenon of stochastic systems, but on 'large' time intervals. The interpretation of 'large' time intervals and 'large' perturbations usually depends on the application one has in mind.

Applications of almost invariance include, e.g., the analysis of molecular dynamics where they can symbolize conformations of a protein that are essential for its chemical properties (see, for instance, Deuflhard, Huisinga, Fischer, and Schütte [3]); the study of set oriented numerical methods for dynamical systems (see, e.g., Dellnitz and Junge [2]); the analysis of dynamic reliability when one tries to estimate rare occurrences of system failure due to large perturbations (see, e.g., Colonius et al. in [1]); and other models in science.

The goal of this paper is to develop a theory that

- defines a plausible concept of 'almost invariant sets' based on the actual system dynamics of Markov diffusion processes,
- illuminates the idea of 'large' noise perturbations turning invariant sets for smaller noise ranges into transient sets,
- explores the idea of invariance over 'large' time intervals,
- and allows for numerical computation of almost invariant sets, the exit times from these sets, and the exit locations under varying perturbation ranges.

Our approach is, roughly, as follows:

- We consider dynamical systems with perturbations entering as parameter or additive noise into the system dynamics, which are modeled as a set of ordinary di.erential equations on a finite dimensional manifold. We model the stochastic perturbations as a function of a background noise, which we assume to be a stationary, ergodic Markov process.
- We treat the noise range as a parameter of the system by introducing a family of functions that maps the background noise into the system dynamics such that the sets of perturbation values increase with the parameter. We recover the unperturbed dynamics if we set the perturbation to zero.
- We identify the invariant sets of the stochastic system, depending on the noise range. Under mild conditions, the invariant control sets of an associated control system are the supports of the invariant measures and they form the cores of the invariant sets for the system.
- Analyzing the change of the invariant sets as the noise range increases leads to the study of the loss of invariance, specifically to the analysis of bifurcation points where an invariant set loses its invariance and becomes transient or 'almost invariant'.
- Finally, we study the exit time distributions from invariant sets as they become transient under the influence of larger perturbations.

This approach develops a concept for almost invariance starting from sets that are actually invariant under smaller perturbations. In other approaches the term 'almost invariance' is used to describe the behavior in certain regions, usually in relation to an invariant probability measure with support on the whole state space. In the approach outlined above, such a reference measure need not exist, and we suggest the term 'near invariance' for the concept developed here.

References:

- F. Colonius, G. Häckl, W. Kliemann, Dynamic reliability of nonlinear systems under random excitation, in L.A. Bergman, B.F. Spencer (eds.), Vibration and Control of Stochastic Dynamical Systems, Amer. Soc. Mech. Engrg. ASME DE 84 (1) (1995), 1007-1024.
- [2] M. Dellnitz, O. Junge, Set oriented numerical methods for dynamical systems, in B. Fiedler, G. Iooss, N. Kopell (eds.), Handbook of Dynamical Systems III: Towards Applications, (World Scientific, 2002) 221-264.
- [3] P. Deuflhard, W. Huisinga, A. Fischer, and Ch. Schütte, Identification of almost invariant aggregates in reversible nearly uncoupled Markov chains, Lin. Alg. Appl. 315 (2000), 39-59.

ID of Contribution: 04 - 381

# STOCHASTIC STABILITY OF THIN-WALLED COMPOSITE SHAFTS WITH OVALIZING PHENOMENON

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Recently, composite materials find more and more applications for high-performance rotating shafts. Thin-walled tubes relatively easy meet requirements of torsional strength and stiffness but are more flexible to bending and have specific elastic and damping properties which depend on the system geometry, physical properties of plies and on the laminate arrangement. Thin-walled shalls reveal a considerable deformation of cross-section contour during bending. The ovalizing phenomenon implying a degresive elastic behaviour is named Brazier's effect [1].

In our dynamics study the rotating angle-ply symmetrically laminated circular cylindrical shell will be treated as a beam-like structure. The shaft is assumed to be subjected to a stochastic torque destabilizing the rectilinear shape. The increase of constant torque component leads to a noncirculatory problem and buckling, while the increase of time-dependent component results in the growing parametric vibration.

The system of nonlinear partial differential equations with time dependent torque is obtained. Assuming that the stochastic torque force L has the mean value Lo and the time dependent wide-band Gaussian part, which can be expressed as the formal time-derivative of the Wiener process, the dynamic equations are rewritten in the Ito form. The shaft is assumed to be simply supported at its ends.

Despine the nonlinearity, the equations of motion have the trivial solution and the main purpose of the paper is to derive sufficient conditions for the uniform stochastic stability of the shaft equilibria. The direct Liapunov method is used to

analyse the uniform stochastic stability of the equilibrium state. We choose the Liapunov functional in the energy-like form [2].

Since the dynamic equations are strongly nonlinear, special attention is paid to a positive-definiteness of the appropriate energy-like Liapunov functional V. Analysing the local positive-definiteness and integrating by parts with using the boundary conditions we calculate the differential dV along the trajectory of dynamic equations. Using the supermartingale property we find that the trivial solutions of shaft dynamics equations are uniformly stochastically stable if an auxiliary purely deterministic functional is positive-definite. It is equivalent to the sufficient stability conditions.

The main conclusion is, that due to the ovalization of composite shafts and weakening geometrical nonlinearity the derived stability criteria have the local character. The critical parameters (e.g. rotation speed) depend on the nonlinearity parameter bounding the measure of disturbed solutions. The increase of the constant component and the intensity of stochastic torque destabilize steady-state shaft vibrations.

References:

- [1] Reissner, E.: On finite bending of pressured tubes, ASME J. Applied Mechanics, 26, 366-392, 1959.
- [2] Tylikowski, A., and Hetnarski, R. B., Semiactive Control of a Shape Memory Alloy Hybrid Composite Rotating Shaft, International Journal of Solids and Structures, 38, 9347-9357, 2001.

ID of Contribution: 04 - 440

# LINEAR AND NON-LINEAR PARAMETRIC OSCILLATIONS OF A BEAM UNDER RANDOM POISSON PULSES

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The dynamic analysis of beams is of significant importance for industrial and civil applications. In particular, beams with thin walls are commonly utilized in civil and aeronautical industry. As well known, this class of beams can exhibit flexural-torsional eulerian buckling when subjected to conservative forces. If non-conservative loads are applied, such as those caused by the thrust of rocket and jet engines, dry friction in automotive disk and drum-brake systems, different critical behaviours arise. Several reviews of problems involving non-conservative forces have been published, as well as books on this subject [1]. These works are mainly confined to the linearized stability analysis, while the post critical behaviour in presence of non-conservative forces has not yet been thoroughly addressed. Recently the authors devoted particular attention to the study of simple as well as multiple dynamic bifurcation points for continuous autonomous systems [2]: flutter and divergence boundaries have been determined and their linear and nonlinear interaction investigated.

The main goal of this paper is to extend the stability analysis of a beam model of the generalized Beck's column to randomly forced mechanical systems. The dynamic stability of a cantilever beam with rectangular cross section under the combined action of both a stochastic follower tangential force and a bending couple at the free end is first investigated. The beam model herein considered is the non linear Cosserat rod model. Internal kinematic constraints are introduced in order to ensure the equilibrium of the rectilinear initial configuration for all the control parameters' values. These conditions allow to derive the non linear equations of motions in terms of two kinematics displacement only. In particular, nonlinear partial integro-differential equations of motion are derived, expanded up to cubic terms, in terms of the transversal displacement and the torsional angle of the beam. In order to overcome the difficulties prompted by the continuos problem, a reduced model obtained through a Galerkin approach is derived. Moment stability is then performed to a four dimensional system, see e.g. [3], [4].

- [1] Langthjem, M.A. and Sugiyama, Y., (2000), Dynamic stability of columns subjected to follower loads: a survey, Journal of Sound and Vibrations, vol.238(5), pp.809-851, 2000.
- [2] Paolone, A., Vasta, M., and Luongo, A., Flexural-Torsional Bifurcations \\of a cantilever beam under potential and circulatory forces, submitted on International Journal of Nonlinear Mechanics.

- [3] Doyle, M.M., Namachchivaya, N.S., Van Roessel, H.J., Asymptotic stability of structural systems based on Lyapunov exponents and moment Lyapunov exponents, International Journal of Nonlinear Mechanics, Vol.32, No.4, pp.681-692, 1997.
- [4] Lin, Y.K., and Cai, G.Q., Probabilistic Structural Analysis: advanced theory and application, McGraw Hill, New York, 1995.

ID of Contribution: 04 - 442

### NOICE-INDUCED TRANSITIONS IN RADAR RANGE TRACKING LOOPS

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Nonlinear dynamical models of a class of radar range tracking systems were introduced in [1] as a tool for analyzing the behavior of centroid tracking-based radar trackers in the presence of multiple competing targets. The equilibrium, bifurcation and stability properties of these models in the case of deterministic target models were studied in [1]. Stochastic extension of the models and stability analysis was carried out in further work of the authors and in the dissertation [2]. In this paper, we show the presence of a variety of noise-induced transitions in radar tracking systems, a phenomenon not previously reported in this application. The transitions result in unanticipated changes in the bifurcation behavior in the presence of noise. The relative impact of noise amplitude and target separation on the noise induced-transitions is studied.

- [1] E.H. Abed, A.J. Goldberg and R.E. Gover, "Nonlinear modeling of gated range tracker dynamics with application to radar range resolution," IEEE Trans. Aerospace and Electronic Systems, Vol. 27, No. 1, pp. 68-82, Jan. 1991.
- [2] R.E. Gover, Nonlinear Deterministic and Stochastic Modeling and Stability of Radar Tracking Systems, Ph.D. Thesis, Dept. of Electrical Engineering, University of Maryland: August 1995.

# **MINI-SYMPOSIUM 5**

# **Optimization of Dynamical Systems**

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#### ID of Contribution: 05 - 011

# NONLINEAR DYNAMIC REANALYSIS FOR STRUCTURAL OPTIMIZATION

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The cost of structural analysis and its practical feasibility depend to a considerable degree on the algorithms available for the solution of the equilibrium equations. The time required for solving these equations can be significant, particularly in nonlinear dynamic analysis problems. One of the main obstacles in optimization of large-scale structures is the need to repeat the analysis many times due to changes in the design variables. In problems of nonlinear analysis, each nonlinear analysis usually involves repeated solutions of linear problems. These operations might involve prohibitive computational effort in the solution of large-scale structures.

The problem of nonlinear dynamic reanalysis considered in this study can be formulated as follows. Given an initial structure and its corresponding response due to a dynamic load, the object is to find efficiently the response of a modified structure obtained by some changes in the design variables. Dynamic analysis is usually carried out either by direct integration or by mode superposition methods. In linear analysis, mode superposition can be more effective than direct integration in cases where only the lowest mode shapes may be considered and the integration must be carried out for many time steps. A major difficulty in using mode superposition in nonlinear dynamic reanalysis is the need for repeated solutions of eigenproblems due to changes in the material properties (material nonlinearity) and in the design variables.

In this study, a nonlinear dynamic reanalysis procedure, using a mode superposition method, is presented. The solution is based on the Combined Approximations (CA) approach, developed originally for linear static problems [1]. Recently, it was found that accurate results can be achieved by this approach for eigenproblem reanalysis [2, 3]. The CA approach is based on the integration of several concepts and methods, including series expansion, reduced basis, matrix factorization and Gram-Schmidt orthogonalization. The advantage is that efficient local approximations and accurate global approximations are combined to achieve an effective solution procedure. In the procedure developed for material nonlinear behavior, the CA approach is used to obtain updated eigenpairs during the solution process. Numerical examples illustrate the efficiency of the calculations and the accuracy of the results. It is shown that the approach can be used effectively for nonlinear dynamic reanalysis problems.

In summary, the main advantages of the CA approach have been studied in terms of several criteria, including:

- a. Generality. Different structures and design variables may be considered.
- b. Accuracy. Accurate results are achieved for large changes in design variables.
- c. Efficiency. The computational effort is significantly reduced, compared with complete analysis of a modified design.
- d. Ease of implementation. The solution steps are straightforward and the approach can be readily used with general finite element systems.

- [1] Kirsch, U., Design-oriented analysis of structures, Kluwer Academic, Dordrecht, 2002.
- [2] Kirsch, U. Approximate Vibration Reanalysis of Structures, AIAA Journal, 41, 504-511, 2003.
- [3] Kirsch, U. Bogomolni, M. Procedures for Approximate Eigenproblem Reanalysis of Structures, to be published, International J. for Num. Meth. Engrg., 60, 1969-1986, 2004.

# STRUCTURAL DYNAMICS MODIFICATION VIA REORIENTATION OF MODIFICATION ELEMENTS

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Present paper describes an optimization of structural dynamics modification (SDM) by attaching and reorienting modification structural elements on the baseline structure. The present approach is different from existing SDM in that whereas most existing SDM approaches vary material properties or geometrical dimensions, the present approach determines both the position and orientation of the modification structural elements to be placed on the base structure for raising the natural frequencies of the resulting structure.

For an effective implementation, substructure coupling concept is used in SDM when attaching modification structures to the baseline structure. Each of the substructure is modeled separately and assembled into a whole structure without having to generate a new mesh. However, node mismatch problem can occur on the interfacing surface of the substructures. This is particularly true in layout optimization, for which the attaching structural members move continuously on the baseline structure such that interface nodes usually do not match.

A challenge in the proposed approach is how to resolve grid non-matching problem between the baseline structure and modification elements, for which a virtual interface frame concept between the nodes of the baseline and modification structures is employed. Through this interface frame, the interfacing displacements of modifying substructures are constrained to those of the baseline structure during optimization process, thus circumventing remeshing.

Since the attaching structure moves continuously on the baseline structure, sensitivities to determine the moving direction are essential for each optimization iteration. The eigenvalue sensitivities of the attaching structure to the moving direction of the attaching members are formulated using the Simpson method. Finally, the optimal structural modification is obtained by iteratively carrying out the eigenvalue sensitivities and eigenvalue reanalysis.

The present SDM method is applied to determine the position and orientation of a beam stiffener to increase the natural frequency of the baseline plate and compared to the size optimization that employs the beam width as the design variable.

- K. C. Park and Carlos A. Felippa, "A Variational Principle for The Formulation of Partitioned Structural Systems." International Journal for Numerical Methods in Engineering 47, pp. 395-418, 2000.
- [2] A. Simpson, "The Krons methodology and Practical Algorithms for eigenvalue, sensitivity and response analysis of large scale structural systems.", Aeronautical Journal 84, pp. 417-433, 1980.
- [3] Yong-Hwa Park and Youn-Sik Park, "Structure Optimization To Enhance Its Natural Frequencies Based On Measured Frequency Response Functions.", Journal of Sound and Vibration, 229(5), pp. 1235-1255, 2000

#### ID of Contribution: 05 - 184

# MINIMUM-TIME TRAJECTORY OPTIMIZATION OF HYDRAULIC MANIPULATORS

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Tasks performed by many hydraulic manipulators consist in moving the end-effector along predefined paths in work space. In many cases, the speed of motion of the end effector does not affect the quality of performance of the machine. If this is the case, it is advantageous to speed up the movement of the arm along the given path, to minimize the duration of the working cycle of the machine. In this paper, a method of optimizing for speed the motion of non-redundant hydraulic manipulators along prescribed paths is presented.

In non-redundant manipulators, the position and/or orientation of the end-effector uniquely determine the joint-space configuration of the entire arm. Therefore, the original problem can be reformulated, as the problem of optimizing for speed the movement of the manipulator along a given parametric curve in the arm's joint space. It is thus assumed, that the reference path is given explicitly as a parametric path in joint space. The task further reduces to finding the optimum distribution of the given path parameter in time – which is essentially a one dimensional problem.

The equations of motion of the manipulator consist of two groups. The first are Lagrange equations of motion of the arm under generalized piston forces. The second are equations of motion of the hydraulic system, which are assumed as first order relations between rates of change of piston fluid pressures and control inputs. The control inputs are displacements of the spools of servovalves, governing fluid flow to and from hydraulic piston chambers.

The proposed optimization procedure has the following form. The distribution of the trajectory parameter s in time t (which can be assumed to be an increasing function in t) is approximated by a fixed number of points, equally spaced along the s direction. The distances in time between successive points are chosen as optimization parameters. For a given distribution of points, values of constraints can be calculated, on the basis of equations of motion of the manipulator. First, time derivatives of the s-curve are approximately calculated, as forward differences between successive points. From those values, time derivatives of the given parametric trajectory are computed at chosen points. Then, from the equations of motion, the corresponding values of piston chamber pressures are determined on assumption, that hydraulic fluid is incompressible. Finally, the necessary servovalve spool displacements are calculated. All obtained values (computed only approximately at chosen points) are next compared with their assumed bounds, giving values of constraints. Overall optimization is performed by methods of constrained nonlinear programming, with the optimization index being the sum of time intervals between chosen points on the s-curve.

The paper is illustrated by results of sample optimizations, performed on a three link hydraulic excavator. The proposed method of optimization works fast, and allows incorporation of various types of constraints in the optimization process.

#### ID of Contribution: 05 - 185

# **MODEL PREDICTIVE CONTROL OF GUYED MAST VIBRATIONS**

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Guyed masts used in radio and television industry, constitute a class of vibration-prone structures. Ice, together with wind pressure, are the most common reasons of mast failures.

In this project, a numerical simulation of a control process will be presented, which is expected to minimise amplitudes of transverse structural vibrations of the top of the mast, caused by wind pressure. To achieve this objective, a feedback control system is proposed, which consists of: velocity sensor, digital controller and hydraulic actuator. In the controller, information from the sensor is processed, to provide control signal used by the actuator. As a result of this, the control forces are applied in such a way, that they change tension in guy cables.

For the purpose of simulation the mast was discretized, following the finite element approach. Next, equations of motions are translated into a discrete time state-space formulation. Wind fluctuations are obtained, by applying a purely random sequence as input to a filter, that approximates the Davenport spectrum within the desired bandwidth.

Before designing a control system, controllability is checked. For the guyed mast under consideration it is observed, that control forces very weakly affect the axially-symetrical mode shapes of cables, but they have significant influence on those involving transverse vibrations of the column.

The adoped control strategy is Model Predictive Control. The algorithm can be summarized in the following steps:

- (i) at each time instant estimate current state vector
- (ii) solve on-line the optimal control problem over some future interval
- (iii) use the first step in the computed optimal control sequence

Optimal control of a dynamical system requires knowledge of the state of that system, which is in practise unavailable. Measurement can usually be made only of functions of state variables. Therefore the use of the estimator is required. The best estimate of a future state vector, which is needed to implement MPC, is obtained, by taking the expected value of the forward solution of the discrete state equations, calculated on the basis of the current estimate.

Given knowledge of the current state estimate, the optimization procedure finds an N-step control sequence. Quadratic progamming with constraints is used for this purpose, with quadratic cost function on state error and control effort and constraints on control force ampltudes in the form linear inequalities. After solution, the first signal in the optimal control sequence is applied, and the whole procedure is repeated at the next time instant. Similarly to the case of the state estimator, assessment of the mast parameters is done by the Kalman filter.

Results of numerical simulations will be shown. The disturbing forces are applied in the form of random fluctuations with Davenport spectrum. In the case of the transverse displacement of the top of the mast, a significant reduction of amplitudes of vibrations can be observed.

#### ID of Contribution: 05 - 208

# **OPTIMAL DESIGN OF PLATE STRUCTURES FOR LOW VIBRATION LEVELS**

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Plates with a periodic modulation of the material properties may prohibit propagation of elastic waves, commonly referred to as the elastic (or phononic) band gap phenomenon [1]. This, can in turn lead to very low vibration levels for harmonic loads at certain frequencies, and can thus be useful for designing plate structures that are usable to protect sensitive equipment from surrounding vibrations, or alternatively to insulate noisey machinery from the surroundings.

In this work we use topology optimization [2] as a method to design bi-material plate structures with large band gaps for bending vibrations and we test these experimentally. The analysis of the bending vibrations is based on a Finite Element analysis of a periodic Mindlin plate model consisting of an infinite number of copies of a unit cell made up of a base material with one or more inclusions of another material constituent. The reason for considering an infinite periodic structure is that we only need to carry out the numerical analysis for a single unit cell rather than for the whole finite periodic plate considered in the experiment. The analysis is based on Bloch theory.

In [1] it was shown that the choice of the periodic configuration and the materials are very critical for preventing bending vibrations in thin plates and only a few examples were found where (small) band gaps existed. Here we extend this study by optimizing in a structured manner these parameters as well as the unit cell topology for maximum band gaps. Previous studies [3] indicate that rhombic unit cells result in larger band gaps than quadratic ones. As a first step, we therefore choose a rhombic unit cell with a circular inclusion and choose the base and inclusion materials on the outcome of a parameter study. For the given rhombic periodic model as well as the found base and inclusion materials, we then topology optimize the unit cell i.e. we find the material distribution that produces the largest relative band gap.

The experimental test is carried out using a plate with at least 10 times 10 repetitions of the designed unit cell. Previous results [3] indicate that finite-size effects may then be neglected except near the structural boundaries. The plate is vertically suspended from the ceiling. The vibrations are generated by a shaker and recorded by an accelerometer.

#### References:

- M. M. Sigalas, E. N. Economou. Elastic waves in plates with periodically placed inclusions. Journal of Applied Physics, 75(6), 2845-2850, 1994.
- [2] M. P. Bendsøe, O. Sigmund. Topology optimization Theory, Methods and Applications. Springer-Verlag, Berlin Heidelberg 2003.
- [3] S. Halkjær, O. Sigmund, J. S. Jensen. Inverse Design of phononic crystals by topology optimization. Accepted for publishing in Z. Kristallogr, 2005.

#### ID of Contribution: 05 - 266

# **EXPLOITING JACOBIAN SPARSITY IN A LARGE-SCALE DISTILLATION COLUMN**

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Derivative information is one of the most important issues in dynamic optimization of various models describing industrial processes. For the evaluation of derivatives of the state variables of the system with respect to some optimization parameters, iterative methods are widely used. In such kind of optimization algorithms the information of the directional derivatives is of great interest. Rather than explicitly calculating full Jacobian of the system and then post-multiplying it with a vector, stating a subsequent search direction, it is more advantageous to use methods which provide such products at once. Automatic differentiation (AD) supports the calculation of accurate directional derivatives with a low additional cost. The AD-derivatives are truncation error-free and, in contrast to divided differences, they do not depend on the choice of the step size.

These model equations are nowadays often generated by some object-oriented modeling tool. This type of approach is very well suited for formulation of models for large-scale industrial problems including e.g. chemical processes. An interesting example is a hierarchically built distillation column. It consists of some number of connected column trays, which together with swamp and condenser form the whole column model. Each element (tray, swamp and condenser) is defined as a separate submodel, and contains its own variables and equations. These elements can be aggregated using some connecting equations to build a more complex model.

The Jacobian of this system, due to its hierarchical construction, has a sparsity structure which should be exploited. The nonzero elements build a number of blocks situated on the diagonal of the Jacobian matrix. Each block represents nonzero Jacobian values for one of the connected column trays. The Jacobian matrix can be represented in a compressed form, reducing the storage considerably. We demonstrate how the compressed Jacobian is computed using a sparsity-aware seeding procedure of AD.

The industrial system is represented in the form of a language called CapeML. This language is designed as an XMLbased intermediate format used in process engineering. The idea behind CapeML is as follows. Modeling tools usually use their own language definitions, which may cause some difficulties when exchanging models or reusing already designed ones in another larger project or in another application. Designing a common and accessible form of representation of such equation-oriented models has gained a lot of interest among software developers. A goal is to develop a language independent intermediate format to reduce human effort when exchanging models or building largescale projects.

We present a prototype of a novel AD tool, called ADiCape, which employs the forward mode of AD and is based on a source transformation approach. It uses the XSLT template-based language which is able to transform any XML-like code. ADiCape, an XSLT stylesheet, is applied to the CapeML representation of the system equations and it generates the directional derivatives for the optimization algorithms.

#### ID of Contribution: 05 - 320

# MULTIDISCIPLINARY DESIGN OPTIMIZATION OF SUSPENSION SYSTEM FOR VIBRATION REDUCTION OF DRUM TYPE WASHER

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In order to minimize the vibration of the cabinet of a drum type washing machine, the multidisciplinary design optimization technique is applied. The desired performance of a drum type washing machine is to minimize the vibration of the cabinet while satisfying operational constraints on the displacements at 7 points and geometrical constraints on the cabinet. The design variables selected are the position and properties of the suspension system, the shape of cabinet beads, and a the counter weight.

A dynamic analysis and a structural analysis are executed by using commercial programs to obtain reliable responses. In addition, analysis models are compared with the experimental responses and validated for accuracy of the models. To analyze a drum type washing machine that includes a driving part, a suspension system, a cabinet, and legs, a dynamic analysis is performed by DADS and a structural analysis is performed by ANSYS. The dynamic analysis is designed to offer robust solutions requested by the optimization program and the structural analysis is focused on considering both efficiency and accuracy by using the superposition method. Two commercial programs are integrated by using a design framework FRAMAX, which is commercialized based on EMDIOS developed by iDOT. FRAMAX provides convenient interfaces that link the analyzers and performs design optimization.

The use of gradient-based optimization methods for the design is restricted because this design problem is characterized by the presence of numerical noise. Therefore, the design optimization is executed by a function-based optimization method. We employ progressive quadratic response surface modeling (PQRSM) which is one of the function-based optimization methods. This method is loaded in FRAMAX and helps reduce the time and cost of the optimization because PQRSM can efficiently build a response surface model. In the SAO, PQRSM requires only one center point plus 2n axial points for each quadratic approximation. Nevertheless, because this method can build but a full quadratic model, not a linear model, using this method we can optimize the design problem efficiently.

To summarize, using the integrated analysis, multidisciplinary design optimization was executed to determine the properties of the suspension system, to adjust the position of the suspension system, and to define the shape of the cabinet. In this research, we could obtain an optimum design that reduces the magnitude of amplitude by about 33% compared with the original design and this optimum design satisfies all operational and geometrical constraints. Consequently, the multidisciplinary design optimization technique is applied successfully and the optimum design is planned to reflect a new model of a drum type washing machine. It is believed that the proposed methodology can be applied to other optimizations of dynamic systems which include various disciplines.

#### ID of Contribution: 05 - 334

# **OPTIMIZATION OF LASER PULSE FOR PENDANT DROPLET FORMATION**

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In a laser droplet formation process a molten droplet is produced from the metal wire by a laser beam. This process can be divided into two phases: (1) formation of a pendant droplet on the tip of the wire, and (2) its detachment from the wire. In our investigations we have focused on the first part of the process where the properties of the droplet such as temperature, size and amount of energy are essentially influenced. In order to form a droplet of suitable properties, the heat input should be precisely determined. The heat input and, consequently, the pendant droplet formation process are influenced by wire properties, laser beam parameters and wire feed parameters. Experiments reveal that the most important parameters are time dependant laser power P(t) and wire feed velocity v(t). The objective of the article is to determine the optimal power  $P_o(t)$  and velocity  $v_o(t)$ , which yield the highest amount of melted material and lowest energy losses at the selected pulse duration time. For the optimization of these two parameters, physical and numerical models of the process are developed. The prevailing physical phenomena in the phase of pendant droplet formation are absorption, heat conduction, melting and major energy losses. These are included in the model, which enables simulation of a 3D temperature field of the wire and the portion of melted material during the heating process. The wire and laser beam properties, time dependant profiles of laser power P(t), and wire feed velocity v(t) can be varied in the model. Because of the limitations of our experimental setup, a set of experimentally feasible velocity profiles  $v_s(t)$  is selected for the calculations. The corresponding power  $P_s(t)$  and portion of melted material are calculated for these velocities using the minimum of energy losses as the optimization criterion. From the obtained set of calculated  $P_s(t)$ and  $v_s(t)$ , the selected velocity profile  $v_0(t)$  and the corresponding power profile  $P_0(t)$ , which yield the highest amount of melted material, are selected and verified experimentally. For the purpose of comparison, heuristically defined nonoptimal pulses P(t) of the same energy as the optimal pulse were tested with the selected velocity profile  $v_0(t)$ . The experiments show that the melting of the wire tip depends significantly on the laser pulse form P(t). With respect to the obtained shape of the molten wire tip, the optimal pulse derived from the model is found to be the most appropriate for the formation of pendant droplets.

ID of Contribution: 05 - 379

# A DYNAMIC PROGRAMMING MODEL FOR A MINIMIZING ENERGY CONSUMPTION ON NATURAL GAS PIPELINE

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Optimization techniques can be used to generate, in advance, control strategies for efficiently operating pipelines through periods of fluctuating loads. A control strategy is simply a specific schedule for changing compressor station set point values during a particular scenario period.

This paper presents a dynamic programming model for a steady state optimization and for the optimal line-pack management strategies for particular expected load. The dynamic behavior of the gas flow is described by nonlinear partial differential equations that describe pipe flow together with nonlinear algebraic equations that describe the quasisteady flow through the compressors. The set of equations describing pipe flow, compressor performance and throughput, and the equations that describe the performance and operation of the compressor driver must be solved simultaneously to obtain a realistic representation of the overall compressor station performance.

The solution method is the fully implicit finite difference method, which provides solution stability, even for relatively large time steps. The algorithm for solving the nonlinear finite difference equations of pipe flow is based on the Newton-Raphson Method. The compressors within the compressor station are modeled using centrifugal compressor map-based polynomial equations.

The paper shows how this detailed compressor station model can be used to determine compressor speed, power requirement, engine fuel consumption, and head for each compressor with respect to time. This work was realized with Matlab 6.5.

The algorithm proposed utilizes dominance criteria and lower bounds in order to reduce the total number of states.

#### ID of Contribution: 05 - 419

# **OPTIMIZATION OF FLEXIBLE MULTIBODY SYSTEMS USING COMPOSITE MATERIALS COMPONENTS**

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The design of complex flexible multibody systems for industrial applications requires not only the use of powerful methodologies for the system analysis but also the ability to iterate on the potential designs and to decide on the merits of each one of them. The use of optimization methodologies has been established for a long time in many areas of application, including multibody dynamics. The paper presents a methodology for the application of structural optimization to find the optimal layouts of fiber composite structures components used in multibody systems. The goal of the optimization process is to minimize the structural deformation and, simultaneously, to fulfill a set of multidisciplinary constraints. Considering this requirements, the optimal values for the fiber orientation of composite structures must be determined. These methodologies rely on the efficient and accurate calculation of the system sensitivities to support the optimization algorithms. In this work a general formulation for the computation of the first order analytical sensitivities based on the direct method is used. The direct method for sensitivity calculation is obtained by differentiating the equations defining the response of the structure with respect the design variables. The equations of motion and sensitivities of the flexible multibody system are solved simultaneously and, therefore, the accelerations and velocities of the system and the sensitivities of the accelerations and of the velocities are integrated in time using a multi-step multi-order integration algorithm. The methodologies proposed here are demonstrated with the optimization of a simple flexible multibody system to highlight their potential. Different models for the flexible components of the system, using beam and plate elements, are considered. The optimization of the multibody composite components is performed by taking the ply orientations of laminated as continuous design variables. The procedure proposed here intends to include the concepts of structural optimization of laminates in multibody optimization methodologies. Through the discussion of the results obtained with the application to the simple multibody system it is possible to identify the potential dangers and difficulties in the optimization of composite flexible multibody systems.

98

# MINI-SYMPOSIUM 6 Reduced-Order Modeling

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# TYPE OF NON-LINEARITY OF SHALLOW SPHERICAL SHELLS USING NON-LINEAR NORMAL MODES

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Non-linear (large-amplitude) vibration of continuous structures such as shells, is a problem of widespread relevance from the engineering as well as from the theoretical viewpoint. Despite numerous studies on these subjects, some important features still remain partially or completely unsolved, due to the intrinsic non-linear nature of the problem, which renders the solutions difficult. For example, predicting the correct trend of non-linearity (i.e. the hardening or softening behaviour displayed by each mode of the structure) has raised a number of controversial discussions since the sixties, especially for circular cylindrical shells.

The main difficulty relies in the truncation one has to use for analyzing the PDE of motion. It has been shown that too severe truncations (using for example a single linear mode) may predict an incorrect trend of non-linearity, due to specific interactions, neglected in the approximated solution.

One method to overcome these errors consists in keeping numerous basis functions and perform intensive numerical computations in order to derive the correct trend of non-linearity. This has been successively achieved by Pellicano et al [1] for circular cylindrical shells.

An alternative consists in using reduced-order models that are able to predict the correct trend of non-linearity, while still keeping a single-oscillator equation. Non-linear normal modes (NNMs), defined as invariant manifolds in phase space and computed by real normal form theory, offers a clean framework to perform these kind of analysis, as it has been shown in [2]. It is the aim of the present contribution to use this methodology in order to predict the correct trend of non-linearity displayed by shallow spherical shells, as a function of its geometry (radius of curvature R, thickness h and outer diameter 2a).

A model for the geometrically non-linear vibrations of free-edge shallow spherical shells, based on the analog of Von Karman's theory for large deflection of plates, is briefly recalled [3]. NNMs are then used to derive the analytical expression of the coefficient governing the trend of non-linearity, for each mode of the shell: axisymmetric as well as asymmetric. This coefficient is then numerically computed as a function of the aspect ratio of the shell. Flat plates (obtained as R tends to infinity) are known to display a hardening behaviour, whereas shells generally behaves in a softening way. The transition between these two types of non-linear behaviour is explicitly studied, and the specific role of 2:1 internal resonance in this process is clarified. Finally, experimental validations are shown.

- [1] F.Pellicano, M. Amabili and M. P. Païdoussis. Effect of the geometry on the non-linear vibration of circular cylindrical shells. Int. J. Non-linear mechanics, 37, pp 1181-1198, 2002.
- [2] C. Touzé, O. Thomas and A. Chaigne. Hardening/softening behaviour in non-linear oscillations of structural systems using non-linear normal modes. J. Sound Vib., 273(1-2), pp. 77-101, 2004.
- [3] O. Thomas, C. Touzé and A. Chaigne. Non-linear vibrations of free-edge thin spherical shells: modal interaction rules and 1:1:2 internal resonance. Int. J. Solids Structures. Accepted for publication, 2004.

# DYNAMICS AND BIFURCATIONS OF FLUID-FILLED CYLINDRICAL SHELLS UNDER AXIAL LOADS

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Recently Gonçalves and Del Prado [1] studied the dynamic instability of empty circular cylindrical shells subjected to harmonic axial loads. Several issues, such as parametric instability, snap-through buckling, truncation of modal solutions, fractal stability boundaries, were studied in detail. In the present study a low dimensional model which retains the essential nonlinear terms is used to study the effect of an internal fluid on the nonlinear oscillations and instabilities of an axially loaded thin-walled cylindrical shell. The theoretical basis of this low-dimensional model is presented and discussed by the authors in [2]. A detailed review of studies on geometrically nonlinear vibrations of fluid-filled cylindrical shells is found in Amabili and Païdoussis [4]

Donnell shallow shell equations in terms of the transversal displacement and a stress function are used to model the shell. The influence of geometric imperfections is also taken into account in the formulation. A modal solution, based on previous works [1,2] are used together with the Galerkin method to obtain a set of time-dependent ordinary differential equations which are solved by numerical integration. The fluid is modeled as non-viscous and incompressible. The irrotational motion of the fluid is described by a velocity potential which must satisfy the Laplace equation e the proper boundary conditions on the shell-fluid interface [3]. The influence of the fluid medium, geometric imperfections and load control parameters on the non-linear oscillations and bifurcations is studied. In particular, the influence of these parameters on the evolution of basins of attraction is studied in detail. As parameters are varied basins of attraction undergo quantitative and qualitative changes that may affect seriously the safety and stability of the shell. To study the nonlinear behavior of the shell, several numerical strategies are used to obtain time response, Poincaré maps, bifurcation diagrams and basins of attraction.

- Gonçalves, P. B. and Del Prado. Nonlinear oscilations and stability of parametrically excited cylindrical shells. Meccanica, 2002, (37): 569-597
- [2] Gonçalves, P. B. and Del Prado. Low-dimensional Galerkin Models for Nonlinear Vibration and Instability Analysis of Cylindrical Shells. Nonlinear Dynamics, 2004 (in press)
- [3] Gonçalves, P. B.; Batista, R. C. Non-Linear Vibration Analysis of Fluid-Filled Cylindrical Shells. Journal of Sound and Vibration 1988; (127): 133-143.
- [4] Amabili M and Païdoussis M.P. Review of studies on geometrically nonlinear vibrations and dynamics of circular cylindrical shells and panels, with and without fluid-structure interaction. Applied Mechanics Review, ASME, 2003, (56):349-381.

# ASYMPTOTIC ANALYSIS OF CYLINDRICAL SHELLS NONLINEAR DYNAMICS USING A REDUCED MODEL

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Free and forced oscillations of simply supported cylindrical shells and parametrically excited clamped-free shell with big mass at the top are considered. The dynamics of simply supported shells are modeled by the Donnell shell theory. The shell oscillations are presented by three modes: two of them are conjugate modes and the third mode is axisymmetric [1, 2].

Free oscillations of the cylindrical shell with initial imperfections are described by the system of two essentially nonlinear differential equations. Using the nonlinear normal mode theory, it is derived, that only one nonlinear normal mode determined by the initial imperfections, exists in the differential system. The multiple scale method is used to study stability and bifurcations of this normal mode. In particular, a bifurcation of stable almost periodic motions is obtained.

Forced oscillations of simply supported cylindrical shell are investigated too. We study an internal resonance between eigenfrequencies of the conjugate modes and axisymmetric one. Additionally, one considers the resonance condition for external force, which frequency is close to the eigenfrequency of conjugate mode. This case is studied by the multiple scales method. As a result the system of six modulation equations is derived. Fixed points of this system present both standing and traveling waves. The frequency response is obtained.

The dynamics of clamped-free shell with big mass at the end is modeled by the Sanders-Koiter theory. A suitable modal expansion, including beam-like and shell-like modes, have been used to reduce the original partial differential equation problem (PDE) to a set of ordinary differential equations. A linear analysis of the free oscillation behavior is carried out and theoretical results are validated through experimental data. The model of nine DOF is studied in normal coordinates and reduced to the three DOF model. By using the multiple scales method the dynamic response of the shell and the stability regions boundaries are obtained analytically. Moreover, an analysis of the shell dynamic instability and the nonlinear response is carried out by using the numerical continuation techniques.

- [1] F Pellicano, Yu. Mikhlin and I. Zolotarev, Nonlinear Dynamics of Shells with Fluid-Structure Interaction, published by Inst. of Thermomechanics AS CR, Prague, 2002.
- [2] F. Pellicano and M. Amabili, Stability and vibration of empty and fluid-filled circular cylindrical shells under static and periodic axial loads. Int. J. of Solids and Structures 40, 2003, 3229- 3251.
- [3] K. Avramov, Nonlinear beam oscillations excited by lateral force at combination resonance. J. of Sound and Vibration, 257 (2), 2002, 337-359.

# REGULAR AND CHAOTIC MOTION EXHIBITED BY A SHAFT-BUSH SYSTEM WITH HEAT, WEAR AND FRICTION PROCESSES

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Both methods of analysis and modelling of contact bush-shaft systems exhibiting heat generation and wear due to friction are presented [1-2]. The considered problem is reduced to analysis of ordinary differential equations governing velocities change of the contacting bodies, and to the integral Volterra type equation governing contact pressure behaviour. Thresholds of chaos have been found due to analysis of Lyapunov exponents, phase portraits, Poincaré maps and power spectra. The following theoretical approaches are applied: perturbation methods, Melnikov techniques, Laplace transformations, theory of integral equations and various variants of numerical analysis.

It should be emphasized that usually either tribological processes occurring on the contact surfaces are not accounted, or inertial effects are neglected. In other words, both mentioned processes are treated separately. In this work both elements of complex contact behaviour are simultaneously included into consideration, which allows for a proper modelling of the real contact system dynamics. Analytical and numerical analyses are carried out in a wide aspect through investigation of various types of nonlinearities, dampings and excitations applied to the analysed system. A Duffing type elastic nonlinearity, a nonlinear density of the frictional energy stream, a nonlinear friction dependence versus velocity and a nonlinear contact temperature characteristic, as well as nonlinear character of a wear are accounted, among others.

We consider thermoelastic contact of a solid isotropic circular shaft (cylinder) with a cylindrical tube-like rigid bush, where the bush is linked with the housing by springs and a damper.

We assume, that: (i) the bush is a perfect rigid body and is fixed by non-linear springs and dampers; (ii) the cylinder rotates with a such angular velocity, that the centrifugal forces can be neglected; (iii) the angular speed of the shaft rotation changes harmonically; (iv) between bush and shaft dry friction occurs, which depends on a relative velocity; (v) friction force yields heat generated on the contact surface, and wear on the bush occurs. (vi) the frictional work is transformed to heat energy. Finally, it is further assumed that the bush transfers heat ideally, and that between both shaft and bush the Newton's heat exchange occurs.

This paper extends analysis carried out in reference [2]. In contrary to the previous results, a novel mechanism of contact between bush and shaft is proposed, a viscous damping is added, and an influence of tribologic factors as well as chaotic dynamics is analysed. It has been shown that (owing to wear) chaos vanishes, since there is a lack of contact between both bodies. Owing to heat generation through friction, either chaos vanishes or thermal instability appears.

- [1] I.R. Barber, Thermoelasticity and contact, Journal of Thermal Stresses 22, 1999, 513-525.
- [2] J. Awrejcewicz and Yu. Pyryev, Influence of Tribological Processes on a Chaotic Motion of a Bush in a Cylinder-Bush System, Meccanica 38(6), 2003, 749-761.

# **UNSTABLE PERIODIC ORBITS OF PERTURBED LORENZ EQUATIONS**

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Self-exciting dynamos are nonlinear electro-mechanical engineering devices or naturally-occurring magnetohydrodynamic fluid systems such as the geodynamo, operating within the Earth's liquid metallic outer core, that convert mechanical energy into magnetic energy through the action of motional induction without involving permanent magnets. Because of the intractability of the governing nonlinear partial differential equations in four independent variables, low-dimensional analogues, capable of providing valuable insights into the on-going physical processes have been proposed and investigated.

There has been considerable interest in recent years in identifying the spectrum of underlying unstable periodic orbits (upos), associated with chaotic time series, as a way of characterising the attractors of nonlinear dynamical systems such as the Lorenz equations, themselves the lowest order truncation of the partial differential equations governing Benard convection. While a chaotic attractor possesses an infinite number of upos, many properties may be determined from those orbits of lowest period.

Investigations of several different self-exciting Faraday disk dynamos have shown the classic Lorenz equations to result in a special limit when one of the key bifurcation parameters, beta, measuring the inverse moment of inertia of the armature of the dynamo motor, vanishes, the extended Malkus-Robbins dynamo (EMR), a system of four coupled nonlinear odes being one such model (Moroz, 2004a).

In a recent study Moroz (2004b) investigated what happened to the lowest order upos of the Lorenz limit (beta =0) of the EMR dynamo, as beta was increased to the end of the chaotic regime, using two cases of Moroz (2004a) to guide the investigations, but with the classic Lorenz parameter choices of r=28, sigma =10 and b = 8/3. The same initial data was used in each integration. In one of the two cases, it was possible to trace the evolution of some of the leading upos through to the onset of stable periodic oscillations. In the other case, the effects of the additional equation destroyed the elegant character of the Poincare return map.

In this paper, we extend the preliminary work of Moroz (2004b) and perform a more extensive investigation of the EMR dynamo, using the original parameters of Moroz (2004a) amongst others.

- [1] M. Moroz (2004a) The extended Malkus-Robbins dynamo with a nonlinear motor. I.J.B.C. vol 14 To Appear.
- [2] I.M. Moroz (2004b) The extended Malkus-Robbins dynamo as a perturbed Lorenz equation. J. Nonlinear Dynamics To Appear.

# **REDUCED-ORDER MODELS OF THE MARTIAN ATMOSPHERIC DYNAMICS**

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There are studies that suggest that Martian atmospheric dynamics, or at least an important part of its large-scale variability, take place in a phase space of relatively low dimension [1]. Thus, the motivation and primary objectives of this study are to investigate the possibilities of deriving low-order models for the baroclinic wave behaviour in a general circulation model (GCM) of the Martian atmosphere by extracting empirical orthogonal functions (EOFs) from numerically simulated data. The present study builds upon previous work by Whitehouse et al. [2,3] who developed low-order models for a Mars-like spherical planet with no bottom topography and simple parameterisations of physical processes. The atmospheric streamfunction was decomposed into a set of vertical modes, derived from the quasi-geostrophic vertical structure equation, and horizontal modes, using Proper Orthogonal Decomposition (POD) with the total energy as metric [1].

Through the vertical decomposition we were able to derive a set of around twenty vertical modes, each one characterized by a different total energy content, which allowed us to select those modes that contain most total energy of the original data. The subsequent POD was performed only on the chosen modes, which determined the number of vertical modes in each EOF.

To carry out the POD in spectral space the streamfunction was decomposed into two parts: a zonal and an eddy field. The POD on the zonal part showed that most of the energy was contained in the first four EOFs. In the case of the eddy component, the energy content was distributed among more modes (21 EOFs are necessary to explain 95% of the total energy of the original data). However, the analysis showed that 90% of the total energy was concentrated in the first seven EOFs.

We also analysed the behaviour of the time-dependent coefficients (principal components (PCs)) associated with each EOF using Fourier analysis to identify the most influential frequencies present in each PC. It was possible to observe a strong influence from the diurnal cycle on the evolution of each EOF, and to identify the motion of baroclinic waves and to observe amplitude vacillation in the third EOF. PCs also may be used to reconstruct phase portraits in the reduced space and to calculate dynamical invariants.

The results of this study reinforce the idea that reduced-order models of the Martian atmosphere could be used to explain the most important energetic processes. The next step is to derive these models; a task for future research. Once such models are available we shall embark upon a thorough analysis using the tools of nonlinear systems.

- [1] M. Collins, S.R. Lewis, P.L. Read and F. Hourdin. Baroclinic wave transitions in the Martian atmosphere. Icarus, 120:344-357, 1996.
- [2] S.G. Whitehouse, S.R. Lewis, I.M. Moroz and P.L. Read. A simplified model of the Martian atmosphere. Part 1: a diagnostic analysis. In preparation, 2004.
- [3] S.G. Whitehouse, S.R. Lewis, I.M. Moroz and P.L. Read. A simplified model of the Martian atmosphere. Part 2: a POD-Galerkin analysis. In preparation, 2004.

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# REDUCTION OF INTERFACE DEGREES OF FREEDOM IN FLEXIBILITY-BASED COMPONENT MODE SYNTHESIS

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A flexibility-based component mode synthesis (CMS) is proposed for reduced-order modeling of dynamic behavior of large structures. The approach employs partitioning via the localized Lagrange multiplier method (e.g. see [1]). The use of the localized Lagrange multipliers leads to, unlike the classical Lagrange multipliers, a linearly independent set of interface forces without any redundancies at multiply connected interface nodes. The flexibility-based CMS method [2] has shown significant advantages over the classical Craig-Bampton method. A key feature of the method is its substructural mode selection criterion that is independent of loading conditions. Numerical experiments have shown that the mode selection criterion offers a reliable guide for the reduced-order, low-frequency modeling of complex structures. In addition, as the method uses only free-free component eigenmodes, one can combine experimentally obtained modes with the computed ones.

The method proposed in [2] as well as the majority of available CMS approaches retain the full dimension of partition boundary degrees of freedom (DOFs). However, for large structures that are partioned into several structures, the number of boundary DOFs becomes significant, especially when dealing with 3D problems. The objective of this work is to reduce the partition boundary DOFs while maintaining an adequate accuracy level. The present reduction of partition boundary DOFs is demonstrated for simple plates partioned into several substructures.

References:

- [1] Park, K.C. and Felippa, C.A., 'A variational principle for the formulation of partitioned structural systems', Int.J.Numer.Meth.Engng, Vol. 47, 2000, p. 395-418
- [2] Park, K.C. and Park, Y.H., 'Partitioned Component Mode Synthesis via a Flexibility Approach', AIAA, Vol. 42, No. 6, 2004, p. 1236-1245

ID of Contribution: 06 - 173

# QUASIPERIODIC RESPONSE REGIMES OF LINEAR OSCILLATOR COUPLED TO NONLINEAR ENERGY SINK UNDER PERIODIC FORCING

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Quasiperiodic response of a linear oscillator attached to nonlinear energy sink (NES) with relatively small mass under external sinusoidal forcing in a vicinity of main (1:1) resonance is studied analytically and numerically. It is shown that the quasiperiodic response is exhibited in well - defined amplitude - frequency range of the external force. This dynamic regime occurs due to interaction of the dynamical flow with invariant manifold of damped - forced nonlinear normal mode of the system [1], resulting in hysteretic motion of the flow in the vicinity of this mode. Parameters of external forcing giving rise to the quasiperiodic response are predicted by means of simplified analytic model. The model also allows predicting that the stable quasiperiodic regimes appear for certain range of damping coefficient; insufficient damping results in chaotic regimes. All findings of the simplified analytic model are verified numerically and considerable agreement is observed.

Quasiperiodic regimes are commonly accepted as jeopardizing the dynamical performance of nonlinear vibration absorbers [2,3]. Still, it is demonstrated that for certain region in the parameter space the NES in the regime of quasiperiodic response is demonstrated to provide more efficient vibration suppression (from viewpoint of energy criterion) then the best - tuned linear absorber having the same mass.

References:

- [1] S.W.Shaw and C. Pierre, Normal modes for Nonlinear Vibratory Systems, Journal of Sound and Vibration, 164, 1993, 85-124
- [2] G.S.Agnes and D.J.Inman, Nonlinear Piezoelectric Vibration Absorbers, Smart Mater. Struct., 5, 1996, 704-714
- [3] S. Natsiavas, Steady State Oscillations and Stability of Non-linear Vibration Absorbers, Journal of Sound and Vibration, 156, 1992, 227-245

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# REDUCTION METHODS IN FINITE ELEMENT ANALYSIS OF NONLINEAR STRUCTURAL DYNAMICS

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The computation of the motion of large structures with implicit time integration schemes is usually costly, especially in the nonlinear case. In each time step a large system of linear equations must be solved several times. In Finite Element models, often a fine discretization is necessary to represent the geometry and to yield accurate results for the stress field. Especially three dimensional models often have some ten or hundred thousand degrees of freedom, thus computations may last up to several days. Therefore the use of reduction methods is promising in this context.

For nonlinear problems, there is no standard reduction method, such as a modal analysis of linear problems. Due to nonlinearities the behavior of a system can change significantly during a computation. Quite a number of reduction methods were developed, but they are not suitable for all kinds of problems.

Classic approaches use tangent modes, which are solutions of the eigenproblem of mass and tangent stiffness matrix. This approach is costly, as it requires repeated solutions of large eigenproblems. Improved methods use information on the load to construct the subspace, e.g. Ritz or Lanczos vectors. However these need to be updated during a nonlinear solution, usually based on an error estimator.

Another approach is the use of a basis obtained by a Proper Orthogonal Decomposition of the result of a previous computation. This limits the application on cases where several computations with similar load are needed.

The presentation compares the effectivity of these methods for some examples, showing their weaknesses and advantages.

Even though the time integration scheme is applied to the reduced system, it is necessary to compute the residual of the complete system in each solution step. For a full Newton solution, also the tangent matrix of the complete system must be computed and transformed. The modified Newton algorithm does not converge well for systems with significant nonlinearities. In the presentation it is shown, that the BFGS update technique for the stiffness matrix can reduce the computational cost significantly.

# NUMERICAL METHODS AND PROPER ORTHOGONAL DECOMPOSITION OF FLAPPING AIRFOIL

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Recently, flapping flight has been suggested as a means of propulsion for micro-aerial vehicles flying machines. There are many outstanding problems that must be solved before flapping flight can be considered as a practical means of propulsion. This paper focuses on two important aspects of flapping flight:

- the physics of the flow of a fluid around a heaving airfoil and
- the development of a reduced-order model for the control of a flapping airfoil.

To study the physics of the flow, a numerical model for the two-dimensional flow around an airfoil undergoing prescribed oscillatory motions in a viscous flow is described. The model is used to examine the flow characteristics and power coefficients of a symmetric airfoil heaving sinusoidally over a range of frequencies and amplitudes. Both periodic and aperiodic solutions are found. Additionally, some flows are asymmetric in that the up-stroke is not a mirror image of the down-stroke.

For a given Strouhal number - defined as the product of dimensionless frequency and heave amplitude - the maximum efficiency occurs at an intermediate heaving frequency. This is in contrast to ideal flow, models, in which efficiency increases monotonically as frequency decreases. Below a threshold frequency, the separation of the leading edge vortices early in each stroke reduces the force on the airfoil and leads to diminished thrust and efficiency. Above the optimum frequency, the efficiency decreases similarly to inviscid theory. For most cases, the efficiency can be correlated to interactions between leading and trailing edge vortices, with positive reinforcement leading to relatively low efficiency. Additionally, the efficiency is related to the proximity of the heaving frequency to the frequency of the most spatially unstable mode of the average velocity of the wake; the greatest efficiency occurs when the two frequencies are nearly identical. The importance of viscous effects for low Reynolds number flapping flight is discussed.

The computational model is used as the basis for developing a reduced-order model for active control of flapping wing. Using proper orthogonal decomposition (POD), sets of orthogonal basis functions are generated for simulating flows at the various heaving and pitching parameters. With POD, most of the energy in the flow is concentrated in just a few basis functions. These functions are used for the projection of the Navier-Stokes equations using a Galerkin projection, reducing them to a small set of coupled, non-linear ordinary differential equations. The Galerkin projection is used to simulate oscillatory motions that are both similar to, and different from, the motion used to generate the POD modes; however, errors are introduced into the model from several sources. The focus of the current work is on the causes and effects of errors in the model on important aspects of the flow, chiefly input and output power and efficiency. The suitability of this approach for controlling a flapping wing over a broad range of parameters is analysed.

- Arian, E., Fahl, M., Sachs, E.W., Trust-region proper orthogonal decomposition for flow control, Tech Rep. ICASE Report No. 2000-25. NASA, 2000.
- [2] Cazemier, W., Verstappen, R. W. C.P., Veldman, A.E.P., Proper orthogonal decomposition and low-dimensional models for driven cavity flows, Physics of Fluids 10 (7), 1998, 1685-1699.
- [3] Jones, K. D., Platzer, M. F., Numerical computation of flapping-wing propulsion and power extraction, AIAA Ppaer 97-0826, 35th AIAA Aerospace Sciences Meeting, 1997, Reno NV.
- [4] Gopalkrishnan, R., Triantafyllou, M.S., Triantafyllou, G.S., Barret, D., Active vorticity control in a shear flow using a flapping foil, J. Fluid Mech. 274, 1994, 1-21.
- [5] Hall, K.C., Hall, S.R., Minimum induced power requirement for flapping flight, J. Flui Mech., 323, 1996, 285-315.
- [6] Hall, K.C., Pigott, S.A., Hall, S.R., Power requirements for large amplitude flapping flight, .J. of Aircraft 35(3), 1998, 352-361.
- [7] Liu, P., Bose, N., Propulsive performance from oscillating propulsors with spanwise flexibility, Proc. R. Soc. Lond. A 453, 1997, 1763-1770.
- [8] Ly, H.V., Tran, H.T., Modeling and control of physical processes using proper orthogonal decomposition, Math. and Comp. Modeling 33, 2001, 223-236.

[9] Rivandran, S.S., A reduced-order approach for optimal control of fluids using proper orthogonal decomposition, Int. J. Numer. Meth. Fluids 34, 2000, 425-448.

#### ID of Contribution: 06 - 219

#### FEEDBACK CONTROL OF FLOW SEPARATION NEAR A NO-SLIP BOUNDARY

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We discuss an analytic approach to two-dimensional unsteady flow-separation control by feedback. With two wallbased actuators and an array of distributed skin-friction sensors between the actuators, we control the skin-friction distribution on the wall to induce unsteady separation or reattachment at desired locations. Our controller uses a reduced-order model of the skin-friction field on the no-slip wall. Using this approach, we induce separation in steady and unsteady channel flows, and reduce the size of the recirculation zone behind a backward-facing step.

#### ID of Contribution: 06 - 260

# SYSTEM ORDER REDUCTION OF THE DYNAMICS OF RAILWAY WHEELSETS

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Nonlinear dynamics of railway wheelsets are not only caused by geometrical shapes of wheel rims and rail surfaces and the elastic behavior of axle and wheels. Moreover, the wheel-rail-contact drastically influences the wheelset dynamics. Sophisticated models that combine the wheelset elasticity with the contact dynamics lead to complex mathematical formulations and result in high numerical simulation costs ([Kaiser 2003], et al.).

Accounting for the complexity and sensitivity of wheel-rail-systems an approach to non-model based system analysis is investigated. The Karhunen-Loève-Transform is applied to detect coherencies in dynamic system behavior and to derive reduced order descriptions of railway wheelset dynamics. Previous applications of the Karhunen-Loève-Transform, e.g. as in [Steindl 1997] focused on model-order-reduction of nonlinear dynamical systems during a 'stationary state'. In addition to deriving a limited set of variables and spatial ansatz-functions for a reduced description of system dynamics, the main goal of this approach is to characterize different 'states' of wheelset dynamics.

For the analysis of the mechanical systems, the Karhunen-Loève-Transform provides a measure for the kinetic power and gives the principal dynamics, that span a reduced surrogate state space [Glösmann 2004]. Furthermore, the results of the Karhunen-Loève-Transform allow simultaneous spectral analyses of multi-dimensional systems.

After an introduction of the mathematical concept of the Karhunen-Loève-Transform, we will present examples for system-order-reduction and state-characterization of the dynamic behavior of railway wheelsets. In addition, we discuss the possibility of multi-dimensional spectral analysis by postprocessing the results of Karhunen-Loève-Transform.

#### **References:**

- [1] [Kaiser 2003] Kaiser, I., Popp, K., 2003, "Modeling and Simulation of the Mid-Frequency Behavior of an Elastic Bogie", in K. Popp, W. Schiehlen (Eds.): System Dynamics and Long-Term Behavior of Railway Vehicles, Track and Subgrade, Springer-Verlag, Berlin, pp. 101--120.
- [2] [Steindl 1997] Steindl, A., Troger, H., and Zemann, J. V., 1997, "Nonlinear Galerkin Methods Applied in the Dimension Reduction of Vibrating Fluid Conveying Tubes", Proc., 4th International Symposium on Fluid-

#### ENOC-2005, Eindhoven, the Netherlands

Structure Interactions, Aeroelasticity, Flow-Induced Vibration and Noise, M. P. Paidoussis, et al., eds., ASME, 53-1, pp. 273--280.

[3] [Glösmann 2004] Glösmann, P., Kreuzer, E., (accepted 2004), "Nonlinear System Analysis with Karhunen-Loève-Transform", Nonlinear Dynamics. Special Issue on Model Order Reduction Techniques.

ID of Contribution: 06 - 278

# A REDUCTION METHOD FOR DYNAMIC FINITE ELEMENT ANALYSIS OF IMPERFECT STRUCTURES

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Thin-walled structures constitute main structural components in numerous branches of engineering. Their high strengthto-weight ratio together with their slenderness renders the buckling strength one of the key design criteria. In most cases, such structures can exploit relevant post-buckling deformations yet remaining in the elastic range.

Optimization procedures often lead to clustering of buckling loads. Buckling modes are likely to interact and enhance imperfection sensitivity and mode jumping.

The response of (thin-walled) structures under dynamic loads is of major interest. Depending of the time history of the load, the limit point of a given structure can be considerably different from the one corresponding to a static load of the same maximum magnitude.

Full nonlinear dynamic finite element analysis (FEA) can in principle tackle this class of problems. Their applicability is still limited by the high computational cost. The complex modal interaction could render the results of a full FEA difficult to interpret.

Our objective is to develop an efficient finite element based reduction method for the nonlinear dynamic response of a generic thin-walled structure when subjected to loads that can lead to instability.

Perturbation methods have been recently implemented into a FEA framework to study the static initial post-buckling behavior of arbitrary thin-walled structures. [1.] This class of methods has a number of advantages. First, the load-deflection path is reconstructed via a series of expansion coefficients that are a 'property' of the perfect structure, i.e. are calculated once for all for a given structure. Then, the contribution of an initial geometric imperfection can just be added a posteriori with negligible additional computational cost. Moreover, the theory can be extended to analyze the important case of interaction of modes by explicitly including the relevant modes in the analysis. This feature of Koiter's perturbation analysis allows the analyst to gain physical insight into the post-buckling behavior. The framework stemming from a perturbation approach, combined with the generality of the finite element method, is appealing also for dynamic buckling problems.

We extend Koiter's multi-mode static analysis method to the dynamic case by taking into account the inertial contributions of the buckling modes. [2.] The accuracy of the results can be increased by using a displacement field assumption based upon interpolation between vibration and buckling modes.

The proposed reduction method is implemented into a finite element framework. Results are currently available for two dimensional beam structures that exhibit modal interaction. Future work will consider three-dimensional shell structures examples.

The method proves to be an effective reduction tool for nonlinear dynamic FEA. The results show fairly good accuracy when compared to full model simulations. Further investigations on consistent and accurate displacement assumptions are currently performed.

References:

- [1.] G. Garcea, G.A. Trunfio and G. Casciaro, Path following analysis of thin-walled structures and comparison with asymptotic post-critical solutions, Int. J. Numer. Meth. Engng., 55:73-100,2002
- [2.] B. Budiansky, Dynamic buckling of Elastic Structures: criteria and estimates, in Dynamic Stability of Structures, Pergamon Press, 1965

ID of Contribution: 06 - 301

# SMOOTH ORTHOGONAL DECOMPOSITION BASED MODEL REDUCTION

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A new multivariate data analysis method called smooth orthogonal decomposition (SOD) is proposed to provide modes of projection for a nonlinear multi-degree-of-freedom discrete vibration system. The SOD can be viewed as a constrained version of the proper orthogonal decomposition (POD), where the orthogonal coordinates are required to be as smooth as possible. The SOD procedure is also shown to yield approximate solutions to the Rayleigh's Quotient stationary value problem for all active eigenvalues and mode shapes. It is demonstrated that for the undamped free vibration of a linear system, the computed smooth orthogonal modes approximate well the actual linear vibration modes and smooth orthogonal values provide estimates of the corresponding natural frequencies. The same is also true for the lightly damped free vibration response of a system. In contrast to the intrinsic limitations of the proper orthogonal decomposition (POD) analysis, which requires the knowledge of the mass matrix to extract vibration modes and cannot uniquely identify the modal subspaces that have similar proper orthogonal values, SOD is shown to overcome these deficiencies. The method is applied to a discrete model of a buckled beam vibration in a nonlinear potential field. Chaotic response of the beam is investigated using numerical simulations. The standard long-time measures like greatest Lyapunov exponent and the correlation dimension are evaluated for both full and reduced-order models. The results demonstrate that the SOD procedure yields a considerably improved reduced order models for this chaotic system when compared to the POD method.

ID of Contribution: 06 - 319

# REDUCED-ORDER MODELS FOR NONLINEAR VIBRATIONS OF CIRCULAR CYLINDRICAL SHELLS

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Shell structures are widely used in mechanical and aerospace engineering. It is well known that these thin-walled structures are prone to buckling instabilities under static and dynamic compressive loading. Moreover, they may be directly or parametrically excited into resonance at their natural frequencies by dynamic loads, and they may experience flutter in a flow.

Fast and accurate tools to simulate the nonlinear dynamic behaviour of shells are necessary for parametric studies and design purposes, while at the same time a thorough understanding of the physics of the problem is indispensable. The nonlinear dynamic behaviour of shells, and in particular the reduced-order modelling of this behaviour has recently attracted considerable attention [1,2,3]. In the present paper the characteristics of different reduced-order models for the fundamental problem of the nonlinear flexural vibration behaviour of thin cylindrical shells are discussed in detail.

Starting point of the reduced-order models are Donnell-type equations for a circular cylindrical shell, with the radial displacement and an Airy stress function as variables. The first reduced-order model considered contains two generalized coordinates, the amplitudes of the 'primary', 'driven' mode, and the amplitude of the 'companion' mode. The method of averaging was used to eliminate the time dependence, which results in two coupled nonlinear algebraic equations for the average vibration amplitudes. In the second model the amplitudes of the additional 'secondary'

ENOC-2005, Eindhoven, the Netherlands

axisymmetric modes are retained as generalized coordinates, and in the third model the assumed displacement function includes an additional coordinate, the amplitude of the 'secondary' double harmonic in the circumferential direction. In the two latter cases the dynamic response is obtained via numerical time-integration of the resulting set of differential equations.

The importance of the inclusion of axisymmetric modes and the influence of stresses that are constant over the shell are shown. The various reduced-order models are compared and the differences between the various models are discussed. The physical interpretation of the models is emphasized. Results of the reduced-order models are also compared with results from more accurate analysis tools.

The present reduced-order models provide basic tools to analyse the nonlinear vibration behaviour of shells, and they are also important for the development of reduced-order models in other dynamic analysis cases like parametric excitation, dynamic buckling, and flutter. A careful consideration of the models provides insight in the physics of the nonlinear vibration problem and is helpful in establishing the range of applicability of the reduced-order models.

References:

- [1] M. Amabili and M.P. Païdoussis. Review of studies on geometrically nonlinear vibrations and dynamics of circular cylindrical shells and panels, with and without fluidstructure interaction. Appl. Mech. Rev., 56(4):349 381, 2003.
- [2] P. B. Gonçalves and Z. J. G. N. Del Prado. Nonlinear oscillations and stability of parametrically excited cylindrical shells. Meccanica, 37:569 597, 2002.
- [3] E. L. Jansen. A comparison of analytical-numerical models for nonlinear vibrations of cylindrical shells. Computers & Structures, 2004. Accepted for publication.

ID of Contribution: 06 - 325

# A REDUCED ORDER MODEL FOR THE LOW FREQUENCY RESPONSE OF NONLINEAR RODS IN PLANAR MOTION

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Complex structural systems (dissipative) when forced by exterior forces or driven by controlled forces may respond by activating only a few degrees-of-freedom. In view of this fact, the essential dynamics of a dissipative system can be computed by appropriate reduced order models [1]. Usually reduced order systems are derived by exploiting the completeness of the basis functions furnished by the linear normal modes of vibration. However, these reduced models cease being optimal when the dynamics is nonlinear. The dynamics of an infinite nonlinear system (irrespectively of geometric complexity, nonlinearity and involved fields) can be characterized by Proper Orthogonal Decomposition modes [2]. These modes, being optimal by construction, can be used to derive optimal reduced models for coupled infinite systems [3]. We have derived one, two, and three-degrees-of-freedom reduced order models for a simply supported planar rod [3]. In this work, we present a systematic study of higher order reduced models for the low frequency response of planar nonlinear rods for various boundary conditions. The POD modes are extracted from the finite element dynamics of periodic attractors (steady-state vibrations). For all boundary conditions, small amplitude attractors are dominated by a single POD mode. A 1-DOF (one-degree-of-freedom) reduced model is derived by projecting the equations of motion onto the function space spanned by the shape of the dominant POD mode. This reduced system approximates exceptionally well the dynamics of the full order system as long as the motions have very small amplitude and there are no qualitative changes in the dynamics such as bifurcations and jumps. When we have bifurcations and jumps in the frequency and amplitude and sweep the 1-DOF reduced system does not predict very well the dynamics of the full order system. We then refine the reduced model by including at least one to two more POD modes. Even thought these modes contain very small amounts of auto-correlation energy, they play they affect considerably the predictability of the reduced order system. We find that the 3-DOF system converges to the 2-DOF system. The 2-DOD and 3-DOF systems are used to compute the qualitative dynamics in the low frequency response. The low frequency response at very low energy level is essentially the dynamics of the fundamental normal mode of vibration. Optimal reduced models can be obtained if the full order system is restricted on an invariant manifold of motion and the spatial structure of the manifold is characterized by POD modes.

114

- [1] Steindl, A. and Troger, H., 2001, "Methods for dimension reduction and their application in nonlinear dynamics," International Journal of Solids and Structures 38, 2131-2147.
- [2] Georgiou, I. T., 2004, "On Proper Orthogonal Decompositions for one-dimensional coupled structural dynamics: characterization of coupled vibrations in nonlinear elastic rods," (submitted).
- [3] Georgiou, I. T., 2004, "Identification and construction of reduced order models for infinite-dimensional systems in nonlinear elastodynamics," Proceedings of IUTAM Symposium on Chaotic Dynamics and Control of Systems and Processes in Mechanics, June 8-13, 2003, Rome, Italy.

#### ID of Contribution: 06 - 326

# MINIMAL DYNAMICAL MODELS FROM NONLINEAR PARTIAL DIFFERENTIAL EQUATIONS

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The construction of reduced-order dynamical models for systems described by nonlinear partial differential equations is considered. The governing equation is projected linearly onto a limited number of modes determined from data of the system. Finding basis functions for efficiently spanning the dynamics is the crucial issue for the quality of such an approximation. The most obvious and straightforward choice are modes from a proper orthogonal decomposition (POD). They optimize the variance captured by a truncated expansion using a given number of modes and are easily obtained as eigenfunctions of a linear eigenvalue problem. In recent years, the more dynamically motivated approach of principal interaction patterns (PIPs) has been proposed [1,2,3]. The PIPs are defined by minimizing the mean squared error in the time derivative between the reduced model and the complete system. An extension from instantaneous tendencies to trajectories over a finite time is possible.

The present paper compares/contrasts these different approaches. Applications range from the Kuramoto- Sivashinsky equation over the Ginzburg-Landau equation to a baroclinic quasi-geostrophic model of large-scale atmospheric circulation with realistic variability. In all cases, reduced models based on PIPs outperform reduced models based on POD modes. This improvement is most prominent for systems in which the linear operator is strongly nonnormal.

References:

- [1] Kwasniok, F.; 1996: The reduction of complex dynamical systems using principal interaction patterns, Physica D 92, 28-60.
- [2] Kwasniok, F.; 1997: Optimal Galerkin approximations of partial differential equations using principal interaction patterns, Physical Review E 55, 5365-5375.
- [3] Kwasniok, F.; 2004: Reduced atmospheric models using dynamically motivated basis functions, Journal of the Atmospheric Sciences, accepted.

#### ID of Contribution: 06 - 388

# REDUCED ORDER MODELING AND MODEL COMPARISON USING SPECTRAL THEORY OF DYNAMICAL SYSTEMS

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We present a formalism for comparing the asymptotic dynamics of dynamical systems with physical systems that they model based on the spectral properties of the Koopman operator. We first compare invariant measures and discuss this in terms of a 'statistical Takens' theorem. We also identify the need to go beyond comparing only invariant ergodic measures of systems and introduce an ergodic-theoretic treatment of a class of spectral functionals that allow for this. The formalism is extended for a class of stochastic systems: discrete Random Dynamical Systems. The ideas introduced are used for parameter identification and model validation of driven nonlinear models with complicated behavior. We apply this theory to obtain a decomposition of the process that utilizes spectral properties of the linear Koopman

# ENOC-2005, Eindhoven, the Netherlands

operator associated with the asymptotic dynamics on the attractor. This allows us to extract the almost periodic part of the evolving process. The remainder of the process has continuous spectrum.

ID of Contribution: 06 - 391

# LERAY-SCHAUDER DEGREE THEORY FOR THE APPROXIMATION OF LIBRATIONS OF SATELLITES ON AN ELLIPTIC ORBIT

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A background for the computational approach to construct solutions to differential equation for librations and rotations of a satellite in the elliptic orbit is given. Torques of gravity and solar light pressure are taken into account. Limit case of the parabolic orbit is also included into a general consideration. Weight Sobolev space metric is used as a measure of the proximity for solutions. In such a case one can construct an approximation of solution uniform with respect to the orbital eccentricity.

Because the operators arising on this way are not regular enough but are compact then to prove an existence of such approximation the theory of the Leray-Schauder degree is used [1, 2]. The Krasnoselsky theorem for Galerkin's approximations of the completely continuous vector fields is adopted properly to the case under consideration [3]. To make a uniform bound for the rate of convergence of approximate solution to the exact one the modification of the corresponding Krasnoselsky's theorem also applied.

The constructs have been built can be considered as an illustration to the general case of differential equations having a singular perturbations. In the problem under consideration concerning the satellite one can compute the solutions over the orbital revolution period using regularizing independent variable when approaching the limit case of the parabolic orbit. However the computational complexity of such a problem increases infinitely as the eccentricity approaches the unit, its limit value. Indeed, in this case one needs infinitely large time to integrate regularized equations numerically. Such an approach leads us to the development of an algorithms depending on the parameter singularly.

In the current work a procedures providing the regularization of the numeric algorithm for all admissible parameter values including limit one are presented. The algorithm of an approximation itself don't 'feels' the passage of the parameter through its singular value. Such a regularization of the numeric procedure one can gain due to refusal from the uniform metric in the space of accelerations and velocities and use of weight integral metrics. Thus one can consider the topology more coarse than the uniform one as a measure of computational complexity for the problem of approximation the solutions to the equation of the satellite librations.

- Leray, J. et Schauder, J. (1934) Topologie et equations fonctionnelles. Annales de l'Ecole Norm. sup., 13, pp. 45– 78.
- [2] Nirenberg, L., (1974). Topics in Nonlinear Functional Analysis. Courant Institute of Mathematical Sciences, New York University, New York.
- [3] Krasnoselsky, M. A. (1964). Topological Methods in the Theory of Nonlinear Integral Equations. Mac Millan. New York.

# DYNAMICS OF LARGE SCALE MECHANICAL MODELS WITH SUBSTRUCTURING METHODOLOGIES

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Efforts to determine dynamic response of large scale mechanical models has progressively become more systematic and intensive, especially during the last three decades, due to growing industrial needs. These efforts were significantly assisted by the simultaneous rapid improvements in computer technology and numerical analysis methods, which has resulted in a considerable progress in many technological fields. However, there is still much room for improvements when large scale dynamical systems are considered.

The main objective of the present work is to compare results obtained by the application of substructuring methodologies to complex mechanical systems. In their simplest version, the models examined are assumed to possess linear characteristics. For such systems, it is possible to apply both frequency and time domain methodologies. However, in many cases significant nonlinearities appear in the formulation, especially in places where the substructures are interconnected. For systems possesing nonlinear characteristics only time domain methodologies are directly applicable. The accuracy and effectiveness of the methodologies applied in the present study was illustrated by numerical results obtained for a geared rotordynamic system and a complete vehicle model. In particular, frequency spectra of several response quantities related to model performance were constructed for steady state motions resulting from periodic excitation. Among other things, the results indicate that the residual flexibility effects are necessary for improving the model accuracy throughout the low frequency range. Moreover, there appear substantial differences in the response diagrams of the fully nonlinear models examined and their corresponding linearized versions.

ID of Contribution: 06 - 410

# ON REPLACING A NONLINEAR SYSTEM WITH AN UNCERTAIN LINEAR MODEL: PART II – THE FREQUENCY-DOMAIN

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In Part I of this paper, the effects of modelling a nonlinear system by an uncertain linear system in the time-domain were investigated. A Duffing oscillator system was modelled by an interval-valued ARX (Auto-Regressive with eXogenous inputs) system. In this paper, the effects of the replacement in the frequency-domain are examined. The uncertain FRF is computed using both interval and affine arithmetic and is compared to the (input-dependent) linearisation obtained by spectral methods. The uncertain Volterra kernel transforms are also computed for the nonlinear system and a further comparison is made with the uncertain linear system.

117

# **ROTATING CYCLIC SYSTEMS WITH ORDER-TUNED VIBRATION ABSORBERS**

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We consider the vibratory response of a class of rotating systems which possess cyclic symmetry and are subjected to The primary application of such systems is in the area of bladed-disk assemblies in harmonic excitation. turbomachinery, wherein a series of flexible blades are symmetrically placed around a disk, and they are excited by a rotating wave that is synched to the rotor speed (so-called engine-order excitation). The blades experience nearestneighbor coupling through the elasticity of the disk and through aerodynamic effects. In this work we focus on the steady-state response of such systems wherein each blade is fitted with an order-tuned vibration absorber that is designed to attenuate blade vibrations. While the blades experience small amplitude motions and behave linearly, the absorbers can undergo large amplitude motions, and nonlinear behavior must be accounted for in their design. The governing equations of motion are analyzed using reduced-order models that exploit the system symmetry and the nature of the excitation. It is known that reduced-order models for the linearized versions of these systems can be very cleanly generated using the theory of circulant matrices, which allows one to efficiently uncouple the equations of motion. This results in a set of low-order sub-systems that depend only on the characteristics of an individual sector (defined by a single blade and the attendant wedge of the disk) and the inter-sector coupling. The excitation acts on only one such sub-system, analysis of which provides an exact result for the steady-state system response that can be used to design the small amplitude features of the absorbers. For finite-amplitude absorber motions, one can exploit the symmetry to analyze the corresponding traveling-wave response mode and its stability using perturbation techniques. It is shown that the absorbers, when moving in the preferred traveling wave, are capable of reducing the vibration levels of the blades, and can experience a range of possible behaviors, depending on how they are tuned and their amplitude of oscillation.

ID of Contribution: 06 - 443

# APPLICATION OF DIMENSION REDUCTION METHODS TO THE DYNAMICS OF A FLUID CONVEYING TUBE

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Realistically modelled mechanical systems usually are represented in an infinite dimensional phase space. This fact creates great diffculties in analyzing their dynamics both qualitatively and quantitatively. Hence, if possible at all, one always will try to reduce the original system to a low dimensional system. However this is useful only if a good approximation of the original dynamics is achieved. This goal can be reached for certain dissipative systems, basically by properly eliminating so-called inessential degrees of freedom of the system.

It is a well known fact both from experiments and engineering experience that the asymptotic behavior of high dimensional or even infinite dimensional dissipative dynamical systems often can be described by the deterministic (possibly chaotic) flow on a low dimensional attractor.

In this talk we consider dimension reduction methods for the simulation of the dynamics of the discretized equations of motion for a fluid conveying tube. Due to the presence of viscous internal damping in the equations of motion the spectrum of the linear operator has a finite accumulation point, which strongly influences the applicability of Approximate Inertial Manifolds: Even if a considerable number of modes is chosen as dominating modes, the long term behaviour of the full system and the reduced system differ considerably. The difficulty can also be observed in a very simple system with two degrees of freedom, where the stiff oscillator is damped and the slow mode oscillates linearly: While the simple ansatz for Approximate Inertial Manifolds doesn't show any influence of the fast mode on the slow

ENOC-2005, Eindhoven, the Netherlands

motion, the Center Manifold reduction changes the dynamics significantly and the results agree perfectly with the simulation of the full system. Unfortunately the Center Manifold calculations become too involved, if many degrees of freedom in the master and slave modes and higher order terms in the equations have to be considered. Therefore it is essential to develop simpler reduction methods, which still yield reliable results.

Numerical calculations indicate, that the eigenfunctions of the linear operator do not behave as well as expected, mainly due to the presence of the accumulation point. We therefore investigate different methods to construct appropriate linear bases. So called beam-modes performed rather well in a number of tests. Also the basis from a coarser discretization of the system looks quite promising, because in simulations with different element sizes only small differences were observed.

#### ID of Contribution: 06 - 468

# **REDUCED ORDER MAPPING FOR PIECEWISE LINEAR OSCILLATOR**

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An oscillator with symmetrical constraints in the form of piecewise linear restoring forces is investigated. The discontinuous nature of the system prohibits the use of standard tools, however, this can be addressed by the introduction of a methodology for reducing such a flow described by three linear differential equations to a two dimensional map which is similar to one described in [1]. First a definition of a piecewise smooth system is introduced in terms of its smooth subspaces. Solutions of the differential equations are constructed for each subspace, which allows a set of local maps for the surfaces of the subspaces to be created. A global iterative map is composed of the local maps, and it provides an exact solution to the corresponding piecewise differential equations. In this way the problem of finding solutions for a set of linear differential equations is transformed to one of solving a set of nonlinear algebraic equations.

Numerical routines have been developed providing solutions of enhanced accuracy, far superior to straightforward numerical iteration of the differential equations. Standard nonlinear dynamics techniques are then used to uncover the global behaviour the system. The bifurcation scenarios are studied under variation of frequency, damping, forcing amplitude and stiffness ratio. The stability of periodic regimes is examined using Jacobian matrices which are constructed implicitly from the mappings. A range of nonlinear dynamical responses is observed, including coexistence of attractors, period halving and period doubling cascades, chaotic response, and grazing bifurcations.

Piecewise smooth systems can provide an accurate description of a wide range of physical phenomena including impacts and dry friction problems, and analysis of such systems is often conducted using only numerical methods, of additional importance where exact solutions exist is the comparison of these to the numerical results. The range of global behaviours in parameter space is considered for both cases, specifically the types of attractors and their variation in parameter space are compared.

References:

[1] Pavlovskaia, E.E., Wiercigroch, M. and Grebogi, C. (2004) Physical Review E 70, 036201 (10 pages). Two dimensional map for impact oscillator with drift.
# **ORDER REDUCTION OF PERIODIC-QUASIPERIODIC NONLINEAR SYSTEMS**

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In this work, some techniques for order reduction of nonlinear systems involving periodic/quasiperiodic coefficients are presented. The periodicity of the linear terms is assumed to be non-commensurate with the periodicity of either the nonlinear terms or the forcing vector. The dynamical evolution equations are transformed using the Lyapunov-Floquet (L-F) transformation such that the linear parts of the resulting equations become time-invariant while the nonlinear parts and forcing take the form of quasiperiodic functions. The techniques proposed here construct a reduced order equivalent system by expressing the non-dominant states as time-modulated function of the dominant (master) states. This reduced order model preserves stability properties and is easier to analyze, simulate and control since it consists of relatively small number of states.

Four methods are proposed to carry out this model order reduction (MOR). First type of MOR technique is a linear method similar to the 'Guyan reduction', the second technique is a nonlinear projection method based on singular perturbation. The third approach is based on 'post-processing' while the fourth method utilizes the concept of 'quasiperiodic invariant manifold'. Order reduction approach based on an invariant manifold technique yields a unique 'generalized reducibility condition'. If this 'reducibility condition' is satisfied only then an accurate order reduction via invariant manifold is possible.

Next, the proposed methodologies are extended to solve the forced problem. All order reduction approaches except the invariant manifold technique can be applied in a straightforward way. The invariant manifold formulation is modified to take into account the effects of forcing and nonlinear coupling. This approach not only yields accurate reduced order models but also explains the consequences of various 'primary' and 'secondary resonances' present in the system. One can also recover all 'resonance conditions' obtained via perturbation techniques by assuming weak parametric excitation. This technique is capable of handing systems with strong parametric excitations subjected to periodic and quasi-periodic excitations. These methodologies are applied to some typical problems and results for large-scale and reduced order models are compared. It is anticipated that these techniques will provide a useful tool in the analysis and control system design of large-scale parametrically excited nonlinear systems.

- [1] Redkar, Sangram 2005, "Some techniques for order reduction of parametrically excited nonlinear systems" PhD Dissertation, Auburn University, Auburn, AL, USA
- [2] S. C. Sinha, Sangram Redkar and Eric Butcher, "Order Reduction of Parametrically Excited Nonlinear Systems using Invariant Manifolds", Journal of Sound and Vibration, to appear 2004/2005
- [3] S. C. Sinha, Sangram Redkar and Eric A. Butcher, "Macromodeling of Nonlinear Time Periodic Systems", Communications in Nonlinear Science and Numerical Simulation, to appear 2005.

# **MINI-SYMPOSIUM 7**

# **Synchronization of Oscillatory Systems**

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# TOMOGRAPHIC MAPPING OF FUNCTIONAL CONNECTIVITY FROM MAGNETOENCEPHALOGRAPHIC RECORDINGS

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It is well-known that specialized areas in the human brain are heavily interconnected. Although the functional significance of these anatomical connections for even very basic information processing is evident, we are just beginning to understand the mechanisms and rules governing interareal communication. Invasive neurophysiological animal studies have provided convincing evidence that neural synchronization, i.e. temporally precise interactions between neurons, represents an important code for information processing. The sophisticated technical and methodological tools which are needed to non-invasively observe the highly dynamic interactions in the human brain were developed only recently and still offer a large potential for substantial improvements.

Due to its excellent temporal resolution magnetoencephalography lends itself optimally to the study of neural dynamics and is ideal to complement fMRI connectivity studies. Unfortunately, MEG/EEG connectivity studies suffered until very recently from the missing localization of the interacting brain areas since interactions were only quantified as they appeared at the MEG/EEG sensors. Recent methodological developments aimed at extending the realm of MEG-studies towards the investigation of long-range interactions at the level of macroscopic brain areas. These methodological advances represent an important step towards a spatio-temporal characterization of neural interactions in the human brain. This spatio-temporal characterization is likely to substantially deepen our understanding of information processing in the human brain due to the well-accepted fact that neural interactions are fundamental to normal and pathological brain functions.

The analysis technique "Dynamic Imaging of Coherent Sources (DICS)" has recently been introduced [1] for the tomographic mapping of power and coherence from MEG recordings in the entire brain. Coherence describes the dependence of two signals and is commonly taken as a measure of functional coupling. DICS is based on a spatial filter algorithm that provides high-resolution tomographic maps at low computational costs. The forward solution is obtained from individual boundary-element models. After specification of a frequency band of interest a tomographic map of power in this frequency band is computed in the entire brain. More interestingly, a tomographic map of coherence to an external reference signal or the activity of a cerebral reference may be computed. We will demonstrate how the mapping of coherence to tremor muscle activity measured with surface electrodes allows the localization of tremor-related cerebral areas. Using these areas as cerebral reference points the cerebro-cerebral coherence may be tomographically mapped leading to the identification of frequency-specific interacting brain areas. The coupling of these areas can be further characterized by computing power or coherence spectra or phase synchronization.

We will present and discuss our experiences with this methodological approach to study functional connectivity with MEG, specify the current limitations and outline preliminary ideas for future developments.

# References:

[1] Gross, J., Kujala, J., Hamalainen, M., Timmermann, L., Schnitzler, A. and Salmelin, R. (2001). Dynamic imaging of coherent sources: Studying neural interactions in the human brain. Proc Natl Acad Sci U S A 98, 694-699.

#### ID of Contribution: 07 - 084

# CHAOTIC TIME SERIES MODELING USING NEURAL NETWORK AND ITS APPLICATION IN SECURE COMMUNICATIONS

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Synchronization of chaotic system is a subject of great interest in many science and technology fields such as physics, biology, and engineering due to its rich dynamical properties. An effective method by neural network was created for modeling of strong nonlinear systems while the artificial neural network theory was provided. Billings et al. employed a traditional parameter evaluation method (i. e., a recursive prediction error (RPE) algorithm) instead of using the back-propagation method to learning and training of multi-layer network [1]. For the modeling, the algorithm possesses the advantages of quick iteration convergence and high prediction accuracy, meanwhile the fractals and Lyapunov exponentials can be calculated accurately even in the case of noisy chaotic time series or insufficient data.

In this work, the modeling approach of chaotic time series with observing noise by a prediction error technique of neural networks for realizing the secure communication via chaotic synchronization is provided. The recursive prediction error algorithm for learning and training a three layer neural network is generalized to abstract the useful information from a noisy chaotic time series. Using the criterion of the contraction map synchronization on the discrete chaotic system further, a method for designing the secure communication via chaotic synchronization is given. The calculating results of an example are shown such that the method is effective.

For an one-dimensional chaotic time series y(t), t=1,...,N, the structure of a single hidden layer neural network is used in modeling. The element number of input layer, n is chosen to be equal to such a dimension number which is an embedding dimension of phase space reconstruction of time series determined by Takens phase space reconstruction theory, and the element number of hidden layer,  $n_i$  is chosen to be greater than n. Defining criterion of prediction error, the useful chaotic time series model from the originally noisy time series data can be established by the iterations of learning and training of the neural network. The example of modeling noisy time series of He'non map is done effectively.

In the chaotic synchronization analysis based on contraction map, a chaotic discrete time system is decomposed into two parts, transmitting system and receiving system, and two improvements for [2] are provided. If a chaotic discrete time system can be written as Lur'e form then the synchronization of these two sub-systems can be reached definitely. Some discussions and the relation between Lur'e demodulation and this synchronization are provided. Hénon map system is employed to discuss Lur'e demodulation and synchronization.

Using above technique, the synchronization of the transmitting system and the receiving system will be reached. In the case of unknown receiving end equation, the technique to realize secure communication via chaotic synchronization is provided. The result of error of training and the result of synchronization are shown in the Figures. The result of chaotic synchronization secure communication is shown such that the method is effective.

- [1] Billings, et al, Mechanical Systems and Signal Processing, 1991.5
- [2] Ushio T. Phys. Lett. A, 1995, 198 (1): 14

# SYNCHRONIZATION IS ENHANCED IN WEIGHTED COMPLEX NETWORKS

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We study the propensity for synchronization of coupled oscillators on scale free-networks. Instead of considering symmetrical and unweighted coupling schemes (networks with uniform coupling strength), we consider networks with directed and weighted links. By means of a linear stability analysis of the synchronous state (the master stability function), we find an optimal condition for enhanced synchronization of chaotic oscillators on networks with different degree distributions. We show that a weighting procedure based upon the global structure of network pathways (quantified by the load of each link) enhances complete synchronization of identical dynamical units in scale free networks. Although this approach is analytically valid for complete synchronization of identical oscillators, we find through numerics that very similar conditions hold for phase synchronization of nonidentical chaotic oscillators.

#### ID of Contribution: 07 - 203

# FORWARD MODELS FOR MULTIMODAL BRAIN IMAGING

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It is generally accepted that the integration of hemodynamic and electromagnetic measures of brain activity has an important role in characterising brain responses. True integration of multimodal data requires a common temporal forward model that links the underlying neuronal dynamics of interest to measured hemodynamic and electrical responses. Here we have used perhaps the simplest of models, a dimensional analysis and biophysical model, that can be used to explain some of the empirical observations in EEG/fMRI integration. Although many of the assumptions of the model are not correct in detail, the overall picture afforded may provide a new perspective on some important issues in neuroimaging.

First, it re-frames the notion of 'activation' in dynamic terms, suggesting that activation is not simply an excess of spikes, or greater power in any particular EEG frequency band. Activation may correspond to an acceleration of dynamics, subserving more rapid computations. This sort of activation can manifest with no overall change in power but a change in the frequencies at which power is expressed.

Second, a speeding up of the dynamics corresponds to a decrease in the width of the cross-correlation functions between all pairs of units in the population. (At the macroscopic level of EEG the synchronisation between pairs of units, as measured by the cross-correlation function, is captured in the width of the auto-correlation of the EEG, because the EEG is a measure of synchronous neural activity). This width is a ubiquitous measure of synchronisation that transcends any frequency-specific changes in coherence.

Third, the underlying 'activation' status of neuronal systems is not expressed at any single frequency but is exhibited across the spectral profile. If one only considered modulations in spectral density at one frequency one would conclude that the effect of activation was a desynchronisation of low frequency components. According to the heuristic however the effect of activation is a shift in the entire spectral profile to higher frequencies with a concomitant attenuation in amplitude of all frequencies.

Fourth, one of the assumptions treats neuronal systems as autonomous, such that the evolution of their states is determined in an autonomous fashion. This translates into the assumption that the pre-synaptic influence of intrinsic connections completely overshadows extrinsic inputs. This is the basis of non-linear coupling in the brain and may represent, quantitatively, a much more important form of integration than simple linear coupling. This issue has been addressed both empirically and theoretically [1,2]. In brief, if extrinsic inputs affect the excitability of neurons, as apposed to simply driving a response, the coupling can be understood in terms of changes in the system parameters, namely the Jacobian. This means the response to input will be nonlinear.

# References:

- [1] Breakspear, M, et al.. 2003. Modulation of excitatory synaptic coupling facilitates synchronization and complex dynamics in a biophysical model of neuronal dynamics. Network. 2003 14:703-32.
- [2] Friston, KJ 2000. The labile brain I. Neuronal transients and nonlinear coupling. Phil Trans R Soc. London B 355:215-236.

# ID of Contribution: 07 - 282

# SYNCHRONIZATION IN THE WINFREE MODEL OF COUPLED NONLINEAR OSCILLATORS

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We study synchronization in a population of phase oscillators with mean-field coupling-a special case of the more general Winfree model. In this system, each oscillator is coupled to the mean-field with a strength dependent on its phase. This coupling, described through a phase-response curve, can either advance or delay the phase of the oscillator, so that the coupling cannot be described as strictly excitatory or inhibitory. Moreover, the uncoupled frequency of each oscillator is distributed as a population density, leading to an integro-differential equation. We consider the response of this system as two parameters are varied. The first describes the strength of the coupling between each oscillator while the second characterizes the distribution of uncoupled frequencies in the population.

This work is based on analysis by Ariaratnam and Strogatz, in which a uniform population distribution was considered. The authors classified several different qualitatively different states for the population, including incoherence, synchronization, and oscillator death. As the above parameters are varied, the synchronous solution can disappear as oscillators near the edge of the population (large deviation of their natural frequency from the population mean) no longer remain locked to the mean frequency. However, in Ariaratnam and Strogatz the bifurcation curve describing the loss of synchronicity was only determined numerically. For the uniform population distribution the bifurcation curve contains a singularity in the coefficients of the perturbation expansion. We generalize this analysis to consider any even distribution for the uncoupled frequency of the population.

Using a Poincare-Linstedt analysis, the bifurcation describing the loss of synchronicity is characterized in terms of the population distribution of the oscillators and the coupling to the mean-field. The bifurcation is then calculated for several different population distributions, including even polynomial distributions and populations that correspond to a discrete system of N oscillators. One novel feature of this analysis is that by formulating the discrete system in a continuum framework, we can carry through the analysis and calculate the bifurcation curve for arbitrarily large discrete populations. Results of the discrete system will be presented from N=2 to  $N=10^6$  oscillators. As the number of discrete oscillators increases, approaching the continuum uniform distribution, the cubic coefficient of the bifurcation curve increases. Finally, a co-dimension two bifurcation is shown to occur for the uniform distribution originally considered by Ariaratnam and Strogatz.

References:

 J. T. Ariaratnam and S. H. Strogatz. 'Phase diagram for the Winfree model of coupled nonlinear oscillators.' Physical Review Letters, 86(19):4278-4281, 2001.

# SYNCHRONIZATION OF SPIKE-BURST NETWORKS UNDER CHANGES OF TIME DELAY AND DISPERSION

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Certain cells in the brain, for example thalamic neurons during sleep, show spiking-bursting activity. We study such a spike-burst neural activity and the transitions to a synchronized state using electrically coupled chaotic neurons. In particular, we consider network synchronization from three points of view:

1) We present evidence that the coupling strength can increase incoherence first and then induce two different transitions to synchronized states, one associated with burst (slow time-scale dynamics) and the other with spikes (fast time-scale dynamics). We find that a subset of Lyapunov exponents associated with transverse directions to the synchronized manifold can become negative from positive at different coupling strengths, indicating synchrony on different time-scales of oscillations. These results suggest that synchronization of spike-burst activity is a multi-time scale phenomenon and burst synchrony is easier to achieve than spike synchrony (see reference [1] for more details).

2) When introducing a fixed time-delay into the coupling terms, we uncover a phenomenon of enhancement of spike synchrony by time delay. Even for significant time delays, a stable synchronized state exists at a very low coupling strength, which may account for long-range neural synchrony observed in experiments. By formulating a master stability equation for time-delayed networks of Hindmarsh-Rose neurons, we show that there is always an extended region of stable synchronous activity corresponding to low coupling strengths. Such synchrony could be achieved in the undelayed system only by much higher coupling strengths. This phenomenon of enhanced neural synchrony by delay has important implications, in particular, in understanding synchronization of distant neurons and information processing in the brain (see reference [2] for more details).

3) If the neurons are not identical, then the network dynamics will become a function of the magnitude of parameter dispersion. Here we consider the case of networks with non-identical nodes and global coupling. Such networks are known to display various dynamic behaviors including phase clustered solutions, synchrony, and oscillator death. A simple mean field approach will only be able to capture the completely synchronous state, but will be doomed to fail for phase clustered solutions. To capture a wider spectrum of synchronization behaviors, we propose a mode decomposition in the parameter space, which provides a low-dimensional network description and captures the mean field approach as a special case (see reference [3] for more details). We discuss the example of globally coupled Fitzhugh-Nagumo neurons and present first results on globally coupled chaotic Hindmarsh-Rose neurons.

- [1] M. Dhamala, V.K. Jirsa, M. Ding. Transitions to synchrony in coupled bursting neurons. PRL 92, 028101 (2004)
- [2] M. Dhamala, V.K. Jirsa, M. Ding. Enhancement of Neural Synchrony by Time Delay. PRL 92, 074104 (2004)
- [3] C.G. Assisi, V.K. Jirsa, J.A.S. Kelso: Synchrony and clustering in heterogeneous networks with global coupling and parameter dispersion. PRL (in press, 2004)

#### ID of Contribution: 07 - 401

# THE LINEAR METHODS STRIKE BACK: DETECTING TRUE BRAIN INTERACTION FROM IMAGINARY COHERENCY

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The main obstacle in interpreting EEG/MEG data in terms of brain connectivity is the fact that because of volume conduction, the activity of a single brain source can be observed in many channels. Here, we assume that the quasistatic approximation of EEG/MEG is valid, which is indeed an excellent approximation [1]. One can then easily show that the (complex) coherency of non-interacting sources is necessarily real and, hence, the imaginary part of coherency provides an excellent candidate for studying brain interactions. Although the usual magnitude and phase of coherency contain, mathematically speaking, the same information as the real and imaginary parts, we argue that the Cartesian representation is far superior for studying brain interactions.

A method which is completely insensitive to artefacts of volume conduction not only leads to stronger claims but is also capable to reveal new structures which are usually hidden behind huge artefacts as will be shown. We are not aware that any other method – linear or nonlinear - has such a property in this strict sense.

The main practical question is whether a nonvanishing imaginary part is observable in real data. We will show a couple EEG/MEG measurements under rest condition containing significant imaginary parts for various frequencies revealing rich spatial structures which wait to be interpreted. In an EEG measurement before, during and after voluntary movement of the left and right hand fingers we demonstrate interaction between left and right motor areas starting already 5 seconds before movement in sharp contrast to findings using 'classical' coherence [2] while avoiding at the same time the typical debate whether the findings reflect brain interaction at all.

To localize the sources of an observed interaction we fit a model cross-spectrum consisting of N interacting dipoles to the sample cross-spectrum. The method is illustrated for MEG data of human alpha rhythm in eyes closed condition for three subjects. Fits of 2 to 5 dipoles in a realistic volume conductor all resulted in locations scattered in the mesial part of the occipital lobe [3]. While the proposed inverse method is used here to localize the interacting part of rhythmic brain activity it applies equally well to any case of zero mean activity.

- [1] Stinstra JG, Peters MJ. The volume conductor may act as a temporal filter on the ECG and EEG. Med Biol Eng Comput. 1998;36:711-6.
- [2] Nolte G, Bai O, Wheaton L, Mari Z, Vorbach S, Hallett M. Identifying true brain interaction from EEG data using the imaginary part of coherency. Clinical Neurophysiology. 2004 Oct;115(10):2292-307.
- [3] Nolte G, Holroyd T, Carver F, Coppola R, Hallett M. Localizing brain interactions from rhythmic EEG/MEG data. Proceedings of the 26th Annual International Conference of the IEEE EMBS: 998-1001.

# ADAPTIVE GROWTH OF A WELL-CONNECTED BRAIN

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Interactions between active brain regions could be represented in functional connectivity networks. Using fMRI (Eguiluz et al 2003), EEG and MEG (Stam 2004; Stam & de Bruin, 2004), it has been possible to study these networks. The observed functional connectivity shares fundamental properties with that observed in cell cultures of hippocampal neurons (Kudoh et al. 2004; Shefi et al., 2002). The networks have both small world and scale-free connectivity.

This connectivity could be seen as optimal in the sense that small-world gives both clustering and short paths, whereas scale-freeness renders the system robust against random lesions. Our question is: if this structure is desirable for the brain, how is it obtained?

The best-known scenario for generating small-world networks (Watts & Strogatz, 1998) is critically dependent on a few long-range connections (and hence not scale-free). The one for growing scale-free networks (Barabasi & Albert, 1999) leaves a system lacking in clustering (and thus is not a small-world network). Algorithms have been developed for generating networks that are both scale-free and small worlds (Klemm & Eguiluz, 2002) but these are lacking in neural plausibility.

Gong & Van Leeuwen (2003, 2004) demonstrated that a network of coupled oscillators evolves from an initially random to a small-world network. The network evolved according to a simple Hebbian rewiring rule. When, in addition, the network was allowed to grow new connections, the system assumed a scale-free structure as well. The evolution is robustly observed.

Chaotic activity is essential for these networks to arise. Chaotic bursting was confirmed in slice preparations (Nakatani et al. 2003), suggesting suggest that bursting activity helps establishing a well-connected brain.

References:

- [1] Barabasi, A.L. & Albert, R. (1999) Emergence of scaling in random networks. Science, 286, 509-512.
- [2] Eguíluz, V.M., Cecchi,G., Chialvo, D.R., Baliki, M. & Apkarian, A.V. (2003) Scale-free structure of brain functional networks. (arXiv:cond-mat/0309092, 2003)
- [3] Gong, P. & van Leeuwen, C. (2003). Emergence of scale-free network with chaotic units. Physica A, Statistical mechanics and its applications, 321, 679-688.
- [4] Gong, P. & van Leeuwen, C. (2004) Evolution to a small-world network with chaotic units. Europhysics Letters, 67, 328-333.
- [5] Klemm, K., & Eguiluz, V.M. (2002) Growing scale-free networks with small-world behavior. Physical Review E, 65, Art. No. 057102.
- [6] Kudoh, S.N. (2004). Conference proceedings. Journal manuscript submitted.

#### ID of Contribution: 07 - 473

# **CURRENT CHALLENGES IN STUDIES OF NEURONAL SYNCHRONIZATION**

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The study of neuronal synchronization offers exciting potential in computational, theoretical and experimental fields. Most significantly, it may facilitate crucial aspects of the way the brain represents, makes inferences on, and initiates interactions with the external environment. In the final talk of the mini-symposium we will explore some of the more difficult challenges in this field. These include disambiguating neuronal sources of multivariate covariance from that due to the limitations of the available experimental signals, and balancing the need for biophysical realism with the desire for mathematical tractability. The talk will be conducted with the mini-symposium co-chair, Prof. Van Leeuwan and be open for audience feedback.

# **MINI-SYMPOSIUM 8** Systems with Time Delay

**Chairs / Organizers:** 

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# INSTABILITIES OF EQUILIBRIA OF DELAY-DIFFERENTIAL EQUATIONS WITH LARGE DELAY

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We describe possible instabilities of stationary states of delay equations with large delay, which can be equivalently considered as singularly perturbed delay equations. In particular, we show a connection between the characteristic roots of the stationary states and multipliers of the mapping obtained via the formal limit when delay tends to infinity. We illustrate the results using an example of the system describing semiconductor laser with optical feedback.

ID of Contribution: 08 - 028

# STOCHASTIC STABILITY OF VARIABLE SPEED MACHINING

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This paper addresses the suppression of machine tool chatter in machining processes. The mathematical models representing chatter dynamics have been cast as differential equations with delay. Chatter manifests itself as a vibration between workpiece and cutting tool, leading to poor dimensional accuracy and surface finish of the workpiece.

A chatter suppression method that has received attention in recent years is the variable speed machining, whereby greater widths of cut are achieved by modulating the spindle speed continuously. Although many researchers have developed variable~(Sinusoidal) speed chatter suppression techniques, to date, they have not been widely implemented in practice because the effectiveness of chatter suppression depends on how precisely the dynamic characteristics of the machine tool are known.

A natural way to account for such inevitable changes in tool dynamic characteristics and operational changes would be to consider random spindle speed variations. This paper presents a novel chatter suppression methodology where the spindle speed is varied in a random manner.

- [1] Namachchivaya, N. Sri, and Van Roessel, H. J., "A Center Manifold Analysis of Variable Speed Machining", Dynamical Systems Vol. 18(3), 2003, pp. 245--270.
- [2] Namachchivaya, N. Sri, and Beddini, R., "Spindle Speed Variation for the Suppression of egenerative Chatter", Journal of Nonlinear Science Vol. 13(3), 2003, pp. 265--288.

ID of Contribution: 08 - 059

# OBSERVATION OF DYNAMICAL BEHAVIORS WITH TIME-DELAYED FEEDBACK IN A LABORATORY PLASMA

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Over the past decade, the problem of controlling chaos has attracted great interest in many fields, motivated by the importance of the role. Plasma, which often appears in a nature, is a typical nonlinear dynamical system with a large number of degree of freedom and it is of interest as a medium for testing the universal characteristics of chaos such as the low-dimensional behavior and certain route to chaos. In the field of plasma physics, the serious role of turbulence in fusion-oriented plasmas creates a special interest in controlling chaos. The appearance of time delay is an unavoidable problem in controlling chaos. In particular plasma is a nonlinear dynamical system with many degrees of freedom over space. Spatially extended systems such as plasma and fluid have time delay in themselves and the control over space and time is expected as a next problem. Therefore, investigations about the behavior of nonlinear systems against time delay are needed as a present issue. Here, controlling chaos caused by the current-driven ion acoustic instability is attempted using the time-delayed continuous feedback method, i.e., the time-delayed auto synchronization (TDAS) method introduced by Pyragas [Phys. Lett. A 170 (1992) 421.] with flexibility. When the bias of mesh grid inserted in a plasma exceeds a threshold, the current-driven ion acoustic instability is excited, and then, according to increasing the bias of a grid, the system demonstrates chaotic oscillation via bifurcation. When the TDAS control is applied to the typical chaotic state, chaotic orbit changes to periodic one, maintaining the instability. The chaotic state caused by the current-driven ion acoustic instability is well controlled using the TDAS method. It is found that the control is achieved when a delay time is chosen near the unstable periodic orbit corresponding to the fundamental mode embedding in the chaotic system [1]. Furthermore, when the delayed feedback is applied to a periodic nonlinear regime, the periodic state is leaded to various motions as a control parameter of arbitrary time delay. As a related topic, the synchronization between two instabilities of autonomous discharge tubes in a glow discharge is investigated. Two tubes are settled independently and interacting each other through the coupling of capacitor and variable resister. When the value of resister is changed as the strength of coupling, coupled systems show a state such as synchronization over time and space.

References:

[1] T. Fukuyama, H. Shirahama, and Y. Kawai, Phys. Plasmas 9 (2002) 4525.

ID of Contribution: 08 - 080

# LOCAL BIFURCATIONS OF EQUILIBRIA IN DELAYED COUPLED TYPE II EXCITABLE SYSTEMS

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Creation and destructions of oscillations in delayed coupled type II excitable systems is studied. Numerical calculations indicate types of relevant bifurcations [1]. In order to explain the numerical results we prove two theorems concerning these bifurcations. It is shown that codimension 2 generalized Hopf bifurcation acts as the organizing center for the dynamics of DDE's for small time-lags. This is used to explain important qualitative properties, like the phenomenon of oscillator death, of the exact dynamics for small time-delays.

References:

[1] Nikola Buric and Dragana Todorovic, Dynamics of FitzHugh-Nagumo excitable systems with delayed coupling, Physical Review E67, 066222 (2003).

# ID of Contribution: 08 - 102

# **DYNAMICS OF DELAYED RELAY SYSTEMS**

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Relay systems are systems of differential equations that follow two different smooth vector fields in two different regions of their physical space. We consider systems where the relay switch between the two vector fields is subject to a time delay, giving rise to an infinite-dimensional phase space, the space of continuous functions on the history interval. This type of systems occurs whenever one implements a control using a relay switch since any control introduces invariably a latency due to the reaction time. Typically, this time delay induces periodic orbits that switch back and forth between the two vector fields. This paper focuses on the dynamics in the vicinity of periodic orbits of this type.

First, it turns out that the evolution depends continuously on its initial value in the periodic orbit itself (but not in an open neighborhood of the periodic orbit) if the periodic orbits intersects the switching manifold only in finitely many points. Thus, it makes sense to define a return (or Poincare) map. Second, if two genericity conditions are satisfied, Poincare maps of these periodic orbits have a finite-dimensional invariant manifold. Restricted to this manifold the Poincare map is a smooth map in a finite-dimensional space. This property makes the dynamics near periodic orbits particularly easy to study as it reduces the corresponding theory to the theory of finite-dimensional maps.

If one of the two genericity conditions is violated, a grazing event (called non-standard bifurcation in the theory of Filippov or impacting systems) occurs. There are two codimension one events each one related to a violation of one of the genericity conditions. The first event, a tangential interaction of the periodic orbit with the switching manifold, gives rise to an asymptotically piecewise square-root like return map. This implies the potential occurrence of phenomena like a sudden transition from a simple periodic orbit to chaos, or period-adding sequences. It also implies that the introduction of an arbitrarily small delay into the switching function in a Filippov system can turn a system with only stable periodic orbit with the switching manifold gives rise to an asymptotically piecewise inear return map.

The study of this type of equations is motivated by a relevant application, the stabilization of an unstable equilibrium by feedback control in the presence of delay in the feedback loop. Whereas linear stabilization of the equilibrium with a finite-dimensional control scheme becomes impossible if the delay is larger than a critical value, this limit does not apply for relay systems. One can construct simple switching manifolds that permit stable periodic orbits even with arbitrary large delays in the control loop.

In summary, the local bifurcation theory for periodic orbits in dynamical systems with delayed relay is easily accessible but still unexplored. It shows that delayed relay systems exhibit interesting phenomena that can be exploited in applications.

# THE ROLE OF THE REACTION-TIME DELAY IN THE DYNAMICS OF VEHICULAR TRAFFIC

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There are several methods for modelling the dynamics of highway traffic and one of those is the so-called car-following approach. In such models vehicles are considered as discrete entities following each other in continuous time and space. Using this approach it is possible to include explicitly the reaction-time delay of drivers, which results in a system of delay differential equations.

The class of car-following models includes optimal velocity models, where drivers aim to reach a velocity that depends on the distance to the preceding vehicle (often called the headway). It is reasonable to assume that drivers react to their headway via a reaction-time delay. If we consider drivers with identical characteristics and place vehicles on a circular road, the resulting system of delay differential equations has a relatively simple structure.

Firstly, we linearize the delayed system around an equilibrium, where cars are equidistant and travel at the same velocity. The linear analysis shows that when parameters change the equilibrium undergoes a sequence of Hopf bifurcations, so that oscillations belonging to different numbers of traffic jams arise. The boundaries belonging to these Hopf bifurcations are shown in three-dimensional parameter space.

After eliminating a singularity related to a continuous translational symmetry [1], the weakly nonlinear behavior of the system is investigated in the vicinity of the Hopf boundaries by using the Taylor series expansion of the nonlinearity. This analysis reveals that the Hopf bifurcation is usually subcritical. This leads to the possibility of coexistence of several periodic solutions for particular fixed parameter values.

In order to investigate the periodic solutions far from bifurcation, we apply the continuation package DDE-BIFTOOL. This package is able to follow branches of periodic solutions as functions of parameters, even when the solutions are unstable [2]. It is also possible to detect bifurcations, e.g., fold bifurcation, on these branches. Thus we are able to determine boundaries in parameter space where the number of coexisting periodic solutions changes. Further, behavior such as collision and stopping can also be examined and shown in the parameter space.

According to the continuation results the branches of periodic solutions belonging to different numbers of traffic jams are not connected. However, numerical simulation shows that traffic jams may amalgamate or disperse during the time evolution of the system. This behavior can be explained by examining the slow dynamics taking place on the low-dimensional unstable manifolds of the periodic solutions [3].

The results presented here show that the inclusion of delay influences the qualitative dynamics of the system on the linear as well as on the nonlinear level.

- [1] G. Orosz and G. Stépán. Hopf bifurcation calculations in delayed systems with translational symmetry. Journal of Nonlinear Science, 14:to appear, 2004.
- [2] G. Orosz, R.E. Wilson, and B. Krauskopf. Global bifurcation investigation of an optimal velocity traffic model with driver reaction time. Physical Review E, 70(2):026207, 2004.
- [3] G. Orosz, B. Krauskopf, and R.E. Wilson. Bifurcations and multiple traffic jams in a car-following model with reaction time-delay. preprint, 2004.

137

# UPDATED TOOL PATH MODELLING WITH PERIODIC DELAY FOR CHATTER PREDICTION IN MILLING

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The material removal rate in the milling process is often limited by the occurrence of chatter, which is an undesired instability phenomenon. In order to maximise the material removal rate, accurate models are necessary to predict the occurrence of chatter.

In the milling process, the tooth path is most often approximated by a circular arc [1]. Moreover, the delay, which is necessary to retrieve the so-called dynamic chip thickness, is assumed to be constant. However, in practice the path is trochoidal [3]. Taking a trochoidal tooth path into account has several consequences. First, the undeformed chip thickness needs a more accurate modelling. Next, the delay becomes time dependent instead of a constant. Finally, the assumption that for a full immersion cut, the entry and exit angles are 0 and 180 degrees, respectively, is no longer valid.

In this study, an updated function of the undeformed chip thickness is derived. Since it is not possible to find an analytic solution, a Taylor series approximation is used. Moreover, the delay is described by a function, which is periodic with the tooth passing time and functions are given for the entry and exit angles in case of end milling. From [3], it was found that the largest differences between the approximated and the actual chip thickness are found when the angle of the tooth is close to 0 or close to 180 degrees. Therefore, it is likely that especially for low immersion cuts, it is necessary to take this updated tooth path into account.

An existing model for the milling process [2] is updated with these new expressions. Time domain simulations are performed for both high and low immersion cuts at various spindle speeds and axial depths of cut. For the circular arc, the stability boundary is found using the collocation method. For the trochoidal tooth path, the stability boundary is determined from the time domain simulations.

Based on these results, we can conclude that for low immersion cuts, the stability boundary using a trochoidal tooth path can differ up to 20% compared to the stability limit for a circular arc. For high immersion cuts, the differences are very small. This means that for low immersion cuts, it is necessary to take the trochoidal tooth path into account for accurate stability prediction. For higher immersion cuts, this is not necessary and the stability lobes can be generated using methods such as the collocation method.

- [1] Y. Altintas. Manufacturing Automation. Cambridge University Press, 2000.
- [2] R.P.H. Faassen, N. van de Wouw, J.A.J. Oosterling, and H. Nijmeijer. Prediction of regenerative chatter by modelling and analysis of high-speed milling. International Journal of Machine Tools and Manufacture, 43(14):1437-1446, 2003.
- [3] H.Z. Li, K. Liu, and X.P. Li. A new method for determining the undeformed chip thickness in milling. Journal of Materials Processing Technology, 113:378-384, 2001.

#### ID of Contribution: 08 - 171

# NONLINEAR DYNAMICS RECONSTRUCTION FOR TIME-DELAY SYSTEMS USING **MODULAR NEURAL NETWORKS**

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A new type of modular neural network [1,2] have been used to reconstruct the nonlinear dynamics of time-delay systems. Time series data from numerical simulation and an electronic analog circuit of the Mackey-Glass system have been used to train the neural network (NN).

According to the structure of the system, neural networks with two modules have been used: one for non-feedback part with input data delayed by the embedding time, and a second one for the feedback part with input data delayed by the feedback time. A feed-forward (FF) neural network is used for the second module. Better results have been obtained for the modular than for FF neural networks for the same number of parameters. We have also analyzed nonlinear dynamics extraction for different delay times. It is found that the complexity of the neural network model required to reconstruct nonlinear dynamics with a small training error (of order 0.001) does not increase with the delay time.

Synchronization between the data and the model with diffusive coupling have been used to test the similarity of the system and the NN model. It is shown that smaller synchronization errors are obtained with the modular than for FF neural networks.

It has been shown that the nonlinear dynamics of the electronic circuit can be reconstructed with a simple 2:2 modular NN for different values of the feedback delay time (5.26 ms and 20.6 ms). We have also shown by iterating the model from the present point that the dynamics can be predicted with a forecast horizon (20 ms and 45 ms, respectively) larger than the feedback delay time.

We have considered an alternative technique for anticipating the dynamics of the chaotic systems using anticipated synchronization [3] with diffusive coupling. In this scheme the driving signal is provided by the experimental data. A cascade of systems have been used to increase the anticipation time. Our results show that the maximum prediction time (around 1 ms) is limited by the linear response time.

References:

[1] E. Castillo, J. M. Gutiérrez, Phys. Lett. A 244, 71 (2004) [2] S. Ortín, J. M. Gutiérrez, L. Pesquera, H. Vásquez, Physica A (2005)

[3] H. U. Voss, Chaos 13, 327 (2003)

ID of Contribution: 08 - 232

# **INFLUENCE OF THE IMPULSE LENGTH IN POINCARE-BASED CHAOS CONTROL**

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A new stability analysis [1,2] of the two elementary Poincaré-based chaos control schemes, OGY and difference control, is given by means of Floquet theory. This approach allows to calculate exactly the stability restrictions occuring for small measurement delays and for an impulse length shorter than the length of the orbit. This is of practical experimental relevance; to avoid a selection of the relative impulse length by trial and error, it is advised to investigate whether the used control scheme itself bears systematic limitations on the choice of the impulse length. To investigate

ENOC-2005, Eindhoven, the Netherlands

this point, a Floquet analysis is performed, similar to that of (Just et al. 1997, PRL 78, 203) for the time-continuous Pyragas scheme. Here the expansion dynamics in vicinity of the orbit is assumed to be homogeneous along the orbit, which is of course a simplification to have a model situation to obtain qualitative results. As an unexpected result, while for OGY control the influence of the impulse length is marginal, difference control is shown to fail when the impulse length is taken longer than one half of the orbit length [1,2]. This impulse length limitation has been reproduced also experimentally [3]. The linear model approach is extended to the case where the local Ljapunov exponent varies along the orbit to be stabilized; the dynamics of the system with applied OGY control can be piecewise integrated as before to show that the qualitative result survives if the simplifying assumption of a constant local Ljapunov exponent is relaxed.

#### References:

[1] J.C.Claussen, e-print nlin.CD/0204060; J.C.Claussen, PhD thesis (in german), Kiel, 1998.

[2] J.C.Claussen, Proc. 2003 Int. Conf. on Physics and Control, St. Petersburg, Russia, edited by A. L. Fradkov and A. N. Churilov (IEEE, St. Petersburg, 2003), Vol. 4, pp. 1296-1302.

[3] T. Mausbach, PhD thesis (in german), Kiel, 1998.

ID of Contribution: 08 - 237

# TIME-DELAY FEEDBACK CONTROL OF NONLINEAR STOCHASTIC OSCILLATIONS

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Effects of time-delay feedback on noisy dynamics of nonlinear oscillators are studied both analytically and numerically. It is shown that such a feedback in the form proposed earlier by Pyragas [1] for the control of chaotic oscillations can be used for effective manipulation of the statistics of noisy oscillations either above or below the Hopf bifurcation of the deterministic dynamic system; however, the action of the feedback in those two cases is different. We discuss this difference from the viewpoint of amplitude and phase dynamics and explain its origin. As a particular, paradigmatic model we analyse a Van der Pol oscillator under the influence of white noise in the regime below the Hopf bifurcation where the deterministic system has a stable fixed point [2]. We show that both the coherence and the frequency of the noise-induced oscillations can be controlled by varying the delay time and the strength of the control force. Approximate analytical expressions for the power spectral density and the coherence properties of the stochastic delay differential equation are developed, and are in good agreement with our numerical simulations. Our analytical results elucidate how the correlation time of the controlled stochastic oscillations can be maximized as a function of delay and feedback strength.

#### References:

[1] K. Pyragas, Phys. Lett. A 170, 421 (1992).

[2] N.B. Janson, A.G. Balanov, and E. Schöll, Phys. Rev. Lett. 93, 010601 (2004).

# TIME-DELAY SYSTEMS WITH BAND-LIMITED FEEDBACK

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Fast nonlinear devices with time-delayed feedback, developed for applications such as communications and ranging, typically include components that are AC-coupled, i.e. components that block zero frequencies. In the context of timedelay systems, nonlinear devices without AC-coupling have been studied intensely, starting with the work of Ikeda et al. [Physica D 29 (1987) 223-235]. On the other hand, little is known concerning the dynamics of systems where the feedback signal is high-pass filtered due to AC-coupling.

As an example of such a system, we describe a new opto-electronic device with band-limited feedback that uses a Mach-Zehnder interferometer as passive nonlinearity and a semiconductor laser as a current-to-optical-frequency converter. Our implementation of the device produces oscillations in the frequency range of tens to hundreds of MHz. We observe periodic oscillations created through a Hopf bifurcation of the steady state as well as quasiperiodic and high dimensional chaotic oscillations.

Motivated by the experimental results, we investigate the steady-state solution and it's bifurcations in time-delay systems with band-limited feedback and arbitrary nonlinearity. This is a first step in a rigorous theoretical study concerning the effects of AC-coupled components. We show that the steady state is globally stable for small feedback gain and that local stability is lost, generically, through a Hopf bifurcation for larger feedback gain. The use of center-manifold techniques allows us to derive simple criteria that determine whether the Hopf bifurcation is supercritical or subcritical based on the knowledge of the first three terms in the Taylor-expansion of the nonlinearity. Furthermore, the presence of double-Hopf bifurcations of the steady state is shown, which indicates the existence of quasiperiodic and chaotic dynamics in these systems.

As a result of this investigation, we find that band-limited feedback introduces practical advantages, such as the ability to control the characteristic time-scale of the dynamics, and that it introduces differences to systems of Ikeda-type already at the level of steady-state bifurcations, e.g. bifurcations exist in which limit cycles are created with periods other than the fundamental "period-2" mode found in Ikeda-type systems.

ID of Contribution: 08 - 242

# TIME-DELAYED FEEDBACK CONTROL: TOPOLOGICAL CONSTRAINTS AND GLOBAL PROPERTIES

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Control of complex and chaotic behaviour has been one of the most rapidly developing topics in applied nonlinear science for more than a decade [1]. Time-delayed feedback control (TDFC) has been introduced as a powerful tool for the control of unstable periodic orbits in chaotic dynamical systems. From the experimental point of view its strength is based on the fact that the application of this method requires just the measurement of simple signals. No data processing is required and no information about the structure of the underlying motion is needed. Thus the method is very robust and flexible, and it has been successfully applied in physics, chemistry, and biology.

TDFC is an interesting and challenging topic even from the theoretical perspective since one is dealing from the very beginning with infinite-dimensional delay dynamics. It has been shown that only a certain class of periodic orbits characterized by a finite torsion can be stabilized by TDFC. Such a topological constraint means that any unstable periodic orbit with an odd number of real Floquet multipliers larger than unity can never be stabilized by TDFC.

Different strategies have been applied to overcome this constraint. The so-called rhythmic control is based on the periodic modulation of the control parameters with a period different from that of the orbit. Another way suggested recently [2] is based on the counter-intuitive idea of introducing an unstable degree of freedom into the control device. The key idea is to provide an even number of real Floquet multipliers by including an unstable degree of freedom in the feedback loop and to overcome the limitation mentioned above. Both methods were successfully applied to control torsion-free unstable periodic orbits in numerical simulations as well as in real experiments on nonlinear electronic circuits.

While chaos control by time-delayed feedback is meanwhile quite well understood from the point of view of linear stability analysis, very little is known about global features of the control problem. From an experimental perspective the question which type of initial condition yields successful stabilisation, i.e. in theoretical terms the basin of attraction, is of utmost importance. Applying general arguments from bifurcation theory we propose that discontinuous transitions at the control boundaries, i.e. subcritical behaviour, severely limit such basins. We illustrate our theoretical concept by numerical simulations and electronic circuit experiments [3].

References:

[1] Handbook of Chaos Control, ed. H.G. Schuster (Wiley-VCH, Berlin, 1999).

[2] K. Pyragas, Phys. Rev. Lett. 86, 2265 (2001).

[3] C.v. Loewenich, H. Benner and W. Just, Phys. Rev. Lett. 93, 174101 (2004).

ID of Contribution: 08 - 273

# STATE DEPENDENT DELAY MODEL FOR REGENERATIVE CUTTING PROCESSES

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Systems with state dependent delays are rarely used in mechanical engineering applications. In this study, machine tool chatter is investigated, and it is shown that state dependent delays arise if the regenerative effect is modeled accurately.

Traditional models of regenerative machine tool chatter use constant time delays assuming that the period between two subsequent cuts at the same part of the workpiece is a constant determined definitely by the spindle speed. These models result in delay-differential equations with constant time delay. In order to determine local dynamic behavior of the system, these equations can be linearized and stability analysis can be performed either analytically or numerically.

If the vibrations of the tool relatively to the workpiece are also included in the surface regeneration model, then the time delay is not constant, but it depends on the actual and a delayed position of the tool. In this case, the governing equation is a delay-differential equation with state dependent time delay. Equations with state dependent delays can not be linearized in the traditional sense, but there exists linear equations that can be associated to them. This way, the local behavior of the system with state dependent delays can be investigated.

In this study, a two degree of freedom model is presented for turning process. A thorough modeling of the regeneration effect results in the governing delay-differential equation with state dependent time delay. The associated linear equation is determined and linear stability properties are investigated.

# EXTENDED CIRCLE CRITERION WITH APPLICATION TO THE MASTER-SLAVE SYNCHRONIZATION WITH DELAY

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In this paper delay independent absolute stability of the delayed nonlinear dynamical systems (DNDS) has been studied, and an extended version of the Kalman-Yakubovich-Popov (KYP) lemma for the delayed linear dynamical system (DLDS) and an Extended Circle Criterion has been derived for the DNDS.

The results have been applied to the synchronization of identical chaotic systems with master-slave delayed coupling presented in [1] where the global asymptotic stability conditions have been given as the solution of Linear Matrix Inequalities (LMIs) for a given value of delay. In the synchronization of such a unilateral system, the objective is to obtain the slave system's output tracking the master system's output. For this objective the error term has been defined as the difference between the output states of the master system and the slave system, and the resulting error system has been represented in the Lur'e form, which has a DLDS in its forward path and a sector bounded nonlinearity in its feedback path. Then the delay independent absolute stability conditions have been derived for this error system.

The elements of the transfer matrix  $H(s,e^{-s})$  of the DLDS of the error system in the Lur'e form are transcendental functions of the complex frequency "s" and the extended KYP lemma for the DLDS has been given for the strict positive realness of its transfer matrix. In the derivation of the extended KYP lemma, the conditions for the asymptotic stability of the homogenous part of the DLDS in the forward path of the Lur'e system and the minimality (i.e, controllability and observability) of the DLDS of the Lur'e system, given in [2], has been assumed. Then an extended version of the Circle Criterion has been proposed and proved by considering a quadratic Lyapunov-Krasovskii functional and using the extended KYP lemma.

Another delay independent circle criterion has been also presented in [3] as strict positive realness of I+k  $H(s,e^{-s})$  and internal stability, which has been stated as a solution of an LMI while in our proposition the KYP Lemma has been extended, instead.

Our proposition, which is very similar to the delay free case, states that the system is absolutely stable if  $I+k H(s,e^{-s})$  is strictly positive real, where "k" is the sector bound of the nonlinearity in the feedback loop of the error system. Thus the absolute stability condition for the error system, (i.e. the synchronization condition) has been derived not for a given nonlinearity, rather for a class of nonlinearities that belongs to a sector bound.

- [1] M.E. Yalcin, J.A.K. Suykens and J. Vandewalle, "Master-Slave Synchronization of Lur'e Systems with Time-Delay", International Journal of Bifurcation and Chaos, Vol. 11, No. 6, pp. 1707-1721, 2001.
- [2] L.C.G.J.M. Habets, "Algebraic and Computational Aspects of Time-Delay Systems", PhD Thesis, Eindhoven University of Technology, 1994.
- [3] P.-A. Bliman, "Nonconservative LMI Criteria for Characterization of Delay Independent Properties of Delay Systems", INRIA Research Report, No. 4278, 2001

# AXIAL STICK-SLIP LIMIT CYCLING IN DRILL-STRING DYNAMICS WITH DELAY

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Self-excited vibrations are common phenomena observed in drilling systems used by oil industries. Authors usually models such system with a single DOF in torsional direction and a velocity weakening law at the bit/rock interface, as an intrinsic property of the bit/rock interaction.

A novel approach with 2 DOF in axial and torsion presented by [1] exhibits similar behaviors although all parameters are rate independent. The apparent decrease of the friction coefficient is directly related to axial vibrations of the bit and more precisely to intermittent losses of frictional contact.

Because of the helical motion of the bit, the cutting forces depend on a varying delayed axial position of the bit. This delay dependence is ultimately responsible for the coupling of the two modes of oscillations and for the existence of self-excited vibrations. Numerical simulations showed that they may degenerate into stick-slip oscillations or bit bouncing for sets of parameters in accordance with quantities measured in real field operations. Such extreme types of vibrations are at the origin of important bit or drillstring failures.

However, another regime characterized by a low amplitude of the torsional vibrations and a high drilling efficiency is also observed for some sets of parameters. In order to understand its origin, we first study the axial equation with a fixed delay as a direct consequence of the small variations of the bit angular velocity. This equation becomes therefore decoupled from the torsional one. Particularities of this equation lie in the delayed term, a non smooth non linearity and a non proper limit cycle in the state space of the axial position and velocity.

We present results and limitations of semi analytical (Describing Functions Method) and numerical procedures (Finite Difference Method, Shooting Method, Collocation Method) used to characterize the limit cycle of this DDE with non smooth nonlinearity. Moreover, we will use these numerical techniques to investigate the bifurcations occurring in the system responsible for the occurrence or destruction of these preferred regimes. Furthermore, it will be used to define the loss of stability of the axial limit cycle which leads directly to a damaging bit bouncing regime.

#### References:

[1] T. Richard, C. Germay, E. Detournay, Self-excited stick-slip oscillations of drill bits, C.R. Mecanique 332 (2004), 619-626.

ID of Contribution: 08 - 313

# APPLICATION OF FUZZY LOGIC CONTROLLER IN NIP INSTALLATION STRUCTURE

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In this paper, the dynamic behaviors of a roll nip installation of paper machine in paper manufacturing industry is studied by applying fuzzy logic control in numerical simulation environment. A typical nip unit consists of one hard metal roll and one soft polymer covered roll. A time delay term providing an important additional effect on roll

ENOC-2005, Eindhoven, the Netherlands

deformation and vibration of the system has been taken into account. The application of the fuzzy logic controller will improve the performance of the system by avoiding the harmful delay effect.

To obtain good quality paper with appropriate properties and grade, the paper pulp is processed through different nip units in paper mill plants, and in the final set of units the paper web is conditioned by deposition of a protecting film giving the paper its soft aspect. Because the paper is passing in between at least two rotating horizontal rolls in rolling contact, it exhibits high sensitivity to irregularities generating large vibrations in the system at higher rotation speed, especially when the roll contact is a rigid metallic one. A way to lower this effect is to coat one of the roll with a cover material of polymer type the role of which is to create a compliant link smoothing out roll interaction. However, the polymer material is deformable and may have a longer recovery time than the characteristic rotation time. In this case, the deformation still remains when the coincident cover point returns to the rolling interaction line, and a memory effect is added to the direct one at each crossing. A nip test installation, just similar to the ones in mill scale paper manufacturing systems, has been constructed recent years in the laboratory of Machine Design at TUT. A coupled system of time delay equations will be derived in the sequel for the class of oscillatory time dependent perturbations likely to exist in this structure.

In this work, fuzzy logic controllers based on soft computing will be applied in a multi-degree-of-freedom model with delay effect through 'if-then' reasoning rules. The fuzzy model describes the interference of the running procedures. Time domain simulations carried out in SIMULINK indicate the promising result that a reduction in oscillation level is reached by the controller based on a parameter controlling method. Numerical results verify that the stability of the system is increased after applying the fuzzy control.

#### References:

- [1] F. C. Moon, Dynamics and Chaos in Manufacturing Processes, John Wiley&Sons, Inc., 1998.
- [2] N. Olgac, M. Hosek, Active Vibration Absorption and Delayed Feedback Tuning, The Mechanical Systems Design Handbook, CRC Press LLC, 2002.
- [3] D. Driankov, H. Hellendoorn, M. Reinfrank, An Introduction to Fuzzy Control, Springer-Verlag, 1993

ID of Contribution: 08 - 328

# CONTROL OF NONLINEAR SYSTEMS WITH TIME-DELAY USING STATE PREDICTOR BASED ON SYNCHRONIZATION

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Recently the study of time-delay systems has received attention in various fields, such as mathematics, information technology, applied physics, biology and social science. Of course, control of time-delay systems has continued to be a hot topic in control engineering and science. In particular, a large number of useful and important results have been obtained for linear time-delay systems. While in practice most systems contain nonlinear elements and are described as nonlinear time-delay systems, the study of control theory for such systems is in progress.

In this paper, we consider control of nonlinear systems with time-delay, and we propose a control design method of nonlinear systems with time-delay using a state prediction based on synchronization. The state prediction scheme based on synchronization (Oguchi and Nijmeijer, 2004) has been developed by the authors in order to predict the behaviour of complex systems with time-delay and it is designed by using a delay-dependent stability or stabilizability conditions based on a Lyapunov-Krasovskii functional. This method can be considered as an extension of the anticipating synchronization of chaotic systems proposed by Voss (Voss, 2000). In this paper, we show the robust convergency of the synchronized predictor under perturbations and model uncertainties. First, we derive a sufficient condition for the zero solution of retarded nonlinear systems with perturbation to be asymptotically stable by using Lyapunov-Razumikhin approach. In addition, we also derive a sufficient condition for practical stability of the retarded nonlinear systems with perturbations, we show that the proposed prediction scheme works well even if the system has model uncertainties, perturbations and nonlinear terms which are not contained in the predictor. In addition, we propose a controller design method of nonlinear systems with time-delays by using the

proposed predictor. Finally, we show the effectiveness of the proposed controller by a numerical simulation of a boiler system.

References:

- [1] T. Oguchi and H. Nijmeijer: Prediction of Chaotic Behaviour using Synchronization, Proceedings of 5th IFAC Workshop on Time Delay Systems (2004)
- [2] H. Voss: Anticipating Chaotic Synchronization, Phys. Rev. E, Vol.61, No.5, 5115/5119 (2000)

ID of Contribution: 08 - 375

# **PERTURBATION THEORY FOR 04 WITH TIME DELAYS**

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Time-delayed system and, in particular, biological time-delayed systems often exhibit fluctuations. For this reason, there is a great interest in deriving analytical expressions describing the stationary behavior of stochastic time-delayed systems. While for linear time delayed stochastic systems analytical expressions for stationary distributions have been derived, for nonlinear systems in the general case such expressions have not been found so far. We consider systems that involve a time-delayed variable with fixed time delay and a nonlinearity that represent a perturbation term with respect to the whole system dynamics. Using a Fokker-Planck approach to time-delayed stochastic systems (Guillouzic/L'Heureux/Longtin 1999; Frank et al. 2003, 2004), it is shown how to determine analytical expressions for the stationary behavior in first order approximations.

References:

[1] Guillouzic et al. Phys. Rev. E 59 (1999) 3970

[2] Frank et al. Phys. Rev. E 68 (2003) 021912; 69 (2004) 061104

ID of Contribution: 08 - 405

# ANALYTICAL TREATMENT OF DELAYED FEEDBACK CONTROL METHOD AT HOPF BIFURCATIONS

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Delayed feedback control (DFC) [1] is a convenient tool to stabilize unstable periodic orbits (UPO's) embedded in the strange attractors of chaotic systems. The method is reference free; it makes use of a control signal obtained from the difference between the current state of the system and the state of the system delayed by one period of the unstable periodic orbit. The method allows us to treat the controlled system as a black box; no exact knowledge of either the form of the periodic orbit or the system equations is needed. By giving only the period of the unstable orbit the system under control automatically settles on the desired periodic motion, and stability of this motion is maintained with only tiny perturbations.

The delayed feedback control algorithm is especially superior for fast dynamical systems, since it does not require any real-time computer processing. Successful implementation of this algorithm has been attained in quite diverse experimental systems.

Despite a certain progress in experiment the theory of delayed feedback control is far from being completed. This theory is rather intricate since it involves nonlinear delay differential equations [2]. We show that an analytical approach based on classical asymptotic methods of nonlinear dynamics is possible if the system is close to a Hopf bifurcation. We consider two problems, namely, the control of UPOs at subcritical and suppercritical Hopf bifurcations.

In the first case, the UPO is torsion-free and we use an unstable delayed feedback controller [3] for stabilization. In the second case, we consider the problem of synchronization of a nonautonomous weakly nonlinear oscillator under the DFC. We show that the DFC enlarges the synchronization domain of the oscillator. In both cases we obtain closed analytical expressions that allow us to optimize the parameters of the delayed feedback controller.

# References:

- [1] K. Pyragas, Phys. Lett. A 170, 421 (1992).
- [2] K. Pyragas, Phys. Rev. E 66, 026207 (2002).
- [3] K. Pyragas, Phys. Rev. Lett. 86, 2265 (2001).

# ID of Contribution: 08 - 430

# SPECTRO-TEMPORAL DEFECTS IN A DELAYED SYSTEM WITH FRUSTRATION

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In a free-electron laser, an optical pulse experiences round-trips between two mirrors, and is amplified by its periodic interaction with the electron bunch of an accelerator. The evolution of the pulse shape versus time can be described by a delay differential equation model. The frustration due to the mismatch between the pulse round-trip period and the delay leads to instabilities. Thanks to the small dissipation in this system, the model can be reduced to a convection-diffusion equation. The convective nature is responsible for the appearance of an hypersensitivity to noise (transient growth), characterized by drifts of the spatial structures.

We show that the first step of the destabilization is associated with the appearance of spectrotemporal defects, recalling the Eckhaus-type phase-slips. Finally we show that the main features of the instability are kept in simple Ginzburg-Landau equations with advection. The situations of local and global coupling are compared.

# **MINI-SYMPOSIUM 9**

# **Time Series and Reconstruction**

**Chairs / Organizers:** 

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# ESTIMATION OF MEASUREMENT NOISE AND DYNAMICAL PARAMETERS FROM TIME SERIES DATA

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We present a general method to extract drift and diffusion functions of stochastic processes from experimental time series. This is based on a procedure recently published by Siegert et al[1]. However, our approach also applies for data sets sampled at modest frequencies.

Drift and diffusion coefficients are embedded into families of functions depending on a set of parameters  $\sigma$ . A first estimate is given by the evaluation of drift and diffusion using the smallest available time increment[1]. An optimal set of parameters is obtained by an iteration procedure minimizing the Kullback-Leibler distance between the measured and the calculated two point joined pdf. This pdf is obtained either by a simulation of the Langevin equation of a numerical solution of the corresponding Fokker-Planck equation for the parameter set  $\sigma$ .

For unidimensional data our method substantially can be simplified to analyse processes containing additive and multiplicative noise terms.

References:

[1] S. Siegert et al., Physics Letters A 243, 275-280 (1998)

ID of Contribution: 09 - 224

# DETECTING GENERALIZED SYNCHRONIZATION FROM TIME SERIES

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After a brief introduction to synchronization phenomena of dynamical systems we shall discuss different cases of generalized synchronization and present methods for detecting them from time series. In particular we shall focus on synchronization resulting in complex (non-smooth and/or non-invertible) functional relations between drive and response. It will be demonstrated that for detecting synchronization in these cases, a suitable delay embedding is crucial taking into account both time series (drive and response) when constructing delay vectors. This method may be viewed as a purely time series based implementation of the wellknown auxiliary systems approach of Abarbanel et al. In the second part of the talk we shall present a method for detecting weak interrelations (much below the threshold of synchronization) by means of a surrogate data test based on randomized delay embeddings. All these methods will be illustrated with numerical examples

#### ID of Contribution: 09 - 250

# NONLINEAR TIME SERIES PREDICTION USING LOCAL MODELLING: A COMPARISON OF DIFFERENT APPROACHES

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Predicting the future evolution of dynamical systems is a major goal in many areas of science. Often the underlying dynamical equations are unknown and only a single-channel time series is available. If the time series originates from a deterministic dynamical system, prediction methodologies based on embedding and attractor reconstruction using local statistical models constructed from the data are well-established. A variety of approaches for building local models from data has been proposed: local polynomial models based on nearest neighbours and radial basis function models. More recent additions include the quite general and flexible framework of cluster-weighted modelling also referred to as probabilistic network [1] and adaptive local polynomial models [2].

The present study compares/contrasts all these different approaches both on known mathematical systems and on real observations including measurements from an electronic circuit. Both best guess and probabilistic prediction is considered.

#### References:

- [1] Gershenfeld, N. A.; Schoner, B.; Metois, E.; 1999: Cluster-weighted modeling for time series prediction and characterization, Nature 397, 329-332.
- [2] Kwasniok, F.; Smith, L. A.; 2004: Real-time construction of optimized predictors from data streams, Physical Review Letters 92, 164101.

#### ID of Contribution: 09 - 274

#### **OPEN QUESTIONS IN TIME SERIES RECONSTRUCTION**

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In the two decades since a firm foundation for the reconstruction of deterministic dynamics from time series were set down, a huge variety of applications have been developed both for the analysis of time series and for their use in applications. We will consider several of the open questions which remain in three areas of interest: Can we find an internally consistent measure of what makes a good nonlinear model (whether from reconstruction or from parameter estimation of some functional form)? Can we develop methods which exploit the potentially huge volumes of data required for accurate reconstructions, and which are now often available operationally? Can we account for observational noise, dynamic noise and model inadequacy in a robust fashion, and if so what might the resulting reconstructions tell us about the system and its dynamics?

From a statistical point of view, there remain many interesting issues to address in the next few decades. Statistical estimation is founded upon distinguishing a sample-statistic from the corresponding 'true' statistic of the underlying process: knowing the process, we can describe how the sample-mean is likely to converge to the mean in the limit of large duration. While we will all agree on the value of a sample-mean given the same data set, it is not clear that the notion of 'sample-Lyapunov exponent' is uniquely defined. Secondly, minimising root-mean-square (RMS) error is at the heart of many statistical estimation algorithms, yet this is nonsensical in nonlinear models (where such a goal is likely to reject the model that generated the data!). An alternative approach is to replace root-mean-square evaluation with a probabilistic skill score which can account for nonlinearities in the model; yet these scores may also prove misleading when the mathematical structure of the model is imperfect, which is arguably always the case in practice. Will attempts to maximise probabilistic skill given an imperfect model class lead us astray in a similar fashion as misguided attempts to maximise RMS skill given noisy data and a nonlinear model have in the past?

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The value of reconstruction methods in practice is largely determined by the marginal value of knowing our current 'laws of physics' given observations over a significant duration; to what extent can reconstruction methods complement this understanding and extend it? Although these questions will be addressed in a general context, the discussion will consider real time series and physical systems like the UK electricity grid, laboratory experiments, the Earth's weather and climate systems, and our models of each.

# References:

- K. Judd and L.A. Smith (2004) Indistinguishable States II: The Imperfect Model Scenario, Physica D 196: 224-242.
- [2] F. Kwasniok and L.A. Smith (2004) Model Reconstruction from Data Streams, Phys. Rev. Lett. 92 (16).
- [3] P.E. McSharry and L.A. Smith (2004) Consistent Nonlinear Dynamics: identifying model inadequacy, Physica D 192: 1-22.

# ID of Contribution: 09 - 304

# SMOOTH ORTHOGONAL DECOMPOSITION BASED RECONSTRUCTION OF A SLOW-TIME TRAJECTORY

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This paper presents a method for reconstructing a slow-time phase space trajectory using only fast-time measurements of a hierarchical dynamical system. This system describes two coupled subsystems, where a slow-time subsystem causes the parameter drifts in a fast-time subsystem. This drift in parameters results in altering (warping) the system's fast-time trajectory evolution. The slow-time tracking feature vectors are developed based on the phase space warping (PSW) concept [1-2] that refers to this changes in a trajectory evolution. The phase space trajectory is reconstructed from the recorded fast-time data using delay coordinate embedding. Short-time evolution for each point in the reconstructed phase space is compared to the corresponding evolution of points on the reference system's trajectory. This difference in short-time evolution is used to quantify PSW and develop appropriate averaged feature vector for each data record.

The slow-time process is identified by applying a smooth orthogonal decomposition (SOD) to this feature vectors. The SOD can be viewed as an extension to proper orthogonal decomposition (POD), where an additional constraint is imposed on the proper orthogonal coordinates (POCs). In particular, we require that smooth orthogonal coordinates (SOCs) were as smooth as possible. The discredited version of the SOCs can be obtained using generalized singular value decomposition.

The validity of method is demonstrated by numerical and physical experiments on a vibrating structure with slowly drifting potential field. The experimental data is collected from an electromechanical system affected by a twodimensional slow-time process. This processes is realized by two powered electromagnets that are perturbing a magnetic potential field of a vibrating cantilever beam. The voltages of the electromagnets are altered using a programmable power supply to provide a circular or figure eight trajectories in a phase plane of the supply voltage. In numerical experiments a mathematical model corresponding to the experimental system is used. The feature vectors, estimated from the recorded strain time series using the PSW statistics are used in the SOD procedure. It is demonstrated that the SOD provides topologically equivalent reconstruction of the original voltage trajectory. In particular, it is demonstrated that there is an affine coordinate transform relating the reconstructed trajectory to the original.

# References:

[1] Chelidze, D., Cusumano, J.P., and Chatterjee, A., "Dynamical Systems Approach to Damage Evolution Tracking, Part 1: Description and Experimental Application," Journal of Vibration & Acoustics, 124 (2) (2002) 250–257. [2] Cusumano, J.P., Chelidze, D., and Chatterjee, A., "Dynamical Systems Approach to Damage Evolution Tracking, Part 2: Model-Based Validation and Physical Interpretation," Journal of Vibration & Acoustics, 124 (2) (2002) 258-264.

# **MINI-SYMPOSIUM 10**

# **Control of Chaos**

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# ANTI-CONTROL OF DISCRETE CHAOS IN BANACH SPACES

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Chaos control has been developed so far in two different directions: control of chaos and anti-control of chaos or chaotification. A process of making a chaotic system non-chaotic or stable is called control of chaos. Over the last decade, research on control of chaos has been rapidly developed. Anti-control of chaos, on the other hand, is a process that makes a non-chaotic system chaotic, or enhances a chaotic system to present stronger or different chaos. In recent years, it has been found that chaos can actually be very useful under some circumstances. Due to the great potentials of chaos in many non-traditional applications, there is growing interest in research on chaotification of dynamical systems today.

In research on chaotification for discrete dynamical systems, a mathematically rigorous chaotification method was first developed by Chen and Lai from a feedback control approach. They showed that the Lyapunov exponents of the controlled system are positive, and the controlled system via the mod-operation is chaotic in the sense of Devaney when the original system is linear, and is chaotic in a weaker sense of Wiggins when the original system is nonlinear [1]. Later, chaos generated by their method was shown to be in the sense of Li-Yorke. This method plays an important role in studying chaotification problems of discrete dynamical systems. We have noticed that all the chaotification problems for discrete dynamical systems studied so far are assumed in finite-dimensional real spaces. To the best of our knowledge, no results have been reported on chaotification for infinite-dimensional discrete dynamical systems.

Now we investigate chaotification for discrete dynamical systems in Banach spaces, via feedback controltechniques. Discussions are carried out in general and some special Banach spaces. Two simple feedback controllers have been designed for chaotification of discrete dynamical systems in general and special Banach spaces. In particular, the controllers can be designed as a generalization of the classical sawtooth and sine functions in some special Banach spaces. The controlled systems have been proved to be chaotic in the sense of both Devaney and Li-Yorke. As a consequence, the finite-dimensional controlled system discussed in [2] has also been proved to be chaotic not only in the sense of Li-Yorke but also in the sense of Devaney. In addition, the Chen-Lai anti-control algorithm via feedback control with mod-operation in a finite-dimensional real space developed in [1] has been further extended to a certain infinite-dimensional Banach space. This controlled system has been shown to be chaotic in the the sense of Devaney, Li-Yorke, and Wiggins. Consequently, the controlled system discussed in [1] has been shown to be chaotic in the the sense of Devaney, Li-Yorke, and Wiggins.

- [1] Chen, G. and Lai, D., Feedback anticontrol o discrete chaos, Int. J. Bifurcation and Chaos 8(1998), 1585-1590.
- [2] Wang, X. F. and Chen, G., Chaotification via arbitrary small feedback controls, Int. J. Bifurcation and Chaos 10(2000), 549-570.

ID of Contribution: 10 - 053

# **EXPANSION MAPS AND HIGHER-DIMENSIONAL LI-YORKE CHAOS**

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In this paper, the concepts of (quasi-)contraction maps, (quasi-)expansion maps, and point-wise expansion maps, defined in some convex sets of  $\mathbb{R}^n$ , are introduced. Several results on these maps are established. Moreover, the original Marotto Theorem for higher dimensional discrete maps is rephrased and discussed.

ID of Contribution: 10 - 064

# **CONTROLLING DC-DC CONVERTER WITH CHAOS-BASED PWM**

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This paper presents an overview of recent studies on the interactions between fuzzy logic and chaos theory. First, it is shown that chaotic systems can be fuzzy modeled by either model-free approach or model-based approach. Accordingly, it means that fuzzy systems can also be chaotic. Here, we focus on fuzzy modeling with model-free approaches, i.e., using Mamdani fuzzy model.

The model-free approach allows the modeling of processes in a linguistic manner. The different states of each variable are labelled with a set of adjectives (fuzzy sets) and the qualitative description of the variable behaviors is given in terms of membership degrees of each variable to each one of the fuzzy sets defined on it. A fuzzy model consists of a set of rules which relate the actual value of the state to the previous one.

A definition of chaotic behaviors involves the three fundamental concepts of transitivity, density of periodic orbits and sensitivity to initial conditions, which can be used to describe the chaotic trajectories by monitoring the time evolution of trajectories emanating from nearby points on the attractor. In a chaotic system, points which are close each other repel themselves so that the flow stretches. Such behavior can not combine with the boundness of the attractor without the presence of a folding action. The stretching and folding features of the flow are responsible for the sensitivity to initial conditions, and characterize chaotic behavior. Theoretically, using this method can create any preferred chaotic attractor.

Then, it is also shown that Takagi-Sugeno (TS) fuzzy systems can be made chaotic (or chaotified) with some simple and implementable controllers, which can be either discrete-time or continuous-time. The chaotification approaches are very different for discrete-time or continuous-time fuzzy systems, and the existing chaotification approaches are mathematically rigorous in the sense of some commonly used mathematical criteria for chaos such as those defined by Deveney and by Li-Yorke.

For chaotifying discrete-time TS fuzzy systems, we employ the parallel distributed compensation (PDC) to determine the structure of a fuzzy controller so as to make all the Lyapunov exponents of the controlled TS fuzzy system strictly positive. But for continuous-time ones, the chaotification approach is based on the fuzzy feedback linearization and a suitable approximate relationship between a time-delay differential equation and a discrete map. The time-delay feedback controller, chosen among several candidates, is a simple sinusoidal function of the delay states of the system, which has small amplitude.

ENOC-2005, Eindhoven, the Netherlands

Finally, some fuzzy-chaos-based applications will be mentioned. A foundation is thus laid for further exploration on the new research direction of the interactions between fuzzy logic and chaos theory.

# ID of Contribution: 10 - 074

# CHAOS EXHIBITED BY CLOSED FLEXIBLE CYLINDRICAL SHELLS

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In this work complex vibrations of closed infinite length cylindrical shells of circle type cross section subject to transversal local load in frame of non-linear classical theory are studied. A transition from PDEs to ODEs (Cauchy problem) is carried out using the higher order Bubnov-Galerkin approach and Fourier representation. On the other hand, the Cauchy problem is solved using the 4th order Runge-Kutta method. Results are analysed owing to application of nonlinear dynamics and qualitative theory of differential equations.

The work consists of two parts. In the first part static problems of theory of closed cylindrical shells are studied. A problem of reliability of the obtained results is verified owing to comparison of the results with those taken from literature. The second part is devoted to analysis of dynamics of closed cylindrical shells. An influence of sign-changeable external pressure vs control parameters, such as length of pressure width, relative linear shell dimension, excitation frequency and amplitude of external transversal load, is outlined.

It has been found that character of investigated shell vibrations depends essentially of the loading angle. For small values of this angle the summed surface of chaos is high, whereas increase of loading of cylindrical shell yields a decrease of space of chaos which is shifted into low and averaged frequencies. For large surface of external pressure chaotic areas are concentrated on the whole chart, but the largest part is located in the vicinity of frequencies less than the eigenfrequency. The corresponding summed surface of chaotic zone is essentially high. Also areas associated with Hopf bifurcations located in vicinity of frequencies larger than the eigenfrequency are relatively high.

The novel criterion of stiff stability loss has been detected, and analysis of exciting load amplitude on the form of stability loss has been carried out. It has been shown, among others, that stiff stability loss is associated with an occurrence of the first Andronov-Hopf bifurcation and transition into vibrations with the first subharmonic frequency, which can be either harmonic or chaotic ones. New scenarios of transition of our shell vibrations from harmonic to chaotic ones have been detected and illustrated. It is worth noticing that in this work some novel scenarios of transition of vibrations of our analysed mechanical system into spatial and temporal chaos are detected, as well as validity of already known exciting scenarios are verified.

- [1] J. Awrejcewicz, V. A. Krysko, Feigenbaum scenario exhibited by thin plate dynamics, Nonlinear Dynamics, 24, 2001, 373-398.
- [2] J. Awrejcewicz, V. A. Krysko, A. V. Krysko, Spatio-temporal chaos and solitons exhibited by von Kármán model, International Journal of Bifurcation and Chaos, 12(7), 2002, 1465-1513.
- [3] J. Awrejcewicz, A. V. Krysko, Nonclassical Thermoelastic Problems in Nonlinear Dynamics of Shells, Springer-Verlag, Berlin 2003.

#### ID of Contribution: 10 - 139

# STABILIZATION OF CHAOTIC BEHAVIOUR IN THE RESTRICTED THREE-BODY PROBLEM

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An analitical approach to the problem of stabilization of chaotic behaviour of the restricted three body problem is given. A part of this problem is reduced to the well-known Sitnikov case: Two equal masses orbit around their barycenter. A third, massless, body moves in their gravitational field perpendicular to the surface of motion of the primaries. Under certain circumstances, it can be shown, that the oscillation of the third body is chaotic. Our approach is based on the analysis of separatrix contours. The main obtained result is the following: three body planetary system can exhibit stabilized behaviour due to the comet orbiting near by third body.

#### ID of Contribution: 10 - 160

# ON BIFURCATION CONTROL OF AN UNDERACTUATED MECHANICAL DEVICE

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This paper deals with a (partial) global bifurcation analysis of a controlled underactuated mechanical system. The mechanical device is an inertia wheel pendulum consisting of a pendulum with a rotating disk at the end. The pendulum can rotate freely, i.e. it is not directly actuated, but the disk is driven by means of a small DC motor. Swinging-up and stabilizing the pendulum at the inverted position is impaired because the applied voltage and maximum torque delivered by the motor are bounded. The underlying constraint is that the supplied torque is not sufficient to dominate the effect of the gravity on the pendulum, and the only way it can reach the upward position is by means of oscillations of increasing amplitude. Classical nonlinear controller design methods, such as those based on Hamiltonian approaches or Lyapunov theory, result in cumbersome procedures when the control action is bounded. On the other hand, bifurcation theory can provide some insights on the system behavior when some control parameters are varied with the purpose of finding a region in the parameter space where the control objective is achieved.

In this paper the closed-loop dynamics of the inertia wheel pendulum is analyzed in terms of certain control gains. The controller is derived to ensure local stability of the upward position, resembling those derived from Hamiltonian techniques, and it is followed by a smooth saturation function restricting its magnitude (see [1]). After an analytical local bifurcation study, a numerical bifurcation analysis is performed to characterize the dynamical behavior over a larger domain. A rich dynamical scenario is depicted, including pitchfork and Hopf bifurcations of equilibria, saddle-node bifurcations of periodic orbits, homoclinic and heteroclinic bifurcations, cuspidal points of cyclic fold bifurcations, and chaotic motions. A partial two-parameter bifurcation diagram helps to identify regions in the parameter space where the expected dynamical behavior is achieved. For example, selecting appropriately control gain values one can avoid complex behaviors and eventually achieve simultaneous stabilization of the upright position together with a large basin of attraction. Due to the inherent symmetry of the system, its dynamical behavior over that slice of the control parameter space is organized around two (coincident) double zero bifurcation points with rotational symmetry.

The unfolding of these singularities is associated to the Khorozov-Takens or resonance 1:2 normal form. It is worth mentioning that the true organizing centre of the dynamics is a triple-zero eigenvalue bifurcation and the described scenario should be present in the unfolding of that singularity. The methodology presented here (see also [2]) can be helpful to obtain new insights on the system dynamics to design more efficient controllers for mechanical systems.

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References:

- Alonso, D. M., Paolini, E. E., and Moiola, J. L., "Controlling an inverted pendulum with bounded controls", in Dynamics, Bifurcations, and Control, L. Gruene and F. Colonius (eds.), LNCIS 273, Springer-Verlag, Berlin, 2002, pp. 3--16.
- [2] Sieber, J., and Krauskopf, B., "Bifurcation analysis of an inverted pendulum with delayed feedback control near a triple-zero eigenvalue singularity", Nonlinearity 17(1), 2004, 85--103.

ID of Contribution: 10 - 229

# CONTROLLING CHAOS IN THE JULIA SET OF THE QUADRATIC MAP $Z \rightarrow Z^2 + C$

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The Julia set, J(P), is the closure of the set of repelling periodic points in the complex space of the polynomial P. Some of its properties are: repulsion; invariance; an orbit on J(P) can be periodic or chaotic; all unstable periodic orbits (UPO) are on J(P); and J(P) almost always has fractal structure. The algorithm to generate J(P) is based on the fact that, whereas J(P) is a repellor under the forward iterative map, J(P) will become an attractor under an inverse map. By selecting any point in the complex plane the backward iterates then approach points of J(P). From above and because it exhibits sensitivity to initial conditions, the Julia set of any polynomial is a strange attractor.

The iterative function  $z(k+1) \rightarrow z(k)^2+c$ , where z, c are complex numbers, produces the Mandelbrot set, M. J(M) is obtained by starting the backward iteration of the previous map in the repelling fixed point. Any complex number inside M corresponds to a connected J(M); if it lies outside, J(M) is a Cantor set. Because J(M) is invariant any UPO in J(M) will map to other UPO in J(M).

In this paper, UPOs of the Julia set that are produced from the Mandelbrot set are controlled. The sensitivity of chaotic systems to small perturbations is exploited to stabilize the dynamics of J(M) and to direct the chaotic trajectories to a desired state by using Shinbrot's method [2]. The problem encountered when producing every iteration of J(M) is that it generates  $2^k$  values; it has a two-valued inverse, and twice as many predecessors are generated on each iteration. This means that the M map is not invertible; i.e. when defining the inverse function it does not give the result uniquely. In the end there will be  $2^k$  roots, k is the number of iterations.

The new proposed algorithm overcomes this difficulty by the arbitrary selection of one of the values at each iteration and then directing it to the target by applying small perturbations to the system. The size of perturbation is constrained to certain value. Because the pole placement technique is used the choice of the regulator poles is done at every iteration. This is done in order for the poles to be inside the unit circle at a convenient place. This will steer the trajectory of a starting point in J(M) to the desired UPO in J(M).

Also, J(M) is linearized about the fixed point. With the resulting linear system the LQR method is used to design a state variable feedback controller, see [3]. The controller will guarantee asymptotic stability in some neighborhood containing the repelling fixed point. A Lyapunov function is determined from the linear system to obtain a controllable target for J(M).

- [1] Devaney, An Introduction to Chaotic Dynamical Systems. Westview Press.,-(2003)
- [2] Shinbrot,-Grebogi,-Ott,-Yorke, Using chaos to direct trajectories to targets Physical Review Letters (1990)-Vol.65,pp.3215-3218
- [3] Vincent, Control Using Chaos . IEEE-Control Systems Magazine,-(1997)-Vol.17(6).pp.65-76

# DELAYED MEASURED SYSTEMS IN POINCARE-BASED CHAOS CONTROL

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This talk first discusses the effect of measurement delay on Poincare-based chaos control. When stabilization of unstable periodic orbits or fixed points by the method given by Ott, Grebogi, and Yorke (OGY) must be based on a measurement delayed by tau orbit lengths, the performance of unmodified OGY method is expected to decline. For experimental considerations, it is desired to know the range of stability with minimal knowledge of the system. As discussed in [1,3], unmodified OGY control fails beyond a maximal Lyapunov number of lambda max = 1 + (1/tau). The area of stability is investigated both for OGY control of known fixed points and for difference control of unknown or inaccurately known fixed points. An estimated value of the control gain is given. Using the Jury criterion, the stability diagrams can be calculated analytically. Hence, both unmodified Ott-Grebogi-Yorke control and difference control can be successfully applied only for a certain range of Lyapunov numbers depending on the delay time. The second part addresses the question of how the control of delayed measured chaotic systems can be improved, i.e. what extensions must be considered if one wants to stabilize fixed points with Lyapunov numbers above lambda max. This limitation can be overcome by at least two classes of methods, namely, by rhythmic control and by the memory methods of linear predictive logging control and memory difference control [2,3]. While the first fits well within the conceptual line of e.g. model predictive control, for the case of difference control (counterintuitively) it is also possible to give an explicit deadbeat control scheme that allows (in linear approximation) to perform control without principal limitations in delay time, dimension, and Ljapunov numbers.

**References:** 

[1] J.C.Claussen, Phys. Rev. E 70, 046205 (2004).

[2] J.C.Claussen and H.G. Schuster, Phys. Rev. E 70, 056225 (2004)

[3] J.C.Claussen, Proc. 2003 Int. Conf. on Physics and Control, St. Petersburg, Russia, edited by A. L. Fradkov and A. N. Churilov (IEEE, St. Petersburg, 2003), Vol. 4, pp. 1296-1302.

ID of Contribution: 10 - 263

# MULTIPLE DELAY FEEDBACK CONTROL A DELAY METHOD FOR STABILIZING FIZED POINTS

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We present Multiple Delay Feedback Control (MDFC) as an efficient method for stabilizing fixed points (equilibria) of various chaotic dynamical systems. MDFC uses two or more different and independent delay times which enter independent control terms. A comparison with delayed feedback control methods that are based on a single (fundmental) delay time (Pyragas' TDAS, ETDAS) shows that MDFC is (much) more efficient for fixed point stabilization, in particular with large delay times. To demonstrate this approach for stabilizing unstable fixed points we present numerical simulations of various well-known theoretical systems (Chua's circuit, Rössler, Lorenz etc.) and successful experimental applications for stabilizing the output power of a chaotic frequency-doubled Nd:YAG laser as well as the steady states of a fast Chua's circuit.
161

## CONTROLLING MULTIPLE UNSTABLE PERIODIC ORBITS OF THE *n*-SCROLL CHUA'S CIRCUIT

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This work is a followed research on the control of the chaotic behavior in higher-order dynamical systems by using the method given in [Boukabou & Mansouri, 2004]. It will be shown how chaotic systems with multiple unstable periodic orbits (UPOs) detected in the Poincaré section can be controlled as well as taking the system dynamics from one UPO to another. Realization of these control objectives is demonstrated using a numerical example, the *n*-scroll Chua's system.

ID of Contribution: 10 - 288

## **EXPERIMENTAL CONTROL OF CHAOS IN PLASMA**

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The control of chaos in the plasma devices is very important for applications, especially for the improvement of fusion reactors [1]. Here we report on experimental results concerning the control of chaos in the diffusion plasma of a DP (double plasma) machine. The methods are based on the control of emergence and dynamics of a complex space charge configuration (CSCC) in front of a positively biased electrode immersed in plasma. The methods are very simple and efficient, using just passive elements in the external electrical circuit, like capacitors and coils.

Under certain experimental conditions (gas pressure, plasma density, electron temperature), in front of a positively biased electrode immersed into plasma a CSCC can appear in form of a positive nucleus (positive ion – rich plasma) confined by an electrical double layer (DL). The static current-voltage (I-V) characteristic of the electrode shows at least two regions of negative differential resistance (NDR), one S-type and one N-type, associated with hysteresis effects. The S-type NDR is related to the appearance and disappearance of the CSCC, whereas the N-type NDR is related to the spatio-temporal nonlinear dynamics of the CSCC [2], or to the onset of low-frequency instabilities. Between these two regions uncorrelated low-frequency oscillations with a continuous power spectrum can appear. Since the oscillations are uncorrelated, the plasma system enters into a chaotic state. To avoid this, we inserted a capacitor between the electrode and the ground. In this way, the chaotic state is superseded by a regular oscillatory one. The frequency of the observed oscillations depends on the charging and discharging time constants of the capacitor. The physical mechanism of these oscillations was extensively investigated.

In the N-type NDR the plasma system performs strongly nonlinear oscillations, characterized by the presence of many higher harmonics in their power spectrum. But, for many applications, harmonic oscillations are required, so we need to suppress all higher harmonics. This was possible by inserting an inductance into the external electrical circuit, in series with the electrode and the power supply. The frequency of the obtained harmonic oscillations depends on the inductance according to Thomson formula.

The investigation of the appearance and dynamics of a CSCC in plasma can be very important in connection with the controlled fusion program. A certain striking similarity between these phenomena and the L-H (low to high) transition

in tokamak plasma was observed [3]. The control of such phenomena can lead to the improvement of tokamak plasma confinement by the reduction of fluctuations and the elimination of some instabilities.

References:

- [1] T. Klinger, C. Schröder, Phys. Plasmas 8 (2001) 1961;
- [2] M. Sanduloviciu, C. Borcia, G. Leu, Phys. Lett. A 208 (1995) 136.
- [3] D. G. Dimitriu, 4th International Workshop and School "Towards Fusion Energy Plasma Physics, Diagnostics, Applications", Kudowa Zdroj, Poland, 2004.

ID of Contribution: 10 - 303

## SWING-UP CONTROL OF A DOUBLE PENDULUM: A CHAOS BASED ADAPTIVE APPROACH

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This paper discusses a novel approach to chaos control based on the use of the so-called Minimal Control Synthesis algorithm. The strategies presented are based on the explicit exploitation of different properties of chaotic systems including the boundedness of the chaotic attractors and their ergodicity. It is shown that chaos can be exploited to synthesise more efficient control techniques for nonlinear systems. For instance, by using the ergodicity of the chaotic trajectory we show that a local control strategy can be used to synthesise a global controller. An application is presented to the swing-up control of a double inverted pendulum. Specifically, a two-phase control strategy is presented where chaos is exploited to swing up the pendulum to its desired position while an adaptive algorithm is used for its stabilization in the inverted position. In so doing, no extra actuator is used on the double pendulum joint. The chaos based methodology will be compared with the energy-based swing up control approach recently presented in [1]. It will be shown that the chaotic enhanced adaptive strategy is effective in controlling the system while requiring a minimal control energy.

References:

[1] KJ Astrom, K Furuta, Swinging-up a pendulum by energy control, Proc IFAC World Congress, San Francisco, USA; 1996

ID of Contribution: 10 - 305

## BIFURCATION-BASED SWITCHING CONTROL OF SMOOTH SYSTEMS: A NOVEL DESIGN APPROACH

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The aim of this paper is to present a novel approach to control smooth dynamical systems. Namely, an appropriate switching controller is synthesised by using results from the heory of bifurcation in nonsmooth system. Rather than aiming at changing the entire dynamics of the system of interest, we shall seek to design a controller acting in a local neighborhood of the target evolution. The analysis is based on the study of the system Poincaré map and relies on the theory of nonsmooth bifurcations recently presented in [1]. For example, we will show that it is possible to control the amplitude of an oscillatory motion, or even suppress it (if unwanted) by means of a switching controller acting in a relatively small neighborhood of the limit cycle. By appropriately selecting the switching manifolds and the control action, it is possible to move the flixed point corresponding to the target limit cycle on the Poincaré map and hence control the cycle itself. In so doing, the control effort is low as control is only activated in a small neighborhood of the cycle. To synthesize the controller, we will proceed in two separate stages. A control law, based on cancellation, is used

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as a first step towards the synthesis of a controller which instead will not rely on cancellation. To select the features of the limit cycles in a controlled way, we will use the strategy to classify so-called border-collisions (or C-bifurcations) of fixed points of nonsmooth maps recently presented in [2]. Note that we are not designing a controller to change the bifurcation properties of the system, but rather choosing a local control strategy to place the system close to a known bifurcation phenomenon. We will then use our analytical understanding of such phenomenon to achieve the control goal, i.e. suppress or modify the limit cycle of interest. Namely, the controller applied to the system flow will be based on a switching action which is designed by taking into account a nearby nonsmooth bifurcation of the cycle under control used to change the properties of the associated Poincaré map according to the classification strategy presented in [1]. In so doing, we will do explicit use of the technique to derive the approximate Poincaré map of the system analytically during the control design stage.

#### References:

- M. di Bernardo, F. Garofalo, L. Iannelli, F. Vasca, 'Bifurcations in piecewise smooth feedback systems', Special Issue on Switched, piecewise and polytopic linear systems, International Journal of Control, Vol. 75 Nos 16/17, pp 1243-1259, 2002
- [2] M. di Bernardo, M.I. Feigin, S.J. Hogan, M.E. Homer, "Local analysis of C-bifurcations in n-dimensional piecewise-smooth dynamical systems", Chaos, Solitons and Fractals, vol. 10, no. 11, pp. 1881-1908, 1999

#### ID of Contribution: 10 - 374

## ON SINGULAR ATTRACTORS OF DISSIPATIVE SYSTEMS OF NONLINEAR ORDINARY DIFFERENTIAL EQUATIONS

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Some previous studies during last years have shown that all 3-d chaotic systems of ordinary differential equations have a common scenario of transition to chaos. It consists of Feigenbaum's cascade of double period bifurcations of stable (orbitally stable) cycles, then Sharkovskii's cascade of bifurcations of stable cycles of any period up to the cycle of period three and then the homoclinic cascade of bifurcations of stable cycles which tend to homoclinic contours of singular points [1-3]. The theoretical basis of this scenario is presented in the following report.

Definition 1. We state that a singular point of 2-d non-autonomous real system of ordinary differential equations with periodic coefficients of its main linear part is a rotor if the Floquet's exponents of the linear part are complex and have the same imaginary and different real parts.

We prove that a scenario of transition to chaos in 2-d non-autonomous system of ordinary differential equations with rotor analogical to the scenario of transition to chaos in 1-d continuous but not one-to-one map, described by the theory of Feigenbaum and Sharkovskii. Any irregular attractor of 2-d non-autonomous system of ordinary differential equations with rotor is a singular attractor [2,3]. It is closure of a semi-stable aperiodic trajectory and it exists only for the separate accumulation point of bifurcation values of the system parameter.

Then we consider a 3-d autonomous system of ordinary differential equations. Let it has a limit cycle. We construct some 2-d surface moving transversally to the cycle (not Poincare section) in which the obtained 2-d non-autonomous system has a zero singular point which corresponds to the initial limit cycle of the 3-d autonomous system.

Definition 2. We state that the limit cycle of a 3-d autonomous system of ordinary differential equations is a singular cycle if the corresponding singular point of the 2-d non-autonomous system is rotor.

We prove that a scenario of transition to chaos in 3-d autonomous systems of ordinary differential equations is the same as in 2-d non-autonomous systems of ordinary differential equations with rotors and all irregular attractors of 3-d autonomous systems are singular attractors.

Theorem. When changing the bifurcation parameter, the 3-d autonomous system of ordinary differential equations can have infinitely many singular attractors of different complexity and infinitely many stable or unstable limit cycles in compliance with the Sharkovskii's order. All regular (stable limit cycles) and singular attractors belong to the closure of a 2-d unstable invariant manifold of the initial singular saddle cycle.

Examples of 2-d non-autonomous and 3-d autonomous systems of ordinary differential equations with singular attractors in compliance with proved theorem are constructed.

References:

- [1] Magnitskii N.A., Sidorov S.V., A New View of the Lorenz Attractor, Differential Equations, vol.37, No.11, 2001, pp. 1568-1579.
- [2] Magnitskii N.A., On Nature of Chaotic Attractors of Nonlinear Dissipative Systems of Ordinary Differential Equations, Nonlinear Dynamics and Control, vol.4, 2004 (in Russian, be published in English).
- [3] Magnitskii N.A., Sidorov S.V., New Methods for Chaotic Dynamics, Moscow, 2004, 320p.p.(in Russian).

#### ID of Contribution: 10 - 412

## HOW MUCH CONTROL NEEDS CONTROL OF CHAOS?

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For almost three decades chaotic phenomena and chaotic behavior attract an attention of several different scientific communities. Engineering applications are rapidly developing in areas such as lasers and plasma technologies, mechanical and chemical engineering and telecommunications. It is then not surprising that the matter of controlling chaotic systems has come under detailed investigation. Surprisingly, the development of the field was triggered by essentially one paper, by E.Ott, C.Grebogi and J.Yorke [1] where the term "controlling chaos" was coined. Perhaps, the key achievement of the paper [1] was demonstration of the fact that a significant change in the behavior of a chaotic system can be made by a "tiny" adjustment of its parameters. This observation led to emerging interest in changing behavior of natural systems without interfering with their inherent properties. Starting with a few papers in 1990, the number of publications in peer reviewed journals exceeded 400 per year in 2001-2003. It is worth noting that, in spite of the enormous number of published papers, very few rigorous results are so far available. Many problems still remain unsolved.

One important problem is to evaluate time and energy required for control of chaos. First result of such kind was obtained in the pioneer paper [1], where the time required for stabilizing of an unstable trajectory with a low intensity control was evaluated for a second order system. It was shown that the time required for control depends on control intensity according to the power law. It can be shown that, in a sense, OGY-like control algorithms with outer deadzone correspond to a case of "weak" chaos. Recently a new control algorithm based on symbolic dynamics approach was proposed [2,3], providing for hyperbolic systems, corresponding to a "strong" haos logarithmic dependence of control time on control intensity. The energy required for control of "strong" chaos can be ade arbitrarily small for small control intensity

In our survey recent developments in control of chaos will be outlined based on surveys [4] and some recent publications. Special attention will be focused on results on evaluation of time and energy required for control, including estimates of transient time and traveling time over attractor.

- [1] Ott E., C. Grebogi, J. Yorke. Controlling chaos. Phys. Rev. Lett., 64(11), 1990.
- [2] Khryashchev S.M., Osipenko G. S. Studying controllability by symbolic dynamics methods. E-journal 'Differential equations and control processes' http://www.neva.ru/journal, (1), 1997, pp.78--90.
- [3] Khryaschev S.M. Estimation of control time for systems with chaotic behavior. Autom. Remote Control. Part I. Vol. 64, No. 10, 2004, Part II. Vol. 64, No. 11, 2004. [4]. Andrievsky B.R., Fradkov A.L. Control of chaos. I.Methods. Autom. Remote Control. Vol. 64, No. 5, 2003. II. Applications. Autom. Remote Control. Vol. 64, No. 4, 2004.

# **MINI-SYMPOSIUM 11**

# **Fractional Derivatives and Their Applications**

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### FRACTIONAL HAMILTONIAN QUANTIZATION OF CONSTRAINED SYSTEMS

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During the last three decades the fractional calculus has become a field of growing interest because of its multiple and interesting applications in several fields such as mathematics, physics and engineering. Based on the Riemann-Liouville fractional derivatives, Agrawal extended the traditional calculus of variations for systems containing fractional derivatives [1]. This method was applied recently to several constrained systems and very recently the corresponding fractional Hamiltonian approach was investigated [2]. One of the main advantages of using Riemann-Liouville fractional derivatives within the variational principles is that we can define the integration by parts and the fractional Euler-Lagrange equations become the usual ones when  $\alpha$  becomes integer. An important issue is to quantize the fractional Hamiltonian corresponding to a given fractional Lagrangian and to find its corresponding path integral. This problem is not an easy task because we have to take into account that our theory is non-local. In addition, the systems with constraints are present in a great variety of environment like robotics, wheeled vehicle and satellite dynamics, manipulation devices and locomotion systems. Holonomic constraints are those which can be expressed in terms of configuration variable only. This case represents the case of the robotic manipulator.

On the other hand, taking into account the constrained systems play an important role in gauge theories and the distinguishing feature of singular Lagrangian theories in the Hamiltonian formulation is the presence of constraints, we believe that the application of fractional calculus to constrained systems presents interest both from theoretical and practical point of views. In this paper the Hamiltonian was constructed for fractional Lagrangians possessing constraints. We generalized the proposed Riewe's formalism [3] by considering a Lagrangian involving the Lagrange multipliers. The formulation Hamiltonian equations were obtained for both unconstrained and constrained variational problem, in the same way as those obtained by using the formulation of Euler-Lagrange equations for variational problems introduced by Agrawal [1]. Three examples of constrained systems were investigated in detailed and their corresponding fractional path integral were obtained. The first example represents a system with a primary first class constraint. The second example is dealing with the fractional Hamiltonian description of the damped oscillator. As the third example we consider the fractional Hamiltonian of the following constrained fractional variational problem from the optimal control theory: minimize

$$S[x_1, x_2] = \frac{1}{2} \int_{0}^{1} [x_1^2 + x_2^2] dt$$

such that

$${}_{0}D_{t}^{a}x_{1} = -x_{1} + x_{2},$$
  
 $x_{1}(0) = 1$ 

- [1]. O. P. Agrawal, Formulation of Euler-Lagrange equations for fractional variational problems, J. Math. Anal. Appl. vol.272, (2002), 368-379.
- [2]. D. Baleanu and T. Avkar, Lagrangians with linear velocities within Riemann-Liouville fractional derivatives, Nuovo Cimento B Vol.119, (2004) 73,
- [3] S. Muslih and D. Baleanu, Hamiltonian formulation of systems with linear velocities within Riemann-Liouville fractional derivatives, in press, J. Math. Anal. Appl.

## EVOLUTIONARY DESIGN OF COMBINATIONAL CIRCUITS USING FRACTIONAL-ORDER FITNESS FUNCTIONS

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In the last decade genetic algorithms (GAs) have been applied in the design of elec-tronic circuits, leading to a novel area of research called Evolutionary Electronics (EE) or Evolvable Hardware (EH) [1]. EE considers the concept for automatic design of electronic systems. Instead of using human conceived models, abstractions and techniques, EE employs search algorithms to develop good designs.

Looking for better performance GAs, this paper proposes a GA for the design of com-binational logic circuits using fractional-order dynamic fitness functions.

The area of Fractional Calculus (FC) deals with the operators of integration and differ-entiation to an arbitrary (including noninteger) order and is as old as the theory of classical differential calculus. Nevertheless, the application of FC has been scarce until recently, but the advances on the theory of chaos motivated a renewed interest in this field [2].

To design combinational logic circuits is adopted a GA strategy. The circuits are specified by a truth table and the goal is to implement a functional circuit with the least possi-ble complexity [3]. The goal of this study is to find new ways of evaluating the individuals (circuits) of the population in order to achieve better performance GAs.

In this paper we propose a new concept for the fitness function, namely a dynamic fitness function FD. The concept of dynamic fitness function FD results from an analogy with control systems where we have a variable to be controlled similarly with the GA case where we master the population through the fitness function. Applying a classical (static) fitness function corresponds to using a kind of proportional algorithm. If we want to implement a fractional-order proportional-derivative or a proportional-integral evolution the fitness function needs a different new scheme.

Since, having a superior GA performance means achieving solutions with a smaller number of generations and a smaller standard deviation in order to reduce the stochastic nature of the algorithm, in general we conclude that the FD concept produces better results particularly for the differential scheme.

In conclusion we can say that this paper presented a new technique for improving the GA performance and that the concept of fractional-order dynamic fitness function demonstrates to be an important method that outperforms the traditional static fitness function approach. As the tuning of the 'optimal' parameters was established by trial and error, future research will address the problem of having a more systematic design method.

These conclusions encourage further studies using not only proportional-differential or proportional-integral schemes but also proportional-integral-derivative control schemes.

- Zebulum, R. S., Pacheco, M. A. and Vellasco, M. M., Evolutionary Electronics: Automatic Design of Electronic Circuits and Systems by Genetic Algorithms, CRC Press, 2001.
- [2] J. A. Tenreiro Machado. Analysis and Design of Fractional-Order Digital Control Systems. SAMS Journal Systems Analysis, Modelling, Simulation, vol. 27: 107-122, 1997.
- [3] Cecília Reis, J. A. Tenreiro Machado, and J. Boaventura Cunha, "Evolutionary Design of Combinational Logic Circuits", Journal of Advanced Computational Intelligence and Intel-ligent Informatics, Fuji Technology Press, Vol. 8, No. 5, pp. 507-513, Sep. 2004.

169

## FRACTIONAL ORDER DYNAMICS IN CLASSICAL ELECTROMAGNETIC PHENOMENA

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The Maxwell equations play a fundamental role in the well established formulation of the electromagnetic theory. These equations lead to the derivation of precise mathematical models useful in many applications in physics and engineering. The Maxwell equations involve only the integer-order calculus and, therefore, it is natural that the resulting classical models adopted in electrical engineering reflect this perspective.

Recently, a closer look of some phenomena present in electrical systems, such as motors, transformers and lines, and the motivation towards the development of comprehensive models, seem to point out the requirement for a fractional calculus approach.

Bearing these ideas in mind, in this study we shall address the well-known 'skin effect'. We start by recalling the classical model development for this electromagnetic phenomenon and, in a second phase, we re-evaluate the results demonstrating its fractional-order dynamics. After clarifying the fundamental concepts it is addressed the case of Eddy (or Foucault) currents that occur in electrical machines.

References:

- [1] W. Malpica Albert, J. Fernando Silva, J. Tenreiro Machado, M. T. Correia de Barros, Fractional Order Calculus on the Estimation of Short-Circuit Impedance of Power Transformers, 1st IFAC Workshop on Fractional Differentiation and its Application, 19-21 July 2004, Bordeaux, France.
- [2] J. A. Tenreiro Machado, Isabel S. Jesus, "A Suggestion from the Past?", FCAA Journal of Fractional Calculus & Applied Analysis.
- [3] K. Küpfmüller, Einführung in die Theoretische Elektrotechnik, Springer-Verlag, Berlin, 1939.

**ID of Contribution: 11 - 067** 

## COMPARISON OF THREE ALGORITHMS FOR LEVY NOISE GENERATION

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In this paper, we describe three algorithms for the generation of symmetric Levy noise [1,2,3] and we discuss the relative performance in terms of time of execution on an Intel Pentium M processor at 1500 MHz.

The advantages and weaknesses of the algorithms are evidenced and their portability to FPGAs is considered.

The first algorithm uses Gaussian variables that are then transformed and summed. The approximate Levy noise generation is a consequence of the Central Limit Theorem [1].

The second algorithm involves a nonlinear transformation of two independent uniform random variables into one stable random variable. The latter is a continous function of each of the uniform random variables [2].

The third algorithm is the standard rejection method [3].

The relative performance of the three algorithm is given as a function of the Levy stable index alpha.

References:

- R.N. Mantegna, Fast, accurate algorithm for numerical simulation of Levy stable stochastic processes, Physical Review E, vol. 49, 4677-4683, 1994.
- [2] J.M. Chambers, C.L. Mallows, and B.W. Stuck, A method for simulating stable random variables, Journal of the American Statistical Association, vol. 71, 340-344, 1976. The algorithm is used in the implementation by J.H. McCulloch at Ohio State University.
- [3] W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, Numerical Recipes in C, Cambridge University Press, 1993.

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## A FRACTIONAL DIFFERENCES INTEGRAL REPRESENTATION AND ITS USE TO DEFINE FRACTIONAL DIFFERINTEGRATIONS

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In [1] Diaz and Osler presented a brief insight into the differences, mainly the fractional ones. They proposed an integral formulation for the differences and conjectured about the possibility of using it for defining a fractional derivative. This problem was also discussed in a round table held at the International Conference on "Transform Methods & Special Functions", Varna'96 as stated by Kiryakova [2]. In this paper, the validity of such conjecture is proved. We will show how to obtain the Cauchy Integrals from the differences and simultaneously generalise it to the fractional case. We must refer that we will not address the existence problem. We are mainly interested in obtaining a generalisation of a well known formulation. We will introduce the general formulation for the differences, considering two cases: direct and reverse. For these, integral representations will be proposed. From these representations we obtain the derivative integrals by using the properties of the Gamma function. The integration path is a parabola-like contour that encircles all the poles and "closes at infinite". A generalisation of the usual derivative definition is obtained that agrees with the usual derivative definition when  $\alpha$  is a positive integer and corresponds to the so-called left-hand sided Grünwald-Letnikov fractional derivative. Using the asymptotic properties of the Gamma function, we are able to obtain a generalisation of Cauchy formula and is valid for all real a, having a derivative (a>0) or integral (a<0) - fractional differintegration. There are infinite ways of computing a fractional differintegration; we only have to choose a branch cut line and fix a suitable integration path. If  $\alpha$  is a positive integer, we have an integrand with a pole: this is the well known Cauchy formula. It is important to remark that accordingly to the equivalence of the Cauchy and the Grünwald-Letnikov derivative, the integration path has necessarily a form like we referred above, unless a is a positive integer. In computations we should use a Hankel contour. This means that the differintegration definitions based in finite straight line segments are not valid.

- [1] Diaz, J.B. and Osler, T.J., "Differences of Fractional Order", Mathematics of Computation, Vol. 28, Number 125, Jan. 1974.
- [2] Kiryakova, V., "A long standing conjecture failed?" Proceedings of the 2nd International Workshop on Transform Methods & Special Functions, Varna'96. Aug 1996.

## DYNAMICS OF THE VAN DER POL OSCILLATOR WITH FRACTIONAL DERIVATIVES

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The study of nonlinear oscillators has been important in the devolopment of the theory of dynamical systems. The Van der Pol oscillator (VPO), described by a second-order nonlinear differential equation which can be considered as a special case of the Liénard's equation, can be regarded as describing a mass-spring-damper system with a nonlinear position-dependent damping coefficient or, equivalently, an RLC electrical circuit with a negative-nonlinear resistor, and has been used for modeling in many application fields, as biology, acoustics or mobile phones. A fractional version of the VPO was analyzed in [1], in which the dependent variable and/or its first derivative occur to some fractional power. In this paper, extending the work presented in [2], a different family of fractional VPO's are analyzed, by using not fractional powers of the dependent variable or its derivatives, but fractional order derivatives into the dynamic equation. After a brief introduction to fractional calculus, we propose several modified versions of the classical VPO obtained by introducing fractional – order time derivatives into the state space equations in several ways: in one of the state variables or in both of them. Similar fractional versions of other well known nonlinear systems has been made for exploring the relation between fractional order and chaos (see [3] for aditional references). Different schemes are used for simulations, as well as different approximations for the fractional - order operators. The resulting fractional order VPO's are analyzed by using several domains and methods: phase portraits, time domain, describing function, spectral analysis, and bifurcation diagrams. From the results, it can be concluded that, with the introduction of fractional order derivatives, the systems can exhibit behaviours very different from the classical VPO, depending on both, the total system order and the structure of the state - space equations. Finally, part of this analysis is extended to the forced VPO, which reveals interesting results. Along the paper, some physical interpretation of the fractional - order derivatives into the systems are made.

- [1] R. E. Mickens, "Fractional Van der Pol Equations", Journal of Sound and Vibration (2003) 259 (2), 457-460.
- [2] Ramiro S. Barbosa, J. A. T. Machado, Isabel M. Ferreira, József K. Tar, "Dynamics of the Fractional Order Van der Pol Oscillator", Proceedings of the IEEE International Conference on Computational Cybernetics, Vienna, Austria, 2004.
- [3] P. Arena, R. Caponetto, L. Fortuna, D. Porto (2000), Nonlinear Noninteger Order Circuits and Systems An Introduction, World Scientific.

## STEP-BY-STEP PRESENTATION OF A 3RD GENERATION CRONE CONTROLLER DESIGN WITH AN ANTI-WINDUP SYSTEM

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CRONE control methodology is one of the most developed approaches to design robust and fractional-order controllers. Depending on the plant nature and on the required performance, one of the three generations of the CRONE (frequency-domain) methodology can be used. First and second generations are really easy to be used, the third one a little less but more performing.

The first generation is particularly adapted to control plants with a frequency response whose magnitude only is perturbed around the required closed-loop cutoff frequency and whose phase is constant with respect to the frequency around this cutoff frequency. Thus, the CRONE controller is defined by a fractional-order n transfer function that can be considered as that of a fractional PIDn controller.

The second generation is also adapted to plant with a perturbed magnitude around the cutoff frequency but can deal with variable plant phase with respect to the frequency around this cutoff frequency. In the second CRONE generation it is now the open-loop transfer function that is defined from a fractional-order n integrator. Then, as for the first generation, the rational controller can be obtained by using the well-known Oustaloup approximation method.

Unluckily, these two generations are not always sufficient to handle: more general plant perturbations than gain-like, nonminimum phase plants, time-delay or unstable plants, plants with bending modes, very various and hard to meet specification, etc. For the third generation that needs to be used, the nominal open-loop transfer function is defined from a band-limited complex fractional-order integrator and its few high-level parameters are optimized to minimize the sensitivity of the closed-loop stability degree to the perturbed plant parameters and to permit the respect of the closed-loop required performance. Before designing the robust and performing control-system, it is sometime difficult to translate the initial (time-domain) requirements to frequency-domain design specification and to fix some of the open-loop parameters. As the robust controller is designed only taking into account low-level exogenous signals, an anti windup system often needs to be included.

If several papers already presents the application of the third generation CRONE design methodology for the control of very specific plants, none presents step-by-step the design of the up-to-date version of a third generation CRONE controller including an anti-windup system. The purpose of this paper is to fill this lack.

Using a laboratory plant digitally controlled as illustration example, this paper proposes to explain in detail: how the uncertainty of plant parameters is taken into account; how the digital implementation way could be taken into account correctly; how magnitude bounds are defined from specification to constraint the four common closed-loop sensitivity functions; how some open-loop transfer function parameters are fixed and how the others are initialized and then optimized; how the rational robust controller is synthesized; how an anti-windup system is included; and finally how the controller is implemented. All these different steps will be illustrated using the CRONE Control-System Design Toolbox developed for Matlab/Simulink.

## SPACE FRACTIONAL DIFFUSION AND REFLECTIVE BOUNDARY CONDITION

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The spreading of matter in saturated heteogeneous soils does not always follow Fick's law, according to now classical experimental results. Various models involving fractional derivatives are meant to describe the evolution of the concentration of a solute, dissolved in the saturating fluid. The models are strongly connected with the nature of the internal, highly uncorrelated motions, the fluid and the solute are supposed to undergo due to the disordered geometry of the pores when a pressure gradient is applied.

Here we focus on media, characterized by the possible existence of preferntial pathways: particles may travel very far very quickly. On the small scale, their motions can be represented by Continuous Time Random Walks, and here we focus on Lévy flights, in order to take account of possible long jumps.

For matter, spreading according to Lévy flights, the concentration (on the macroscopic scale) was shown in [1] to evolve according to a space fractional diffusion equation, which is a variant of Fourier's law. But the Laplacean is replaced by a Riesz-Feller fractional derivative with order between 1 and 2. In general, it is not easy to check directly whether Lévy flights really are a good small scale model for contaminant spreading in a given concrete medium, and experiments are necessary. Since many laboratory devices cannot avoid at least one boundary condition, we consider here what happens when particles undergo Lévy flights in a half space, limited by a reflective wall.

Following the lines of [1], we show that then, the space fractional diffusion equation has to be modified: the kernel of the Riesz-Feller operator has to take account of the boundary condition. The saturating fluid may flow or remain at rest.

A numerical explicit scheme, developped in [2] for infinite media, adapts here. When the global speed v of the saturating fluid is zero, exact solutions are available and fit the results of the numerical simulation. When v is different from zero, the stability condition given in [2] has to be complemented. Then, the numerical simulation is checked against a Monte Carlo method, adapted to Lévy flights and taking account of the boundary condition.

#### References:

- [1] A. Compte, Stochastic foundations of fractional dynamics, Phys. Rev. E. 53, 4191 (1996)
- [2] R. Gorenflo, F. Mainardi, D. Moretti, G. Pagnini, P. Pardisi, Discrete random walks models for space time fractional diffusion, Chemical Physics 284, 521 (2002)

#### ID of Contribution: 11 - 155

## LEVY'S IDENTIFICATION METHOD EXTENDED TO COMMENSURATE FRACTIONAL ORDER TRANSFER FUNCTIONS

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In this paper Levy's identification method is extended to handle fractional order systems, that is to say, transfer functions including non-integer powers of Laplace operator s. Iterative improvements of Levy's method suggested by Sanathatan and Koerner and by Lawrence and Rogers are handled; the possibility of using weights, such as those

ENOC-2005, Eindhoven, the Netherlands

suggested by Vinagre, is addressed. Some numerical considerations are also given. The extended methods and its integer-order counterparts to identify models from frequency data seem to share the same good characteristics and to suffer from the same drawbacks (like needing a model structure chosen beforehand, and being sensible to some levels of noise).

ID of Contribution: 11 - 230

#### **ON FRACTIONAL SLIDING MODE CONTROL**

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Pioneering works in variable structure control systems (VSCS) were made in Russia in the 1960s, and the fundamental ideas were published in English in the mid 1970s. After that, VSCS concepts have been used in robust control, adaptive and model reference systems, tracking, state observes and fault detection (see [1] for additional information and references). Sliding mode control (SMC) is a particular type of VSCS designed to drive and then constrain the system state to lie within a neighbourhood of the decision rule or switching function, and it is well known for its robustness to disturbances and parameters variations. On the other hand, fractional order control (FOC), that is, the use of fractional order derivatives and integrals into the control laws, has been recognized as an alternative strategy for solving robust control problems (see [2] for a survey on the topic and additional references). The purpose of this work is to study the consequences of introducing FOC in SMC in two ways, taking into account the two components of the sliding mode design approach, the first one involving the design of a switching function so that the sliding motion satisfies the design specifications, and the second one concerning with the selection of a control law which will enforce the sliding mode, therefore existence and reachability conditions are satisfied. So, FOC is introduced in SMC by using, in one hand, fractional order sliding surfaces or switching functions, and, on the other hand, control laws with fractional order derivatives and integrals. The first approach was introduced in [3] applied to a power electronic Buck converter with very interesting and successful experimental results. In this work we study in a more extended way this first approach and introduce the second one. Furthermore, considerations about existence and reachability conditions are made. For a clear illustration of the proposed control strategies, the well known double integrator is considered as the system to be controlled. This system, representing single-degree-of-freedom translational and rotational motion, can be considered as a linear approximation of some interesting mechanical and electromechanical systems, as the low friction servo or the pendulum.

- [1] Christopher Edwards and Sarah K. Spurgeon (1998), Sliding Mode Control Theory and Applications, Taylor & Francis.
- [2] B. M. Vinagre and Y. Q. Chen, eds. (2002), Lecture Notes on Fractional Calculus Applications in Automatic Control and Robotics, 41st IEEE International Conference on Decision and Control, Tutorial Workshop 2 (310 pp.). (Available at: http://mechatronics.ece.usu.edu/foc/cdc02tw/cdrom/lectures/book.pdf)
- [3] A. J. Calderón, B. M. Vinagre, V. Feliu (2003), "Fractional Sliding Mode Control of a DC DC Buck Converter with Application to DC Motor Drives", Proceedings of the 11th International Conference on Advanced Robotics, Coimbra, Portugal, pp. 252 - 257.

## NON INTEGER ORDER PD CONTROLLERS: APPLICATION TO SYSTEMS WITH DELAY

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Non integer order controllers, and in particular of non integer order PID [1][2] have been recently become subject of study in the field of control engineering. From the examination of their general properties (a short overview is given), it can be shown that the extension of derivation and integration order from integer to non integer numbers allows the proposed controllers to have remarkable advantages [3], especially in phase-lead and phase-lag flexibility.

In particular, a new way for analytical tuning of a non integer order PD is described in details and applied for controlling systems having a delay, that usually are not easily controllable with traditional strategies. This fact opens the way in the designing of a more flexible class of controllers and therefore towards the solution of wider variety of control problems, such as, for example, the control of non integer order systems themselves. Some experimental results can also be reported in order to validate the proposed approach.

References:

- [1] I. Podlubny, Fractional order systems and PID controllers. IEEE Transaction on Automatic Control, vol. 44, no 1, pp 208-214, 1999.
- [2] R.Caponetto, L.Fortuna, D.Porto, "A New Tuning Strategy for a Non-Integer Order PID Controller", Workshop on Fractional Differentiation and its Applications (FDA' 04), Bordeaux, France, July 2004
- [3] P. Arena, R. Caponetto, L. Fortuna and D. Porto, "Non Linear Non Integer Order Systems- An Introduction", Series A- vol. 38 Nonlinear Science, World Scientific, Singapore, 2000.

ID of Contribution: 11 - 329

## REALIZATION OF THE RIEMANN-LIOUVILLE INTEGRALS ON NEW SELF-SIMILAR OBJECTS

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We suggest new type of fractals (quasi-fractals) having unusual (logarithmic ~  $\exp(\gamma \ln(n))$  in comparison with conventional scaling properties (~  $\exp(n\ln(\gamma))$ , which serves a generalization of conventional fractals.

These new type of fractals can find their application in description of various heterogeneous structures, in particular, for description of clusters formed in the result of the diffusion limited aggregation (DLA). Any quasi-fractal having spherical symmetry can be presented in the form of circles (spheres in 3D-case), which is growing from the growth center. Unfortunately in the format required (plane text only) we cannot give the recurrence formulae and desired figures for construction and presentation of these quasi-fractals. One can prove that the averaging procedure of a smooth function over quasi-fractals with given dimension (which can be negative!) leads to the fractional Riemann-Liouville and its generalizations.

These fractals are appeared in the results of generalization of the coordination sphere model when  $n \equiv \varphi(n)$  considered initially in the book [1]. This new sort of fractals opens new possibilities for realization of non-integer differentiation

(integration) operations for a wide class of heterogeneous medium on mesoscale region.

**References:** 

[1] A. Le Mehaute, R.R. Nigmatullin and L. Nivanen. Fleches du temps et geometrie fractale, Paris, Hermes, 1998. (in French).

**ID of Contribution: 11 - 338** 

## A TESTING BENCH FOR FRACTIONAL SYSTEM TEACHING

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These last ten years, gave rise to many applications of fractional (or non integer) differentiation in a large number of fields such as physics, rheology, econophysics [1][2][3][4], but also in the field of automatic control and robotics thought applications in: system modelling, system identification, diagnostic, control and robust control, path planning.

Given this increasing interest in fractional systems, some universities and engineering schools have integrated courses on fractional systems and their applications in their teaching module [5] as ENSEIRB engineering school (www.enseirb.fr).

This paper is in this evolution given that it presents a testing bench which can be used for student initiation to fractional systems. This is a very simple and cheap bench constituted of an insulated aluminium rod heated by a resistance at one of his end. In addition to a presentation of the technical characteristics of this bench, this paper demonstrates its interest for education through :

- its modelling by a fractional order model and the demonstration of fractional order approach interest in thermal diffusion modelling problems,
- its identification by fractional order models,
- the simulation of the obtained models by various numerical simulation methods,
- the implementation of fractional order observers,
- its control by pole placement method.

#### References:

- [1] K.S. Miller, B. Ross An introduction to the fractional calculus and fractional differential equations Wiley-Interscience Publication, 1993.
- [2] S.G. Samko, A.A. Kilbas, O.I. Marichev Fractional Integrals and Derivatives Gordon and Breach Science Publishers, 1993.
- [3] A. Oustaloup La dérivation non entière, théorie, synthèse et applications Editions Hermès, Paris, France, 1995.
- [4] A. Oustaloup et B. Mathieu La commande CRONE : du scalaire au multivariable Editions Hermès, Paris, 1999.
- [5] http://www.uniud.it/cism/corsi96/scaling/scope.html.

#### ID of Contribution: 11 - 354

#### FRACTIONAL KINETICS IN PSEUDOCHAOTIC SYSTEMS AND ITS APPLICATIONS

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Dynamics in polygonal billiards are widely used models for different physical problems such as wave propagation in different media, particle dynamics in plasma and fluids, and general theory of dynamical systems. A specific feature for of the polygonal billiards is that the Lyapunov exponent is zero for all trajectories and the corresponding dynamics is pseudochaotic and weakly mixing. This creates a specific randomness of the dynamics with strong intermittency and

ENOC-2005, Eindhoven, the Netherlands

bursts in time evolution of an ensemble of particles. We demonstrate that for many cases the corresponding kinetic equation has a form of the generalized Fokker-Planck-Kolmogorov equation (FFPK) with fractional derivatives in space and time. The corresponding orders of the derivatives can be linked to specific dynamical properties of the trajectories, which are responsible for the space-time scaling parameters of the dynamics. Particularly, the transport of particles in such billiards is anomalous and superdiffusive.

#### ID of Contribution: 11 - 363

#### SOME APPLICATIONS OF SEMI-DERIVATIVES AND SEMI-INTEGRALS IN PHYSICS

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This paper gives a short review about the properties of the Abel-type integral transform with the kernel  $(t^2-x^2)^{-1/2}$  and shows some of its practical application for instrumentation in accelerator physics, combustion research, interferometry, plasma physics, and spectroscopy. It deals further with a space-like description of the wave function of spin-half particles within the Schrödinger picture, one of the most famous non-integer phenomena in physics. It will be shown, that assuming the existence of half-integer derivatives, wave functions for spin 1/2 particles can be derived in just the same way as for the normal angular momentum. These functions satisfies the eigenvalue equations for spin  $\pm 1/2$ , as well as the change of the spin state applying the creation and annihilation operators. These wave functions display directly the observed 4 Pi symmetry of fermions. This description is complementary to the common description using Pauli matrices and spinors.

ID of Contribution: 11 - 364

## THE MESOSCOPIC 'FRACTIONAL' KINETIC EQUATIONS AND THE GENERALIZED RIEMANN-LIOUVILLE INTEGRAL

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It has been proved that kinetic equations containing non-integer integrals and derivatives are appeared in the result of reduction of a set of micromotions to a collective motion taking place on mesoscale region. In other words, for the Fourier/Laplace component of a memory function the so-called 'universal' decoupling procedure leading to the kinetic equations with non-integer operators of differentiation/integration has been suggested. This decoupling procedure can be applied in the theory of linear response, for solution of kinetic equations in the Mori-Zwanzig formalism and other microscopic approaches containing memory function. From physical point of view it means that in some intermediate interval of frequencies a set of micromotions interacting with other degrees of freedom of a self-similar system (or with thermostat) and describing by a microscopic function  $f(\omega)$  is averaged. In the result of such averaging the power-law relationships are appeared, which depend only on asymptotic behavior of the microscopic function but independent on concrete functional form of the function  $f(\omega)$  describing a type of interaction with thermostat. Considering different asymptotics of the function  $f(\omega)$  one can obtain the generalization of the conventional Riemann-Liouville integral, which is appeared in the result of solution of some functional equation. One can receive also more deep understanding of the stretched exponential relaxation law suggested by Kohlrausch-Williams-Watts [1] which can be derived easily from consideration of a self-similar branching model of relaxation described by expression. The basic results of the generalized model of relaxation following to the stretched exponential law were confirmed on consideration of postsynaptic signals which are measured in the result of excitation of a living muscle of a frog (classical Volta experiments). The results of such kind of decoupling for a memory function are confirmed also in dielectric relaxation, where some basic experimental facts find their explanation. This 'universal' decoupling procedure allows to find a proper place for the 'fractional' kinetic equations, containing non-integer operators of differentiation/integration with real and complex exponents. These kinetic equations should describe different relaxation or diffusion processes in the intermediate (mesoscale) region.

References:

[1] Kohlrausch R., Ann. Phys. (Leipzig) 12 (1847) 393.

[2] Williams G., Watts D.C., Trans. Faraday Soc., 66 (1970) 80.

ID of Contribution: 11 - 365

## ACTIVE VIBRATION CONTROL OF A FLEXIBLE STRUCTURE FORMULATED BY USE OF FRACTIONAL CALCULUS

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Recently, the active wave control theory gathers a great interest as a novel vibration control methodology corresponding to a Large Space Structure (LSS), because it can be applied to suppress vibration occurring in large flexible structures which have high modal density even in the relatively low frequency range. In this report, in order to formulate the feedback type active wave control law described as a transfer function including s to the 1/2th power or s to the 3/2th power term. Fractional order derivatives/integrals of the structural response are introduced to the vibration suppression of a light and thin cantilevered beam as an example.

ID of Contribution: 11 – 393

## FRACTIONAL DIFFUSION IN HETEROGENEOUS POROUS MEDIA: AN APPROACH, VIA THE METHOD OF SUCCESSIVE APPROXIMATIONS

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The spreading of matter in very heterogeneous but saturated porous media is a subject which finds applications in the management of the water resource. Several partial differential equations involving fractional derivatives are meant to model the evolution of the concentration of some solute in those media. Many models are based upon the highly disordered and unsteady internal motions, the geometry of the pores imposes to the saturating fluid when a pressure gradient is applied. Depending on whether the occurrence of preferential pathways dominates over the possible existence of traps, partial differential equations involving derivatives of fractional order with respect to space or to time are relevant in media where the saturating fluid is moving.

In fact, deviations from pure diffusion also occur when the saturating fluid is at rest. This was shown in [1] for rather special media, made of intertwisted tubes. Under some hypotheses, concerning the geometry of the pores, solute spreads in those media according to a variant of Fourier's law, involving a non local term which combines a fractional derivative with respect to time and a derivative of integer order with respect to space.

Here we address more general porous media, whose internal disorder is connected to the porosity, itself being represented on the small scale by a random process. A perturbation method yields a partial differential equation for the evolution of the concentration of solute, on the macroscopic scale. The randomness of the porosity still results in modifying Fourier's law by introducing a fractional derivative with respect to time, thus generalizing the results of [1] to more realistic three dimensional porous media.

 K. Logvinova and M.C.Néel, A fractional equation for anomalous diffusion in a randomly heterogeneous porous medium, Chaos, vol. 14 n 4, (2004)

## THE LIFETIMES OF PHYSICAL PROCESSES (DERIVED USING MODELS WITH FRACTIONAL DERIVATIVES)

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According to Hooke's law the stress in a bar produces a proportional strain of the bar. The input stress and the output strain are in phase, which means that the model is loss-free. This conventional model is too simple for many purposes. We know, for example, that a bar of metal becomes hot when worked and that its lifetime is limited due to fatigue. Properly speaking Hooke's law contains two model constants, the module of elasticity and the phase angle which is zero.

In order to improve the agreement between model and the causal reality we introduce a new model where the phase lag between input and output is constant but not zero. This implies that the loss-fraction is the same at all frequencies. This fraction also determines the negative fractional order of the derivative that is used to express the transfer function in the time domain. This results in a causal model built on two model constants. Three signals are involved: cause, effect, and losses. It is not always easy to figure out what is what.

In the new two-parameter model of elasticity the cause comes first, then the effect. Thus the model is causal. In addition the new model has properties such as irreversibility, memory, ageing & lifetime and many others. All these properties originate entirely from our giving the input-output phase angle difference a value differing from zero.

Now we can consider the lifetime of an elastic process. Suppose that we apply a constant input to the process. The strain will increase in a transient course. In conventional theory we are used to arrive at a stationary state after a time constant. The causal model comprises all time constants, however, and therefore the transient does not end until the tensile test is terminated by a breakdown. Ageing occurs even if the input is zero, since the fractional derivative contains time.

Other processes discussed are: the earth/moon connection, the Catholic Church, the human heart, red shift

#### References:

- [1] Bohm, D. (1957), Causality and chance in modern physics. Routledge &Kegan Paul Ltd, pp. 1-170.
- [2] Hartwig, G., and Schwarz, G. (1984), Correlation of dielectric and mechanical damping at low temperatures. Proc. of the 5th Int. Cryogenic Conf., Advances in Cryogenic Engineering Mat. Vol. 30, (editors Clark A. F., and Reed, R. P.), Plenum, New York, USA.
- [3] Westerlund, S. (2002), Dead Matter has Memory, Causal Consulting, Kalmar, Sweden pp. 1-219, ISBN 91-631-2332-0
- [4] Westerlund, S. (2003), Relativity and what it really is. Proceedings of the International Carpathian Control Conference (ICCC), High Tatras, Grandhotel Praha, Slovak Republic, May 26-29, 2003, pp. 881-884, ISBN 80-7099-509-2.

## ID of Contribution: 11 - 417

## FRACTIONAL DIFFERENTIAL OPERATOR, ITS APPLICATION TO SPECIAL FUNCTIONS AND ITS CONNECTION TO CERTAIN FRACTIONAL INTEGRAL TRANSFORM

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The idea of fractional integral transforms arose in the same manner as generalized calculus operators, which are also called fractional calculus operators. So, we study the connections between the two, and develop results involving special functions using fractional operators. Also, see [Kalia and Kalia 1998; Kalia, 1993]. We find theorems connecting Fractional Fourier Transform (FRFT), Fourier transform, and Fractional derivative of Riemann-Liouville.

We conclude with a result involving a FRFT extending a theorem to one involving a fractional derivative [Zayed, 1996].

References:

- [1] Inayat-Hussain, A. A.(1987), New properties of hypergeometric series derivable from Feynman integrals: II. A Generalization of the H-function, J. Phys. A. Math. Gen. 20(1987), 4119-4128
- [2] Kalia, R. N. and Kalia, Sneh (1998), Integrals derivable from Feynman integrals, fractional calculus applications to the H-function, and certain Gaussian model in Statistical Mechanics, Math. Sci. Res. Hot-line, 2(7), 19-24.
- [3] Kalia, R. N. (1993), Generalized derivatives and Special Functions, In, Editor, R. N. Kalia, Recent Advances in Fractional Calculus, Global Publishing Company, 971 Sixth Ave N, Sauk Rapids, MN 56379, USA.
- [4] Zayed, Ahmed, I (1996), On the relationship between the Fourier and fractional Fourier transform, IEEE Signal processing letters, 5(12), 310-311.

ID of Contribution: 11 - 426

## PATH TRACKING DESIGN BY FREQUENCY BAND-LIMITED FRACTIONAL DIFFERENTIATOR PREFILTER

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A new approach to path tracking using fractional differentiation prefilter applied to no-varying plants is proposed in this paper. In previous works, a first approach, based on a Davidson-Cole prefilter, has been presented; it permits the generation of optimal movement reference input leading to a minimum path completion time, taking into account both the physical actuators constraints (maximum velocity, acceleration and jerk) and the bandwidth of the closed-loop system. In this paper, an extension of this method is presented: the reference input results from the step response of a Frequency Band-Limited Fractional Differentiator (FBLFD) prefilter whose main properties are having no overshoot on the plant and to have maximum control value for starting time. These properties are available whatever the values of its constitutive parameters which are optimized by minimizing the output settling time of the plant, by maximizing the bandwidth energy transfer between the input and the output, and including the timedomain bound on the control signal. Moreover, it can be implemented as a classical digital filter. A simulation on a motor model validates the methodology. The paper is divided as follow. Section 2, defines the generalized differentiator. Section 3 presents the frequency band-limited fractional differentiator and the prefilter synthesis methodology. Section 4 gives simulation performances obtained using this method on a Parvex RX 120 DC motor. Finally, a conclusion is given in Section 5.

- [1] Davidson D., Cole R., J. Chem. Phys., vol. 19, 1951.
- [2] Melchior P., Orsoni B., Badie Th., Robin G., Oustaloup. A., "Non-Integer Motion Control: Application to an XY Cutting Table", 1st IFAC Conference on Mechatronic Systems, Darmstadt, Germany, Sept 2000.
- [3] Miller K.S., Ross B., "An introduction to the fractional calculus and fractional differential equations", Wiley-Interscience Publication, 1993.
- [4] Orsoni B., Melchior P., Oustaloup A., 'Davidson-Cole transfer function in path tracking', 6th IEEE European Control Conference ECC'2001, pp. 1174-1179, Porto, Portugal, September 4-7, 2001.
- [5] Oustaloup A., "La dérivation non entière : théorie, synthèse et applications", Editions Hermès, 1995.
- [6] Samko S.G., Kilbas A.A., Marichev O.I., "Fractional Integrals and Derivatives", Gordon and Breach Science Publishers, 1993.

## TRANSVERSAL VIBRATIONS OF CREEP-CONNECTED MULTI PLATE HOMOGENEOUS SYSTEM

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The paper gives the derivation of a finite number of coupled partial fractional order differential equations of transversal vibrations in a creep-connected multi plate homogeneous system. The plate's material has the property of creeping, and the constitutive relation of stress-strain state is expressed through members of fractional order derivatives. The creep layer properties are described by the force-deformation state relation expressed by fractional order derivatives. The analytical solution of the system of coupled partial fractional differential equations of corresponding dynamical free and forced processes are obtained by means of Bernoulli's particular integral, and Laplace transform methods. Using the inverse Laplace transform, the time series function was obtained as a particular component of the solution. These components were used to make visualizations and analyze of dynamical creep component processes in transversal plates displacements.

References:

- Hedrih (Stevanovic) K., (2004c), Partial fractional order differential equations of transversal vibrations of creep connected double plates systems, Workshop Preprints/Proceedings No 2004-1 IFAC FDA 04, ENSEIRB, Bordeaux France, July 19-21, 2004., pp. 299-304.
- [2] Hedrih (Stevanovic) Katica, (2004b), Creep Vibrations of a Fractional Derivative Order Constitutive Relation Deformable Bodies, Proceedings Eighth American Congress of Applied Mechanics PACAM VIII. La Habana, Cuba, 5-9 January 2004, Applied Mechanics in Americas, Vol. 10. pp. 548-551, ISBN 959-7056-20-8.
- [3] Hedrih (Stevanovic) K., (2003), Partial Fractional Differential Equations of Creeping and Vibrations of a Plate and Their Solutions, 5th EuroMech Solid Mechanics Conference ESMC-5, European Mechanics Society -EUROMECH, Aristotele University of Thessaloniki - AUT, Thessaloniki, Hellas, 2003., Book of Abstracts, p. 424, Editor E.C. Aifantis, 2003, pp. 142-143.
- [4] Hedrih (Stevanovic) K., (2004), Discrete Continuum Method, COMPUTATIONAL MECHANICS, WCCM VI in conjunction with APCOM'04, Sept. 5-10, 2004, Beijing, China, © 2004 Tsinghua University Press & Springer-Verlag, pp. 1-11, CD.

**ID of Contribution: 11 - 438** 

## FRACTIONAL DAMPING: STATISTICAL ORIGINS AND GALERKIN PROJECTIONS

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Fractional order derivatives have proved useful in the modeling of viscoelastic damping. The aim of this paper is twofold. First we will present, with a fresh engineering flavor, a result that may be found in the physics literature (e.g., [1]) but which seems unknown to engineering audiences (this discussion may be found in [2]). We will show that sufficiently disordered (random) and high dimensional internal integer order damping processes can lead to macroscopically observable fractional order damping. This suggests that such damping may be theoretically expected in many engineering materials with complex internal dissipation mechanisms. Second, we will use the insights obtained from the first part to develop a Galerkin procedure. Using this, accurate finite dimensional approximations can be developed for the fractional derivative term, so that infinite dimensional and memory dependent fractionally damped systems can be accurately approximated by finite dimensional systems without memory. Such finite dimensional approximations have been obtained before for control applications (e.g., [3]), but we think our approach is simpler, direct, and more accessible to some audiences. Results of finite element formulations based on this Galerkin projection will also be presented. The approximations developed have approximately uniform and small error over a broad and user-specified frequency range.

ENOC-2005, Eindhoven, the Netherlands

References:

- Vlad, M.O., Schönfisch, B., and Mackey, M. C., 1996, "Fluctuation- dissipation relations and universal behavior for relaxation processes in systems with static disorder and in the theory of mortality," Physical Review E, Vol. 53, No. 5, 4703–4710.
- [2] Chatterjee, A., "Statistical Origins of Fractional Derivatives in Viscoelasticity," Journal of Sound and Vibration, in press.
- [3] Oustaloup, A., Levron, F., Mathieu, B., and Nanot, F. M., 2000, "Frequency- Band Complex Noninteger Differentiator: Characterization and Synthesis," IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications," Vol. 47, No. 1, 25-39.

#### ID of Contribution: 11 - 444

## INVERSE PROBLEMS: NONLINEAR MODELS OF FRACTIONAL DERIVATIVE VISCOELASTIC BODY

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The experimental study has been conducted for everal years to investigate the nonlinear pseudo-statical and dynamical behavior of viscoelastic body described by the fractional derivative law. Pre-stress due to pre-load induces higher damping capacity during sinusoidal excitation. In order to understand this behavior, non-linear statical and dynamical models are considered. The authors established the appropriate models to describe the behavior of the fractional derivative viscoelastic body. Simulation to recover the behavior has been carried out. The nonlinearity having 2nd order term with respect to pre-displacement is found to be appropriate to describe the viscoelastic damping coefficient.

#### ID of Contribution: 11 - 445

#### A NEW LOOK AT THE DIFFERINTEGRATION DEFINITION

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The fractional calculus is nearly 300 years old. In recent years it has been rediscovered by physicists and engineers and applied in an increasing number of fields, namely in the areas of signal processing, control engineering and electromagnetism. Despite the developments that have been made, several topics remain without a clear and concise formulation, namely and surprisingly, the definition of Fractional Differintegration. In fact, there are several definitions that lead to different results, making difficult the establishment of a systematic theory of fractional linear systems. In facing this problem, we assume here as starting point the unified formulation of integration and differentiation - differintegration - based on Cauchy integral. As proved in a companion paper, this formulation is equivalent to the Grunwald-Letnikov definition that is a generalisation of the usual definition based on the limit of the incremental ratio.

When trying to compute the Cauchy integral using the Hankel contour we conclude that:

- a) the definition implies causality.
- b) the integral have two terms: one corresponds to a derivative and the other to an integral
- c) the exact computation leads to a regularized integral, generalising the well known concept of pseudo-function, but without rejecting any infinite part. The application of the above result to functions with (bilateral) Laplace Transform we obtain the forward and backward Liouville differintegrations.

[1] Kalia, R. N. (Ed.), 'Recent Advances in Fractional Calculus,' Global Publishing Company, 1993.

- [2] Nishimoto, K., 'Fractional Calculus', Descartes Press Co., Koriyama, 1989.
- [3] Samko, S.G., Kilbas, A.A., and Marichev, O.I., 'Fractional Integrals and Derivatives Theory and Applications,' Gordon and Breach Science Publishers, 1987.

#### ENOC-2005, Eindhoven, the Netherlands

[4] Ortigueira, M. D., 'Introduction to Fractional Signal Processing. Part 1: Continuous-Time Systems', IEE Proc. on Vision, Image and Signal Processing, No.1, pp.62-70, Feb. 2000.

ID of Contribution: 11 - 446

## A CUBIC SCHEME FOR NUMERICAL SOLUTION OF FRACTIONAL DIFFERENTIAL EQUATIONS

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This paper presents a numerical scheme for a class of fractional differential equations. In this approach, the differential equations are expressed in terms of Caputo type fractional derivative. Properties of the Caputo derivative allow one to reduce the fractional differential equation into a Volterra type integral equation. Once this is done, a number of numerical schemes developed for Voltera type integral equation can be applied to find numerical solution of fractional differential equations.

In this paper, we present a cubic scheme for this task. The method can be applied for both linear and nonlinear problems. The method is used to solve a simple fractional differential equation. Results obtained using this scheme agree well with the analytical scheme.

# **MINI-SYMPOSIUM 12**

# Oscillatory Motion in Hamiltonian Systems

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## CHAOTIC SCATTERING IN A HAMILTONIAN SYSTEM MODELING TRANSPORT IN A TOPOGRAPHIC EDDY

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We investigate the dynamics of passive particles in a two-dimensional incompressible open flow composed of a fixed vortex and a background current with a periodic component, the model inspired by the phenomenon of topographic eddies over mountains in the ocean and atmosphere [1,2]. We have found and described a non-attracting invariant chaotic set defining chaotic scattering and trapping of incoming particles. A numerical method for identifying unstable periodic orbits, belonging to this set, has been elaborated. Geometry and topology of chaotic scattering have been studied. Scattering functions in the mixing zone have been found to have a fractal structure with a complicated hierarchy that has been described in terms of strophes and epistrophes [3]. A formula, connecting fractal dimension, maximal Lyapunov exponent, and an average trapping time, has been found. A role of a white noise, imposed on the flow, have been investigated.

References:

- M.V. Budyansky, S.V. Prants, M.Yu. Uleysky. Doklady Earth Sciences. V.387 (2002) P.929. [Dokl. Akad. Nauk. V.386 (2002) P.686].
- [2] M. Budyansky, M. Uleysky, S. Prants. Physica D. V. 195 N3-4 (2004) P.369.
- [3] K.A. Mitchell, J.P. Handley, B. Tighe, J.B. Delos, S.K. Knudson. Chaos. V.13 (2003) P.880.

ID of Contribution: 12 - 058

## **QUASI-PERIODICITY IN OSCILLATOR DYNAMICS AND THE LIKE**

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Kolmogorov-Arnold-Moser (or KAM) theory was developed for conservative dynamical systems that are nearly integrable. Integrable systems, such as uncoupled oscillators, in theire phase space usually contain lost of invariant tori and KAM theory establishes persistence of such tori, which carry quasi-periodic dynamics. We sketch this theory, which begins with Kolmogorov's pioneering work from 1954.

## ON THE METHOD OF ASYMPTOTICAL INTEGRATION OF THE HAMILTONIAN SYSTEMS

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In order to investigate non-linear vibrations of a swinging lumped oscillator the method of Poincaré-Birkhoff normal form is applied. As it is known, owing to this method [Poincar'e, 1972; Birkhoff, 1927] the Hamiltonian of a system is outlined in a form of both a square part referred as non-perturbed one, and a sum of terms of powers higher than two.

It is worth noticing that via canonical Hamilton transformations, a system under investigation is essentially simplified. Namely, the Hamiltonian up to the terms of fourth order and higher is integrated. Therefore, an asymptotic solution to non-linear problem is obtained. Traditional methods of normalization of a system with two degrees-of-freedom are rather complicated in some cases for direct investigations [Birkhoff, 1927; Bruno, 1990; Arnold, 1989; Arnold, 1978; Arnold, Kozlov, Neishtadt, 1993]. A change of the variables is either sought using the generating functions, or applying a generating Hamiltonian.

A novel method of construction of canonical variables transformation in the parametric form is proposed, which differs from the existing approaches in Hamiltonian mechanics [Petrov, 2001; Petrov, 2002; Petrov, 2004]. A criterion of existence of parametric variables transformation is first formulated, and then a rule of Hamiltonian transformation is given. The proposed method can be used to find normal forms of Hamiltonians [Petrov, 2002a; Petrov, 2004; Petrov and Zaripov, 2004]. It should be emphasized that we use new concept to define a normal form [Zhuravlev, 1997; Zhuravlev, 2002], which does not require any partition to either autonomous – non-autonomous or resonance – non-resonance cases, but it is treated in the frame of one approach. In order to find the corresponding normal form asympototics, the system of equations is derived analogous to the equations chain obtained earlier [Zhuravlev, 1997; Zhuravlev, 2002]. Instead of the generating function method and the guiding Hamilonian, the parametrized form via some auxilliary function which depends on auxilliary variables is used [Petrov, 2002a; Petrov, 2004]. It allows for direct (without the transformation to an autonomous system [Zhuravlev, 1997; Zhuravlev, 2002]) computation of the equations chain for non-autonomous Hamiltonians [Petrov, 2002a; Petrov, 2002]) computation of the soft of normal forms coincide in the first and second approximations.

The paper consists of two parts. In the first part the parametric form of canonical transformation and the method of normalization are introduced and illustrated. Note that the last mentioned method is sometimes called the method of invariant normalization (see [Zhuravlev, 1997; Zhuravlev, 2002]). The applied method yielded already some important practical results in the article [Klimov, Leonov, Rudenko, 1986], in which on computer algebra REDUCE authors realized the averaging and invariant normalization method for giroscope.

In the second part dynamics of a swinging oscillator is analysed. In what follows the Hamiltonian of the studied system is defined, and also its normal form is constructed. After integration of the system, the asymptotic solution of the investigated non-linear system is obtained [Petrov and Zaripov, 2004].

## ON PHASE CHANGE BETWEEN SEPARATRIX CROSSINGS IN SLOW-FAST HAMILTONIAN SYSTEMS

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We consider a Hamiltonian system with slow and fast motions, one degree of freedom corresponding to fast motion, and the other degrees of freedom corresponding to slow motion. Suppose that at frozen values of the slow variables there is a non-degenerate saddle point and a separatrix on the phase plane of the fast variables. In the process of variation of the slow variables, the projection of a phase trajectory onto phase plane of the fast variables may repeatedly cross the separatrix. These crossings are described by the crossing parameter called pseudo-phase. We obtain an asymptotic formula for the pseudo-phase dependence on the initial conditions, and calculate change of the pseudo-phase between two subsequent separatrix crossings. For Hamiltonian systems depending on slowly varying parameter such formulae were obtained by J. R. Cary, R. T. Skodje (1989).

#### ID of Contribution: 12 - 147

## SURVIVAL CONDITION FOR LOW-FREQUENCY BREATHERS IN A QUASI-1D CRYSTAL

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We investigate a quasi-1D crystal: 2D array of coupled linear chains of particles with strong intra-chain and weak interchain interactions, each chain being subjected to the sine background potential. This Hamiltonian system, dependent on strength of the background potential, models a wide diapason of physical systems: polymer crystals or crystals having heavy and light sublattices as well as array of inductively coupled long Josephson junctions. Nonlinear dynamics of one chain in the array when the rest of chains are fixed is reduced to the well known Frenkel-Kontorova (FK) model. Its continuum limit, sine-Gordon equation, is the only nonlinear wave equation which possesses one-parametric family of exact solutions in the form of low-frequency breathers [1]. The breathers can have sufficiently long lifetime in continuum 1D models including perturbations breaking exact integrability: dissipative and diverse conservative terms, as well as in discrete FK model. Using analytical and numerical techniques we investigate the survival condition for breather in the array of coupled linear chains depending on breather frequency and strength of the background potential. The survival condition bears no relation to resonances between breather frequency and frequencies of propagation band - contrary to the case of the discrete FK model where such resonances break the breathers [2]. Stable breather mode can exist at strong background potential in diapason of low frequencies, and for higher frequencies the survival area is still narrower. The stable breather is mainly localized on one chain, only two chains next to this one have small oscillating excitations. Breathers far away from the survival area have finite short lifetime. Transition from the damped mode to the stable one turns out to be rather sharp.

- [1] S. Kitchenassamy, Communications on Pure and Applied Mathematics 44, 789 (1991)
- [2] R. Boesch, M. Peyrard, Physical Review B 43, 8491 (1991)

## SYMMETRY AND NEAREST-NEIGHBOR INTERACTION IN THE NORMAL FORM OF A HAMILTONIAN LATTICE

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Crystals can often be thought of as a classical mechanical lattice that consists of a regular pattern of particles interacting with their neighbors. Think for instance of the famous Fermi-Pasta-Ulam lattice, which is a one-dimensional array of identical particles with nearest-neighbor interaction. The unexpected statistical behavior of this lattice can to some extent be understood from its symmetries, which express the homogeneity of the lattice. The importance of nearest-neighbor interaction, that is the local character of the equations of motion, unfortunately is not at all clear, although recent results indicate that coupled cell networks comparable to the Fermi-Pasta-Ulam lattice can have surprisingly regular behavior.

The idea is to study the low-energy behavior of a lattice from its Birkhoff normal form, which is a local approximation to the equations of motion. This reveals information about bifurcations, adiabatic invariants and near-integrability. Many structural properties, such as symmetry, reversibility and Hamiltonian character of the equations can be preserved in the normal form. But other essential modelling assumptions such as nearest-neighbor interaction do not carry through so easily. It turns out that the nearest-neighbor character of the equations is of great influence for the lowest order terms of the normal form, but gradually loses its importance at higher order. In this talk I intend to point out the exact physical consequences of nearest-neighbor interaction in Hamiltonian lattice systems.

ID of Contribution: 12 - 216

## UNSTEADY FLUID FLOW SEPARATION BY THE METHOD OF AVERAGING

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Unsteady fluid flow separation has been an unsolved problem ever since the seminal 1904 paper of L. Prandtl on steady boundary-layer separation. Several ad hoc separation criteria have been proposed for unsteady flow, but none of them turned out to be generally applicable.

In this talk, we show the method of averaging can be used to to derive exact separation criteria for two-dimensional unsteady fluid flows with no-slip boundaries. Our results apply to flows that admit a well-defined asymptotic average and conserve mass. Such flows include periodic and quasiperiodic flows, as well as aperiodic flows with a mean component. We show both numerical simulations and experiments that confirm the separation criterion we derive.

191

## FREE AND PARAMETRIC PERIODIC OSCILLATIONS IN SUPERLINEAR AND SUBLINEAR HAMILTONIAN SYSTEMS

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Nonlinear autonomous and parametrically excited Hamiltonian systems are considered. The notion of a superlinear or sublinear Hamiltonian expressed through its Hessian is introduced; it generalizes the notion of hardening or softening elastic characteristic for a system with one degree of freedom. It is assumed that within a given region surrounding the origin, bilateral bounds for the Hessian are known. Non-local criteria for the existence and stability of families of periodic solutions emanating from the origin are obtained. The results are expressed in terms of the linear systems corresponding to the bounds of the Hessian.

In the autonomous case, conditions guaranteeing unique continuation of a Lyapunov family of periodic solutions to the boundary of the indicated region are found. The corresponding period decreases or increases monotonically in the case of a superlinear or sublinear system, respectively (for Hamiltonian systems of the first order, such result was obtained in [1]). Under some extra conditions, a solution is strongly stable (all multipliers of the corresponding variation equation lie on the unit circle and, with the exception of the double unit multiplier, are Krein definite); the proof is based on an analysis of the index function introduced in [2].

For parametrically excited Hamiltonian systems, families of periodic solutions depending on the excitation frequency are considered. Conditions providing unique continuation of such family from the origin to the boundary of the region are found; therewith, in a superlinear (sublinear) system the oscillation period decreases (increases) monotonically. Sufficient conditions for strong stability (all the multipliers lie on the unit circle and are Krein definite) are obtained.

The results are illustrated by examples. A pendulum with a periodically varying length and a system of coupled pendulums with the vibrating suspension point represent sublinear systems. An autonomous string with lumped masses is a superlinear (sublinear) system when the tension in the string is small (large); analogous conclusions are true for a string with a periodically varying tension.

References:

- [1] Zevin A.A. and Pinsky M. A. Monotonicity criteria for the energy-period function in planar Hamiltonian systems. Nonlinearity, 2001, 14, 6, 1425-1432.
- [2] Zevin A.A. New approach to the stability theory of linear canonical systems of differential equations with periodic coefficients. J. Appl. Maths Mechs, 2004, 68, 2, 183-198.

ID of Contribution: 12 - 277

## BREATHERS IN LATTICES OF COUPLED TWO-DIMENSIONAL HAMILTONIAN OSCILLATORS

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A method of proving the existence of breathers in lattices of two-dimensional weakly coupled Hamiltonian oscillators is presented. This method has the advantage that provides a first approximation of the initial conditions of the breather solution together with its linear stability. Since the proof relies on the use of action-angle variables, we also present a method to perform the calculations without knowledge of the specific transformation. We illustrate the results in a lattice of quartic oscillators and in another one that consists of coupled 2D Morse oscillators. Finally we examine the possibility of extending these results in lattices of more than two degrees of freedom per lattice site.

## EXISTENCE OF HORSESHOES IN THE GENERALIZED HÉNON-HEILES SYSTEM UNDER DEGENERATE CONDITIONS

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We consider the generalized Henon-Heiles Hamiltonian  $H = (x_1^2 + x_2^2 + y_1^2 + y_2^2) / 2 + c x_1 y_1^2 + d x_1^3 / 3$ 

The original system studied by Henon and Heiles is the case of c=1 and d=(-1). It is integrable for c/d = 0, 1/6, 1, and it has been proven to be nonintegrable in a complex analytic meaning for the other cases. Moreover, it was shown, for example, in Ref. [1], that there exist horseshoes and chaotic motions occur unless c/d = 0, 1/6, 1/2, 3/4, 1. A Shilnikov type or Melnikov type approach can be used to prove the result and both of them are based on the fact that there is a saddle-center having a homoclinic orbit. A one-parameter family of periodic orbits exists near the saddle-center and their stable and unstable manifolds intersect transversely on their energy level sets.

In this talk, we address the problem on the existence of horseshoes for the remaining cases of c/d = 1/2, 3/4 in the generalized Henon-Heiles Hamiltoinian. When c/d=3/4, the splitting distance between the stable and unstable manifolds of periodic orbits near the saddle-center is proven to be much smaller than that in the case of Ref. [1]. Moreover, when c/d=1/2, not only the splitting distance is still smaller but also the saddle-center becomes degenerate and a pitchfork bifurcation occurs. We extend the Melnikov-type technique of Ref. [1] up to higher order and prove that there exist horseshoes and chaotic motions occur in these degenerate cases. The details on these results are given in Refs. [2,3].

#### References:

- K. Yagasaki, Horseshoes in two-degree-of-freedom Hamiltonian systems with saddle-centers, Arch. Rational Mech. Anal., 154 (2000), 275-296.
- [2] K. Yagasaki, Higher-order Melnikov method and chaos for two-degree-of-freedom Hamiltonian systems with saddle-centers, submitted for publication.
- [3] K. Yagasaki, Existence of horseshoes in the degenerate Henon-Heiles system, in preparation.

#### ID of Contribution: 12 - 330

## PERTURBATIONS OF INTEGRABLE AND SUPERINTEGRABLE HAMILTONIAN SYSTEMS

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Integrable systems admitting a sufficiently large symmetry group are considered. In the non-degenerate case this group is abelian and KAM theory ensures that most of the resulting Lagrangean tori persist under small non-integrable perturbations. For non-commutative symmetry groups the system is superintegrable, having additional integrals of motion that fibre Lagrangean tori into lower dimensional invariant tori. This simplifies the integrable dynamics, but renders the perturbation analysis more complicated. I review important cases where it is possible to find an 'intermediate' integrable system that is non-degenerate and approximates the perturbed dynamics.

## A NONLINEAR MAP APPROACH TO WAVE TRANSMISSION IN OSCILLATORY CHAINS WITH CUBIC NONLINEARITIES

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Free wave propagation properties in one dimensional chains of nonlinear oscillators are investigated by means of nonlinear maps. In this realm, the governing difference equations are regarded as symplectic nonlinear transformations relating the amplitudes in adjacent chain sites (n, n+1) thereby considering a dynamical system where the location index *n* plays the role of the discrete time [1,2]. Thus, wave propagation becomes synonymous of stability: to find regions of propagating wave solutions is equivalent to find regions of linearly stable map solutions. Mechanical models of chains of linearly-coupled nonlinear oscillators are chosen in the form:  $mq \ddot{n} + k_1 q_n + k_3 q_n^3 + k (2q_n - q_{n-1} - q_{n+1}) = 0$ .

Pass and stop band regions are analytically determined for period-q orbits as they are governed by the eigenvalues [3] of the linearized 2D map arising from linear stability analysis of periodic orbits. Then, equivalent chains of nonlinear oscillators in complex domain are tackled. Also in this case, where a 4D real map governs the wave transmission, the nonlinear pass and stop bands for periodic orbits are analytically determined by extending the 2D map analysis. In both cases the nonlinearity causes amplitude dependent pass and stop bands and the occurrence of vibration modes in the linear attenuation zones can thereby be explained [4]

The analytical findings concerning the propagation properties are then compared with numerical results obtained through nonlinear map iteration. The latter are mainly focused on the bounded solutions occurring within the passing band, where, besides periodic orbits, quasiperiodic and chaotic orbits exist. Good agreement between the analytical approximation of the propagation regions and the numerical evidence is found. In particular, it is worth underlying that, regardless of the periodicity q, the bounded orbits region coincides with that of the period-1 case. However, the loss of stability, or orbits' unboundedness, occurring at the upper bound involves different bifurcations if even-period or odd-period orbits lose stability via saddle-node bifurcation. Finite chains are eventually considered in order to determine free vibrations frequency-response curves as well as their relationship with the amplitude dependent frequencies bounding the nonlinear propagation zone.

- [1] Wan Y. and Soukoulis C.M., One-dimensional nonlinear Schrödinger equation: A nonlinear dynamical approach, Physical Review A, 41, 800-809, 1990.
- [2] Hennig D. and Tsironis G.P., Wave transmission in nonlinear lattices, Physics Reports, 307, 333-432, 1999.
- [3] Manevitch L.I., The description of localized normal modes in a chain of nonlinear coupled oscillators using complex variables, Nonlinear Dynamics, 25, 95-109, 2001.
- [4] Romeo F. and Luongo A., Invariant representation of propagation properties for bi-coupled periodic structures, Journal of Sound and Vibration, 257, 869-886, 2002.
- [5] Manevitch L.I., Gendelman O.V., Savin A.V., Nonlinear normal modes and chaotic motions in oscillatory chains, Proc. IUTAM Symposium on Chaotic Dynamics and Control of Systems and Processes in Mechanics, Rome, 8-13 June 2003.

### CHAOS IN HAMILTONIAN SYSTEMS WITH WIDELY SEPARATED FREQUENCIES

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In this paper we consider Hamiltonian systems with three-degrees of freedom with frequency ratio of  $1:2:\varepsilon$ , where  $\varepsilon << 1$ . Using the averaging method, we normalize the Hamiltonian function. After normalization, we reduce the system to two degrees of freedom Hamiltonian systems. The normal form for the Hamiltonian has the form of  $H(q,p) = H_{1:2}(q_{1:}p_{1}) + H_{1:\varepsilon}(q_{2:}p_{2}) + \gamma H_m(q,p)$ , with  $H_{1:2}$  corresponds to the 1:2-resonance,  $H_{1:\varepsilon}$  corresponds to the 1: $\varepsilon$ -resonance, and  $H_m$  corresponds to the interaction term. When  $\gamma=0$ , the Hamiltonian system is integrable. By considering  $\gamma$  as another small parameter, we study the normal form as a near integrable Hamiltonian system, where the integrable part contain homoclinic orbit. This provides a possibility for chaotic dynamics in the perturbed system.

# **MINI-SYMPOSIUM 13**

# Mechanisms for Diffusion in the Phase Space

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## POLYNOMIAL DISPERSION OF TRAJECTORIES IN STICKY DYNAMICS

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Hamiltonian chaotic dynamics is, in general, not ergodic and boundaries of the ergodic area (stochastic sea, stochastic layers, stochastic webs, ets.) are sticky, i.e. trajectories can spend an arbitrary long time in the vicinity of the boundaries. Segments of trajectories, that imposed by the stickiness, are called flights. The flights have polynomial dispersion that can impose non-Gaussian statistics of displacements and anomalous transport in phase space. Particularly, the presence of flights influences the distribution of Poincaré recurrences. We use the distribution function of finite small separation of trajectories that at time instant t and length 1 are separated first time by a given small value. The connection of this function, called complexity function, with distribution of Poincaré recurrences is established for three cases:

- i) for the case of superdiffusion in the standard and web maps for which the stickiness is defined by the boundaries of hierarchical sets of islands
- ii) for the case of Sinai billiard with infinite horizon, where the stickiness is defined by a zero measure slits in the phase space
- iii) for the square billiard with a slit (bar-in-square) where the Lyapunov exponent is zero and the stickiness is defined by a vicinity of the trajectory to the closest periodic trajectories obtained from diophantic approximations.

Finally, the powerwise asymptotics of the Poincaré recurrences can be connected, in some cases, to the anomalous transport exponent.

#### ID of Contribution: 13 - 116

## CHARACTERIZATION OF ORBITS IN THE TRUNCATED AND FORCED NONLINEAR SCHRÖDINGER MODEL

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Classifying all the trajectories in a multi-dimensional chaotic system is, in general, a formidable and unattainable task. For near integrable Hamiltonian systems some rough classification may be found; in some cases, their structure may be well described via the construction of a three level hierarchy of bifurcations [3]. Typical and singular unperturbed solutions on a given energy level are found systematically, as does their dependence on the energy level and the parameters. In particular, all the different types of singular unperturbed solutions arising in a given model may be classified. These are related on one hand to bifurcations in the differential topology structure of the energy surfaces and on the other to certain forms of perturbed solutions [1-3].

The first level of the hierarchy, extensively studied by Smale, Lerman, Fomenko and others, consists of the analysis of the structure of the level sets (the sets of phase space points along which all n constant of motion are fixed) on a single energy surface (the set of phase space points along which the unperturbed energy is fixed). Bifurcation values correspond to the values of the constants of motion across which the topology of the level sets on a given energy surface is changed (the "singularity manifolds"). The energy-momentum bifurcation diagram (EMBD) and the branched surfaces provide a complete description of this level [1]. Furthermore, under some mild conditions, the perturbed energy surfaces are metrically close to the unperturbed surfaces, so their structure supplies a-priori bounds to the perturbed motion [3]. The next level consists of the energy bifurcation values across which the differential topological structure of the energy surfaces is changed. Singularities of the singularity manifolds with respect to the energy axis in the EMBD

ENOC-2005, Eindhoven, the Netherlands

correspond to energy bifurcation values. The simplest singularity (a fold in the co-dimension one singularity surfaces) is associated with resonances - namely with a dynamical phenomena [2]. We list all the other known scenarios creating energy bifurcation values for the 2 d.o.f. case (folds, cusps and their symmetric analogs, curve crossings and asymptotes to infinity) and discuss their dynamical implications in the perturbed system [3]. The last level in the hierarchy is concerned with the parameter dependence of the energy bifurcation values - the parameter values at which the bifurcation sequence of the second level changes. For example, at a parameter value for which the fold energy bifurcation value coincides with the cusp energy bifurcation value - a parabolic resonant torus is created [1,3]. Furthermore, the appearance of such a scenario is persistent in a one-parameter family of near-integrable Hamiltonians [2].

Application of this formulation to an extensively studied model arising in a non-linear optics problem (the forced and truncated NLS equation) demonstrates its potential power. We discover new types of chaotic solutions and a new insight regarding the role of the forcing frequency [3].

#### References:

[1] A. Litvak-Hinenzon and V.Rom-Kedar. SIADS, 2004, to appear.

[2] ----- Nonlinearity, 15(4):1149--1177, 2002.

[3] E. Shlizerman and V. Rom-Kedar, Chaos, 2004, to appear.

ID of Contribution: 13 - 190

## EXPLICIT LOWER BOUNDS OF THE TOPOLOGICAL ENTROPY FOR NEAR-INTEGRABLE ANALYTIC SYSTEMS

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On the annulus  $A^n = T^n \times R^n$ , endowed with its angle-action coordinates  $(\theta, r)$ , we consider nearintegrable Hamiltonian systems of the form  $H_j(\theta, r) = h(r) + \eta \kappa_j(r) f_j(\theta, r)$ , where j is a positive integer, h and  $f_j$  are two analytic functions, with holomorphic continuation on a fixed complex domain D, such that the Sup-norm  $\varepsilon_j$  of the function  $f_j$  on the domain D tends to 0 when j tends to infinity. The function  $\eta \kappa_j$  is a bump function with support in a "test compact set"  $K_j$  of  $\mathbb{R}^n$ , its role is to localize our study to the compact invariant set  $T^n \times K_j$  in order to properly define the topological entropy. The resulting system Hj of course is not globally analytic, but its restriction to the set  $K_j$  is. The compact set  $K_j$  depends on j but remains localized in resonant zones of fixed multiplicity, and we are especially interested in the dependence of the entropy on that multiplicity.

When  $f_j=0$  the system  $H_j=h$  is completely integrable, in the very strong sense that each Lagrangian torus  $T^n \mathbf{x}\{r\}$ , is invariant under the flow. In this case it is possible to prove that the topological entropy of the restriction of the associated time-one map  $\Phi^h$  to each compact set  $T^n \mathbf{x} K$  vanishes.

Our problem is to find lower bounds for the topological entropy of the time-one map  $\Phi^{Hj}$  defined by  $H_j$ , restricted to the compact invariant set  $T^{\prime}\mathbf{x}K_j$ . More exactly, we choose a suitable sequence of analytic functions  $(f_j)$  for which we can estimate  $h_{top}(\Phi^{Hj})$  from below as a function of  $\varepsilon_j$ , and we study the dependence of that lower bound on the position of the compact Kj relatively to the resonant surfaces of the unperturbed Hamiltonian h.

Typically, we choose for  $K_j$  some closed Euclidean ball  $B(r_j, \delta_j]$  centered at  $r_j$  with radius  $\delta j > 0$ , and for  $\eta \kappa_j$  a smooth map with support in  $K_j$  which is equal to 1 on  $B(r_j, \delta_j/2]$ . Our first result is the "maximally resonant case" where the compact  $K_j$  is located near a local minimum of h.

#### Theorem A.

Assume that h is convex and admits a nondegenerate minimum at some  $r^0$  in  $\mathbb{R}^n$ . Then there exists a sequence  $(f_j)$  and two positive constants  $c_1, c_2$  such that if  $K_j = B(r^0, c_1 e_j^{1/2}]$  the topological entropy of  $\Phi^{Hj}$  satisfies the inequality htop $(\Phi^{Hj}) > c_2 e_j^{1/2}$ 

The opposite case is when the compact  $K_j$  is located near simple resonances. Nevertheless, to the sake of simplicity we only investigated the neighborhood of double resonances.

#### Theorem B.

ENOC-2005, Eindhoven, the Netherlands

Assume n > 3 and let  $h(r) = (r_1^2 + ... + r_{n-1}^2)/2 + r_n$ . Then there exists a sequence (fj), a sequence of centers  $(r_{0j})$  near double resonances of h and two positive constants  $c_1, c_2$  such that if  $K_j = B(r_{0j}, c_1 e_j^{1/2}]$  the topological entropy of  $\Phi^{Hj}$  satisfies the inequality  $h_{top}(\Phi^{Hj}) > exp(-c2(1/e_i)^{1/2(n-3)})$ .

ID of Contribution: 13 - 312

## CHAOS AND DIFFUSION IN FOUR-DIMENSIONAL, NON-CONSERVATIVE, REVERSIBLE SYSTEMS WITH SADDLE-CENTERS

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We consider a class of four-dimensional, non-conservative, reversible systems with saddle-centers. It immediately follows that a one-parameter family of periodic orbits near the saddle-center and construct a normally hyperbolic invariant manifold.

We extend a Melnikov-type technique developed in Ref. [1] for two-degree-of-freedom Hamiltonian systems and obtain a criterion for the stable and unstable manifolds of the invariant manifold to intersect transversely. Such intersection also implies that there exist not only homoclinic orbits but also heteroclinic orbits to periodic orbits on the invariant manifold since there is no conserved quantity. So there are infinitely many heteroclinic connections between the periodic orbits and we can find an open set of trajectories traveling near the periodic orbits having heteroclinic connections. A three-dimensional horseshoe can also be constructed for an appropriate Poincaré map.

Thus, very complicated behavior, chaotic dynamics in the hyperbolic directions and diffusion in the center directions, can occur when the stable and unstable manifolds of the invariant manifold intersect transversely. This is very similar to well-known Arnold diffusion in three or more degrees of freedom, near-integrable Hamiltonian systems. Such behavior is also reported in Ref. [2] to occur in three or more degrees of freedom Hamiltonian systems with saddle-centers.

To illustrate the theory, we present an example coming from a nonlinear-optical medium with both quadratic and cubic nonlinearities. Numerical simulation results are also given. The details on these results are given in Ref. [3].

#### References:

- [1] K. Yagasaki, Horseshoes in two-degree-of-freedom Hamiltonian systems with saddle-centers, Arch. Rational Mech. Anal. 154 (2000) 275-296.
- [2] K. Yagasaki, Homoclinic and heteroclinic orbits to invariant tori in multi-degree- of-freedom Hamiltonian systems with saddle-centers, submitted for publication.
- [3] K. Yagasaki, Homoclinic and heteroclinic orbits to periodic orbits, chaos and diffusion in four-dimensional, nonconservative, reversible systems with saddle-centers, in preparation.

ID of Contribution: 13 - 471

## **DIFFUSION SPEED IN THE MATHER PROBLEM**

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In the problem of periodic in time potential perturbation of a geodesic flow on a 2-dimensional torus (the Mather problem) generically there exist solutions with an unbounded grouth of energy. This phenomenon is similar to the Arnold diffusion. We look for solutions with the fastest energy grouth. The main result is the existence of solutions with linear average energy grouth.

## SKEW-PRODUCTS OVER THE BERNOULLI SHIFT WITH AN INFINITE ERGODIC MEASURE

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The random iteration of several maps on the same space gives rise to a skew-product over the Bernoulli shift, particular instances of which can be realized in near-integrable Hamiltonian systems. We indicate sufficient conditions for the skew-product to admit an infinite ergodic measure, and give an example in which they are met.
## **MINI-SYMPOSIUM 14**

### Computational Methods for Non-Smooth Systems

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### HYSTERESIS SIMULATION AND INVESTIGATION OF THE CONTROL PARAMETER PLANES

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There are a lot of different phenomenological approaches for hysteresis modelling [1]. However, recently a large number of publications are devoted to hysteresis simulation, because it is known, that hysteretic systems are complicated for investigation and various difficulties occur during investigation of those models [2]. Unfortunately, the question of multi-purpose and generally valid models describing the wide spectrum of hysteretic phenomena is still open.

In hysteresis simulation a system is frequently viewed as a black box and, supposing that the input of the system is known, the system's output (or response) is modelled with the use of the empirical or the analytical nature of the expressions (e.g. exponential, hyperbolae, polinomials, arctangent, and so on). All other models are based on energetic consideration and result in differential equations.

In the present work hysteresis is simulated by means of additional state variables. That is the energy dissipated in the cycle is simulated with the aid of internal variables.

The models describing systems with hysteresis are discontinuous and contain high nonlinearities with memory dependent properties. The output is delayed with respect to the input and for every input there may be more than one equilibrium states. The chaotic behaviour occurring of the dynamic hysteretic system governed by a coupled differential set is investigated in various parametric planes. This methodology already had been successfully applied in particular to predict stick-slip chaos in two-degree-of-freedom discontinuous systems with friction [3].

Chaos, periodic responses, and hysteresis loss are demonstrated. Among others, substantial influence of a hysteretic dissipation value on the form and location of the regions where chaotic behaviour of the hysteretic oscillators is possible, is displayed.

References:

- [1] I.D. Mayergoyz, Mathematical Models of Hysteresis, Springer, Berlin, 1991.
- [2] H. Kolsch and D. Ottl, Simulation des mechanischen Verhaltens von Bauteilen mit statischer Hysterese, Forschung im Ingenieurwesen 4 (1993) 66-71 (in Germany).
- [3] J. Awrejcewicz, L. Dzyubak and C. Grebogi, A Direct Numerical Method for Quantifying Regular and Chaotic Orbits, Chaos, Solitons and Fractals 19 (2004) 503-507.

### ID of Contribution: 14 - 086

### TIME-OPTIMAL TRAJECTORIES OF A DIFFERENTIAL-DRIVE ROBOT

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The aim of this study is to present a new method for trajectory optimization of structure-variant non-smooth mechanical systems. The relatively recent developments in the numerical solution of measure differential inclusions make new optimal control formulations possible for non-smooth systems with velocity jumps due to impacts or changes in the

### 204

number of degrees of freedom (DOF) due to friction. Time-stepping integration schemes belong to the class of methods which can be used to handle mechanical systems with impacts and friction.

The direct shooting method is used to determine the optimal trajectories of mechanical systems which can exhibit impacts and a change in DOF. Using this suggested method, time optimal trajectories are obtained without specifying in advance the switching time for changes in DOF. A time-stepping discretization is used which enables the incorporation of impact effects.

The considered mechanical system is a 5-DOF differential-drive robot. Since it has three wheels, a rigid body mechanical model can be used which has two modii of operation. When the non-holonomic constraints are fulfilled, the system possesses two degrees of freedom. It is a system with 5-DOF when both wheels slide. This system has been chosen because in the control of nonholonomic systems literature this benchmark mechanical system has been used with different approaches to obtain trajectories. The evaluation of the contact kinematics and dynamics has been handled by the augmented Lagrangian approach in the framework of time-stepping integration. The augmented Lagrangian approach for modeling non-smooth mechanical systems provides an exact regularization of the system enabling to obtain gradients uniquely in some regions of the search space. The direct shooting optimization is performed by the Nelder-Mead method which is a non-derivative based minimization algorithm. The goal criterion has been to reach desired end states by minimizing the required time. A direct shooting approach has been chosen because of the advantages it has compared to indirect shooting methods where the estimation of the adjoint variables constitute a major difficulty even for smooth mechanical systems.

Because of the required intensive numerical evaluations, the model has been kept as simple as possible. In order to achieve a reduced order model the normal contact forces has been calculated by the projection of the changes of linear and angular momentum in the restrained directions of motion. This approach makes possible to use a system with five degrees of freedom instead of an eight degrees of freedom system.

### References:

- [1] R. I. Leine and H. Nijmeijer, 'Dynamics and Bifurcations of Non-smooth Mechanical Systems', Springer Verlag, 2004
- [2] C. Glocker, 'Set Valued Force Laws', Springer Verlag, 2001

ID of Contribution: 14 - 093

### SIMULATION OF NON-SMOOTH MECHANICAL SYSTEMS WITH MANY UNILATERAL CONSTRAINTS

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A ball falling down to the ground is a simple example of a non-smooth mechanical system with one unilateral constraint. In a planar modelling, the ball's three degrees of freedom are reduced to two when the ball touches the ground. If we additionally consider friction, then the degrees of freedom are reduced to one in the case of sticking. Thus, we have different equations of motion for these different contact configurations. In case of an impact, an impact law must be applied. We simulate 1000 balls falling in a funnel, for which about half a million unilateral contacts with friction have to be modelled. It is very difficult to detect all the contact configurations and their associated equation of motion. Also the detection of all impacts and their treatment is cumbersome. The Time-stepping algorithm [1] is a robust algorithm to rigorously handle dynamical problems with many unilateral constraints and friction. It's idea is to calculate velocity updates instead of accelerations. As a consequence, contact behaviour and impact can be treated by the same equations. The unilateral constraints are modelled by set valued force laws [2]. The resulting inequalities can be transformed in a linear complementarity problem [3], or can be directly solved by an Augmented Lagrangian Method. In the paper, we will focus on the Augmented Lagrangian Method, which is especially well suited for three dimensional frictional contact problems.

References:

- Moreau, J.J., Unilateral Contact and Dry Friction in Finite Freedom Dynamics, Non-smooth Mechanics and Applications (Eds. J.J. Moreau, P.D Panagiotopoulos), CISM Courses and Lectures Vol. 302, Springer Verlag, Wien, 1988, 1-82.
- [2] Glocker, Ch., Set-Valued Force Laws: Dynamics of Non-Smooth Systems, Springer Verlag, Berlin Heidelberg, 2001
- [3] Glocker, Ch., Studer, Ch., Formulation and Preparation for Numerical Evaluation of Linear Complementarity Systems in Dynamics, Multibody System Dynamics, Kluwer Akad. Publ., to appear

### ID of Contribution: 14 - 131

### NUMERICAL TIME INTEGRATION OF HIGHER ORDER DYNAMICAL SYSTEMS WITH STATE CONSTRAINTS

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This work addresses the problem of the numerical time integration of the Moreau's Sweeping process and its extensions. The goal of this paper is not to give some rigorous mathematical results on dedicated numerical schemes, but hints and tricks on the ability of the associated time-stepping schemes (without event-handling procedures) to deal with non smooth evolutions. We present also new algorithms for solving higher order non smooth dynamical systems, for IVP and BVP problems.

The sweeping process is a formulation and a mathematical framework for non linear dynamical systems subjected to unilateral constraints and impacts, initiated and developed by J.J. Moreau [1]. This framework has been applied successfully to several fields in nonlinear mechanics (unilateral constraints, plasticity, fluids mechanics, etc ...) and extensively studied from the mathematical point of view (well-posedness, existence and uniqueness). However, majors features of the numerical time-integration of such formulation are not yet well-known and we propose in the first part of this paper to make an general overview of its characteristics and to illustrate its ability on very simple example (Boucing ball on a plane, dry Friction oscillator, nonsmooth electrical networks).

Recently, several extensions have been done, particularly in order to deal with higher order systems, and more precisely, to deal with systems with arbitrary relative degree[2]. In the second part of the paper, we present a new scheme to numerically integrate higher order sweeping process. The algorithm will be detailed and compared to those of Camlibel et al.[3] on linear complementarity systems, where several examples of inconstitency are shown. Finally, we give some qualitative results on the approximation (Bounded variation) and the dissipativity of the scheme which paves the way to convergence results.

- [1] J.J. Moreau (1977), Evolution problem associated with a moving convex set in a Hilbert space, J. Differential Equations, 26, pp 347-374.
- [2] V. Acary and B. Brogliato and D. Goeleven (2004). Higher order Moreau's sweeping process: Mathematical formulation and numerical simulation. Technical Report Nr. RR-5236. INRIA. submitted to Mathematical Programming A.
- [3] K. Camlibel, W.P.M.H. Heemels, J.M. Schumacher (2002), Consistency of a time-stepping method for a class of piecewise-linear networks, IEEE Transactions on Circuits and Systems I, vol.49, pp.349-357.

### **REAL-TIME SIMULATION OF HYBRID AEROSPACE SYSTEMS**

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Aerospace vehicle systems are by nature, complex hybrid systems. The interaction between systems with their environment, and between systems with very different dynamical behaviour adds to the complexity. During design and test of aerospace systems, software representations of (sub) systems are replaced by hardware components. Moreover, training simulators, with humans-in-the-loop pose extra requirements on timely responses. In particular, embedded training, the amalgamation of simulation and training becomes more and more important.

The full paper will give an overview of selected industrial applications in which modelling, simulation and control of hybrid systems play an essential role. Industrial designs of systems are usually driven by operational requirements. Based on these requirements, critical items are identified and feasibility studies are executed, supported by real-time simulation studies. These simulation studies require suitable mathematical models of all components of the system under consideration. We aim at generic models suitable for use in engineering as well as training simulators. As a consequence, proper responses of the models are crucial. Therefore, the mathematical models for hybrid systems must behave very much like the systems would do in the real world. When a simulator is also used for verification and validation purposes, it is advantageous to take real-time aspects into account right from the start. As such real-time simulators require special computational algorithms.

In the last decade, motivated by acquired capabilities of design and training in the field of vehicle dynamics and robotics, generic multi-body models of a wide range of vehicles were made. The mathematical models are realistic representations of mechanical systems, comprising for example, elasticity and damping of the tyre, wheel suspension, chassis stiffness characteristics, and roll, pitch and yaw motions. Of special interest is the interaction of a vehicle with rugged terrain: the impact phenomenon gives rise to discrete-event modelling in combination with continuous-time dynamics. Building a model from sub-models has the advantage that model adaptations are easy, which is important in aerospace design studies.

Satellite systems offer another challenging field of research. The behaviour of cooling and fuel liquid can have a considerable impact in performance and controller demands. The interaction of liquid with the rest of the satellite, or, here on earth, the interaction between a liquid cargo and the truck that is carrying the cargo, require an extension of impact simulation between mechanical systems as done with robotic systems, to systems of a very different physical character.

The full paper will focus on the real-time aspects, i.e. computational methods, of selected hybrid aerospace systems.

- [1] Z. Klaasse and W.F. Lammen, Hybrid models of landing aircraft and planetary rovers: investigations into real-time simulations. In preparation.
- [2] G. Rozema and A.A. ten Dam, Modelling and simulation of vehicles carrying liquid cargo, 2004. NLR internal report.
- [3] B. Brogliato, A.A. ten Dam, L. Paoli, F. Génot, and M. Abadie, Numerical Simulation of Finite Dimensional Multibody Nonsmooth Mechanical Systems, ASME Applied Mechanics Reviews, Volume 55, Number 2, pages 107-150, March 2002.

### ONE-PARAMETER PATH-FOLLOWING OF FIXED POINTS FOR NON-SMOOTH CONTINUOUS SYSTEMS

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The objective of this work is to propose a simple ad-hoc path-following algorithm for piecewise-smooth continuous dynamical systems having a discontinuous Jacobian. It can be used for tracing solution branches with respect to one parameter and location of their bifurcation points [1]. A sketch of the algorithm is outlined below.

It is supposed that surfaces at which the Jacobian has discontinuities are defined explicitly and for each region that results from their overlapping, a smooth dynamical subsystem is provided that defines the whole system behaviour in the region.

The main procedure used by the algorithm consists of the computation of all intersections between fixed-point branches and a given simplicial polytope. We split this task into several independent pieces for each smooth subsystem in the regions that can be captured by the polytope. The final solutions are derived by abandoning those that are out of the subsystem's region of definition.

The intersection finding tasks for each subsystem are further confined to each simplicial facet of the polytope. As we dealing now with smooth equations, we can perform further tesselation of the facet by simplices, until some accuracy of piecewise-linear approximation of the subsystem is achieved. The simplices that contain the intersections are detected by labelling of the simplex vertices. To obtain precise solutions, we apply Newton iterations.

The algorithm can locate bifurcation points by manipulating the polytope diameter. At the beginning, a user-defined conventional polytope diameter is used and new fixed points are detected near a given initial fixed point, which defines the initial polytope centre. If the procedure results in only two new points, we attribute the points to the same branch and begin to trace the branch in two opposite directions. For this, we move the polytope centre into the last computed fixed points (in either directions). After detecting one intersection outside of the previous polytope, we move the centre into that point and repeat the sequence.

In the case of more than one intersection found in one direction, we contract the polytope so that to preserve its centre. This will help to precisely locate branching points during the trace. When the diameter becomes less than some tolerance, we increase it up to some user-defined maximum, while again preserving polytope centre. We mark this centre as a branching point, compute intersections of the new polytope with emanating branches and then trace each new branch separately, starting with normal diameter.

If after the polytope enlargement it is not possible to find any new fixed point, we mark the centre of the polytope as a sharp point and continue the trace with conventional diameter. We also restore polytope diameter to the conventional size if during several consecutive tracing steps the diameter has not been affected.

Despite the lack of proof and unavoidable 'curse of dimensionality' the author believes the algorithm may be of interest. It can greatly benefit from using parallel computational facilities.

References:

[1] M. Demenkov. "One-parameter path-following of fixed points for non-smooth continuous systems". Full-length paper submitted for the ENOC-2005 Conference Proceedings.

### NUMERICAL ANALYSIS OF CHATTERING ORBITS IN VIBRO-02

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Dynamical systems with discontinuities, often referred to as piecewise smooth (PWS) systems, arise in many areas of engineering. Examples of such systems include Braille printers and rattling gears. The analysis of PWS systems has drawn a lot of attention in recent years and lead to many interesting results of which we will focus on results that can be used in numerical algorithms. In particular we will focus on a family of PWS systems that include state jumps, e.g. rigid body systems with impacts. For numerical analysis of such systems it is important to choose a suitable simulation strategy. One way to handle impacting systems is to consider them as deterministic hybrid systems, i.e. as combinations of continuous (non-impacting) systems and discrete maps (representing the impacts or the state variable jumps). A big advantage with this approach is that standard techniques to solve the first variations equations for smooth systems can be extended to also include hybrid systems, and thus methods to determine the stability of limit cycles and to continue them under parameter changes can be developed.

The next task is to pinpoint non-standard situations that are likely to appear in impacting systems, so that treatment of such situations can be included in numerical algorithms. Typical examples include grazing, impacts with zero velocity, and chattering, an infinite number of impacts in a finite time interval, of which we will here focus on the latter. Chattering (also referred to as Zeno phenomena) is a well-known behaviour in vibro-impact systems that can potentially cause additional wear. Numerically there is an obvious problem in that it is impractical to locate a large number of impacts. However, to avoid this problem it is possible to locally predict when and where the impact sequence will end, and thus a chattering map can be used to replace the tail of the chattering sequence. Whereas an impact map is only a reset in the state variables a chattering map also resets the time. A big advantage with chattering maps is that they are easily included in hybrid system simulation environments to reduce the number of event detections that has to be done. In a similar way as for hybrid systems with a low number of impacts it is possible to extend the methods for stability analysis and continuation of limit cycles to include chattering.

In this presentation we will show how chattering can appear in impacting systems. Some numerical examples will be presented to show how to include chattering maps to simulate impacting oscillators with chattering and how they can be used to determine the local stability of limit cycles with chattering. Also, the possibility to detect standard and nonsmooth bifurcations under continuation of such limit cycles will be discussed.

### ID of Contribution: 14 - 255

### NON-STANDARD FINITE DIFFERENCE METHODS; APPLICATIONS TO NON-SMOOTH MECHANICS

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Nonstandard finite difference methods (shortly NSFD) were developed for solving practical problems in applied sciences and engineering (see [3] for a survey on NSFD). In particular these methods were designed so as to 'fit' most of the essential physical properties of the exact solution, such as the conservation of energy, stable and/or unstable states. Since the pioneer works of R.E. Mickens in the mid-1980s, the nonstandard approach has shown great potential in the design of reliable schemes that preserve significant properties of solutions of differential models in sciences and engineering [1] and in particular in smooth mechanics.

Our aim is to study the application of the NSFD methods in non-smooth mechanics. Indeed, non-smooth dynamical systems have such complex behaviors that their numerical treatment by traditional methods is not always successful.

We also design, for single vibro-impact problems and friction problems, non-standard finite difference schemes [3] in which the intrinsic qualitative parameters of the system, like for example the restitution coefficient of the impact law, the oscillation frequency and the structure of the nonlinear terms..., are suitably incorporated [1,2]. The schemes obtained are unconditionally stable and replicate a number of important physical properties of the involved systems.

We also present some examples [2] to show that NSFD methods can be very efficient in comparison with classical methods.

References:

- [1] Anguelov and J.M-S. Lubuma, "Contributions to themathematics of the nonstandard finite difference method and applications", Numer. Methods Partial Differential Eq. 17, 518-543 (2001)
- [2] Y. Dumont and J.M-S. Lubuma, "Non-standard finite difference methods for vibro-impact problems", accepted for publication in Proceedings A of the Royal Society of London.
- [3] R.E. Mickens, "Nonstandard finite difference schemes for differential equations", J. Diff. Equations Appl. 8: 823-847 (2002).

ID of Contribution: 14 - 256

### SIMULATIONS OF BEAM VIBRATIONS BETWEEN STOPS: COMPARISON OF SEVERAL NUMERICAL APPROACHES

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There is considerable interest in industry in dynamic vibrations of mechanical systems. In the automotive industry the noise and vibration characteristics of cars and car components are considered as an important factor in the product customer satisfaction. Some of the unwanted noise is generated by the dynamic contact of parts and components when periodically forced.

We consider an elastic beam that is clamped at one end to a vibrating device while the other end oscillates between two rigid stops. Even such a simple problem can exhibit complicated behavior under periodic forcing: it can oscillate periodically, quasiperiodically or chaotically.

The contact is modeled with the Signorini nonpenetration condition. We also obtain a variational inequality. In order to compute approximate solutions, we use the method of lines which consists of making first a space discretization so as to convert our variational inequality into a differential inclusion. Then we consider time discretizations written in terms of positions or in terms of velocities, such as developed by Paoli, Schatzman and Mabrouk (see [3] for a survey), to obtain a full discretization.

We present a convergence result for a family of fully discretized schemes [2]. We also discuss the properties of several algorithms obtained with different choices for the time and space discretizations [1,2] and we compare some numerical simulations obtained with these different schemes.

- [1] Y. Dumont, "Some remarks on a vibro-impact scheme", Numer. Algorithms, 33, (2003), 227-240.
- [2] Y. Dumont and L. Paoli, "Vibrations of a beam between stops: convergence of a fully discretized scheme", submitted to Numerische Mathematik
- [3] L. Paoli, "Time discretization of Vibro-impact", Phil. Trans. Royal Soc. of London A, 359 (2001), 2405-2428.

### INVESTIGATION OF LARGE SYSTEMS CONSISTING OF MANY SPATIAL POLYHEDRAL BODIES

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Goal of our work is the investigation of the dynamical behaviour of many differently shaped bodies. By means of our granular matter simulations large systems like bulk solids or carriage systems can be investigated. For an efficient simulation of such systems methods from Molecular Dynamics (MD) and Multibody Systems (MBS) are combined.

Originally in MD molecules are investigated and it is the goal to describe their interactions and collective dynamical behaviour. Interactions between particles depend on measurable characteristics of the materials, e.g. viscosity or elasticity. In order to simulate a high number of bodies, in MD the molecules are often modelled as rigid spheres. The material behaviour is then represented by forces acting on the bodies. In MD such forces may be attractive forces such as Van der Waals forces, but also contact forces are investigated. In order to calculate contact forces effectively, overlaps between the particles are accepted and the value of the contact force depends on the distance between the colliding bodies. Another idea, which is used in MD, is neighbourhood search. There, it is possible to search for close body pairs in advance and to evaluate the contact forces only for such colliding body pairs. Different neighbourhood search methods were developed, and we implemented and compared some of the main methods. By means of such methods it is possible to reduce the necessary simulation time of order  $O(n^2)$  in such a way, that linear behaviour O(n) can be obtained.

Simulations of granular material or bulk solids are based on free bodies in space. There, a free body has six degrees of freedom. Then, the equations of motion can be obtained easily taking into account three elementary rotations for example the Kardan-angles and three translational degrees of freedom. After neighbouring body pairs are found, the very time consuming collision detection for polygonal bodies can be accomplished. In order to check whether there is a collision between two neighbouring body pairs, it has to be checked, whether there is a vertex of one body inside the other body. To do so we define a ray of infinite length from the observed point. Point P is inside the other body, if the number of intersections with the surface of the other body is odd for the arbitrary ray, to both sides of the point. Also it can be said, that point P is outside the other body, if the number of intersections is odd for on one side of the ray and even on its other side. For more efficiency some more considerations have to be taken into account, and will be addressed in the talk. Also we will focus shortly on the detection of the contact forces in normal and tangential direction.

ID of Contribution: 14 - 376

### MULTIVALUED STOCHASTIC DIFFERENTIAL EQUATIONS AND MECHANICS

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We study in this work mechanical systems with finite number of degrees of freedom and friction or plasticity via a modelling using maximal monotone operators. The external forces of the system contains a stochastic term and the equations of the dynamics can be expressed under the form of multivalued stochastic differential equations abbreviated in MSDE. We prove the convergence of a numerical scheme in the Euclidean case. We consider also models based on MSDE's on Riemanian manifolds for which we prove the existence and the uniqueness of a solution. A numerical

ENOC-2005, Eindhoven, the Netherlands

scheme closed to that defined in the Euclidean case can be used in the Riemanian framework and the convergence of such a scheme will be a future work. Results of existence and uniqueness are applied to the spherical pendulum with friction.

ID of Contribution: 14 - 397

### NON-SMOOTH DYNAMICS OF A SPUR GEAR PAIR

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In the last twenty years, a continuously increasing interest was addressed to gear noise problems; i.e. on the parameters which affect the vibrational behavior of such systems. A strong interaction between noise and dynamic transmission error (DTE) has been clearly proved; number of experiments on gear systems has shown that several nonlinear phenomena occur when dynamic transmission error is present: multiple coexisting stable motions, sub and super harmonic resonances, fold bifurcations, long period subharmonic motions and chaotic motions have been clearly demonstrated (Kahraman 1997). General approaches (Kim 1991) for predicting these phenomena have been developed using: time varying parametric excitation and piecewise linear characteristic; different analytical and numerical techniques were developed in the past. Many authors also included impacts effect, developing specific theory in order to predict periodic motions in generalized, piecewise linear oscillator with perfectly plastic impacts. This theory is based on generic mapping structures considering discontinuous boundaries in non-smooth dynamic systems (Luo 2004).

In the present study a single degree of freedom oscillator with clearance type non-linearity is considered. Such an oscillator represents the simplest model useful to analyze a single teeth gear pair neglecting: bearings and shafts stiffness; multi mesh interactions. The test case considered in the present work would model an actual gear pair present in a gear box of an agricultural vehicle, which gave rise to noise problems.

The main gear pair characteristics, namely mesh stiffness and inertia, have been evaluated after an accurate geometrical modeling and a finite element analysis, including contact mechanics. Values for the mesh stiffness are evaluated for different positions along one mesh cycle and a Fourier expansion of the time varying stiffness is carried out.

The dynamical model presents a piecewise linear periodic stiffness and a constant viscous damping. A direct numerical integration approach and a smoothing technique have been considered to obtain the dynamic scenario. Bifurcation diagrams and Poincaré maps are plotted according to some sample case study from literature. Comparisons with results present in literature are provided.

- [1] A. Kahraman, G. W. Blankenship, "Experiments on nonlinear dynamic behavior of an oscillator with clearance and periodically time varying parameters", J. of Appl. Mech., 64, 217-226, 1997.
- [2] Y. B. Kim, S. T. Noah, "Stability and bifurcation analysis of oscillators with piecewise linear characteristics: a general approach", J. of Applied Mechanics, 58, 545-553, 1991.
- [3] A. C. J. Luo, "A theory for non-smooth dynamic systems on the connectable domains", Comm. Nonlin. Sci. Num. Sim., 10, 1-55, 2005.

### IDENTIFICATION OF MECHANICAL SYSTEMS WITH BILINEAR STIFFNESS USING DIFFERENTIAL EVOLUTION

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Previous work by the investigators has shown that it is possible to directly identify the parameters of bilinear systems using a Genetic Algorithm (GA). The current paper extends this work to the general case of piecewise linear stiffness. In order to accommodate the possibility of several linear stiffness regimes, it is necessary to move to a variable-length GA and this is the algorithm adopted here. It is shown that the algorithm works particularly well if a refinement step is added. In an attempt to remove the refinement step a real-coded Differential Evolution algorithm was also applied and the results from the two algorithms are compared. The systems investigated are simulated and experimental SDOF systems with bilinear and trilinear stiffnesses.

### ID of Contribution: 14 - 415

### NON SMOOTH MECHANICS AND ROCK AVALANCHES: DESCRIPTION OF THE COLLISIONS AND NUMERICAL SIMULATION OF GRANULAR FLOW

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The use of non smooth efforts to approximate smooth efforts is called atomization of the efforts. This approach is the basic idea of twoo numerical methods : MCD (Modified Contact Dynamics) and MALE (Modified ALE). These methods are used to compute the evolution of discrete or continuous systems submitted to smooth as well as non smooth sollicitations.

ID of Contribution: 14 - 461

### ANALYSIS OF DIFFERENT TIME-INTEGRATION METHODS APPLIED TO A NON-SMOOTH INDUSTRIAL PROBLEM

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Sophisticated computational methods have been established to apply non-smooth mechanical models to a wide range of industrial applications. However, the application of these methods is still limited by high computing times especially when large systems of industrial relevancy have to be simulated. Therefore the improvement of numerical algorithms is a focus of ongoing research. Also the choice of the mechanical model as well as the appropriate time-integration method is essential.

ENOC-2005, Eindhoven, the Netherlands

In this work a non-smooth industrial problem, namely a valve train including the gear wheel drive, is simulated using different time-integration methods. The system consists of a main transmission line between the crankshaft and the camshaft of the engine. Additional gears are needed to drive vehicle auxiliaries. The valves are actuated by a rocker arm setup. The movement of each rocker is defined by the contact between the roller bodies and the cam contour. As this contact may open and close, an impact law has to be considered. A friction law allows for stick-slip transitions in case of a closed contact. The radius of the cam contour is approximated by piecewise defined polynomial functions. As a result transitions of the contact point to another contour section have to be treated as a change in the structure of the system, similar to a closing or opening contact.

In order to deal with the varying structure of the system two different groups of numerical schemes can be used: eventdriven and time-stepping schemes.

Event-driven schemes detect changes of the structure, for example stick-slip or contour transitions, and resolve the exact transition times. Between these events the motion of the system is smooth and can be computed by a standard integrator with root-finding. In this context the ODE-integrator LSODAR and the DAE-solver MEXAX are investigated. One drawback is the fact that the constraints are formulated and therefore only fulfilled at the acceleration level. On the one hand this requires the analytical calculation of the kinematical variables which may be extensive for arbitrary cam contours. On the other hand numerical drift-off effects require additional projection steps to ensure accurate solutions and valid system states.

Time-stepping schemes are based on a time-discretization of the system dynamics including the unilateral constraints. An event-detection is not needed and the discretization can be chosen such that no additional protection steps have to be performed. Unfortunately the common time-discretizations are of order one with a fixed time-step size. As a consequence the step size is strongly limited to ensure stability and the required accuracy especially when dealing with stiff degrees of freedom. In our application this is the case for bearings and tooth engagements.

In order to point out the suitability of each approach to the described problem an analysis in terms of computing times, accuracy and robustness is performed. Moreover, a comparison of the analytical effort is given.

# **MINI-SYMPOSIUM 15**

### Dynamical Concepts in Computational Modeling

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### EXPONENTIALLY SMALL PHENOMENA IN SOME BILLIARD TABLES

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Birkhoff introduced the problem of convex billiard tables as a way to describe the motion of a free particle inside a closed convex curve such that it reflects at the boundary according to the law angle of incidence equals to angle of reflection. He realized that this billiard motion can be modeled by an area-preserving (in fact, twist) diffeomorphism defined on the annulus. If the curve is an ellipse, its billiard map has separatrices, and if it is close to a circumference, the square of its billiard map is close to the identity in a portion of the phase space.

The splitting of separatrices of area-preserving maps close to the identity is one of the most paradigmatic fields related to exponentially small phenomena. The field reached its maturity with the work of V. F. Lazutkin. He gave an asymptotic formula for the splitting size in the standard map and provided the basic lines of a proof.

In this framework, we present a numerical study of some billiard tables depending on a perturbative parameter and a hyperbolicity parameter h. These tables are ellipses when the perturbative parameter vanishes, and they tend to circumferences as h tends to zero. Elliptic billiard tables are integrable and they have four separatrices connecting their hyperbolic two-periodic points. These connections break up under the perturbation.

In the weakly hyperbolic limit (that is, when h tends to zero), the area of the main lobes of the resulting turnstile (which can be interpreted as the difference of the lengths of the symmetric primary homoclinic billiard trajectories) behaves like a term exponentially small in h times an asymptotic series in even powers of h. Besides, the Borel transform of this asymptotic series is convergent on a disk of radius 2\*pi\*pi. The asymptotic series associated to the next exponential term has the same properties. Finally, we have detected some almost invisible homoclinic bifurcations that take place in an exponentially small region of the parameter space.

Our computations have been performed in multiple-precision arithmetic (namely, with several thousands decimal digits) and rely strongly on the expansion of the local invariant curves up to very high orders (namely, with several hundreds Taylor coefficients). Our programs have been written using the PARI system and launched in a Beowulf cluster with several tens of Xeon processors.

### ID of Contribution: 15 - 143

### NONLINEAR TRANSIENT ANALYSIS OF LAMINATED COMPOSITE PLATES

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Dynamic behavior of laminated composite plates is a topic of considerable engineering importance. There is a great number of research work on the elastic behavior of laminated plates. Among the published works, Von Karman plate theory has gathered the most attention for the nonlinear responses of plates going under large deflection.

For the solution of coupled, nonlinear partial differential equations, many linear procedures (such as finite elements, Fourier series, Rayleigh-Ritz and Galerkin) have been used. In a recent work, Chebyshev series technique has been developed for analyzing nonlinear transient problem of laminates [1]. Recent studies have been done on static and dynamic geometrically nonlinear behavior of the laminates by the authors [2,3].

In the present paper geometrically nonlinear analysis of laminated composite plates under dynamic loading is considered. First order shear deformation theory based on Mindlin's hypothesis with Von Karman nonlinearity is utilized and the governing differential equations are solved by using the Galerkin method. Suitable polynomials are

chosen as trial functions to approximate the plate displacement functions. The solutions are compared to that of finite elements and Chebyshev series. A good agreement is observed and the present technique is found to be effective.

References:

- [1] Y. Nath and K.K. Shukla, Non-linear transient analysis of moderately thick laminated composite plates, Journal of Sound and Vibration. 247 3,(2001), pp. 509--526.
- [2] H. Tanriover and E. Senocak, Large deflection analysis of unsymmetrically laminated composite plates: analyticalnumerical type approach, Int. J. Non-Linear Mechanics. 39 8 (2004), pp. 1385-92.
- [3] H. Tanriover and E. Senocak, Dynamic nonlinear behavior of composite plates, Proceedings of ASCE Aerospace Division International Conference on Engineering, Construction, and Operations in Challenging Environments (Earth \& Space 2004), TX, U.S.A., March 07-10, 2004.

**ID of Contribution: 15 - 287** 

### LORENZ MAPS WITH FOLDS IN THERMAL CONVECTION MODELS

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In the Rayleigh-Benard experiment of thermal convection in a fluid layer, the first instability of the steady state can lead to the formation of convection rolls. I will consider a model consisting of a four dimensional system of ordinary differential equations, introduced by F. Busse and coworkers to gain understanding of the loss of stability of these convection rolls through a secondary instability, the skewed varicose instability. A combined numerical and bifurcation study explains the formation of patterns in the model. I will focus in particular on the existence of robustly transitive strange attractors akin to Lorenz attractors but of a different geometric structure.

ID of Contribution: 15 - 385

### VISCOELASTICALLY DAMPED SANDWICH BEAMS

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The aim of this paper is to analyse classical models for viscoelastically damped sandwich beams. Some are based on the kinematics of Kirchhoff-Love, Mindlin, Reddy or Touratier, the others on the zigzag principle (Rao). The accuracy of these models is compared in the static field and the dynamic field. The comparison includes vertical deflection, normal strain and transverse shear strain of simply supported sandwich beams under transverse loading, natural frequencies and loss factors of simply supported beams.

### TRANSITIONS CHAINS CLOSE TO TORI IN THE 3D RESTRICTED THREE-BODY PROBLEM: THEORY AND EXAMPLES

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The spatial restricted three-body problem is considered for small values of the mass parameter and for energy close to the one of the collinear equilibrium point between the primaries. That point is unstable but it has a 4D center manifold. For fixed values of the energy most of the points on the center manifold are on KAM tori. The homoclinic and heteroclinic connections between these tori are studied. For simplicity the study is restricted to primary intersections, that is, the ones which occur after one revolution around the main primary.

On the mass parameter-energy plane the values for which such connections exist are characterized. A theorem about the existence of transition chains is proved. Explicit examples of transitions chains are constructed.

### ID of Contribution: 15 - 452

### **COMPUTING STABLE/UNSTABLE MANIFOLDS BY ORBIT-CONTINUATION**

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A simple technique to compute a 2-dimensional stable or unstable manifold of a fixed point or a periodic orbit is to apply standard pseudo-arclength continuation to an initial, sufficiently long orbit in the manifold. The continuation stepsize is measured in a space that includes the entire orbit as well as appropriate variable scalar quantities. This approach allows the computation of manifolds where simple time integration would be difficult to use, for example in the case where the relevant eigenvalues of a fixed point differ greatly in magnitude. As an application that illustrates the efficacy of the approach we use a model of ionic currents in a cardiac cell, where we consider the phase-resetting response as a function of an external stimulus. The calculations elucidate the apparent discontinuous response as the stimulus passes critical values [1].

References:

[1] T. Krogh-Madsen, E. J. Doedel, L. Glass, M. R. Guevara, 'Apparent discontinuities in the phase-resetting response of cardiac pacemakers', J. Theoretical Biology 230 2004, 499-519. (Special issue commemorating Art Winfree.)

**ID of Contribution: 15 - 453** 

### FRACTALIZATION OF SMOOTH INVARIANT CURVES

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In this talk we plan to present some new results dealing with the destruction of attracting invariant curves in quasiperiodically forced 1-D dynamical systems. More concretely, we will focus on the case in which the length of the curve goes to infinity when a parameter approaches some critical value. We will first discuss some connections between this behaviour and the lack of reducibility of the curve. It will be shown in some cases the curve keeps being a smooth curve as long as it is attracting, although the numerical simulations seem to show that it is not longer a regular curve, but a

ENOC-2005, Eindhoven, the Netherlands

strange nonchaotic attractor (SNA). We will discuss how this phenomenon brings into question the real existence of some of the SNAs observed numerically in the literature.

### **ID of Contribution: 15 - 454**

### SEPARATING MANIFOLDS IN SLOW-FAST SYSTEMS

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The application of dynamical systems theory to biological models often involves different time scales. This is particularly the case for models of neurons, which involve dynamics of ionic channels across the cell membrane. Due to the slow-fast nature of the model it is difficult to use numerical tools for the investigation of the global behaviour. We investigate a Hodgkin-Huxley type model of a neuroendocrine cell that secretes growth hormone. The behaviour of the cell is a periodic process of Calcium storage in the cell (the slow phase) which triggers a rapidly oscillating voltage potential across the cell membrane (the active phase). From a mathematical point of view, the two phases are separated by invariant manifolds of periodic orbits or equilibria that are present in the limit of the fast time scale. The biological goal is to use the mathematical model as a tool to influence the phase of the oscillation via the input of additional current. This so-called phase-resetting is particularly difficult in somatotroph cells, which is clearly explained by the mathematical model.

ID of Contribution: 15 - 455

### SEMI-ANALYTICAL COMPUTATIONS OF INVARIANT MANIFOLDS OF LIBRATION POINT ORBITS AND THEIR APPLICATIONS IN LIBRATION POINT MISSION DESIGN

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Libration point orbits, located in the neighborhood of the so called collinear libration points in the Sun-Earth system have been increasing in importance due to their specific particularities. Nowadays the SOHO spacecraft can be considered as a reference point for this type of missions, but in the near future an increase of demand and complexity of the missions is foreseen.

New space missions requirements are increasingly complex, with ever more demanding constraints and the commitment to minimize the costs. Consequently, a greater understanding of the dynamics near the collinear libration points is not less than ineluctable. As an example, the knowledge of homoclinic and heteroclinic trajectories between libration point orbits can reduce the cost of many transfers to almost zero like in the return of the Genesis spacecraft.

The presentation addresses methodologies to compute the skeleton of the dynamics associated with halo and Lissajous libration point orbits. We will focus on finding homoclinic and heteroclinic connections between libration point orbits in the RTBP or Hill's problem. For this purpose, two methodologies, one based in normal forms and another one based in Lindstedt Poincaré procedures, for the computation of high order expansions of libration points orbits and their manifolds will be presented.

The results will be applied to the exploration of this type of connections and to other problems of the mission design.

### NONCONFORMAL PERTURBATIONS OF THE QUADRATIC MAP: THE 1:3 RESONANCE

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We consider a family of non-conformal maps of the plane, as a perturbation of the quadratic map  $z \rightarrow z^2 + c$ . In particular, a neighborhood in phase-parameter space of the 1:3 resonance of the unperturbed map is analyzed, by theoretical and numerical means, mostly in a local setting, but some more global aspects are discussed as well.

Certain topological constructions, like the Mandelbrot and Julia sets, and external rays, can be carried through to the nonanalytic setting. Other familiar properties of the quadratic map, like the number and possible types of periodic points, are lost under the perturbation.

A bifurcation analysis shows complicated dynamics, where the 1:3 resonance point as well as cusp and Bogdanov-Takens points act as organizing centers. Arnol'd tongues and invariant circles - originating from Neimarck-Sacker bifurcations - also play an important role in structuring the dynamics. Finally, we discuss a planar vector field approximation of the family of maps that can explain part of these phenomena.

ID of Contribution: 15 - 458

### **UNSTABLE PERIODIC ORBITS IN TURBULENCE**

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Lots of work on turbulence is focused on the efficient and meaningful representation of coherent structures. Such structures, called tubes, sheets, worms, hairpins etcetera, are usually extracted form the numerical output of simulations by some statistical analysis.

Examples of this approach are the proper orthogonal decomposition and box counting techniques. Such analysis is of limited use when studying the dynamics and parameter dependence of turbulence. Instead I propose to use Unstable Periodic Orbits to analyse the structure of turbulence. UPO's represent spatiotemporal patterns and can (generically) be continued uniquely in parameters such as the Reynolds number. With the formulation of new numerical algorithms and development of parallel computing it is becoming feasible to find and analyse UPO's in large systems.

As an example I will discuss recent work with Shigeo Kida and Genta Kawahara on isotropic turbulence. I will discuss the correlation between periodic and turbulent motion in a range of values of the Reynolds number. In turn out that a single periodic orbit can, in a sense, represent turbulence. I discuss this result in the light of new theory by Kawasaki and Sasa, based on exact results on a coupled map lattice.

### A NUMERICAL EXPLORATION OF WEAKLY DISSIPATIVE TWO-DIMENSIONAL MAPS

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Weakly dissipative systems provide a more correct model in many situations of real world. The effect of tiny dissipative perturbations in area-preserving maps (APM) is considered. In an equivalent way this can be applied to model the behaviour of Hamiltonian systems with 1+1/2 or 2 degrees of freedom under the effect of a small friction.

The study is done about elliptic fixed points of APM and the dissipation is radial. That is, if (0,0) is such a fixed point and the APM map is  $(x,y) \rightarrow T(x,y)$ , maps of the form (1-epsilon) \* T are considered for very small epsilon>0.

Some of the structure of the conservative case persists. Weakly dissipative diffeomorphisms show properties of both conservative and dissipative maps. For sufficiently small dissipation, in a neighbourhood of an elliptic fixed point, which becomes an attracting focus, some periodic points related to different resonances survive. The invariant manifolds of the hyperbolic ones determine the basin of attraction of the elliptic ones.

Some figures displaying how the manifolds fold to pass through a resonance and how the basins of attraction of different resonances are located will be shown. The illustrations correspond to a dissipative perturbation of the classical Hénon map, but the same patterns are proved to exist for generic maps.

Increasing the dissipation parameter produces the destruction of some resonances. Several figures describing the process of destruction will be also shown. These phenomena implies that the probability of capture by the former elliptic point around which we are looking at the dynamics increases. Some computations of this probability and its behaviour when the conservative case is approached help to understand which attractors play an important role on this dynamics.

The basic model to be used is a resonant Birkhoff normal form adding the effect of perturbation. In the 'easy' domain (for not too small values of epsilon) the local dynamics can be approximated by a flow. It is given by a perturbation of a Hamiltonian pendulum. The most difficult domain in the parameter space appears for very tiny values of epsilon. The flow approximation is no longer valid and one has to deal directly with the diffeomorphism.

At this point the splitting of the separatrices plays a key role. It depends on the derivatives of the rotation number with respect to the action variable for a twist approximation of the APM. Computations of rotation numbers and splitting (both analytical and numerical) will be shown.

### **QUASI-PERIODIC HÉNON-LIKE ATTRACTORS IN 3D DIFFEOMORPHISMS**

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A low dimensional model of general circulation of the atmosphere is investigated [1]. The differential equations are subject to periodic forcing, where the period is one year. A three dimensional Poincaré mapping P depends on three control parameters (F, G, E), the latter being the relative amplitude of the oscillating part of the forcing.

A coherent inventory is presented, concerning the dynamical phenomenology of P as the three parameters are varied.

For E small, both a Hopf-saddle-node bifurcation of fixed points and quasi-periodic Hopf bifurcations of invariant circles occur, persisting from the autonomous case E=0. For E=0.5, the above bifurcations have disappeared.

Moreover, different types of strange attractors are found: Henon-like attractors, Shilnikov-like attractors, and quasiperiodic Henon-like attractors. The latter type of attractor possesses a quasi-periodic component in the dynamics, detected by numerical indicators such as Lyapunov exponents and power spectra. The creation of quasi-periodic Henonlike attractors is put in relation with homoclinic tangencies of invariant circles of saddle type.

### References:

[1] H.W. Broer, C. Simó, R. Vitolo: Bifurcations and strange attractors in the Lorenz-84 climate model with seasonal forcing, Nonlinearity 15(4) (2002), 1205--1267.

# **MINI-SYMPOSIUM 16**

### **Numerical Bifurcation Techniques**

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### **BIFURCATIONS OF SYMMETRIC OPTIMA IN STRUCTURAL DESIGN**

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Motivated by optimization problems in structural engineering, we study the critical points of symmetric, 'reflected', one-parameter family of potentials U(p,x)=max(f(p,x),f(p,-x)), yielding modest generalizations of classical bifurcations, predicted by elementary catastrophe theory. Our theory may help to explain why symmetrical structures are often optimal.

Reflection symmetry can be observed as well in engineering structures as in Nature and this suggests that reflectionsymmetric configurations are often optimal. In case of many optimization problems we associate optima with minima, pessima with maxima of a potential. Symmetry-breaking bifurcations (studied extensively in [1]) associated with oneparameter families of smooth potentials f(p,x), are adequate to model many problems in engineering, however, the classical pitchfork, associated with reflection symmetric problems, predicts that the symmetric solution will become unstable beyond the critical parameter value, i.e. it will cease to be an optimal solution.

This prediction may be correct in some cases, but apparently not in each one: relatively simple structures prove to be optimal in the symmetric configuration even beyond bifurcation points.

The discrepancy between the classical model's prediction and the actual behavior can be explained if we try to define a suitable 'potential' for the optimization problem. Consider that the global optimum is determined by a discrete assembly of 'weak points' the set of which, due to the reflection symmetry, is itself invariant under reflection. The potential associated with each of these 'weak points' behaves smoothly, but the envelope of these potentials will be, in general, non-smooth. In this paper we take a systematic approach to the bifurcations associated with non-smooth potentials of the mentioned type. Analysis of bifurcations associated with special non-smooth potentials can be found in [3] (Section 16), where a generalization of Thom's theorem is introduced in case of the so-called conditional catastrophes, however, symmetrical potentials are not investigated.

We will follow the same line of thought as [2], looking for the Taylor expansion of the generating, smooth potential f(p,x) at x=0. This provides a classification of bifurcation points for the non-smooth optimization potential U(p,x), containing both 'classical' cases as well as some new ones. The latter include bifurcations where the symmetrical solution remains stable (optimal) beyond the critical parameter value. We construct a complete list of these bifurcations and provide structural engineering examples for each bifurcation. We also outline possible applications to mathematical models in evolution.

In case of several optimization parameters the bifurcations of optima offer interesting computational challenges.

- [1] Golubitsky, M., Stewart I. and Schaeffer, D. G., Singularities and Groups in Bifurcation Theory, Vol. 1., Springer Verlag, New York, 1982.
- [2] Thompson, J. M. T. and Hunt, G. W., Elastic Instability Phenomena, Wiley, Chichester, 1984.
- [3] Poston, T. and Stewart, J., Catastrophe theory and its applications, Pitman, London, 1978.

### NUMERICAL CONTINUATION OF FIXED POINTS OF MAPS IN CL\_MATCONT

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Matcont is a Matlab toolbox for the interactive, graphical, numerical study of parameterized ODEs. It has the look - and - feel of Content [2] but is completely rewritten. The current version is freely available at: http://allserv.UGent.be/~ajdhooge where also a slightly more general non - GUI version Cl\_matcont is available.

Limit cycles are important in neural modeling, in particular in the case where each cycle contains a spike (action potential). The phase resetting curve of a limit cycle is a real-valued function defined on the same time interval as the limit cycle itself. Its value in each point is the relative shortening of the period when a pulse in the direction of the voltage component is given in the corresponding point of the limit cycle. Phase resetting curves of neural models are extremely important for the network and synchronization properties of the models since giving a pulse corresponds to receiving a stimulus from a nearby neuron. Their computation is usually done by simulation experiments which is a very time - consuming procedure. In the present talk we discuss the continuation of limit cycles with a free parameter in Cl\_matcont. We show how the phase resetting curves can be obtained cheaply as a byproduct of the continuation. We concentrate on technical - numerical issues, in particular the relation between the undiscretized systems (functions) and the discretized systems (long vectors) present in the computer. The duality between functions represented by their values in the meshpoints of a mesh and their evaluation values in the collocation points of the mesh intervals is already present in Auto [2] and Content [1] but requires a more careful handling in the algorithms that we discuss.

References:

- E. J. Doedel, A. R. Champneys, T. F. Fairgrieve, Yu. A. Kuznetsov, B. Sandstede and X. J. Wang, Auto97-Auto2000: Continuation and Bifurcation Software for Ordinary Differential Equations (with HomCont), User's Guide, Concordia University, Montreal, Canada (1997-2000).
- [2] Yu. A. Kuznetsov and V. V. Levitin, Content: Integrated Environment for analysis of dynamical systems. CWI, Amsterdam (1997).

ID of Contribution: 16 - 097

### FIRST TWO LYAPUNOV EXPONENTS AND THEIR FLUCTUATIONS OF NATURAL CONVECTION IN A RECTANGULAR CAVITY

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The transition of natural convection in a vertical cavity with heated and cooled vertical side walls has been the subject of many research papers. In most of papers such a transition was separately examined by using linear or weakly nonlinear analyses; the method depends on its main flow regime. These methods, however, are not applicable to quantify the conditions of quasi-periodic or chaotic flows. On the other hand, the real parts of the eigenvalues of the stability matrix are known to equal the corresponding Lyapunov exponents and, therefore, Lyapunov exponents can provide the unified measure to examine the transition from any flow regime.

In this study an accurate and simple method numerically to evaluate Lyapunov spectrum was proposed. The method is suited for any discretization method that finally expresses a governing equation system considered as an ordinary differential equation system. In this computation, unsteady main thermal convection and its tangent vectors,

ENOC-2005, Eindhoven, the Netherlands

corresponding to respective Lyapunov exponents, are simultaneously solved. And the method was applied to evaluate the first two Lyapunov exponents (L1 and L2) for the natural convection in a rectangular cavity of aspect ratio A=5 with heated and cooled side walls and their variation against the Rayleigh number Ra was examined. Moreover the fluctuations of the first two local Lyapunov exponents were examined and summarized as structure functions.

As a result, it was found that the first two Lyapunov exponents make it possible quantitatively to classify thermal convection fields into five regimes against Ra: (1) a steady state (S0) with L2<L1<0, (2) a steady state (S1) with L1=L2<0, (3) a periodic state (P) with L1=0>L2, (4) a quasi-periodic state (QP) with L1=L2=0 and (5) chaotic state (C) with L1>0. Consequently, we clarify the transition route from steady state to chaos by identifying the 1st and 2nd Hopf bifurcation, following the Ruelle-Takens-Newhouse scenario. In addition, it was found that the fluctuation of normalized tangent vectors near under a critical Ra well explains that of main thermal convection near over the Ra. Specifically, the fluctuation of thermal convection in (P) is well explained by that of 1st tangent vector in (S1) near the critical Ra between the two flow regimes. Similarly, the fluctuation of the 2nd tangent vector in (P) near the critical Ra. Moreover, it was found that the thermal convection field can be classified from the view point of structure functions of the first two local Lyapunov exponents; the structure function of a Lyapunov exponent are gaussian when the (averaged-)exponent is nearly equal to zero, and non-gaussian elsewhere, having large deviation properties.

### ID of Contribution: 16 - 100

### ALGORITHMS FOR ARNOL'D TONGUES AND QUASIPERIODIC TORI: A CASE STUDY

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Quasiperiodic and phase-locked oscillations are typical phenomena in forced or coupled oscillators. Consider, for example, a system of two coupled nonlinear oscillators, each oscillator possessing a limit cycle, and assume that the coupling of the oscillators and the internal frequency of the first oscillator can be controlled by two external parameters. In the decoupled case the cross-product of these two limit cycles in parameter times phase space forms a family of normally attracting invariant tori with parallel flow. This flow is called quasiperiodic if the rotation number, that is, the ratio of the two internal frequencies, is irrational and resonant otherwise.

Due to normal attractivity the above one-parameter family of invariant tori persists for sufficiently small values of the coupling parameter. However, the flow on the tori may change from parallel to phase-locked. More precisely, in the two-parameter plane exist smooth curves such that the flow on the corresponding tori is quasiperiodic and the irrational rotation number satisfies certain number-theoretical properties. The union of these curves forms a Cantor-like set of positive measure and is nowhere dense. The complementary set consists of so-called Arnol'd tongues and the flow on corresponding tori is typically phase-locked.

This paper presents algorithms for the computation of Arnol'd tongues and curves of quasiperiodicity in a twoparameter plane and demonstrates their performance with an example from nonlinear electrical engineering. The basic idea for the computation of Arnol'd tongues is to parametrise the family of periodic solutions belonging to a particular Arnol'd tongue over the phase space instead of the parameter space. A two-point boundary value problem for a set of such periodic solutions can be derived and its solution continued using AUTO. The primary continuation parameter is the coupling parameter. The boundaries of the Arnol'd tongues are approximated by the minimal and maximal value of the secondary parameter, which is treated as an additional variable.

Curves of quasiperiodicity are obtained by a two-parameter continuation of quasiperiodic invariant tori with fixed rotation number. A quasiperiodic two-torus is a solution of an extended partial differential equation, the so-called invariance equation, where a secondary external parameter enters by means of a solvability condition. The primary continuation parameter is again the coupling parameter.

Both methods are complementary and, together, allow the exploration of the full two-parameter family of invariant tori near a one-parameter family of tori with parallel flow. The algorithms are simple to implement and compute Arnol'd tongues or curves of quasiperiodicity for user-defined rotation numbers. Since Arnol'd tongues are approximated by solutions of two-point boundary value problems, their computation becomes immediately accessible to a user of standard solvers like, for example, AUTO. Furthermore, for very narrow Arnol'd tongues this algorithm provides a 'poor man's approximation' to the phase-locked tori by the covering periodic solutions.

ID of Contribution: 16 - 140

### COMPUTING ONE-DIMENSIONAL UNSTABLE EIGENFUNCTIONS AND MANIFOLDS IN DELAY DIFFERENTIAL EQUATIONS

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In this presentation, we demonstrate how to compute 1D unstable manifolds in delay differential equations (DDEs) with discrete, fixed delays. Specifically, we show how the Matlab continuation package DDE-BIFTOOL can be used to compute the necessary starting data, namely unstable eigenfunctions of a saddle periodic orbit of the DDE. Saddle fixed points along the saddle periodic orbit, together with their unstable eigenfunctions are then extracted from this data. Starting from these initial fixed points, our algorithm grows the manifold as a sequence of points, where the distance between points is governed by the curvature of the one-dimensional intersection curve of the unstable manifold with a suitable Poincare section.

Our algorithm makes it possible to study global bifurcations in DDEs. We illustrate this with an intermittent transition to chaos in a delay system describing a semiconductor laser subject to phase-conjugate feedback.

This software can be downloaded from http://seis.bris.ac.uk/~kg8579/ddeman.html, together with the relevant references:

References:

- [1] B. Krauskopf and K. Green, Computing unstable manifolds of periodic orbits in delay differential equations, Journal of Computational Physics 186 230-249 (2003).
- [2] K. Green, B. Krauskopf and K. Engelborghs, Bistability and torus break-up in a semiconductor laser with phaseconjugate feedback, Physica D 173 114-129 (2002).
- [3] K. Green, B. Krauskopf and K. Engelborghs, One-dimensional unstable eigenfunction and manifold computations in delay differential equations, Journal of Computational Physics 197 86-98 (2004).

### **ID of Contribution: 16 - 141**

### MULTIPARAMETER PARALLEL SEARCH BRANCH SWITCHING

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A continuation method is a way to compute solution curves of a nonlinear system of equations with a parameter. We derive a simple algorithm for branch switching at bifurcation points for multiple parameter continuation, where surfaces bifurcate along singular curves on a surface. It is a generalization of the parallel search technique used in the continuation code AUTO, and avoids the need for second derivatives and a full analysis of the bifurcation point.

The one parameter case is special. While the generalization is not difficult, it is non-trivial, and the geometric interpretation may be of some interest. An additional tangent calculation at a point near the singular point is used to estimate the tangent to the singular set.

### TIME SIMULATION-BASED BIFURCATION ANALYSIS OF WAVES

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In this presentation, we will discuss methods to compute branches of wave solutions for lattice and for PDE problems, and to compute the stability of those solutions.

One of the strategies for PDEs is based on the symmetry reduction that we presented in Nonlinearity 16:1257-1275, 2003. There we derived an equation based on renormalisation ideas which can be used to 'freeze' waves and self-similar solutions, i.e., waves and self-similar solutions become steady-states of the modified equation. This procedure also gives lead to an interesting idea to compute the stability of the wave solutions by solving a generalised eigenvalue problem. When set up properly, the neutral eigenvalues which are typical for wave solutions but don't give any actual information about the stability, are 'deflated to infinity', while the set of finite eigenvalues is precisely the set of eigenvalues that one is interested in.

ID of Contribution: 16 - 161

### BIFURCATION METHODS FOR LARGE-SCALE APPLICATIONS WITH EXAMPLES FROM STRUCTURAL MECHANICS

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Computing families of solutions to nonlinear problems and their bifurcations can provide valuable insight to understanding the dynamics of physical and biological systems. This is particularly true in structural mechanics problems where bifurcations typically give rise to a failure of the system, e.g., buckling. However, developing continuation and bifurcation algorithms that are scalable to a large-scale context and work with existing state-of-the-art application codes is quite challenging. Limited memory, lack of derivative information, inexact linear solves from iterative linear solvers, and dealing with data structures for sparse, distributed matrices severely restrict the algorithmic choices available.

In this talk, we describe continuation and bifurcation techniques that have been implemented in a software package called LOCA, The Library of Continuation Algorithms, that has been developed at Sandia National Laboratories for studying instabilities such as turning point, pitchfork and Hopf bifurcations in large-scale problems. These algorithms have the advantage of requiring little additional information from the application code, and in most cases only require linear solves of the underlying system Jacobian matrix. However, these linear solves become extremely ill-conditioned near a bifurcation point, limiting the accuracy and robustness of the bifurcation algorithm. We then present various approaches to improve the conditioning of the linear solves, including a promising new algorithm based upon the idea of applying the Moore-Penrose pseudo-inverse near the bifurcation point. This approach eliminates the severely ill-conditioned linear solves and improves scalability by allowing bifurcation points to be computed using looser linear solver tolerances, at the expense of requiring a more invasive implementation in the application code. Finally, we present applications of these techniques to several large buckling problems solved on distributed memory computers using large-scale, parallel, finite-element structural mechanics codes developed at Sandia.

### **BIFURCATION APPROACH TO THE RIEMANN HYPOTHESIS**

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In a remarkable paper in 1859 Riemann [1] obtained an analytic formula for the number of primes under a preassigned value. He introduced the so called Riemann zeta function as a function of a complex variable defined in the half plane  $\operatorname{Re}(z) > 1$  as an absolutely convergent series and extended it to the whole complex plane by analytic continuation. Moreover he proved that it is a meromorphic function with a single pole at z=1 and satisfies a functional equation that establishes a certain symmetry along the critical line  $\operatorname{Re}(z)=1/2$ . The Riemann Hypothesis can be easily formulated;

The nontrivial zeros of the zeta function have real part equal to one half.

Motivated by the work of Arias de Reyna [2] we approach the problem from a naive point of view. We introduce an appropriate symmetric function of two real variables G(x,y) and establish a connection between the zeros of the zeta function and the branching bifurcation points of the solution of G(x,y)=0. Making use of the techniques of bifurcation theory, numerical continuation of solutions and a fluid dynamic interpretation we try to shed some light on this notoriously difficult problem.

References:

- B. Riemann, Ueber die Anzahl der Primzahlen unter einer gegebenen Groesse. Monatsber. Koenig. Preus. Akad. Wiss. Berlin (1859), Mathematische Werke, 2nd Auf, Dover, New York, 1953, pp 145-153.
- [2] J. Arias de Reyna, X-Ray of Riemann's zeta function. Preprint.

ID of Contribution: 16 - 199

### **BIFURCATION COMPUTATIONS IN AN EQUATION-FREE FRAMEWORK**

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In current modeling , the best available descriptions of a system often come at a fine level (atomistic, stochastic, microscopic, individual-based) while the questions asked and the tasks required by the modeler (prediction, parametric analysis, optimization and control) are at a much coarser, averaged, macroscopic level. Traditional modeling approaches start by first deriving macroscopic evolution equations from the microscopic models, and then bringing an arsenal of mathematical and algorithmic tools to bear on these macroscopic descriptions. Over the last few years, and with several collaborators, we have developed and validated a mathematically inspired, computational enabling technology that allows the modeler to perform macroscopic tasks acting on the microscopic models directly. We call this the "equation-free" approach, since it circumvents the step of obtaining accurate macroscopic descriptions. The backbone of this approach is the design of (computational) experiments. Ultimately, what makes it all possible is the ability to initialize computational experiments at will. Short bursts of appropriately initialized computational experimentation -through matrix-free numerical analysis and systems theory tools like variance reduction and estimation- bridges microscopic simulation with macroscopic modeling in general (and bifurcation computations in particular).

### **EXPLORING THE DYNAMICS OF NONLINEAR MODELS FOR A PIEZOCERAMIC**

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We analyse the dynamical behaviour of a harmonically excited piezoceramic in dependence of certain design parameters. In particular, we explore its dynamics in dependence of its geometrical shape as well as the influence of nonlinear terms in the associated equations of motion. Based on a Galerkin ansatz for the solution of the system, we derive a two point boundary value problem whose solutions yield certain eigenfunctions of the linearized model. Using the continuation package AUTO2000, we then compute and analyse families of periodic solutions of an associated nonlinear model for different geometries and excitation frequencies. Finally, we explore the dependence of these paths on the weights of the nonlinear terms in the equations of motion. Our analysis shows that, first, it may be worthwhile to consider unusually shaped piezoceramics in order to optimize the performance of a certain actuator and, secondly, in certain circumstances one needs to incorporate nonlinear effects into the model.

ID of Contribution: 16 - 235

### MANIFOLDS AND HETEROCLINIC CONNECTIONS IN THE LORENZ SYSTEM

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The Lorenz system still fascinates many people because of the simplicity of the equations that generate such complicated dynamics on the famous butterfly attractor. The organisation of the dynamics in the Lorenz system and also how the dynamics depends on the system parameters has long been an object of study. This talk addresses the role of the global stable and unstable manifolds in organising the dynamics. More precisely, for the standard system parameters, the origin has a two-dimensional stable manifold and the other two equilibria each have a two-dimensional unstable manifold. The intersections of these two manifolds in the three-dimensional phase space form heteroclinic connections from the nontrivial equilibria to the origin. A parameter-dependent study of these manifolds clarifies not only the creation of these heteroclinic connections, but also helps to explain the dynamics on the attractor by means of symbolic coding in a parameter-dependent way.

### PATCH DYNAMICS FOR MULTISCALE PROBLEMS

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For an important class of multiscale problems, a separation of scales prevails between the (microscopic, detailed) level of description of the available model, and the (macroscopic, continuum) level at which one would like to observe and analyse the system. Consider, for example, a kinetic Monte Carlo model for bacterial growth. While it is known that, under suitable conditions, a deterministic equation should exist in terms of bacteria concentration, it is often not possible to obtain an accurate closed formula explicitly.

For this type of problems, the recent "equation-free" framework was developed [1]; of which patch dynamics is an essential component.

The equation-free approach is built around the central idea of a coarse time-stepper, which is a map from coarse variables to coarse variables. It consists of the following steps: (1) lifting, the creation of appropriate initial conditions for the microscopic model, constrained on the macroscopic state; (2) evolution, using the microscopic model, and possibly some constraints; and (3) restriction, or the projection of the microscopic state after simulation onto the macroscopic variables.

Patch dynamics is designed as a coarse time-stepper for an unavailable partial differential equation on macroscopic time and length scales; it uses appropriately initialised simulations of the available microscopic model in a number of small boxes (patches), which cover only a fraction of the space-time domain. To reduce the effect of the artificially introduced box boundaries, we use buffer regions to "shield" the boundary artefacts from the interior of the domain for short time intervals [2,3]. We show that this time-stepper is a good approximation to a method-of-lines discretization of the (unknown) partial differential equation for some model problems, and we illustrate the performance of the method on a variety of test cases [3].

Once an accurate and efficient time-stepper is constructed, it can be used as input for time-stepper algorithms performing macroscopic numerical analysis tasks. For example, time-stepper based bifurcation analysis methods, such as RPM or Newton-Picard, become readily available.

- I.G. Kevrekidis, C.W. Gear, J. Hyman, P.G. Kevrekidis, O. Runborg, C. Theodoropoulos, Equation-free multiscale computation: enabling microscopic simulators to perform system-level tasks, Comm. Math. Sciences 1 (4) (2003) 715--762.
- [2] G. Samaey, D. Roose and I.G. Kevrekidis, The gap-tooth scheme for homogenization problems, SIAM Multiscale Modeling and Simulation (2004). In press.
- [3] G. Samaey, I.G. Kevrekidis, D. Roose, Patch dynamics with buffers for homogenization problems, Journal of Computational Physics (2004). Submitted.

### LINEAR AND NONLINEAR MECHANISMS FOR TRANSITION TO TURBULENCE

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Despite many decades of study, the fundamental mechanisms of a fluid's transition from laminar to turbulent flow still remain incompletely understood. This paper investigates two competing hypotheses for how this transition takes place: one which relies on linear amplification of external disturbances, and one which is fundamentally nonlinear, involving subcritical bifurcations.

For some flows, linear stability theory correctly predicts transition: that is, as the Reynolds number increases, transition occurs when the linearization about the laminar solution becomes unstable. For other flows, notably channel flows and Couette flows, linear stability theory fails altogether: transition occurs at a much lower Reynolds number than predicted. Indeed, for pipe flow and Couette flow, the linearization is stable for all Reynolds numbers, while experiments display transition at Reynolds numbers of around 1000 and 1500, respectively [White].

Two distinct hypotheses have emerged to explain this failure of the linear theory, and this paper presents some steps towards reconciling them. The first hypothesis is that in these flows, transition is governed by nonlinearities: non-normality of the linearized operator causes large transient growth of finite-amplitude disturbances, and the flow soon leaves the region of attraction of the (stable) laminar equilibrium point, entering a nonlinear regime. The second hypothesis is that transition is fundamentally linear: external disturbances imposed by wall roughness or acoustic waves are amplified by the non-normal (but stable) linearized operator, creating turbulent flow structures, but nonlinearities are not involved, and in the absence of disturbances these structures would decay.

This paper investigates these two mechanisms in a plane channel flow, using both direct numerical simulations and reduced-order models of the linear and nonlinear systems. A new model-reduction procedure called Balanced Proper Orthogonal Decomposition (BPOD) is performed on a linearized channel flow to identify modes of dynamical importance (as opposed to the usual energy-based POD), and both linear and nonlinear systems are projected onto these modes. The reduced-order models are constructed to incorporate the effects of a stochastic input to simulate wall roughness. The mechanisms of transition are then investigated both by a study of the low-dimensional nonlinear model, and by comparing behavior of linear and nonlinear models.

The linearized models do display many of the characteristics of transition (in particular, the appearance of streamwise vortical structures), but the nonlinear models are able to sustain these structures without the presence of disturbances at sufficiently large Reynolds numbers. These results therefore indicate that indeed nonlinearities are important, but that linearized models can give significant insight into the relevant coherent structures present even in the nonlinear system. Ongoing work which will hopefully be included in the final paper includes a numerical study of the bifurcations of both the reduced-order model and the full direct numerical simulation, as Reynolds number varies.

### References:

[1] F.M. White, Viscous Fluid Flow, McGraw-Hill, 1991.

### MULTI-VALUED SOLUTIONS TO NON-LINEAR PDES: AN INVARIANT MANIFOLD APPROACH

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For a first order non-linear boundary problem H(x, grad u(x)) = 0 in  $\operatorname{NOmega} \operatorname{Subset } R^n$ , a smooth solution typically exists only next to the boundary. A physically meaningful (global) weak solution u(x) can often be defined uniquely by imposing additional viscosity or entropy conditions. However, a smooth multi-valued solution is needed instead whenever the behavior of characteristics is still relevant even after their intersection (e.g., in geometric optics, multiple-arrival seismic imaging, and tomography).

Multi-valued solutions are frequently computed using Lagrangian methods (e.g., ray tracing) - solving the (2ndimenisonal system of) characteristic ODEs for a finite number of initial conditions determined by the boundary conditions of the original PDE. The disadvantage of this approach is a poor spatial resolution due to a non-uniform rate of separation for trajectories of the ODE system.

A number of Eulerian methods were proposed to alleviate this problem by solving a corresponding Liouville system of  $n\$  linear PDEs in a 2n-dimensional (x,p) phase space. (In practice, (n-1) equations can be solved instead on a (2n-1)-dimensional manifold Xi defined by H(x,p) = 0.) This approach is particularly useful for the applications where the original non-linear PDE should be solved for a set of all possible boundary conditions simultaneously. Such is, for example, an angle-gather migration in seismic imaging, for which Fomel & Sethian [FS] compute all multi-source multi-target arrival traveltimes by a non-iterative Eulerian method on Xi. However, for specific Dirichlet boundary conditions, the multivalued solution u(x) defines an n-dimensional submanifold Gamma. That submanifold can be quickly recovered once the Liouville system is solved on Xi, but this forces one to use a (2n-1)-dimensional computational domain to approximate a lower dimensional object.

We propose an alternative approach, which restricts the computations to an n-dimensional mesh approximating the invariant manifold. The characteristic ODEs define a vector field on Xi. Non-characteristic boundary conditions specified for the original PDE define an (n-1)-dimensional submanifold  $Gamma_0$  transversal to the flow. Then Gamma is a flow-image of  $Gamma_0$  and a projection of any  $Gamma_t$  to  $Gamma_0$  transversal to the t-level set of the multivalued solution u(x). Following the approach introduced in [GV], we show that Gamma is a graph of the solution of a locally posed system of n-1 quasi-linear static PDEs. That system is then efficiently solved in Eulerian framework: the coordinate system is repeatedly extended in the manifold's tangent bundle, and a non-iterative method solves the discretized system in O(M log M) operations, where M is the total number of mesh points on Gamma. We illustrate our method on several examples of anisotropic wave propagation for n=2.

- [1] [FS] Fomel, S.; Sethian, J. A. Fast-phase space computation of multiple arrivals. Proc. Natl. Acad. Sci. USA 99 (2002), no. 11, 7329-7334
- [2] [GV] Guckenheimer, J.; Vladimirsky, A. A fast method for approximating invariant manifolds. SIAM J. on Applied Dynamical Systems 3 (2004), no. 3, 232--260.

### **ON THE BIFURCATION OF INVARIANT TORI**

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In this talk we will present some numerical methods to deal with codimension-1 bifurcation of reducible invariant tori. The methods are based on the computation of the Floquet matrix and the reducing transformation for the linear dynamics around the torus. We will see, in some concrete examples, how we can use this information to describe the local behaviour around the torus.

ID of Contribution: 16 - 377

### DEGENERATE SUBHARMONIC BRANCHING IN REVERSIBLE SYSTEMS

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In autonomous time-reversible systems periodic orbits typically appear in one-parameter families; along such family simple multipliers can be locked on the unit circle, and when they pass a root of unity one sees under generic conditions two bifurcating branches of subharmonic periodic orbits, one stable, one unstable. These generic conditions are: (i) the simplicity of the multiplier, and (ii) a transversality conditions which requires that the root of unity is passed with non-zero speed. In this talk we will describe what happens when either one of these generic conditions is not satisfied, as can happen in one- or more parameter families of reversible systems. We present both theoretical and numerical results about existence and stability of subharmonics. Particular emphasis will be on a simple explicit example which led to an interesting interaction between the numerics and the development of the theory. The example seems to be perfect to illustrate the theorical branching and stability behaviour which comes out of a generalized Liapunov-Schmidt reduction. However, when the numerics were worked out we found a divergence from what was expected. In the end it appeared that this divergence is due to the fact that the example system is not only reversible but also has a first integral. This in turn was a motivation to refine the theory by taking this first integral explicitly into account.

The work presented in this talk was done in collaboration with Maria-Cristina Ciocci (Imperial College), Francesco Javier Munoz Almaraz, Emilio Freire and Jorge Galan (University of Sevilla).

ID of Contribution: 16 - 382

### **BIFURCATION ANALYSIS IN SHIP DYNAMICS**

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The ship capsizing problem is still one of the major challenges in naval architecture. The current design of ships against capsizing is still based on empirical criteria: the metacentric height and the righting lever curve. It is assumed that a ship, rightened by sufficient hydrostatic forces in calm water, is safe in a seaway too. The influence of dynamical loads in extreme situations is not considered. The department for Mechanics and Ocean Engineering at the Hamburg University of Technology was involved in a research project to find a capsize criterion based on dynamical investigations (ROLL-S). The dynamics of extreme ship motions is governed by nonlinear equations. However, simulations of ship oscillations on their own do not give a reliable prediction of dangerous ship motions. Therefore,

ENOC-2005, Eindhoven, the Netherlands

powerful analytical methods are necessary. By considering capsizing of a ship as a result of a sequence of bifurcations in the ship's motion local bifurcation analysis gives the possibility to predict dangerous states of the movement. These dangerous motions were determined for different sea conditions and collected in a diagram to reveal dangerous from non dangerous areas. The goal of the research on this topic is a monitoring system installed on each ship. Such a system, supplied with information about sea state, motion, geometry and mass data, is able to give the crew advice to prevent capsizing, because in most of the cases where capsizing occurred some small changes in the system's parameters could have avoided dangerous roll motion or capsizing.

The classical strip-model for describing the fluid-ship interaction results in more than 300 state variables. In order to overcome this situation a new model has been developed. In this model the state of the flow is described using memory integrals, based on the idea of Cummins (1962). The model results in twelve state variables only to describe the ship's motion by means of integro-differential-equations. The drawback is that readily available path following techniques can not be applied on that type of mathematical system, because a time continuous flow is necessary to feed the memory integrals.

This unique approach allows searching for bifurcations in a six degrees of freedom ship model where hydrodynamic forces are calculated by using strip theory. As a first result two different types of capsize szenarios could be found. Dangerous and non dangerous regions are shown, but the costs to compute these results are still too high for industrial applications. Further research is intended to improve the model's character. Therefore a model reduction method to reduce the number of state variables without using integro-differential-equations has to be developed.

References:

[1] W.E. Cummins. The impulse response function and ship motions. Schiffstechnik, 9, S. 101-109, 1962.

ID of Contribution: 16 - 399

### **COMPUTATION OF RELATIVE EQUILIBRIA IN EQUIVARIANT PDE'S**

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Spatio-temporal patterns such as traveling fronts and pulses or spiral waves often dominate the longtime behavior of nonlinear parabolic systems that model reaction diffusion processes. On unbounded spatial domains such phenomena can persist for all times and they are therefore part of the asymptotic behavior in the corresponding infinite dimensional dynamical systems. Using the equivariance of the underlying system, e.g. with respect to Euclidean transformations of the domain, such time-dependet solutions may be regarded as relative equilibria or relative periodic orbits. These are generated by a time-dependent group operation from a time-independent or time-periodic spatial profile. Over the last a years a considerable amount of theory has been developed to understand stability and bifurcation of such relative equilibria, see e.g. [2].

In [1] we developed a general approach that allows to separate numerically a time dependent group orbit from a slowly varying spatial profile. The method applies to general initial boundary value problems that are equivariant with respect to the action of a finite dimensional Lie group. Near stable relative equilibria this amounts to computing a comoving frame within which the spatial profile becomes stationary.

In the current talk we will report on extensions of this work that deal with the direct computation of relative equilibria and their bifurcations. The computation of these relative equilibria involves the solution of a partial differential algebraic equation (PDAE) where the number of algebraic variables coincides with the dimension of the underlying Lie group. We will discuss the numerical errors introduced when this PDAE is solved by truncating to a finite domain, by using appropriate boundary conditions and by the subsequent spatial discretization. Several numerical examples will be shown that involve well-known patterns occuring in so called excitable systems. The overall aim of our approach is to develop methods for computing spatio-temporal patterns and to detect their bifurcations independently of their time stability.

- W.-J. Beyn, V. Thuemmler Freezing solutions of equivariant evolution equations SIAM J. Appl. Dyn. Syst. 3 no. 2 (2004) p. 85-116
- [2] P. Chossat, R. Lauterbach Methods in Equivariant Bifurcations and Dynamical Systems, World Scientific 2000.

# **MINI-SYMPOSIUM 17**

### Experiments in Nonlinear Dynamic Systems

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### NONLINEAR EFFECTS IN SUPERCONDUCTING NBN STRIPLINE RESONATORS

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We study superconducting NbN stripline resonators in the nonlinear regime [1]. The measured response, which contains some surprising and unexpected features, strongly suggests that the underlying physics is unique. Similar resonators made of Nb exhibit Duffing-like response in the nonlinear regime, which can be fully explained in terms of kinetic inductance effect. However the nonlinear response of NbN resonators is found to be qualitatively different, thus suggesting that other mechanisms are dominant in the nonlinear regime. The physical origin of the unusual nonlinear response of our NbN samples remains an open question, however, our intensive experimental study of these effects under varying conditions provides some important insight. We consider a hypothesis according to which Josephson junctions forming weak links between the grains of the NbN are responsible for the observed behavior. We show that most of the experimental results are qualitatively consistent with such hypothesis.

While revealing the underlying physics remains an outstanding challenge for future research, the utilization of the unusual nonlinear response for some novel applications is already demonstrated in the present work. In particular we operate the resonator as an intermodulation amplifier and find that the gain can be as high as 15 dB. To the best of our knowledge, intermodulation gain greater than unity in superconducting resonators has not been reported before in the scientific literature. In another application we demonstrate for the first time that the coupling between the resonator and its feed line can be made amplitude dependent. This novel mechanism allows us to tune the resonator into critical coupling conditions. These examples demonstrate that NbN stripline resonators may open the way for a new class of nonlinear applications. The onset of nonlinear effects in NbN occurs at relatively low power, which is, typically 2-3 orders of magnitude lower than Nb for example. Moreover, the relatively high critical temperature makes these devices very attractive in practice. However, to allow such a progress, a further study is needed to substantiate our understanding of these devices.

References:

[1] B. Abdo and E. Buks, unpublished.

ID of Contribution: 17 - 025

### EXPERIMENTAL IRREVERSIBLE PASSIVE ENERGY TRANSFER IN COUPLED NONLINEAR OSCILLATORS

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The focus of this study is on experimental investigation of the transient dynamics of an impulsively loaded linear oscillator coupled to a light-weight nonlinear energy sink. It is shown that this seemingly simple system exhibits complicated dynamics, including nonlinear beating phenomena and resonance captures. It is also demonstrated that, by facilitating targeted energy transfers to the nonlinear energy sink, a significant portion of the total input energy can be absorbed and dissipated in this oscillator.

### NONLINEAR CONTROL FOR LINEAR SYSTEMS; AN OPTICAL STORAGE DRIVE APPLICATION

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Nonlinear control for linear systems offers the possibility to balance linear control design limitations according to the disturbance situation at hand. For optical storage drives (CD or DVD) used in portable or automotive applications, this is an important feature. Because under low-frequency shock and vibration caused by environmental disturbances, increased controller bandwidth generally induces improved disturbance rejection. Often, however, this comes at the cost of deteriorated noise response in view of disc surface defects. In terms of linear control theory, this is the classical tradeoff between disturbance rejection and measurement noise sensitivity (Freudenberg, Middleton, and Stefanopoulou, 2000).

To adapt this tradeoff, the concept of variable gain is used; see also Heertjes & Steinbuch (2004). That is, if the drive is exposed to large low-frequency vibration, a servo controller gain is increased (continuously) after being triggered by a sufficiently large closed loop servo error signal. In view of this concept, two control designs are discussed, design 1, where the overall controller gain is adapted to obtain additional broad-band (< 1kHz) shock suppression, and design 2, where only the controller gain corresponding to the integrator part is adapted to limit the additional broad-band (< 200 Hz) shock suppression but to preserve high-frequency noise response.

Apart from stability, which is guaranteed on the basis of absolute stability theory, performance is assessed experimentally. Hereto, an industrial setup of an optical playback (CD drive) device is considered. With this setup, three types of experiments are conducted: i) a nonlinear process sensitivity analysis to quantify shock performance, ii) a black-dot measurement to quantify time-domain behavior under disc defect disturbance, and iii) a power spectral density measurement to quantify power consumption in the objective lens actuator under nonlinear control.

The results can be summarized as follows. First, up to 21 dB of additional (low-frequency) shock suppression is demonstrated; design 1 shows additional improvement up to 1 kHz (this is 200 Hz for design 2). Second, both designs do not show a significant deterioration in time response under black dot disturbance. For the linear limit values of the controllers, this is explained by considering the clear relation between the system response and the most significant poles obtained from a simplified objective lens model. Third, by measuring both actuator voltage and current, significant additional power consumption is shown for the broad-band nonlinear control design. This is due to additional (high-frequency) controller contribution.

In summary, both nonlinear control designs demonstrate the effective use of additional design freedom in terms of continuously balancing disturbance rejection, time-domain performance measures, and power consumption. Each with a different focus on disturbance characteristics, but both showing the ability to improve linear system performance.

- [1] Freudenberg J, Middleton R, Stefanopoulou A. A survey of inherent design limitations. In Proc. American Control Conference, Chicago, Illinois 2000;2987-3001.
- [2] Heertjes MF and Steinbuch M. Stability and Performance of a Variable Gain Controller with Application to a DVD storage drive, Automatica, 2004;Vol.40(4);591--602.
## **RECURRENCE ANALYSIS OF A MOORE-SPIEGEL ELECTRONIC CIRCUIT**

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An electronic circuit that simulates the Moore-Spiegel [3] equations is presented. Voltages at specific points in the circuit correspond to the three variables in the equations. A comparison of the numerical solution to the equations and the data measured from the circuit indicates striking differences such as nonstationarity and mode transitions.

We argue that recurrence analysis [1, 2] provides a rich framework for assessing the similarities and differences between the two time series. Recurrence is a feature whereby a deterministic system revisits the same region in phase space. It can be exploited by the use of recurrence plots [1], space time separation plots, unstable periodic orbits, and the correlation integral [2]. Application of each of these may require the data to be embedded into higher dimensions, which in turn requires computation of the delay time using the mutual information technique [2]. However, for nonstationary systems, it has been argued that the delay time may be different for different epochs of the time series. For this reason, our initial approach was to measure three variables (corresponding to the equation variables) from the circuit so that we would not have to worry about delay embeddings. We discuss these two approaches.

Theoretical predictions and experimental realisations are further compared via a bifurcation analysis of the equations and extraction of the dominant unstable periodic orbits from both the equations and circuit.

It is demonstrated that the mutual information technique remains useful in choosing the delay time even though the data indicates that the electronic circuit is nonstationary. In fact, although recurrence plots diagnose the circuit as being nonstationary, the delay time does not change significantly with an increasing length of time series. This affords us a reconstruction of the circuit dynamics from a single scalar variable. It turns out that the circuit dynamics have higher dimensions than the original system of equations. In particular, a delay reconstruction of the dynamics in four dimensions reveals more structure in the recurrence plot than just using the three simultaneously measured voltages. We also point out that recurrence plots are superior to space time separation plots in detecting dynamical changes. A visual inspection of the recurrence plots. Nevertheless such plots may still be useful in choosing a window length that we wish to slide across the time series to determine variations of a statistical quantity such as the correlation integral. In particular, the delay time computed in such a window exhibits slight variationas.

The main outcome of our investigation is that recurrence analysis is quite useful in comparing theoretical predictions with actual realisations. Studying dynamical changes on an electronic circuit is a step towards tuning diagnostic techniques and understanding nonstationarity.

- [1] J. -P. Eckman et. al. Europhys Lett, 4:973-977, 1987.
- [2] H. Kantz et.al. Nonlinear time series analysis. CUP, 1999.
- [3] W. D. Moore et. al. The Astrophysical Journal, 143:871-887, 1966.

#### ID of Contribution: 17 - 062

## MODELING AND IDENTIFICATION OF NONLINEAR TORSIONAL STIFFNESS IN HARMONIC DRIVE

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The demand for accurate and reliable positioning in industrial applications, especially in high-precision machines, has led to the increased use of Harmonic Drives (HD). The unique performance features of HD's, such as high reduction ratio and high torque capacity in a compact geometry, justify their widespread application. However, HD's exhibit more complex dynamic behaviour than conventional gear transmissions. Torsional compliance and friction are the most fundamental problems in these components. Accurate modeling of the dynamic behaviour is expected to enable us to improve the performance of the system.

The stiffness curve of a HD shows two typical characteristic properties: increasing (soft wind-up) stiffness with displacement and hysteresis behaviour. In order to capture the nonlinear soft wind-up stiffness behaviour, the manufacturers suggest using piecewise-linear approximations, whereas several independent researchers prefer a polynomial approximation. However, all researchers have noted the inherent difficulties in finding an accurate model for the hysteresis in torsional stiffness of the HD. Here, we show that the friction force dependency on the displacement in the presliding region[1], where the relationship is described by nonlocal-memory hysteresis function of displacement, adequately describes the hysteresis of the corresponding stiffness curve. Thus, in order to mimic the hysteresis behaviour of the torsional compliance, a parallel connection of Maxwell-slip elements is introduced. In this way, the overall torsional stiffness model of the HD is represented as a summation of the corresponding Maxwell-slip elements and piecewise-linear springs.

Another performance metric in which HD behaviour falls short of ideal is (sliding)-frictional dissipation. The frictional losses can be attributed to the sliding part of the HD. The most recent friction model, the Generalized Maxwell-Slip (GMS), is utilized to capture the friction behaviour[2]. The GMS structure has proven capable of modeling the friction behaviour in both presliding and gross sliding regimes. This paper offers a new approach to the modeling of torsional stiffness and the application of a novel model of friction in HD's.

For verification purposes, two test setups were built. Two types of HD, which represent two major classes of design, are used for this purpose, namely the high load and the low load torque HD. The real torsional stiffness obtained from the experimental work is compared to the simulated one. The proposed model gives good identification results and shows that the hysteresis phenomenon in torsional stiffness can be captured very well. A statistical measure of variation, namely minimum-square-error (MSE), gauges the reliability of the estimated parameters for different operating conditions, and quantifies the accuracy and integrity of the proposed model.

The obtained MSE for our proposed model falls below 1.0%, whilst an MSE of less than 5.0% tacitly indicates good agreement. In conclusion, it can be stated that this new approach of torsional stiffness modeling performs very well.

- [1] Parlitz, U. et al., Identification of Presliding Friction Dynamics, Chaos: An Interdisciplinary Journal of Nonlinear Science, 420-430, (2004).
- [2] Lampaert, V. et al., A Generalized Maxwell-Slip Friction Model Appropriate for Control Purpose, Proc. of IEEE International Conference on Physics and Control, (2003).

## NUMERICAL AND EXPERIMENTAL STUDY OF REGULAR AND CHAOTIC BEHAVIOR OF TRIPLE PHYSICAL PENDULUM

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The aim of the work is experimental and numerical analysis of regular and chaotic dynamics exhibited by periodically excited plane three-degrees-of-freedom triple physical pendulum. The triple physical pendulum is a subject of numerical investigation of few papers [1, 2], where three joined externally excited links are analysed, and where the arbitrarily situated rigid limiters of motion are introduced additionally. In that work periodic, quasi-periodic and chaotic attractor are shown with their Lyapunov exponents spectra. The numerical analysis of the orbit stability, seeking for periodic orbits and following their branches as well as bifurcation of periodic orbits analysis are performed also in [1, 2]. The present work bases on those investigations and its aim is to provide experimental confirmation of those results.

The experimental setup is still in progress and now we investigate the system without impacts. The mathematical model for numerical simulation is a special case of the system investigated in works [1, 2], where links are joined with viscous damping and where the first body is excited by periodic moment of force of rectangular shape.

The physical model consists of three links with adjustable lengths and masses suspended on the tripod and joined by the use of radial and axial needle bearings. The external forcing acting on the first body is implemented by the use of the direct-current motor of our own construction with optical commutation. The voltage conveyed to the engine inductors is controlled by the use of special digital system of our own construction in order to obtain desired amplitude and frequency of the forcing. The measurement of the angular position of three links is realized using the precise rotational potentiometers and the LabView measure-programming system including libraries of function and development tools designed especially for data acquisition.

The parameters of the physical model are identified minimizing the function being a sum of square of deviations between the measured signal from physical model and the corresponding signal obtained by simulation of the mathematical model. The frequency and amplitude of the external forcing serve as control parameters, which are changed in order to obtain different behavior of the system.

Then few attractors including periodic and chaotic ones are found in the experimental model fitting well the attractors obtained numerically from mathematical model for the same sets of parameters.

- [1] J. Awrejcewicz, G. Kudra, C.-H. Lamarque, Investigation of triple physical pendulum with impacts using fundamental solution matrices, International Journal of Bifurcation and Chaos 14(12), 2004, to appear.
- [2] G. Kudra, Analysis of Bifurcations and Chaos in Triple Physical Pendulum with Impacts, Ph.D. Thesis, Technical University of Lodz, 2002.

## MODAL ANALYSIS OF VARIABLE-ARC-LENGTH BEAMS WITH LARGE AMPLITUDE FREE VIBRATIONS

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Large amplitude free vibrations of horizontal Variable-Arc-Length (VAL) beams considering the effect of large initial static sag deflections due to self weight have been investigated for the first time. The variability in beam arc-length arises from one end being pinned, and the other end being supported by a frictionless roller at a fixed distance from the pinned end. Finite element formulation based on Lagrange's equation of motion is applied to derive nonlinear equation of motion including the energy dissipation due to large bending using the exact nonlinear expression for curvature and the nonlinearity arising from axial force. The nonlinear eigenvalue is solved by the direct iteration technique to obtain the beam's nonlinear frequencies and corresponding mode shapes for specified vibration amplitudes. The variation of the natural frequencies and mode shapes with various vibration amplitudes demonstrates the non-linear characteristic of beam. As no existing results are available, the large amplitude vibration of VAL beam is investigated experimentally. The beam is excited transversely with harmonic excitation with various vibration amplitudes. The results of experimental modal analysis data are compared with those from finite element code.

ID of Contribution: 17 - 114

## NONLINEAR DYNAMICS OF A CONDUCTING PARTICLE IN AN AC ELECTRIC FIELD

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This work studies the dynamics of a bouncing ball driven by an electric force. The experimental model consists of a spherical conducting particle immersed in a poorly conducting liquid between two horizontal plates.

When a DC voltage is applied between the two electrodes, the particle charges and rises whithin the liquid. Due to the liquid residual conductivity the charge leaks away and the ball falls down. The ball, thus, performs a bouncing motion upon the lower electrode. When an AC voltage is superimposed the time of flight (time between successive impacts) depends on two control parameters: the amplitude and the frequency of the applied voltage. A theoretical model, which provides a discrete nonlinear map for the time of flight, is proposed and discussed in comparison with the experimental results.

It is shown that the system exhibits a period doubling route to chaos and a Tricritical universal scaling at the onset of chaos. Chaotic motion is investigated using the Lyapunov exponents, correlation dimensions and entropies.

- C. Soria, A. Ramos and A. T. Pérez, 'The Charged Bouncing Ball: An Experimental Model for Period-Doubling Bifurcation'. Europhysics Letters, vol. 37, num. 8, pp.541-546, (1997).
- [2] A. Khayari and A. T. Pérez, 'Nonlinear dynamics of a bouncing ball driven by electric forces', Int. J. of Bifurcation and Chaos, vol. 13, No. 10, pp. 2959-2975,(2003).
- [3] A. P. Kuznetsov, S. P. Kuznetsov and I. R. Sataev, 'A variety of period-doubling universality classes in multiparameter analysis of transition to chaos'. Physica D 109, 91-112, (1997).

## ID of Contribution: 17 - 119

## ANALYSIS OF AN AUTOMATIC DYNAMIC BALANCING MECHANISM FOR ECCENTRIC ROTORS

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We present a detailed analysis of the dynamics of an automatic dynamic balancing mechanism for rotating machines. The key idea is to use two or more balls that are free to travel in a race, filled with a viscous fluid, at a fixed distance from the centre of rotation. Under no external force, the balls position themselves to balance any eccentricity in the rotor. In other words, the system is passively controlled and is potentially able to cope with a time-varying unbalance.

After obtaining a Lagrangian description of a Jeffcott rotor fitted with an automatic blancer containing two balls, we employ numerical continuation techniques. In this way, curves are traced of steady states, limit cycles and their bifurcations as parameters are varied. Broad trends are revealed on the existence of a stable dynamically balanced equilibrium for high enough rotation speeds and small enough eccentricity. However, the analysis also reveals other potentially attracting states -- non-trivial steady states, limit cycles, and chaotic motion -- which are not in balance.

The usefulness of this device depends on the balanced steady state solution being achievable and stable. Pseudospectra techniques are employed to investigate transient responses to perturbations of the balanced state, and basins of attraction of various, coexisting solutions are investigated.

Finally, ongoing experimental validation of the device, performed at the Bristol Laboratory for Advanced Dynamic Engineering, will be described. The aim being to design a reliable and robust automatic balancer.

#### ID of Contribution: 17 - 124

## BIFURCATION ANALYSIS OF HIGH-FREQUENCY EXCITED UNDERACTUATED MANIPULATOR

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A technique without feedback control is theoretically analyzed for the swing-up of the free link from the downward vertical position to the upright position and for the stabilization at the upright position.

By introducing two time scales, the effect of the high-frequency excitation is averaged and the autonomous averaged equation is derived. First we show the pitchfork bifurcation is produced in the free link. The bifurcation is perturbed by the configuration of the active link. Namely we can actuate the perturbation of the bifurcation on demand, that is, change the stable steady state of the free link. As a result it is clarified that the control objective is carried out without feedback control.

#### ID of Contribution: 17 - 145

## TOWARDS EFFECTIVE MOTION CONTROL OF ROLLING ELEMENT GUIDEWAYS

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Even nowadays, with the availability of complex control design strategies, performing accurate and small motions with plane or rolling element guideways is, to say the least, a very difficult task to carry out. This is so because of the strongly non-linear behaviour of rolling elements, resulting in amplitude dependent Frequency Response Functions when standard frequency domain identification techniques are used. Therefore, the need for a more thorough analysis of the problem makes itself felt.

In this paper, we report a systematic analysis, which we have carried out to characterise the dynamics of rolling element guideways. The analysis begins with a rudimentary identification of the (rolling) force-displacement characteristics, which reveals a rate-independent hysteresis behaviour. We further established the basic dependence relationships of this behaviour on the design parameters, such as ball and groove geometry, surface material and (pre)load. Thereafter, we show that, for periodic motion, the effect of the hysteresis element (named "hysteresis spring") can be expressed as in terms of equivalent stiffness and equivalent damping, which are amplitude dependent. These characteristics can be further fused into a single characteristic dimensionless parameter, namely the "equivalent damping ratio at resonance", which, although amplitude dependent, shows little sensitivity to position or (pre)load variations.

Second, we have worked out a frequency domain, harmonic analysis method for mass-"hysteresis spring" systems, via application of the Describing Function method, and compared it with a direct Matlab simulations. The results showed that the (amplitude dependent) Frequency Response Maps invariably contain an "anomalous" region where the response is very sensitive to systems parameter variations. This manifests itself in practice in jump-like phenomena, which thus appear to be inherent features of this type of systems. [1]

Third, we carried out a series of experimental verification tests on a number of different test set-ups. The results we obtained establish, at least qualitatively, the basic trends and behavioural features predicted by the theoretical analysis, in particular, the inherent 'jump' phenomenon. [2]

Although we have now effective analysis tools for the problem, that in itself does not straightforwardly result in a control method for the problem at hand. However, based on the analysis results, we were able to derive, in a pragmatic way, an improved general control design framework for the control of rolling element bearings. This framework allows controllers for such systems to be designed in a more systematic way. More research is still needed, however, in order better to establish the developed framework and to implement on experimental setups.

The methodology that is followed in this paper clearly shows the power of dedicated analysis of the non-linear behaviour of practical systems and we believe that this methodology can be successfully applied to other (non-linear) systems as well.

- [1] F. Al-Bender and W. Symens, "Dynamic characterization of hysteresis elements in mechanical Systems, Part I: Theoretical analysis", Chaos : An Interdisciplinary Journal of Nonlinear Science (for the March 2005 issue).
- [2] Ibid, "Part II: Experimental validation", Chaos, (March 2005 issue).

## ELASTIC STRUCTURE EXCITED BY HARMONIC IMPACTOR MOTIONS: EXPERIMENTAL AND NUMERICAL INVESTIGATIONS

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Elastic structures subjected to impact excitations are relevant to many applications including impact dampers, manufacturing processes such as milling, and rotary systems [1, 2]. In this effort, the nonlinear dynamics of an elastic structure excited by a harmonic impactor motion is studied by experimental and numerical means. The test apparatus consisted of a stainless-steel cantilever beam with a tip mass, which is impacted by a shaker that is driven at a specified frequency and amplitude. The excitation frequency and excitation amplitude are used as control parameters. Soft impact and hard impact between the impactor and the structure are considered, and the results are presented in the form of bifurcation diagrams, phase portraits, and time records of force and the measured beam response. Experimental results show that there are periodic motions, chaotic motions, and period-doubling route and other routes to chaos. In addition, grazing bifurcations are also observed in this system. Considering the response of the system to be dominated by the beam's fundamental mode, a single-degree-freedom model is developed and numerical studies are conducted by using this model. The numerical results agree well with the experimental results, and they also show the possibilities for changing the bifurcation location through feedback control.

References:

- Popp, K., Oestreich, M., and Hinrichs, N. (1997). "Numerical and Experimental Investigation of Nonsmooth Mechanical Systems," in Proceedings of the IUTAM-Symposium on New Applications of Nonlinear and Chaotic Dynamics in Mechanics, Moon, F. C. (Ed.), Ithaca, NY, pp. 293-302
- [2] Balachandran, B. (2003). "Dynamics of an Elastic Structure Excited by Harmonic and Aharmonic Impactor Motions," Journal of Vibration and Control, Vol. 9, pp. 265--279.

## ID of Contribution: 17 - 162

#### MOTIONS OF THE PARAMETRIC DOUBLE PENDULUM

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The dynamics of a frictionless simple pendulum of inertia momentum *I*, length *L* and mass *M* is described by  $\ddot{\theta} = -\omega_0^2 \sin(\theta)$ , where  $\theta$  is the angle measured from the vertical axis,  $\omega_0^2 = K/I$ , K = MgL, and *I* the inertia momentum. There are two fixed points, one stable (bottom) at  $\theta_b = 0$  and the other one (top) at  $\theta_t = \pi$  is unstable.

A parametric pendulum when some parameter is time dependant, L = L(t) or g = g(t) (Bergé, 1984; SanJuan, 1998; Butikov, 2002). The last case can be obtained letting the pivot pendulum to oscillate in the vertical direction driving by an external force. The dynamics is given by the same equation above but now with K = K(t) = MLg(t), and the fixed point  $\theta_b = 0$  can lose its stability. For  $\theta$  close to  $\theta_b$  the solution is given by the Floquet theory in which  $\theta(t) = e^{ct} f(t)$ , where f(t) is an approximated solution, and c are the eigenvalues of the multiplication matrix. With  $g(t) = g - \omega^2 A \cos(\omega t)$ , where A and  $\omega$  are respectively the amplitude and frequency of the pivot oscillation, even for a very small value of  $A \ge 0$  there is destabilization of the fixed point  $\theta_b = 0$  at main resonance conditions  $\omega = 2\omega_0$ . The friction does not affect too much these results, but imposes a positive threshold value for A. An interesting result is that the fixed point  $\theta_t$  can be stabilized in some regions of the parameters space ( $\omega$ , A). The double pendulum has two arms, the first one attached to the pivot has the double of mass of the second one ( $M_1 \sim 2M_2$ ), and they have approximately the same length. The dynamical variables are  $\theta_t$  and  $\theta_2$ , and the system dynamics is described by two coupled second order equations  $\ddot{\theta}_i = f_i(\theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2)$ , i=1,2. There are two stable fixed points  $\theta_{1b} = 0$ , and  $\theta_{2b} = 0$ , and two unstable points  $\theta_{1t} = \pi$  and  $\theta_{2t} = \pi$ . We are studying experimentally and numerically the parametric double pendulum having  $\omega$  and A as control parameters. For some pairs of values ( $\omega$ , A) we could observe chaotic behavior; periodic oscillations around  $\theta_{1t} = \pi$  while the second arm oscillates in synchronization around  $\theta_{2b} = 0$  with opposite phase, we also could observe similar movement but around  $\theta_{1b} = 0$ and  $\theta_{2t} = \pi$ . For the same pair of parameters ( $\omega$ , A) the pendulum can reach different behaviors with a slight change of the initial conditions. The stabilization of the unstable fixed points was also observed experimentally.

#### References:

- [1] P. Berge, Y. Pomeau, C. Vidal, Order within chaos, John Willey & Sons, Paris, France (1984).
- [2] M. A. F. SanJuan, Using nonharmonic force to switch the periodicity in nonlinear systems, Phys. Rev. 58, 4377-4382 (1998).
- [3] E. I. Butikov, Subharmonic resonances of the parametrically driven Pendulum, J. Phys. A: Math. Gen. 35, 6209-6231, (2002)

ID of Contribution: 17 - 163

## **APPLICATION OF EMPIRICAL FLOQUET THEORY TO MILLING TIME SERIES**

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Recent approaches for examining the stability behavior of time-delayed systems have shown it is possible to ascertain the stability characteristics of the resulting infinite dimensional system from a finite dimensional phase space. A common goal in these analyses is to transform the original set of equations into the form of a dynamic map that maps the system behavior over a single time delay. However, it is potententially useful to determine the stability behavior solely from experimental or numerical data.

This paper investigates an empirical method for determining the truncated system characteristic multipliers. The technique differs from previous research focused on systems without delays since the dimension of the phase space, or truncated dimension in this case, is not known a priori. Empirical estimates for the system Floquet multipliers are obtained directly from experimental data of coupled tool-workpiece transient interactions at the entry of a milling cutter into the workpiece. Empirical estimates are compared with the results of a semi-analytical approach based upon temporal finite element analysis for the purpose of parameter identification. The presented methods are thought to be applicable to a wide variety of systems with time delays and provide the ability to identify unknown machining processes parameters in a new manner.

## EXPERIMENTAL DYNAMICS OF A FOUR-STOREY BUILDING COUPLED WITH A NONLINEAR ENERGY SINK

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An active research group is now investigating the feasibility to reduce earthquake induced vibrations occurring in buildings by means of a sacrificial nonlinear sub-structure whose mechanical properties (mass, inertia) are relatively light compared to the ones of the master structure and playing the role of an energy sink. A phenomenon often referred as energy pumping in the literature is interestingly used to irreversibly transfer vibratory energy of the leading structure towards an essentially nonlinear slave structure by provoking a nonlinear resonance which may be explained by means of the theory of nonlinear normal modes.

For realistic situations, the nonlinear device should be embedded on top of the structure to absorb vibrations resulting from the main resonance response of the master structure. The general purpose is usually to trap linearized eigen-modes of the leading structure when triggering a resonance with the amplitude-dependant embedded device followed by an irreversible frequency uncoupling obtained when localizing the nonlinear normal mode away from linearized modes of the main structure. This property is virtually important since it enables to drastically reduce the level of vibrations in buildings induced by transient earthquake excitations. Until now, little work has been done experimentally to check the practical feasibility and efficiency of such nonlinear device on actual mechanical systems. Here an experimental study is developed to bring an insight over the nonlinear energy pumping mechanism and to broadly analyze its range of application to passively control building vibrations. The test rig constructed at the Geomaterial Laboratory, ENTPE, France, consists of a small scaled model of a four-storey building clamped on a home-made shaking table including an electromagnetic Linmot linear motor. The nonlinear energy sink which is an independent Frahm-like oscillator placed on top of the leading structure is designed such that the resulting force-response curve approximately matches a cubic polynomial curve. Experimental works are currently focusing on the detection of nonlinear energy pumping within several steady and transient responses of the structure. The study also includes a time-frequency analysis of the system response to track quasi-periodic motions and frequency jumps. The ultimate aim of the present study is to analyze how the presence of the nonlinear energy sink affects the dynamic behavior of the global structure characterized by a multimodal distribution.

ID of Contribution: 17 - 202

## TWO TECHNIQUES FOR MEASURING HIGHER ORDER SINUSOIDAL INPUT DESCRIBING FUNCTIONS

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For high precision motion systems, modeling and control design specifically oriented at friction effects is instrumental. The Sinusoidal Input Describing Function theory represents a solid mathematical framework for analyzing periodic non-linear system behavior (1). This theory however limits the description of the non-linear system behavior to an approximated linear relation between sinusoidal excitation and sinusoidal response. An extension to Higher Order Describing Functions can be realized. This function can be defined as the complex ratio of the nth harmonic component

in the output signal to a virtual nth harmonic signal derived from the excitation signal. This virtual harmonic has equal amplitude as the fundamental sinusoid and zero phase. The resulting Higher Order Sinusoidal Input Describing Functions (HOSIDFs) relate the magnitude and phase of the harmonics of the periodic system response to the magnitude and phase of the sinusoidal excitation.

This paper describes two techniques to measure HOSIDFs. The first technique is FFT based and uses blocks of data. The second technique is based on IQ (in phase/quadrature phase) demodulation and is sample based (2). In a simulation both techniques are tested by comparing the simulation results to analytically derived results from a known (backlash) non-linearity. From these simulations can be concluded that the FFT method is superior with respect to selectivity and dynamic range. This is due to the perfect selectivity of an FFT when processing a harmonic signal with an FFT blocksize equal to an integer amount of periods of the harmonic signal. In the IQ method the digital lowpass filters used only have finite selectivity. This shortcoming manifests itself in poor measurements of even HOSIDFs. In a subsequent practical case study both techniques are used to measure the changes in dynamic behavior of an electric motor as function of drive level due to stiction. The results show three distinctly different regions in the dynamic behavior. In the first region with very low excitation the system behaves linearly and the phase plots are constant. The second region is characterized by an increase in gain of the odd HOSIDFs and negative phase slopes. The third region shows odd HOSIDFs with approximately constant gain and constant phase levels at -(n+1)pi/2 rad. (n is order number) relative to the levels of the region with the lowest excitation levels. The results show that Higher Order Sinusoidal Input Describing Functions can give additional information about periodic non-linear system behavior.

### References:

[1] J. Slotine, Weiping Li, Applied Nonlinear Control, Prentice-Hall International, (1991)

[2] C.M. Rader A simple method for sampling in-phase and quadrature components, IEEE Transactions on Aerospace and Electronic Systems, AES-Vol 20, no 6, (1984), pp. 821-824.

ID of Contribution: 17 - 215

## FRICTION-INDUCED VIBRATIONS IN AN EXPERIMENTAL DRILL-STRING SYSTEM FOR VARIOUS FRICTION SITUATIONS

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Friction is a common phenomenon in mechanical systems and it arises between sliding surfaces due to various complex mechanisms. For some systems, friction is a desired characteristic but usually friction is an unwanted phenomenon. Moreover, the presence of friction can induce self-sustained vibrations which are unwanted in many engineering applications.

In order to gain an improved understanding for the causes of the friction-induced vibrations, an experimental drill-string set-up is built and the behaviour of the set-up is analyzed. The set-up consists of two discs interconnected via a low stiffness string. The upper disc is driven by a DC-motor. In order to induce torsional vibrations at the lower disc, a mechanism consisting of a brake and a small oil-box with felt stripes is fixed to the lower disc. Using this brake, a range of normal forces can be applied which produces various friction situations at the lower disc. The oil-box with the felt stripes is constructed in order to regulate the lubrication conditions in a reproducible way. This oil lubrication proves to be crucial for the existence of torsional vibrations in the set-up.

The set-up is modelled as a linear system with nonlinear discontinuous friction forces present at both discs. The parameters of the set-up are estimated and a validation of the model is performed [2]. Next, the parameters of a model for the friction at the lower disc are estimated for several normal force levels applied at the brake and the steady-state behavior of the set-up is analysed both numerically and experimentally. Based on the proposed model and estimated parameters, both numerical and related experimental bifurcation diagrams are presented.

In the experimental set-up as well as in the simulation model, we encounter an equilibrium set, isolated equilibria and stick-slip limit cycling; phenomena typical for systems with a discontinuity.

## ENOC-2005, Eindhoven, the Netherlands

253

We also observe a 'discontinuous Hopf bifurcation' and a 'discontinuous fold bifurcation' [1]. That gives us an opportunity to analyze and to gain a better understanding of discontinuous bifurcations and other phenomena typical for Filippov systems. Finally, when various normal forces are applied, different friction characteristics occur. Therefore, according to the obtained results we can gain improved understanding on how various friction characteristics influence the friction-induced vibrations in an experimental setting.

#### References:

- [1] Leine, R. I., Nijmeijer, H., (2004), Dynamics and Bifurcations of Non-smooth Mechanical Systems, Springer, Berlin.
- [2] Mihajlovic, N., Van Veggel, A. A., Van de Wouw, N., Nijmeijer, H., (2004), 'Analysis of Friction-Induced Limit Cycling in an Experimental Drill-String Set-Up', ASME Journal of Dynamic Systems, Measurements and Control, to appear in December 2004

ID of Contribution: 17 - 221

## ON THE ROLE OF QUADRATIC DAMPING IN THE PARAMETRIC RESPONSE OF A CANTILEVER BEAM WITH TIP MASS: EXPERIMENTAL INVESTIGATION

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An experimental and theoretical investigation on the effects of low density fluid medium in the nonlinear vibratory response of a slender cantilever beam carrying a lumped mass to a principal parametric base excitation have been performed. Experimentally, the tested model has been subjected to an axial acceleration by attaching it to the exciter table through a test fixture. The translational transverse acceleration of the beam and the input base signals have been measured. Among the traditional experimental modal analysis techniques, the step-relaxation method has been employed to extract the transverse modal characteristics, which in turn, have been used in the nonlinear spatial model and experimental setup. The smoke wire method has been employed for flow visualization around the beam moving end when it undergoes the principal parametric resonance. The photographs of the flow around the structure have shown vortex formation confirming the action of dissipative nonlinear force ue to the fluid medium. Experimentally, frequency-response and amplitude-response curves have been compared with the theoretical results obtained from perturbation solutions of the spatial nonlinear model. The comparative analysis has shown that the inclusion of quadratic viscous damping in the mathematical model significantly improves the agreement between the experimental and theoretical results. The flow visualization and comparative analysis of the classical nonlinear curves confirm that the surrounding fluid medium, even with low density plays an important role in the dynamic response of the structure in the principal parametric resonance.

- [1] Nayfeh, A.H. (2000). Nonlinear Interactions, Wiley & Sons, New York.
- [2] Cartmell, M. P. (1990) Introduction to Linear, Parametric and Nonlinear Vibrations, Chapman and Hall, London.
- [3] Evan-Iwanowski, R. M. (1976) Resonance Oscillations in Mechanical Systems, Elsevier Scientific Publishing Company, New York.

#### ID of Contribution: 17 - 249

## ON THE INTERACTION BETWEEN NON IDEAL ENERGY SOURCES AND A FLEXIBLE STRUCTURE: EXPERIMENTAL RESULTS

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The main goal of this paper is to tackle from an experimental viewpoint the interaction of non ideal excitation sources and a flexible structure. It is well known that a given vibrating structure may in some circumstances exhibit significant interaction with its excitation sources in either laboratory or field testing conditions. Particularly, in the laboratory environment when the electromagnetic vibration exciter is used to drive the test structure the exciter dynamics shows a strong interaction with the resonant structure, specially in the vicinity of structural resonances. Another good example is found in DC motors connected to flexible structures. In this case, the non ideal excitation source comes from unbalanced rotating masses present in the motors, leading to a non linear coupling between the motor dynamics and the structure under test. In this paper a flexible aircraft wing model is specially built with the objective to experimentally observe these non linear events, including the Sommerfeld effect. The flexible wing is driven by one DC motor with limited power over a given frequency range and several vibration signals are gathered by miniature accelerometers positioned along the wing span. Very interesting results were found regarding the interaction between the non ideal DC energy source along with additional results showing interactions between several modes of vibration of the system.

References:

[1] Kononenko, V. O., Vibrating Systems with a Limited Power Supply, 1969.

[2] Balthazar, J. M. et al, An Overview of Non Ideal Vibrations, Meccanica, 330, 1-9, 2002.

[3] Balthazar, J. M., An Experimental Study of Vibrations of Nonideal Systems, Proceedings of DETC 97

ID of Contribution: 17 - 261

## NONLINEAR PARAMETRIC VIBRATIONS OF ELASTIC STRUCTURES CARRYING TWO LIQUID-FILLED TANKS

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Vibrations of elastic structures carrying liquid-filled tanks, as seen in elevated-water tanks and liquefied gas storage tanks, is one of the most important issues in engineering from the viewpoint of disaster prevention [1]. Recently, liquid-filled tanks have been utilized as a vibration suppression device instead of a dynamic damper. However, their theoretical analysis has dealt with one tank although, in reality, multiple tanks are accentually in use. In addition, there are few papers which have examined the effects of a nonlinear hydrodynamic force in such a system [2].

This paper deals with a system of vibration suppression where an elastic structure, carrying two cylindrical liquid-filled tanks, is subjected to a vertical sinusoidal excitation. In this system, the internal resonance condition ratio, 2:1:1, is satisfied among the natural frequencies of the structure and the sloshing in the two tanks. The aim of this paper is to theoretically and experimentally investigate the effects of liquid tanks on the vibration suppression of the structure.

In the theoretical analysis, we introduce the velocity potential for liquid motion and, considering the nonlinear hydrodynamic force, we use Galerkin's method to derive the modal equations involving the viscous damping terms for three different sloshing modes. Then, we determine the frequency response curves of the structure's displacement and liquid elevations, as well as perform their stability analysis, by using Andronov and Witt's method [3]. We have investigated the influences of liquid levels and the deviation of the internal resonance ratio on the resonance curves. As a result, we have obtained results which were different from those obtained in the case of structure with only one liquid-

filled tank. Finally, the experimental results confirmed the validity of the theoretical analysis. Concluding remarks are as follows:

(1) Harmonic oscillations appear in the structure and 1/2-order subharmonic oscillations of sloshing occur on the liquid surfaces.

(2) Two patterns of oscillations in sloshing can occur depending on the excitation frequency and initial condition; one is the pattern where sloshing occurs only in one tank (which is named a single mode) and the other is the pattern where sloshing occurs simultaneously in two tanks (which is named a double mode).

(3) As the liquid level decreases, the location of the single mode shifts to a higher excitation frequency range in the frequency response curve.

(4) Certain deviation of internal resonance ratio may yield amplitude and phase modulated motions. It is found that chaotic vibrations can occur under a certain condition and they are confirmed by the largest Lyapunov exponents.

(5) In the experiments, the theoretical resonance curves were quantitatively in agreement with the experimental results.

#### References:

- [1] Ibrahim, R.A., Pilipchuk, V.N., Ikeda, T., ASME Applied Mechanics Reviews, 54-2(2001), 133-199. Recent advances in liquid sloshing dynamics.
- [2] Ikeda, T., Nonlinear Dynamics 33-1(2003), 43-70. Nonlinear parametric vibrations of an elastic structure with a rectangular liquid tank.
- [3] Stoker, J.J., Nonlinear Vibrations, 153-155, Interscience Publishers, New York, 1950.

#### ID of Contribution: 17 - 285

## ON THE CHAOTIC RESPONSE IN A ROBOT JOINT MECHANISM DUE TO BACKLASH

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Under certain conditions, chaotic response to periodic excitation could occur in a mechanical system. In such cases, the application of modal parameter estimation techniques, namely frequency domain analysis and skeleton reconstruction, are no longer valid and special techniques need to be developed in order to quantify such behaviour. [1]

Backlash in mechanical systems arises because of the wear of components with intermittent contact, so that clearances might increase. Theoretical studies, including the one presented in this paper, show that under different degrees of backlash, there may exist some separate regions for which chaotic vibrations could occur. The points of transition to and from those regions, i.e. the bifurcation points, could be used to assess the evolution of the clearances in a mechanical system.

This paper reports a study of chaotic response in a robot joint mechanism, which includes an artificially introduced backlash. The purpose is firstly to ascertain the existence of regions with chaotic response; secondly to develop a method to quantify that chaotic response and, thirdly, to correlate it with the mechanical system's parameters.

Starting from a simplified model, we have been able to establish by simulation the existence of regions, marked by certain modal parameter values and excitation amplitudes, in which the response of the system becomes chaotic. Furthermore, by application of dimensional analysis, we could group those parameters into dimensionless numbers, which reduces considerably the number of independent parameters of the problem. The evolution of the Lyapunov exponent (1), which we used to characterise chaos, could then be correlated to those dimensionless parameters.

Secondly, we have carried out experiments on a link mechanism, which is driven by a DC motor via a harmonic drive. In this setup, backlash was introduced in the connection of the harmonic drive to the shaft. Under certain excitation and operational conditions, the corresponding mechanism shows indeed chaotic response. In order to be able to characterise this, however, one has to separate the true response from the measurement noise using special technique of noise reduction for chaotic signal. Our paper consequently devotes some attention to the problematic of noise reduction in chaotic signals and its application to our measured data.

Two conclusions are drawn. First, correlating the Lyapunov exponent with the modal parameters could, in principle, yield information on the backlash size. Hence, although quite difficult to perform in practice, chaos quantification could be used as a quantitative mechanical signature of a backlash component. The second conclusion is that for a simple chaotic system, as gauged by its attractor's dimension, the Simple Noise Reduction method gives very good results. This noise reduction method is therefore very suitable for application to simple systems since it is superior in calculation time.

References:

 T. Tjahjowidodo, F. Al-Bender and H. van-Brussel, Identification of Backlash in Mechanical Systems, in: Proceedings of the 2004 ISMA International conference on Noise and Vibration Engineering, Leuven, Belgium, 2004, pp. 2195-2209.

ID of Contribution: 17 - 292

## EXPERIMENTAL INVESTIGATION OF THE EMERGENCE AND DYNAMICS OF MULTIPLE DOUBLE LAYERS IN PLASMA

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By applying a positive potential on an electrode immersed in plasma, a complex space charge configuration (CSCC) appears in front of it. Diagnosis techniques prove that this structure consists from a positive nucleus (ion-rich plasma) confined by an electrical double layer (DL). Under certain experimental conditions, a more complex structure in form of two or more subsequent double layers was observed [1]. It appears as several bright and concentric plasma shells attached to the electrode. Probe measurements emphasized that the axial profile of the plasma potential in front of the electrode has a stair steps shape, with potential jumps close to the ionization potential of the used gas.

If the electrode is large or asymmetric (with one dimension larger than the others) the multiple double layers (MDLs) structure appears as non-concentrically, like a network of plasma spots, each near others, almost equally distributed on the electrode surface [2].

Both types of structures (concentric as well as non-concentric) appear successively at the increasing of the potential on the electrode, simultaneously with current jumps in the static current-voltage characteristic (I-V), associated with hysteresis effects. The size and the number of structures can be controlled by means of both electrode potential and discharge current. Larger potential on the electrode increase the number of structures, while the increase of the discharge current plays the opposite role. In the dynamic state, the experimental results prove that initially each of structures exhibits proper nonlinear dynamics. The uncorrelation which exists between these dynamics leads to the appearance of flicker noise, identified in the power spectrum of the current oscillations. At high values of the potential on the electrode the dynamics of the MDLs becomes correlated and the flicker noise disappears [3].

The experimental investigation proved that a common physical mechanism is at the origin of the emergence and dynamics of concentric as well as non-concentric MDLs. The electron-neutral impact excitation and ionization processes play the most important role in this mechanism. These processes determine the appearance of negative and positive space charge, respectively, spatially well separated because of the dependence of the respective cross-sections on the kinetic electron energy, which varies along the structure according to the potential profile.

References:

[1] L. Conde, L. Leon, Phys. Plasmas 1 (1994) 2441;

[2] Y. A. Astrov, H. G. Purwins, Phys. Lett. A 283 (2001) 349;

[3] C. Ionita, D. G. Dimitriu, R. Schrittwieser, Int. J. Mass Spectrom. 233 (2004) 343.

#### ID of Contribution: 17 - 351

## **OPTIMAL SHAPES OF A BEAM UNDER PARAMETRIC EXCITATION**

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In this contribution, we consider beams of rectangular cross-section with constant thickness and variable width. The length and total volume of the beam are fixed. Elastic supports at both ends are considered, which in particular include the cases of simply supported and clamped boundary conditions. Parametric resonance of the beam under a periodic axial force is studied. Two optimization problems are considered. In the first problem, the range of resonant excitation frequencies is minimized for a given parametric resonance zone and a fixed amplitude of excitation. In the second problem, the minimal (critical) amplitude of the excitation force is maximized.

We prove that two optimization problems under consideration are equivalent in case of small external damping and small excitation force amplitude. Moreover, we show that the optimal designs do not depend on the damping coefficient, on the value of the excitation amplitude in the first problem, and on the resonance number. All these properties reveal strong universal character of optimal beam shapes, which depend only on the natural modes involved in parametric resonance and on the boundary conditions. This universality is of great importance for practical use of optimal designs. Numerical computations show that the optimal shape changes weakly if the parametric excitation is applied to a prestressed beam (with a static axial force lower than the critical Euler force).

In the analysis, we use explicit formulae obtained in [1], which describe the parametric resonance zones as half-cones in the three-parameter space (frequency and amplitude of parametric excitation and damping coefficient). As a result, the optimization problem is reduced to the minimization of an objective functional depending only on natural frequencies and modes involved in parametric resonance. This approach allows avoiding time-consuming multiple integrations of equations of motion required for stability analysis in the Floquet theory, see [1]. Optimal beam shapes are found numerically for different boundary conditions and resonant modes.

Experiments on simple parametric resonance of the first mode are conducted for the uniform and optimal simply supported beams. The reduction of the resonance zone for the optimal beam is shown to be in very good agreement with theoretical prediction. Nonlinear response of the uniform and optimal beams is analyzed experimentally.

#### References:

[1] A.A. Mailybaev, A.P. Seyranian, Multiparameter Stability Theory with Mechanical Applications, World Scientific, Singapore, 2003.

ID of Contribution: 17 - 352

## EXPERIMENTS ON SPATIO-TEMPORAL DYNAMICS OBSERVED IN A LARGE ARRAY OF FLUID-ELASTIC OSCILLATORS

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"Self-organization" is considered to be as one of the key concepts which could become the basis of a new paradigm in a variety of engineering fields, ranging from generation of a new material at the nanometer level to the behavior of human groups at the macroscopic level. In order to bring about progress in these fields, it is important to first clarify the principle of self-organization as it is observed in nonlinear elements.

This research aims at elucidating the basic mechanism of self-organization appearing in nonlinear systems with supermany degrees of-freedom, not only in the field of mechanical engineering, but also in interdisciplinary fields of science and technology. We chose the complex fluid-excited vibrations exhibited by an array of vertically-cantilevered elastic rods densely arranged on a lattice in a uniform cross-flow, as a model experiment. We have performed an experimental study on spatiotemporal pattern formation in a large array of fluid-elastic oscillators. From the viewpoint of the realization of a large number of homogeneous oscillators, this experimental object consisting of many rods is considered to be suitable, as a model, for the verification of the principles involved, because this system cannot be further simplified in the field of mechanical engineering.

Despite their simplicity, such experiments allow the observation of a variety of complex spatiotemporal dynamics. Our previous presentations have reported success in observing hierarchical spatiotemporal pattern formations such as solo rods, rod clusters, and wave motion of cluster-chains in experiments. In addition, the beautiful dynamic structure underlying complex behaviors can be explained in detail. Spatiotemporal patterns, such as wave-like motion emerging in experiments, can be considered as chain reactions of dynamic bifurcations in a two-dimensional set of closely coupled nonlinear oscillators.

Commonly in the study of complex systems, parameter changes create novel relationships among elements. Such relationships enable the self-organization of hierarchical dynamic structures. It is noteworthy that the existence of such phenomena can also be confirmed in the field of mechanical engineering.

This research is directly applicable to nonlinear vibration problems which affect heat-exchanger pipes, pin-fin type heat sinks for personal computers, "honami" waves in rice fields, and the biomechanics of dowl. Moreover, the results of our experiments can also be applied in planning the position of planted trees to ensure wind protection, and in other projects in the fields of civil engineering, forestry, and agriculture. Furthermore, our experiment object may also constitute a two-dimensional analog of flowing granular materials, at least from the viewpoint of impact dynamics.

ID of Contribution: 17 - 367

## EXPERIMENTAL PASSIVELY ACTUATED ROBOT ARM FOR NON-SMOOTH MECHANICS

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Underactuated robot manipulators are present in many fields, both research and applications such as industrial fabrication processes, replacements of human extremities in biomechanics or underwater vessels. The motivation for this work is far more general, namely providing an experimental platform for a non-smooth nonlinear system. While most robots consist of actuated (e.g. by an electric motor) joints and some robots in addition contain joints which are free to move (underactuated joints) the proposed robotic device has passively-actuated joints, where energy can only be dissipated (e.g. by imposing friction or impacts), independent of the moving direction.

The robot manipulator itself is based on a classical two link robotic arm complemented with a brake and a clutch which cause non-smooth dynamic behaviour, such as impact induced velocity jumps as well as changes in the number of degrees of freedom [1]. A modular design has been chosen, which allows for easy exchangeability of underactuated and passively actuated joints.

In order to model and describe the dynamics of the system, a non-smooth dynamics approach [2] is used which properly takes into account impact and friction. A time-stepping algorithm [3] is employed for numerical simulation. The obtained results are finally being used to design the single robot components in detail, especially in order to obtain reasonable estimates for loads occurring during impact.

The experimental results of different testing procedures of the actual robot will be presented, especially in the context of examining to which extent high friction in the underactuated joints can replace impacts in order to induce velocity jumps in the dynamics as closely as possible. Furthermore, test runs incorporating feedback control for optimal trajectories will be addressed as well.

## ENOC-2005, Eindhoven, the Netherlands

References:

- Welge-Lüssen, T., 2004, Modelling and Mechanical Design of Underactuated Robot Manipulators with Impact and Friction PAMM Volume 4, Issue 1, 2004. Pages 175-176, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim
- [2] Glocker, Ch., 2001, Set-Valued Force Laws: Dynamics of Non-Smooth Systems. Lecture Notes in Applied Mechanics 1, Springer Verlag, Berlin Heidelberg
- [3] Leine, R.I., Nijmeijer, H., 2004 Dynamics and Bifurcations in Non-Smooth Mechanical Systems, Lecture Notes in Applied and Computational Mechanics Vol. 18, Springer-Verlag, Berlin Heidelberg New-York

#### ID of Contribution: 17 - 395

## **CURVE SQUEALING OF RAILROAD VEHICLES**

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Curve squealing of railroad vehicles occurs when trains run through narrow curves and a given set of meteorological and mechanical conditions are present. Field measurements have shown that the identification of this set of conditions is difficult [1]. For example, similar trains running through the same curve on the same day may have a very different behavior with respect to curve squealing.

The modal characteristics of the wheel play an important role in this phenomenon and have therefore been studied. The numerical as well as the experimental determination of its eigenforms and eigenvalues have been performed together with the measurement of the damping coefficients. Finite element simulations have indicated that the eigenfrequencies of the wheel are a function of the wheel diameter. This has also been observed in field measurements done in order to investigate the possible connection between the wheel diameter, the squealing occurrence and its frequency.

When curve squealing occurs, it is supposed that a limit cycle between wheel and rail is established. In order to numerically simulate curve squealing, a general multi-body contact problem with Coulomb friction and unilateral contact is set up [2]. A Finite Element Model is used and the dynamic response of the structure is evaluated by superposition of its modes, so the elasticity of the contacting bodies is also considered. The integration is performed with a time stepping method and the solution of the contact problem is conduced with the Augmented Lagrangian algorithm [3].

With our approach it is possible to consider a great number of parameters, such as the contact point position between wheel and rail, the friction coefficient, the wheel diameter and its modal damping coefficients. Our future aim is to determine which modes are more involved in curve squeal.

- [1] R. Stefanelli, Preliminary Measurements for Characterization and Location of Curve Squealing, Forum Acusticum Sevilla 2002, 16-20 September 2002, Sevilla (E)
- [2] Glocker, Ch., Set-Valued Force Laws: Dynamics of Non-Smooth Systems. Lecture Notes in Applied Mechanics 1, Springer Verlag, Berlin, Heidelberg 2001
- [3] R.I. Leine, H. Nijmeijer, Dynamics and Bifurcations in Non-Smooth Mechanical Systems, Lecture Notes in Applied and Computational Mechanics Vol. 18, Berlin Heidelberg New-York, Springer-Verlag, 2004.

## EXPERIMENTAL ANALYSIS OF SEISMICALLY EXCITED CIRCULAR CYLINDRICAL SHELLS

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The stability of shells has been deeply investigated in the past; indeed, such kind of structures have an important role in many fields such as: Nuclear, Aerospace, Civil and Mechanical Engineering. The complexity in finding accurate models useful for practical designers, gave rise to an enormous scientific production, focused in particular on static buckling. Nevertheless, many recent authors state that the general problem of shell stability is still open. An interesting review on shell stability is due to Babcock [1]; after a certain criticism about the number of papers published on the subject, about 50,000!, he focused the attention on the most important topics on this field: post-buckling and imperfection sensitivity; dynamic buckling; plastic buckling; experiments. It is now clear that the most important type of imperfections are the geometrical one; unfortunately, it is not simple to relate them to the knockdown factor. The most of the literature cited in [1] is concerned with dynamic step-loading, i.e. transient analyses.

An interesting experimental study on parametric resonances of cylindrical shells can be found in [2], the author observed a particularly violent instability; it takes place suddenly (the authors defined it a "bang") when there is a transition between stable to unstable regions or between two different instability regions involving different modes. Unfortunately, authors did not explain the nature of such "bang" that often damaged the shell.

In [3] experiments were carried out combining longitudinal and transversal seismic loads, in order to evaluate the reduction of the load carrying capacity in pre and post-buckling, due to seismic effects. A simple two dofs model was developed, without using of any shell theory, in order to simulate the nonlinear response; such model was obtained directly from experimental data.

In the present study an experimental investigation on a seismically excited shell carrying a rigid disk on the top is carried out. An accurate linear modal analysis is performed in order to obtain natural frequencies, damping ratios and vibration modes from experimental data. Nonlinear phenomena arising in the case of resonant seismic periodic loads, giving rise to large amplitude of vibration, are analyzed.

- [1] C. D. Babcock, 1983, "Shell Stability", J. of Applied Mechanics, 50, 935-940.
- [2] A. A. Bondarenko and P.I. Galaka, 1977, "Parametric instability of Glass-plastic cylindrical shells", Soviet Applied Mechanics, 13, 411-414.
- [3] M. Nakagawa, M. Fukuyama, K. Ishihama, H. Ikeuchi, Y. Hagiwara, H. Akiyama, 1995, "Pseudo-dynamic buckling experiments on thin cylindrical shells under biaxial seismic loads", Nuclear Engineering Design, 157, 27-36.

## **IDENTIFICATION OF PRE-SLIDING AND SLIDING FRICTION**

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The hysteretic nonlinear dependence of pre-sliding and sliding friction forces on displacement and velocity is modelled using different physics-based and black-box approaches including various Maxwell-slip models, NARX models, neural networks, nonparametric (local) models and dynamical networks. The effciency and accuracy of these identification methods is compared for an experimental time series where the observed friction force is predicted from the measured displacement and velocity. All models, although varying in their degree of accuracy, show good prediction capability of friction. Finally, it is shown that even better results can be achieved by using an ensemble of the best models for prediction.

**ID of Contribution: 17 - 441** 

## NON-LINEAR CONTROL OF PARAMETRICALLY EXCITED BEAMS VIA NON-COLLOCATED MULTI-FREQUENCY INPUT

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A nonlinear control strategy is applied to a simply supported uniform beam subjected to an end axial force at the principal-parametric resonance frequency of the first skew-symmetric mode. The control input consists of the bending couples delivered by two piezo-ceramic actuators attached onto the beam surface at symmetric locations with respect to the midspan of the beam. The controller action is typical of many single-input control systems; the control authority onto the symmetric modes is high whereas the control authority onto the skew-symmetric modes is zero in a linear sense. The nonlinear coupling between the symmetric and skew-symmetric modes, via the nonlinear inertia and curvature terms, provides the key mechanism for transferring effects from the actuators to the linearly uncontrollable mode.

The method of multiple scales is applied directly to the integral-partial-differential equations and boundary conditions governing nonlinear vibrations of the controlled system. The reduced dynamics of the system suggest the effective form of the control law. The control action turns out to be a harmonic input with two terms having the same frequency and detuning but phase-lagged by 90 degrees. The activated anti-resonance mechanism is a combination resonance. The selected frequency is twice the frequency of the excited mode. This resonance, with the appropriate optimum phase, generates a damping-like term which, in turn, increases the activation threshold for the parametric resonance. Therefore, exerting relatively small control efforts such as to increase the threshold right above the external force level, the parametric resonance is completely cancelled. The integral of the square of the steady-state deflection over the span of the beam is one of the appropriate metrics of the system response; here it is used as the cost function for the evaluation of the optimal control gains so as to minimize the overall residual vibrations resulting from the particular steady-state solution.

This work is not the first to examine the concept of transferring mitigation effects to uncontrollable modes via nonlinear coupling (Lacarbonara et al., 2002; Lacarbonara and Yabuno, 2004). Recently, the authors showed the effectiveness of this control strategy for discrete system, namely a magnetically levitated body under parametric resonance, where a driven pendulum acted as the controller (Yabuno et al., 2004). The present work, however, is the first to show experimentally this active nonlinear control methodology for a distributed-parameter system.

## References:

- [1] W. Lacarbonara, C.M. Chin and R.R. Soper, Open-loop nonlinear vibration control of shallow arches via perturbation approach, Journal of Applied Mechanics 69, 325-334, 2002.
- [2] W. Lacarbonara and H. Yabuno, Closed-loop non-linear control of an initially imperfect beam with non-collocated input, Journal of Sound and Vibration 273, 695-711, 2004.
- [3] H. Yabuno, R. Kanda, W. Lacarbonara and N. Aoshima, Nonlinear active cancellation of the parametric resonance in a magnetically levitated body, Journal of Dynamic Systems, Measurement and Control 126, 433-442, 2004.

ID of Contribution: 17 - 448

## FORCED OSCILLATIONS OF A CONTINUOUS ASYMMETRICAL ROTOR WITH GEOMETRIC NONLINEARITY (MAJOR CRITICAL SPEED AND SECONDARY CRITICAL SPEED)

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A rotor with a directional difference of stiffness is called an asymmetrical rotor. In this paper, forced oscillations in the vicinities of the major critical speed and the secondary critical speed of a continuous asymmetrical rotor with geometric nonlinearity are discussed. When both ends of a slender rotor are supported by self-aligning double-row ball bearings which support the rotor simply and the movements of the bearings in the longitudinal direction are restricted, the geometric nonlinearity appears due to the stiffening effect in elongation of the shaft. The nonlinearity characteristics of this system are different from that due to the clearance of ball bearings in a lumped parameter system. The nonlinearity is symmetric when the rotor is supported vertically, but it becomes asymmetric due to gravity when it is supported horizontally. Since an unstable region occurs due to a parametric excitation in an asymmetrical shaft, it is expected that a different vibration phenomenon from that of a symmetric shaft appears. Because a gyroscopic action becomes small as the model shaft is slender, the natural frequency of a forward whirling mode Pfn and that of a backward whirling mode Pbn have the relation of internal resonance Pfn : Pbn = 1: (-1). Due to the influences of this internal resonance and a lateral force, the complicated resonance phenomena appear in nonlinear resonances. The following are clarified: (i) the unstable range at the major critical speed which appears in a linear system disappears, (ii) the backward component appears simultaneously due to the internal resonance, (iii) the shape of resonance curves and their stability change appreciably, (iv) unique phenomena such as a Hopf bifurcation and an almost periodic motion appear. The influences of the parameters, such as the nonlinearity, the unbalance, the damping, and a lateral force on the vibration characteristics are also examined. These vibration phenomena were verified through numerical simulations, theoretical analysis and experiments.

# **MINI-SYMPOSIUM 18**

## **Laser Dynamics**

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#### ID of Contribution: 18 - 045

## SEMICONDUCTOR LASER WITH FILTERED OPTICAL FEEDBACK: BRIDGE BETWEEN CONVENTIONAL FEEDBACK AND OPTICAL INJECTION

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We study a model for a semiconductor laser subject to filtered optical feedback, as it was introduced in [1] and studied numerically and experimentally in a series of subsequent papers. In this model, the filter is characterised by its mean frequency and filter width. In the limit of a narrow filter the laser equations reduce under some conditions to the equations for a laser with optical injection, whereas they become the Lang-Kobayashi equations in the limit of an unbounded filter width.

We consider the filter width as the main parameter and vary this parameter in order to get analytical insight in the relation between the filter width and the number of possible steady states (external cavity modes). This is done mainly by a bifurcation study of steady state solutions.

In particular we announce the new result, that there exist parameter regions in which the number of possible steady states decreases when the filter width is increased. So far, in experiments and numerical studies, only a proportional increment of the number of steady states with the filter width was observed; see e.g. [2].

References:

- [1] M. Yousefi and D. Lenstra, Dynamical behaviour of a semiconductor laser with filtered external optical feedback, J. Quantum Electronics 35, 970-976 (1999).
- [2] A.P.A. Fischer, O.K. Andersen, M. Yousefi and D. Lenstra, Experimental and theoretical study of filtered optical feedback in a semiconductor laser, IEEE J. Quantum Electron. 36, 375-384 (2000).

ID of Contribution: 18 - 107

## LASER DYNAMICS OF A BI-STABLE RING SYSTEM WITH OPTICAL FEEDBACK

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We report experimental and numerical observations of novel nonlinear dynamics in a system that consists of two unidirectional ring lasers with separate cavities sharing one semiconductor optical amplifier (SOA) that serves as the active element. The light that outputs from the SOA is partly fed back into the amplifier via an external feedback arm (FBA) in the counter propagating direction. This configuration shows bi-stable operation in the sense that only one of the lasers is lasing while the other is off. Such a configuration can serve as an optical flip-flop memory, a key element in all-optical signal processing.

Simulations show that a ring laser with feedback can evolve into different dynamical regimes such as fixed point, limit cycle and chaos, mainly depending on the feedback strength and the ratio between the roundtrip times of the FBA and the ring cavity. If two such ring lasers are coupled together by the same SOA, while sharing the same FBA, the roundtrip conditions for lasing cannot be satisfied for both lasers simultaneously. The ring laser with larger initial

intensity becomes dominant, while the intensity of the other one is suppressed. Switching between the states can be realized by injection of external light at the wavelength of the ring laser that is not lasing.

## ID of Contribution: 18 - 132

## **MUTUALLY-COUPLED LASERS**

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The dynamics of two mutually delay-coupled semiconductor lasers in a face to face configuration will be reviewed. We will present analytical, numerical and experimental results for the case of long delay times.

We will consider the cases in which two edge emitter lasers are either optically coupled [1] [2] or electro-optical coupled [3] [4]. We will also consider that either laser, when decoupled, can operate CW or it can have its own dynamics (self-oscillating laser). Our investigations reveal that the delay time between the emitter and receiver lasers, i.e. the time it takes for the light to travel from one laser to the other, and the coupling strengths play a crucial role. When the lasers are coupled we observe different coupling-induced phenomena including instabilities and chaos, achronal and isochronal synchronization, and locking. The effect of the detuning between the two lasers, either in the emission frequency of the solitary lasers or in the pulsating frequency of the self-oscillating lasers, will be analysed.

References:

- [1] "Chaos Synchronization and Spontaneous Symmetry Breaking in symmetrically Delayed Coupled Semiconductor Lasers", T. Heil, I. Fischer, W. Elsasser, J. Mulet and C. Mirasso, Phys. Rev. Lett. 86, 795 (2001);
- [2] "Synchronization Properties of Two Distant Mutually Coupled Semiconductor Lasers", J. Mulet, C. Mirasso, T. Heil and I. Fischer, J. of Quantum and Semiclassical Optics 6, 7 (2004).
- [3] "Nonlinear Dynamics of Semiconductor Lasers with Mutual Optoelectronic Coupling", S. Tang, R. Vicente, M. Chiang, C. R. Mirasso and J.M. Liu, IEEE J. of Selective Topics in Quantum Electron. 10, 936 (2004);
- [4] "Dynamics of Semiconductor Lasers with Bidirectional Optoelectronic Coupling: Stability, Route to Chaos and Entrainment", R. Vicente, S. Tang, J. Mulet, C. R. Mirasso and J.M. Liu, Physical Review E 70, 46216 (2004).

ID of Contribution: 18 - 148

## NOISE AND COUPLING IN DIODE LASERS

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We review the effects of external fluctuations in semiconductor lasers with feedback, both in isolation and in the presence of coupling from a second laser. Particular attention is paid to the signal detection and processing capabilities of the system. In this sense, a single semiconductor laser with feedback is well known to exhibit stochastic resonance in the response to a single harmonic driving and noise. This behavior has been seen to be substantially enhanced by coupling [1]. Additionally, we have also reported that in the presence of a complex harmonic driving in which the fundamental is missing, the system detects nevertheless the fundamental, in what has been termed ghost resonance [2]. This behavior is also observed in coupled lasers in which the different input harmonics of the complex signals are distributed among the lasers [3], in a nontrivial example of the signal processing capabilities of the system. References:

ENOC-2005, Eindhoven, the Netherlands

[1] J.M. Buldu et al, Appl. Phys. Lett. vol. 81, p. 5105 (2002).

[2] J.M. Buldu et al, Europhys. Lett. vol. 64, p. 178 (2003).

[3] J.M. Buldu et al, Chaos, to appear (2005).

ID of Contribution: 18 - 167

## POLARIZATION DYNAMICS IN VCSELS AND BISTABLE SYSTEMS WITH DELAY

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VCSELs exhibit numerous advantages with respect to conventional edge-emitting lasers and also interesting polarization properties: they usually emit linearly polarized (LP) light but may switch between two orthogonal (x and y) LP modes. The injection of an external light, either from the VCSEL itself (optical feedback) or from another laser (optical injection) may help to control the polarization and lead to a rich nonlinear dynamics. In this talk, we summarize our results concerning 1) polarization switching (PS) induced by optical injection in VCSELs and 2) polarization dynamics in VCSELs subject to optical feedback.

We show that the injection of a LP light orthogonal to that of the free-running VCSEL leads to PS in an otherwise polarization stable VCSEL. Detailed investigations of a rate equation model show that the route to PS is accompanied by a cascade of bifurcations to wave-mixing, time-periodic and chaotic dynamics. Two injection locked solutions may (co)exist: the first one exhibits the polarization of the master laser (y), while the second one corresponds to an elliptically polarized injection locking, i.e. the LP modes of the slave laser both lock to the master laser frequency. Continuation techniques allow us to map the bifurcation boundaries in the plane of the frequency detuning versus the injection strength. Experimental results unveil a rich nonlinear polarization dynamics, including a period doubling route to chaos and different time-periodic dynamics.

A time-delayed optical feedback may also lead to interesting polarization behaviours [1]. A very small amount of optical feedback may induce a polarization mode hopping (PMH) accompanied by a rapid dynamics at the external cavity (EC) frequency. The distribution of the residence time in one LP mode is not a typical Kramers law but exhibits increased probability at the delay time and multiples of it. Moreover, the addition of an optimal amount of noise to the injection current leads to a maximum regularity of the PMH at the time-scale of the delay time (coherence resonance). These features appear to be typical for bistable systems with delay and noise. Finally, we analyze how the polarization competition manifests itself when the EC is short (delay much smaller than the relaxation oscillation period). The laser intensity may then exhibit regular packages of pulses (RPP), i.e. a slow time-periodic modulation of fast pulses at the EC frequency [2]. The RPP appear in the two LP modes with different correlation properties depending on the laser and feedback parameters.

**References:** 

[1] M. Sciamanna et al., Opt. Lett. 28, 1543 (2003).

[2] T. Heil et al., Phys. Rev. Lett. 87, 243901 (2001).

#### ID of Contribution: 18 - 169

## MUTUALLY DELAY-COUPLED SEMICONDUCTOR LASERS: INFLUENCE OF THE PUMP PARAMETER IN THE SYMMETRICAL CASE

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We consider the simple scheme of two identical, mutually delay-coupled semiconductor lasers that receive each others light. The delay in the coupling is given by the finite propagation time of the light between the spatially separated lasers. This system is a prototype example of two delay-coupled oscillators. Furthermore, it is technologically relevant because semiconductor lasers are increasingly coupled together in applications such as optical telecommunication.

The objective of the study is to understand the basic continuous wave states of the system, the compound laser modes (CLMs). These modes form the underlying skeleton that organizes the dynamics of this system. We concentrate on the short coupling-time regime where the number of CLMs is small so that their overall structure can be studied. We restrict our study to the symmetrical case, where both lasers are identical. The system is modelled with Lang-Kobayashi-type rate equations for the inversions of both lasers and the complex envelopes of their optical fields. We perform a bifurcation analysis of the CLMs in this delay differential equation model using numerical continuation techniques. Stability analysis shows that most of the CLMs are unstable; however they may play an important role in the dynamics of the system.

Specifically, we parameterize the CLMs with the coupling phase and study their dependence on the pump parameter. For small values of the pump parameter only constant-phase CLMs are possible. For these CLMs the inversions and intensities of both lasers are identical. As for the Lang-Kobayashi system describing a laser with optical feedback from a regular mirror, the constant-phase CLMs are located on an ellipse in the frequency versus inversion plane.

For low values of the pump parameter, only the low-inversion part of this ellipse is physically relevant, that is, corresponds to real CLMs of the system that are above the threshold of the coupled system. As the pump parameter is increased more constant-phase CLMs are above threshold until the entire ellipse is physically relevant. Furthermore, from a certain pump level on, intermediate-phase CLMs are present in the system. For these CLMs the inversions and the intensities of both lasers are different. Intermediate-phase CLMs are born and destroyed in pitchfork bifurcations of the constant-phase CLMs. When the pump parameter is increased further one encounters a singularity transition in which a separate branch of intermediate-phase CLMs is split off. These CLMs are no longer "connected" with the ellipse of constant-phase CLMs. Instead, they are born and destroyed in saddle-node bifurcations. For even larger pump parameter this geometric picture of the CLMs does not undergo any further qualitative changes. In conclusion we have a comprehensive picture of the CLM structure. This is essential for understanding more complex dynamics.

#### ID of Contribution: 18 - 170

## BIAS LEVEL DEPENDENCE OF DIFFUSIVE TURN-OFF TRANSIENTS IN VERTICAL-CAVITY SURFACE-EMITTING LASERS

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Diffusive turn-off transients are dynamical phenomena that appear in vertical-cavity surface-emitting lasers (VCSELs) as a consequence of the interplay between carrier diffusion and Spatial Hole Burning (SHB). An example of those transients is the generation of significant optical power in secondary pulsations after the switch-off of VCSELs when the laser is modulated from an above threshold state to a bias current that is at or below threshold [1]-[3]. In this case, as the laser is switched-on, a spatial hole is burned in the carrier profile. When the current is reduced to the bias level, carriers redistribute and fill the hole, allowing a transient recovery of the modal gain above the threshold value with the subsequent emission of the secondary pulsation. The study of turn-off transients is of interest since VCSELs are modulated by a digital bit stream when they are used in communication systems. VCSELs in high speed communication systems are usually turned-off with a bias current that is above threshold.

In this work we extend our previous analysis [1] to turn-off transients that appear for bias current above threshold. The dynamical model used in our calculations take into account the spatial profiles of both, the electrical field and carrier profiles. Several differences are found between the above and below threshold situations. First, transverse modal composition of the power during turn-off depends on the value of the bias current: an above (below) threshold operation leads to multimode (single-mode) secondary pulsations. Second, power of secondary pulsations in multimode VCSELs is similar to (much smaller than) the power of those pulsations in single-mode VCSELs when the laser is operated above (below) threshold. These results are explained in terms of the decreasing relative importance of diffusion currents with respect to the bias current as this current is increased above the threshold value.

### References:

- A. Valle, J. Sarma, K. A. Shore, 'Secondary pulsations driven by spatial hole burning in modulated VCSEL diodes', J. Opt. Soc. Am. B, vo. 12, no. 9, 1741-1746, 1995.
- [2] J. J. Morikuni, P. V. Mena, A. V. Harton, K. W. Wyatt, S. M. Kang, 'Spatially independent VCSEL model for the simulation of diffusive turn-off transients', J. of Lightwave Technol., vol. 17, no. 1, 95-102, 1999.
- [3] M. I. Cohen, A. A. Allerman, K. D. Choquette, C. Jagadish, 'Electrically steerable lasers using wide-aperture VCSELs', IEEE Photon. Technol. Lett., vol. 13, no. 6, 544-546, 2001.

ID of Contribution: 18 - 183

## BIFURCATION ANALYSIS BY CONTINUATION METHODS OF LASER SYSTEMS WITH DELAY

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Semiconductor lasers are known to exhibit an amazing range of dynamical behaviour when subjected to external influences; see, for example, [1] and references therein. We concentrate here on the case of laser systems that feature delays, which are given by the finite run-times of the light between different components. Such laser systems with delay are modelled in the rate equation approach by delay differential equations (DDEs) for the electric field(s) and inversion(s) of the laser(s) involved. It is important to realise that DDEs are infinite-dimensional dynamical systems, because an entire history over the (maximal) delay time needs to be known as initial condition to determine the evolution of the system.

The key question is: how does the dynamics of the given laser systems with delay depend on the control parameters?

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In an experiment one records the dynamics as one parameter is changed while the other parameters are kept fixed. This is then repeated for different values for the other parameters. In numerical simulation the procedure is essentially the same, except that now the dynamics of a mathematical model is recorded. The advantage is that more information on the solution, and not just, for example, its spectrum, can be extracted from the simulation. Numerical simulation is relatively straightforward, but is already quite expensive for DDEs because of run-time and data storage requirements.

The complimentary approach presented here (see [2] for a detailed exposition) is that of bifurcation analysis by numerical continuation, which is an established tool for the study of finite-dimensional dynamical systems. It has recently become available also for DDEs in the form of the software package DDE-BIFTOOL. The basic idea is to find a bifurcation, that is, a parameter value where the laser's dynamics changes qualitatively, for example, from stable output to periodic intensity variations. It is then possible to follow or continue this bifurcation in several parameters. In this way, one traces out the boundaries between regions of qualitatively different laser dynamics, the collection of which forms the bifurcation diagram.

Bifurcation analysis is not as easy to perform as numerical simulation. Apart from some getting used to to continuation software, it requires a knowlegde of bifurcation theory, which tells one what bifurcation to expect. However, the pay-off is that bifurcation analysis is a very powerful tool.

From the physical point of view, this allows one, for example, to find the effect of key parameters on regions of stable laser operation, to find stable-unstable mode beating phenomena, and to identify relevant frequencies of the dynamics. This will be demonstrated with examples of semiconductor lasers with different kinds of optical feedback.

### References:

- [1] B. Krauskopf and D. Lenstra (Eds.), Fundamental Issues of Nonlinear Laser Dynamics, AIP Conference Proceedings 548 (2000)
- [2] B. Krauskopf, Bifurcation analysis of lasers with delay, in D.M. Kane and K.A. Shore (Eds.), Unlocking Dynamical Diversity: Optical Feedback Effects on Semiconductor Lasers, Wiley (2005) 147-183

ID of Contribution: 18 - 197

## **TOPOLOGICAL SIGNATURE OF CHAOS FOR SHORT TIME TRACES**

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Most quantitative measures of chaos (e.g., fractal dimensions or Lyapunov exponents rely on constructing an approximation of the natural measure on a strange attractor, which requires observing the system for at least a few hundreds of cycles at fixed control parameters. Thus, it is extremely difficult to assess deterministic chaos in a real system that experiences parameter drifts on a time scale comparable to the mean dynamical period. A natural question then is: can we infer the existence of an underlying chaotic dynamics from a very short, nonstationary, time series?

We will present an experimental case in which this question can be answered positively: by applying topological tools [1] to a burst of irregular behavior recorded in a triply resonant optical parametric oscillator subject to thermal effects, we have extracted a clearcut signature of deterministic chaos from an extremely short time series segment of only 9 cycles [2]. Indeed, this segment shadows an unstable periodic orbit whose knot type can only occur in a chaotic system. Moreover, this topological approach provides us with quantitative estimates of chaos, as a lower bound on the topological entropy of the system can be determined from the knot structure. Two positive-entropy orbits are detected in a time series of about 40 cycles, suggesting that the presence of such orbits in a time series is generic.

Unfortunately, these techniques so far can only be applied to chaotic systems that can be embedded in a threedimensional phase space, whereas they would be most useful in high-dimensional systems, where time series are inherently too short. What is lacking so far is a way to associate a periodic orbit with an entropy in arbitrary phase space dimension. As a first step towards a theory applicable in higher dimensions, we have recently designed a knotless formalism that simplifies significantly the computation of topological entropies of three-dimensional periodic orbits. References:

- [1] R. Gilmore and M. Lefranc, 'The Topology of Chaos: Alice in Stretch and Squeezeland' (Wiley, New-York, 2002)
- [2] A. Amon and M. Lefranc, 'Topological signature of deterministic chaos in short nonstationary signals from an optical parametric oscillator', Phys. Rev. Lett. 92, 094101 (2004).

ID of Contribution: 18 - 265

## SYNCHRONOUS AND ASYNCHRONOUS INSTABILITIES OF TWO LASERS WITH DELAYED COUPLING

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We investigate a system of delay-differential equations, describing a pair of semiconductor lasers with mutual delayed coupling. The single lasers are assumed to be single-moded, and hence the resulting system is of Lang-Kobayashi type. For identical lasers there exist synchronized states, where both lasers behave identically. We present different scenarios of destabilization of the synchronized state. In particular, we consider seperately the situation of small and large delay. To this end, we perform a bifurcation analysis, taking into account the symmetries of the system and singular pertubation methods. For small delay, we identyfy a codimension two bifurcation as the organizing centre for the onset of complicated dynamics. In the case of large delay, we employ a new mathematical approach to classify different types of instabilities by their scaling properties.

References:

- [1] T. Heil et al., Phys. Rev Lett 86, 795, (2001).
- [2] S.Yanchuk et al., Phys. Rev. E 69, 056221 (2004).

ID of Contribution: 18 - 269

## A SHORT CAVITY SEMICONDUCTOR LASER SYSTEM: DYNAMICS BEYOND LANG-KOBAYASHI

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Semiconductor lasers (SL) subject to delayed optical feedback are well-known to exhibit complicated emission dynamics. Controlled delayed optical feedback can be studied with external cavity configurations. Depending on the system parameters, a variety of fundamental dynamical phenomena have been observed and studied under well-defined conditions, approving these SL-systems as important systems for nonlinear dynamics.

In recent years, research has focused on systems with weak to moderate feedback levels and short external cavities. In this so-called Short Cavity Regime (SCR), the external cavity round trip frequency is larger than the relaxation oscillation frequency of the laser. The major characteristics of the intensity dynamics in the SCR have been successfully described by the well-known Lang-Kobayashi (LK) rate equations [1]. However, general applicability of the model is not given, since it is based on several assumptions. In particular, the spatial extension of the laser is neglected. In addition, only one single mode of the solitary laser is considered. Nevertheless, several features of the dynamics of

multimode lasers can be explained within the single mode LK-model or with extended LK-models considering weak coupling of several longitudinal modes. However, if the ratio between the external cavity length and the effective length of the laser cavity becomes small, spatial effects might become relevant for the dynamics. Such systems can still be described with traveling wave models. Up to now, investigations have been mainly focused on systems with weakly coupled longitudinal modes, while studies on multimode systems with strongly coupled modes and non-negligible spatial extension of the laser are still lacking.

We present results for a multimode SL system subject to moderate optical feedback operating in the SCR. Here, the ratio between the external cavity length and the optical path length in the laser cavity has been chosen between 2 and 4. We study the influence of the injection current and the feedback phase on the dynamics under resonant coupling conditions of the modes. As in the case of the SCR, we find a cyclic scenario of the dynamics depending on the feedback phase. Within one cycle, the dynamics evolve from stable emission to periodic states and, finally, to chaos. In contrast to common (LK-) SCR dynamics [2], the chaotic dynamics in this system involves an unusually high number of longitudinal modes; this number can exceed 100 leading to an optical bandwidth of approximately 7nm. This dynamics is associated with broad band intensity rf spectra with a bandwidth of  $\sim$ 5GHz.

We discuss this behavior in the context of feedback induced spectral dynamics and modal overlap leading to strong interactions between the modes, demonstrating how this behavior goes beyond the LK-description. Our results suggest, that new models are required in order to gain deeper insight into the nonlinear dynamics of such multimode systems. The control over such an extended range of bandwidth offers new perspectives for applications where (in-)coherence properties are of importance.

References:

R.Lang and K.Kobayashi, IEEE Journal of Quantum. Electron., vol. QE-16, pp. 347-355, 1980.
T.Heil et al., Phys. Rev. Lett. 87, 243901, 2001.

ID of Contribution: 18 - 286

## SELF-ORGANIZATION PHENOMENA IN NONLINEAR OPTICAL SYSTEMS

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The spontaneous formation of spatially extended as well as spatially localized structures in self-organizing nonlinear systems is ubiquitous in nature. Recently transverse nonlinear optics proved to be attractive for systematic studies of self-organized structures, since here a wealth of phenomena is associated with a high level of control and - in many cases - convenient time and length scales. Suitably prepared systems allow also for a detailed comparison between experiment and theoretical predictions.

The scheme considered is an archetypical system for optical pattern formation [1]. It is based on a thin sample of a nonlinear optical medium and a single plane mirror providing feedback. If sodium vapor is used as the nonlinear medium, the polarization state of the light field and/or an external magnetic field can be used to change drastically the nonlinear properties of the system [2]. In the experiment a cross section of approximately ten square mm is driven by a cw laser beam with a power of about 100 mW. The laser frequency is tuned in the vicinity of the sodium D1-resonance.

If a l/8-retardation plate is placed in the feedback loop, the system exhibits a symmetry breaking pitchfork bifurcation leading to (nearly) equivalent homogeneous or patterned states with different polarization. By means of an addressing beam a circular domain of one polarization state existing on a background of the other can be ignited, which is interpreted as a dissipative spatial soliton. A discrete family of spatial solitons can be stabilized if an operation point close to or above the threshold of a modulational instability is chosen. Solitons of different order differ in their effective widths, since they contain different numbers of radial high-amplitude radial oscillations. The stabilization of these structures due to an interplay of curvature-induced dynamics, pressure-induced dynamics (due to an imperfection of the pitchfork bifurcation) and the pinning at the modulated background is studied. In addition, we observe clusters of different solitons, tightly bound compound states of solitons and solitons interacting with fronts.

In a second experiment we address the properties of spatio-temporal patterns which arise, if an additional, oblique magnetic field is applied. Beyond a certain input intensity, self-organized inwardly moving targets and spirals emerge in the transverse intensity profile. For the same set of parameters, targets and spirals with different numbers of arms are observed; the system is multistable. In experiments, in which the intensity is switched abruptly from zero to a value beyond threshold, histograms of the number of spiral-arms are obtained. The dependence of the most frequent number of arms on parameters is investigated experimentally and theoretically.

References:

- [1] G. D'Alessandro and W. J. Firth. Phys. Rev. Lett. 66, 2597 (1991).
- [2] T. Ackemann and W. Lange. Appl. Phys. B 72, 21 (2001).

#### ID of Contribution: 18 - 349

## **CONTROLLING LASERS: A BRIEF OVERVIEW AND NEW PERSPECTIVES**

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Class B lasers are well known to present a delay in response to a rapid variation of a control parameter and to relax towards the new emission state with damped oscillations. This phenomenon is observed not only in solid state and carbon-dioxide lasers, but also in semiconductor lasers. For the latter group, ringing is accompanied by a frequency chirp which further disturbs telecommunications due the ensuing frequency spread: propagation over long distances at wavelength far from the dispersion minimum in an optical fibre contributes with an additional degradation of the signal.

For a number of applications, in would be highly desirable to succesfully engineer a transition between two different states of emission of a Class B laser where the delay time is minimum and the oscillations are entirely removed. For example, a reduction in the delay would increase the transmission rate in telecommunications; in addition the optimal, oscillation-free switch could improve the quality of the signal to the point of permitting large gains in modulation speed. If successfully applied to inexpensive, low speed lasers, this technique could widen the use for optical transmissions, e.g., in local area networks.

We will review the attempts, carried out over decades, at constructing appropriate switching trajectories and the reasons for repeated failure - or of only partial success. In the past five years, substantial advances have been obtained thanks to the increased understanding of the response of a nonlinear system. This understanding has been translated more or less explicitly in different techniques, based on the topology of the phase space ("phase space steering" [1]), but also on direct "guesses" which have resulted in surprisingly good results.

Even more recently, a more traditional and powerful approach, based on formal optimisation theory, has proven that optical systems can be effectively treated with standard mathematical techniques [2]. We will briefly review some results obtained by different groups and discuss in more detail the optimization of the switching of a telecom semiconductor laser. Various issues related to sensitivity to noise and external fluctuations will be addressed, and we will show that numerical predictions hold great promises for speed improvements as large as one order of magnitude. Finally, we will present the results of an experiment aimed at testing the steering principle on a commercial laser. We will discuss the procedure followed for obtaining the actual optimization parameter values and we will present the experimental results, which support the theoretical and numerical predictions obtained so far.

- G.L. Lippi, S. Barland, N. Dokhane, F. Monsieur, P.A. Porta, H. Grassi, and L.M. Hoffer, "Phase space techniques for steering laser transients", J. Opt. B: Quantum Semiclass. Opt. 2, 375-381 (2000).
- [2] J.-H.R. Kim, G.L. Lippi, and H. Maurer, "Minimizing the Transition Time in Lasers by Optimal Control Methods. Single Mode Semiconductor Laser with Homogeneous Transverse Profile", Physica D 191, 238-260 (2004).

## SYNCHRONIZATION MAP OF TWO UNI-DIRECTIONALLY COUPLED CHAOTIC SEMICONDUCTOR LASERS

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Optical injection exhibits different behaviors, showing frequency locking, wave mixing, relaxation regimes, period doubling, and chaos. Map versus the optical injected power from the master and the detuning between the slave and the master frequency can show at a glance these different regimes. Usual values for the detuning and the injected power are respectively -100-100 GHz and -50 dBm-0 dBm ( $100 \mu$ W-1 mW).

Optical injection is also the fundamental process, which enables the synchronization of two uni-directionally-coupled chaotic semiconductor lasers. The chaos is generated through optical feedback and the general idea is to inject light from an external cavity laser (ECL) into a second laser with the same strength as for the ECL in order to duplicate the first system. All these experiments describe high dimensional chaos brought by a delayed system. We propose here an optical set-up, which enables the synchronization of two lasers exhibiting chaos, described by a low dimensional model, easier to analyze. This scheme enables us to draw maps in an injected power-detuning chart, showing the degree of correlation between these two lasers, as well as to have a strict comparison and correlation with the optical injection by a continuous wave signal. The robustness of synchronization with respect to the detuning and the injected power can be thus evaluated

ID of Contribution: 18 - 429

## WAVELENGTH OSCILLATIONS PRODUCED BY A DIODE LASER WITH DELAYED FILTERED OPTICAL FEEDBACK

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We report experimental observation of a controlled period doubling scenario in the recently discovered wavelength oscillations [1] for a semiconductor diode laser with delayed filtered external feedback. The dynamics driving the all-optical system exhibit oscillations in the frequency, or wavelength, with a period related to the external cavity round trip time, while at the same time the output intensity remains constant within the experimental accuracy. These dynamics are observed through a series of RIN spectra taken from the frequency oscillations.

A complete sequence of spectra showing each step of the route and the frequencies involved in the dynamics will be presented.

A theoretical analysis using both simulations and a continuation method for delay-differential equations shows that frequency oscillations with nearly constant intensity are born in a super-critical Hopf bifurcation out of a stable external

cavity mode. These frequency oscillations undergo a torus bifurcation, however period doubling bifurcations can be found on unstable branches of frequency oscillations.

References:

[1] Alexis P. A. Fischer, Mirvais Yousefi, Daan Lenstra, Michael W. Carter, and Gautam Vemuri ' Filtered Optical Feedback Induced Frequency Dynamics in Semiconductor Lasers', Phys. Rev. Let., 16 Jan. 2004 Vol. 92, N 2.

ID of Contribution: 18 - 431

## ANALYSIS OF SELF-PULSATING DBR LASING DYNAMICS WITH A NOVEL FORMULATION

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All-optical clock recovery and 3R-regeneration will play a leading role in the all-optical systems. Recently, the simple three sections Distributed Bragg Reflector (DBR) lasers have been presented as self-pulsating devices [1]. The dynamical properties of a self-pulsating DBR laser are investigated here with a novel rate-equations time domain model [2] for lasers with grating-filtered optical feedback. The model takes into account non linear effects like four wave mixing and gain compression, thus it is particularly suitable to analyze a self-pulsating device where mode coupling is paramount to get proper device behaviour. The simulation results show that the linewidth enhancement factor plays an important role and that FWM is responsible for the self-pulsations. The numerical analysis on the simulation results shows that self-pulsations are obtained through the beating of adjacent modes with constant phase difference.

References:

- Duan G.-H., Gosset C., Lavigne B., Brenot R., Thedrez B., Jacquet J., Leclerc O., "40GHz all-optical clock recovery using polarization insensitive distributed Bragg reflector lasers," in ECIO 2003, 11th Europen Conference on Integrated Optics, 2-4 April 2003, pp. 175–178.
- [2] E. Detoma, B. Tromborg, and I. Montrosset, "The complex way to laser diode spectra: Example of an external cavity laser with strong optical feedback," IEEE Journal of Quantum Electronics, 2005, accepted for publication.

## ID of Contribution: 18 - 447

## MODELING A MULTIMODE SEMICONDUCTOR LASER WITH EXTERNAL FEEDBACK

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I plan to review and present the case for models that describe a multimode semiconductor laser with external feedback (MSLEF). These systems are described by nonlinear delay differential equations. Because the physics of these devices is very complex, it is not possible to derive dynamical equations from first principles. Hence, models are introduced on a phenomenological basis. In the spirit of the normal form analysis, one tries to construct the simplest model that reproduces the essential features of the physical system.

Two groups of models based on modal field amplitudes have been proposed: in one group (model A) it is assumed that the modal field amplitudes are coupled through the space average of the free-carrier density [1]. In the other group (model B), it is assumed that each mode of the field is coupled to a nonlinear modal gain which is related to the projection of the free carrier density on the lasing mode basis [2].

For a MSLEF, one can measure experimentally the fluctuations of the modal and the total lasing output. A discussion of the bifurcation diagram of the two models indicates that only model B can account for the two observed properties: (i) although the devices are manifestly multimode, the single mode theory has unacceptable success; (ii) there are domains in which nearly perfect compensation of the fluctuations in the total output is observed while each lasing mode has large amplitude fluctuations; this occurs for any number of modes. Both features are related to the existence of a degenerate Hopf bifurcation.

To be complete, one has to verify that model B is not the singular limit of a more general model. I shall focus on three effects:

1. Introducing different modal gains to remove the degeneracy of the Hopf bifurcation.

- 2. Introducing white noise in each mode of the field.
- 3. Introducing free carrier diffusion that washes out any spatial inhomogeneity.

I shall show that the results obtained from model B are robust against any of these sources of perturbations. Part of this analysis is published now [3].

References:

[1] D.W. Sukow, T. Heil, I. Fischer, A. Gavrielides, A. Hohl-AbiChedid, and W. Elsässer, Phys. Rev. A 60 (1999) 667.

[2] E. A. Viktorov and P. Mandel, Phys. Rev. Lett. 85 (2000) 3157; T.M. Carr, D. Pieroux, and P. Mandel, Phys. Rev. A 63 (2001) 033817.

[3] I. V. Koryukin and P. Mandel, Phys. Rev. A 70 (2004) 053819.

ID of Contribution: 18 - 466

## THE DYNAMICS OF A SEMICONDUCTOR LASER SUBJECT TO FILTERED OPTICAL FEEDBACK

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A laser subject to filtered optical feedback shows a large set of dynamics, on several timescales. We present an overview of this system and investigate its dynamics using a set of rate equations. These calculations are compared with experimental data and good agreement is found.

The dynamics displayed by optical systems with a time delay have attracted substantial attention, due to their complexity and thus their potential application in fields such as chaotic encryption of telecommunications signal. Currently, the most favored delay optical configuration consists of a semiconductor laser, where a part of the output light is fed back into the laser after some time delay, which is accumulated in the so-called external cavity. This feedback light causes instabilities in the laser output and the laser with feedback shows a large variety of non-linear dynamics. Generally, the dynamics of such a delay system are very sensitive to parameter fluctuations and are therefore very difficult to control. Recently, the concept of filtered optical feedback (FOF) was introduced [1], where a frequency filter is placed in the external cavity, allowing additional control of the feedback light. Thus, the filter provides a control mechanism for the delay system and dynamics may be induced in a more ordered fashion.

The Filtered Optical Feedback (FOF) system differs in many aspects from the Conventional Optical Feedback (COF) system. For instance, the number of steady states, or fixed points, of the FOF system are generally fewer than the COF system. Also, due to the presence of the filter in the external cavity, the dynamics show strong frequency dependence in the FOF system. This allows for the control of the dynamics through the laser pump-current. The filter bandwidth is another parameter that plays an important role, since it controls the amount of light fed back into the system. Still, the it remains a delay system and the complexity of the dynamics is comparable to that of COF.

We model this system by a set of ordinary differential delay equations and investigate the possible dynamics of the system using dynamical systems tools. A deep understanding of the underlying physics can be gained already by studying the fixed points, while several bifurcations can be identified in the analysis of the dynamics. We compare these

calculations with recent experiments on FOF system and can demonstrate good agreement between theory and experiment. Also, the recently discovered external cavity time-scale dynamics, which are unique to the FOF system, will be briefly addressed. Again, theory shows very good agreement with the experiments and in fact identifies effects related to the origin of these dynamics, which were not visible in the experiments.

- [1] M. Yousefi and D. Lenstra, IEEE JQE-35, pp. 970-976 (1999).
- [2] M. Yousefi, D. Lenstra, G. Vemuri, Phys. Rev. E., 67, 046213, (2003).
- [3]A.P.A. Fischer, M. Yousefi, D. Lenstra, M.W. Carter and G. Vemuri, Phys. Rev. Lett. 91, 023901 (2003).

# **MINI-SYMPOSIUM 19**

# Micro- and Nano-Electro-Mechanical Systems

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## ID of Contribution: 19 - 015

## NONLINEAR DAMPING IN NANOMECHANICAL BEAM OSCILLATOR

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Nonlinear effects play an important role in the dynamics of nano-scale mechanical devices. The present talk reviews our recent experimental studies of some of these effects including (a) nonlinear dynamics of a metastable mechanical state, (b) intermodulation gain of mechanical motion, and (c) nonlinear dynamics of a large-scale array of coupled resonators.

Electrostatic and Casimir interactions may give rise to positional metastability of electrostatically-actuated or capacitively-coupled mechanical devices. We investigate experimentally such metastability for a generic system consisting of a doubly-clamped Au suspended beam, capacitively-coupled to an adjacent stationary electrode [2]. The mechanical properties of the beam, both in the linear and nonlinear regimes, are monitored as the attractive forces are increased to the point of instability. There pull-in occurs, which results in permanent adhesion between the electrodes. We investigate, both experimentally and theoretically, the position-dependent lifetimes of the free state before pull-in. We find that the data cannot be accounted for by simple theory; the discrepancy may be reflective of internal structural instabilities within the electrodes.

The relatively strong nonlinear effects in nano-scale mechanical devices can be employed for parametric amplification of mechanical vibrations. To demonstrate this we employ a doubly clamp beam coupled capacitively to a nearby parallel electrode [3]. Employing intermodulation setup we bias the side electrode with a driving force combined of an intense 'pump' an low amplitude 'signal', both having frequencies within the bandwidth of a resonance. The nonlinearity of the device gives rise to frequency mixing resulting in 'idler' component in the spectrum of vibration of the beam. The intermodulation gain, namely the ration between the 'idler' and 'signal' amplitudes, is measured under varying conditions. We find that when operating close to the onset of Duffing instability the gain obtains a peak.

In another experiment [4] we study nonlinear mechanical vibrations of an array of nano-mechanical resonators. Implementing tunable electrostatic coupling between the suspended, doubly-clamped Au beams leads to the formation of a band of collective vibrational modes within these devices. The evolution of these modes with coupling strength is clearly manifested in the optical diffraction pattern of light transmitted through the array. Comparing the experimental results with theoretical predictions [5, 6] yields qualitative agreement. These structures offer unique prospects for spectral analysis of complex mechanical stimuli.

- [1] E. Buks and M. L. Roukes, Phys. Rev. B63, 033402 (2001).
- [2] E. Buks and M. L. Roukes, EuroPhys. Lett. 54, 220 (2001).
- [3] R. Almog, S. Zaitsev, and E. Buks, unpublished.
- [4] E. Buks and M. L. Roukes, JMEMS 11, 802 (2002).
- [5] R. Lifshitz and M. C. Cross, Phys. Rev. B 67, 134302 (2003).
- [6] O. Gottlieb, unpublished.
#### ID of Contribution: 19 - 101

## NEAR-GRAZING DYNAMICS IN TAPPING-MODE ATOMIC FORCE MICROSCOPY

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Nanostructured materials and devices can be endowed with novel physical properties that make them suitable for a wide range of applications. Carbon nanostructures exhibit hydrogen-adsorbing characteristics that make them attractive candidates as hydrogen storage devices. Similarly, self-assembly of ferromagnetic nanoparticles is a promising technique for producing high-density magnetic data storage devices and biomedical materials with desirable surface properties.

Characterization techniques of carbon nanotubes through electron microscopy are tedious and destroy the sample integrity. Similarly, as many of the structures resulting from self assembly of nanoparticles are soft and fragile, their topography can be damaged by the use of conventional nanoscale materials characterization instrumentation.

Less destructive characterization is possible using scanning-probe microscopy, e.g., intermittent-contact (TappingModeTM) atomic-force microscopy. Here, however, nonlinear effects due to large variations in the force field on the probe tip over very small length scales and the intermittency of contact may induce strong dynamical instabilities. These can result in a sudden loss of stability of low-contact-velocity oscillations of the atomic-force-microscope tip in favor of oscillations with high contact velocity and destructive, nonrepeatable, and unreliable characterization of the nanostructure.

In tapping-mode microscopy, the onset of instability can be traced to a critical choice of values for system parameters, for which a periodic trajectory exists that achieves zero-normal-velocity (grazing) contact with a system discontinuity. Dynamical-systems methods for the analysis of mechanical and physical systems with intermittent contact can be employed to formulate normal-form descriptions of the near-grazing dynamics that capture the destabilizing effects of contact (cf. [1, 2], but see also [3]). In particular, near-grazing dynamics can be analyzed through the introduction of a discontinuity mapping that i) captures the local dynamics in the vicinity of the grazing contact including variations in time-of-flight to the discontinuity and the contact behavior; ii) can be entirely characterized by conditions at the grazing contact; iii) is nonsmooth in the deviation from the point of grazing contact; and iv) can be studied to arbitrary order of accuracy.

In this paper, a discontinuity-mapping analysis is employed to investigate the near-grazing dynamics in a lumped-mass model of an oscillating atomic-force-microscope cantilever tip interacting with a sample surface. Here, surface interactions are modeled through a combination of the attraction due to Van-der-Waals forces and the repulsion due to Pauli and ionic exclusion. Two different normal forms are derived that capture the critical transition between noncontact oscillations that experience only surface attraction and intermittent-contact oscillations that also experience the repelling response of the sample. The analysis predicts the loss of stability associated with near-grazing contact and suggests ways to suppress such loss through passive redesign and active control.

- Dankowicz, H., Nordmark, A.B., 'On the origin and bifurcations of stick-slip oscillations,' Physica D 136(3-4), pp. 280-302, 2000.
- [2] Di Bernardo, M., Budd, C.J., Champneys, A.R., 'Normal form maps for grazing bifurcations in n-dimensional piecewise-smooth dynamical systems,' Physica D 160(3-4), pp. 222-254, 2001.
- [3] Van de Water, W. Molenaar, J., 'Dynamics of vibrating atomic force microscopy,' Nanotechnology, 11, pp. 192-199, 2000.

## PARAMETRIC IDENTIFICATION OF PIEZOELECTRIC MICRO-SCALE RESONATORS

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In this study, the nonlinear frequency-response behavior of piezoelectric micro-scale resonators is examined. Data collected from micro-resonators has been seen to display classic Düffing-oscillator type hardening behavior. A nonlinear parametric identification scheme is developed and applied to the data collected from these resonators. Parameter values obtained from multiple sets of data are also used to characterize trends with respect to various input signals and environmental conditions.

Piezoelectrically actuated micro-scale resonators [1] are attractive for communication and signal processing applications. Within this study, thin film lead zirconate titanate (PZT) is employed as the piezoelectric material for driving and sensing. These devices utilize the electromechanical coupling and the dynamic characteristics of the structure to filter the input signal. As pointed out in recent work [2] these resonators exhibit nonlinear characteristics, some of which may be explained as oscillations about a non-flat equilibrium position caused by buckling. The identification method developed within this paper makes use of an approach similar in some respects to previous work [3] on characterization of MEMS devices. A Düffing oscillator model is used to obtain the linear and nonlinear parameter values for the micro-structures. Within this method i) the parameter values are determined solely from the nonlinear frequency-response curves, ii) the stability information is used, and iii) the procedure is applied to piezoelectric resonators and provides residual stress information. This method also uses data that is easier to obtain than previous method.

To develop a parametric model, a nonlinear Euler-Bernoulli beam model is selected to model the resonators. Assuming single-mode oscillations, use of the Galerkin procedure produces a forced Düffing oscillator with a cubic nonlinearity. Perturbation techniques are used to obtain an approximation of the solution which in turn yields the nonlinear frequency-response equation. Least squares minimization is then used to fit the analytical frequency-response curve to the data. The basis for this approach is obtained from the work of Nayfeh and Balachandran. A finite element model of the resonator is also used to obtain additional system parameters. The parameter values obtained are compared with theoretical values calculated from the nonlinear Euler-Bernoulli beam model and good agreement is seen. The sensitivity of the various system parameters such as the damping coefficient, the linear stiffness coefficient, and the nonlinear stiffness coefficient to the input signal level and the environmental conditions are also examined using the developed identification scheme.

With the application of this nonlinear parametric identification scheme to micro-scale resonators, behavior of their system parameters can be better understood as well as how they relate to their macro-scale counterparts. This insight into the behavior of the resonators will enable improved designs and optimized performance.

- [1] D. DeVoe, Sensors and Actuators, 88 (2001) pp. 263-272.
- [2] B. Balachandran and S. Preidikman, Progress in Computational Structures Technology, Saxe-Coburg, Ch. 13, pp. 327-352, 2004.
- [3] F. Ayela and T. Fournier, Meas. Sci. Technol., 9 (1998) pp. 1821-1830.

#### ID of Contribution: 19 - 240

## **BUCKLING INSTABILITIES IN COUPLED NANOBEAMS**

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We consider the bending of two nanotubes coupled together with Van der Waal forces acting transverse to the axis, and subject to axial loads. The nanotubes are modeled as elastica while the interaction forces are derived from a Lennard-Jones 12-6 potential. The elastica are assumed to be a fixed distance apart at their ends, not necessarily equal to the equilibrium distance as identified from the Lennard-Jones potential. Therefore, the equilibrium configuration is not necessarily straight. As the compressive axial increases the beams can undergo buckling instability and the critical load depends not only on the material properties of the structure, but the geometry of the system as well.

The continuum model is subjected to a Galerkin reduction to develop a reduced set of equations that can be used to calculate the equilibrium configuration of the system as well as the stability of these configurations. We show that the buckling instability in this model is significantly affected by the presence of the interaction force as well as the separation of the nanotubes at their ends.

ID of Contribution: 19 - 293

## STABILIZATION OF ELECTROSTATICALLY ACTUATED MICROSTRUCTURES USING PARAMETRIC EXCITATION

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Electrostatically actuated microstructures are inherently nonlinear and can become unstable. Pull-in instability is encountered as a basic static instability mechanism. We demonstrate, analytically, numerically and experimentally, that the parametric excitation of a microstructure by periodic (AC) voltages may have a stabilizing effect and permits an increase of the steady (DC) component of the actuation voltage beyond the pull-in value.

The interest of investigators in parametrically excited microstructures; [1] is explained mainly by applications where the resonant amplification is beneficial or, in contrast, should be avoided. In the present work the emphasis is on the dynamics of the parametrically excited microstructure near and beyond the static instability point. We investigate the applicability of the well-established theory of parametric excitation to the stability study of electrostatic microstructures. It should be noted that while the influence of high-frequency excitation on the dynamics of macro-scale structures was the subject of many investigations [2, 3], the practical realization of this approach in real engineering systems is somehow difficult since it requires integration of active actuating elements. In micro scale systems, actuating elements are usually an integral part of the system while implementation of feed-back is complicated by the small amplitude of output signals.

An elastic string and a cantilever beam actuated by continuously distributed electrostatic forces are considered in order to illustrate the stabilizing influence of fast-scale excitation on the slow-scale behavior. Since the electrostatic force acting on the microstructure is proportional to the square of the actuation voltage, a term proportional to twice the AC voltage frequency appears in the equation. Boundaries of the stability regions given by the damped Hill equations are obtained by the harmonic balance method and mapped into the space of physical parameters, namely excitation (AC) voltage and frequency. Theoretical results are verified by numerical analysis of microstructures subject to nonlinear

#### ENOC-2005, Eindhoven, the Netherlands

electrostatic forces and squeeze film damping. The computations are performed by using Galerkin decomposition with undamped linear modes as base functions. Parametric stabilization of a cantilever beam is demonstrated experimentally and stability regions are mapped on the voltage-frequency plane. Agreement between the experimental and theoretical results is observed.

The work is relevant to a large variety of applications where simultaneous application of AC and DC voltages is common including RF devices, switches, mass sensors, and nano-resonators. The advantage of open-loop stabilization is particularly meaningful in nano-devices where the realization of feedback sensing is difficult due to the very small amplitudes of output signals.

#### References:

- [1] Napoli, M. Baskaran, R. Turner, K. L. and Bamieh, B. (2003) "Understanding mechanical domain parametric resonance in microcantilevers," Proc. IEEE Sixteenth International Annual Conference on MEMS (MEMS' 2003) 169–172.
- [2] Blekhman, I. I. and Perelman, M. (1999) Vibrational Mechanics: Nonlinear Dynamics Effects, General Approach, Applications (World Scientific Publishing Company).
- [3] Thomsen, J. J. (2003) "Theories and experiments on the stiffening effect of high-frequency excitation for continuous elastic systems," J. of Sound and Vib. 260 117–139.

ID of Contribution: 19 - 307

## NONLINEAR ANALYSES FOR THE DYNAMICS OF MICROCANTILEVERS IN TAPPING MODE ATOMIC FORCE MICROSCOPY

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In this talk I present my recent results of Refs. [1,2] on atomic force microscopy microcantilevers tapping on samples. A single-degree-of-freedom system is adopted as a theoretical model and tip-surface interaction is represented by the Van der Waals and Derjaguin-Muller-Toporov (DMT) contact forces. In particular, an analytical framework to describe nonlinear oscillations, including their stability, bifurcations and chaos, due to the DMT force is given. When the distance between the tip and sample surface is relatively large and the Van der Waals force has only a secondary influence on the dynamics of the microcantilever, theoretical explanations for some findings of numerical computations and experimental measurements in the previous work are given. Moreover, when the tip is closer to the sample surface and the Van der Waals force has a primary influence, it is shown that abundant bifurcation behavior and chaotic motions occur.

The analytical techniques used here are the averaging method, an extended version of the subharmonic Melnikov method; [3], and the homoclinic Melnikov method. Necessary computations for the subharmonic and homoclinic Melnikov methods are performed numerically. Numerical bifurcation analysis results by the computer softwares AUTO and HomMap and numerical simulation results by the computer software Dynamics are also given to demonstrate the theoretical results.

- [1] K. Yagasaki, Nonlinear dynamics of vibrating microcantilevers in tapping mode atomic force microscopy, Physical Review B, in press.
- [2] K. Yagasaki, Bifurcations and chaos in tapping mode atomic force microscopy, in preparation.
- [3] K. Yagasaki, The Melnikov theory for subharmonics and their bifurcations in forced oscillations, SIAM J. Appl. Math., 56 (1996), 1720-1765.

## NONLINEAR MODELING OF NOVEL MEMS RESONATORS

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Micromechanical resonators constitute a key component of many microelectromechanical systems (MEMS) devices such as accelerometers, pressure and temperature sensors, microvibromotors for controlled movement at small scale, and in radio frequency (RF) filter systems such as hand-held communicator devices. Geometric and inertial nonlinearities due to structure as well as the nonlinearities due to actuation mechanisms play important role in the dynamics of these microstructures. Younis and Nayfeh [1] in a recent study stressed the importance of accounting for nonlinearities in modeling Microsystems.

The objective of this study is to propose innovative and novel micro-resonator designs which utilize the internal resonance phenomenon. Specifically, motivated by structures designed on macro scale, we design and model microstructures that exhibit various quadratic nonlinearities, and are thus candidates for 1:2 internal resonance between the various degrees of freedom. For example, Balachandran and Nayfeh [2] carefully modeled a L-beam structure designed to have 1:2 internal resonance between the first two modes and compared the simulation results with experimental results. In such a system the directly excited mode at higher frequency, f, in turn excites a lower frequency mode with frequency f/2 due to quadratic nonlinear coupling between the two modes. This phenomenon of nonlinear modal interactions and transfer of energy between modes has been utilized for designing autoparametric vibration absorber. See Vyas et al. [3] for a recent study.

For the system with 1:2 autoparametric internal resonance, the lower-frequency mode undergoes large-amplitude oscillations due to parametric resonance, and thus its response exhibits very strong frequency selectivity. This parametric resonance with the accompanying high-amplitude response is exploited in this study to develop autoparametric MEMS resonators. Plausible microstructure designs include a micro L-beam structure and a micro T-beam structure. For these designs, nonlinear structural models are carefully developed. These models account for geometric and inertial structural nonlinearities, as well as nonlinearities that arise due to the electrostatic actuation [1]. For the resulting nonlinear models, multi-mode approximations are being created to simulate and study the response of the microsystems. The resulting equations are being studied for their nonlinear responses using the asymptotic method of averaging or the method of multiple time scales. The effects of system design parameters will be studied to explore the potential of internal resonance based microstructures. It is believed that these microstructures hold great potential from the applications perspective because of their unique characteristics of high frequency-selectivity and the expected high quality factors.

- [1] Younis, M.I. and Nayfeh, A.H., "A Study of the Nonlinear Response of a Resonant Microbeam to an Electric Actuation", Nonlinear Dynamics, vol. 31, pp. 91-117, 2003.
- [2] Balachandran B., and Nayfeh, A.H., "Nonlinear Motions of a Beam-Mass Structure", Nonlinear Dynamics, vol. 1, pp. 39-61, 1990.
- [3] Vyas A., Bajaj A.K. and Raman A., "Dynamics of Structures with Wideband Autoparametric Vibration Absorbers Theory", Proc. Royal Society of London, vol. 460, No. 2046, 2004.

#### ID of Contribution: 19 - 346

## CONTROL OF HOMOCLINIC BIFURCATION OF A NONLINEAR THERMOELASTIC ELECTRODYNAMICALLY ACTUATED MICROBEAM

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Some aspects of the nonlinear dynamics and control of a Micro-Electro-Mechanical System (MEMS) are investigated. MEMS are a new technology which exploits existing microelectronics infrastructures to create complex machines with micron feature sizes. These machines have many functions, including sensing and actuation, and extensive applications. At this scale, inertia and gravity forces can be comparable with the atomic and surface forces, and specific dynamics interactions must be considered. However, MEMS are often constituted by standard structural elements such as (micro)beams and (micro)plates.

Recently, Gottlieb and Champneys [1] proposed a model of a thermoelastic microbeam for a MEMS sensor subject to electrodynamic actuation. They obtained the two-field PDEs taking into account nonlinear membrane stiffness and a thermoelastic field, and focus on single mode two-field dynamics. The three resulting ODEs are Hamiltonian plus perturbations due to electrodynamic force, viscoelastic damping and thermoelastic dissipation. The Hamiltonian has the typical  $(1-x)^{-1}$  singularity which is observed also in other MEMS [2], and entailing a single-well potential surrounded by the homoclinic loop of an hilltop saddle. The Melnikov method for determining the homoclinic bifurcation in the presence of perturbations is applied and the resulting threshold is used for estimating from below the escape from the potential well, which represents the collapse of the beam, herein corresponding to the beam pulled into the substrate.

In this work the problem of controlling the homoclinic bifurcation of Gottlieb and Champneys' model is considered. A method previously developed in [3] and based on shifting the bifurcation threshold by optimally modifying the excitation shape is employed.

The exact reduced order model is addressed first. In spite of the fact that the unperturbed homoclinic loop can be written analytically in implicit form, the Melnikov function cannot be computed analytically. Therefore, it has to be computed numerically, by solving the optimization problem providing the best excitation shape.

Then, the control method is applied to a polynomial third order approximation of the actual reduced order potential, still proposed by Gottlieb and Champneys, which permits analytical computation of the Melnikov function. The resulting model is governed by the Helmholtz equation, to which the control method was previously applied [3]. These results are recalled and then applied to the considered case, and the mechanical consequences discussed in depth.

Finally, to balance the opposite features of the previous two models (exact with numerical control versus approximate with analytical control), a fifth order polynomial approximation of the potential is considered, with the aim of improving the accuracy of the escape threshold estimation, by still pursuing an analytical treatment.

- Gottlieb, Champneys, 2004, "Global bifurcations of nonlinear thermoelastic microbeams subject to electrodynamic actuation," Proc. IUTAM Symposium "Chaotic Dynamics and Control of Systems and Processes in Mechanics", 8-13 June 2003, Rome.
- [2] Zhao, Dankowicz, Reddy, Nayfeh, 2004, "Modelling and simulation methodology for impact microactuators," J. Micromech. Microeng., 14, 775-784.
- [3] Lenci, Rega, 2003, "Optimal control of homoclinic bifurcation: Theoretical treatment and practical reduction of safe basin erosion in the Helmholtz oscillator", J. Vibr. Control, 9, 281-316.

#### ID of Contribution: 19 - 400

## EFFECT OF TEMPERATURE AND GEOMETRIC NONLINEARITY IN MEMS-BASED DIAPHRAGM DEVICES MODELING

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MEMS-based diaphragm devices constitute more than 50 percent of the MEMS-based devices. Examples are microsensors, micropumps, microvalves, and a class of microswitches. Structural modeling of these devices is one of the major interests to designers and analysts. In this paper, we model the diaphragm in a general model that can lend itself to linear and nonlinear forms. Then we solve the model using reduced-order model based on Galerkin approximation. The solution is carried out to calculate the structural response of the diaphragm, in which we study the influence of nonlinearity upon the deflection od diaphragms under electrostatic loading. Finally, we conclude by studying what we can gain from the linear approach and what we miss.

ID of Contribution: 19 - 402

## MODELLING OF MICRO/NANO ELECTROMECHANICAL SYSTEMS WITH STATE-SPACE DILATION AND CONTRACTION

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Many micro/nano electromechanical dynamic systems whose structures may vary due to reconfiguration, self-assembly, aggregation, decomposition, and changes in their degrees of freedom. The mathematical modelling of such systems leads naturally to dynamical systems or semi-flows with state-space dilation and contraction. This paper considers the modelling and analysis of this class of systems. To illustrate the basic ideas, a variable structure micro-electromechanical system and a molecular dynamic system involving the formation and breakup of atom chains are discussed first. Then, mathematical models for more general systems are formulated in terms of the classical Lagrange equations along with the introduction of two specific types of state-space dilation and contraction, namely, sequential and conditional state-space dilation/contraction. The former type involves an increase/decrease in the state-space dimension is governed by certain prescribed time instants, while in the latter type, the change in the state-space dimension is governed by certain prescribed conditions depending on the system state. The notions of invariant sets and their stability in the sense of Lyapunov are extended to this class of systems. The applications of their notions are illustrated by a few examples derived from reconfigurable micro-electromechanical systems,

ID of Contribution: 19 - 423

## GENERALIZED PARAMETRIC RESONANCE IN ELECTROSTATICALLY-ACTUATED MICROELECTROMECHANICAL SYSTEMS

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Parametric excitation arises quite naturally in many microelectromechanical (MEM) systems, due to the nature of electrostatic actuation. In this work we consider the response of a simple microelectromechanical (MEM) oscillator that is electrostatically driven by a non-interdigitated comb drive. The equation of motion that characterizes this system is

ENOC-2005, Eindhoven, the Netherlands

relatively simple; it is a harmonic oscillator with a nonlinear mechanical restoring force and nonlinear electrostatic actuation and restoring forces, which due to their dependence on the oscillator's position, result in an effective parametric excitation that acts on both the linear and nonlinear terms of the equation. (This is in contrast to the case of purely linear parametric excitation, which occurs in the nonlinear Mathieu equation.) This simple, yet fundamental, difference significantly complicates the response in a manner that has been experimentally observed, yet not previously explained. Specifically, it is observed that the effective nonlinearity for the overall system depends in a qualitative manner on the amplitude of the excitation. In fact, the system has distinct effective nonlinearities for each branch of its nontrivial response, and these change in a qualitative manner as the amplitude varies. As such, the system can exhibit not only hardening and softening nonlinearities, but also mixed nonlinearities, wherein the response branches in the system's frequency response bend toward or away from one another near resonance. In addition, the interaction between the nontrivial branches can be quite intricate, and even involve global bifurcations. The presentation includes a brief derivation of the equation of motion under consideration, an outline of the analytical techniques used to reach the aforementioned results, detailed stability and bifurcation results for the system response, numerical simulations using data from an actual device, and experimental observations which clearly demonstrate the analytically predicted behavior. Relevant issues pertaining to the practical design of parametrically-excited MEM devices are also considered.

#### ID of Contribution: 19 - 464

## A QUASI-CONTINUUM APPROACH TO NONLINEAR DYNAMICS OF NANORESONATORS: THEORY AND EXPERIMENT

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Nonlinear response of a very-high-frequency nanoresonator has been documented recently [1]. The experiment consisted of a clamped platinum nanowire (with length and diameter of 1.3microns and 43nm respectively) that was subject to periodic agnetomotive excitation in a low damping environment (Q~8500). Indirect measurements of the motional impedance revealed a classical hardening frequency response centered about a primary resonance of 105 MHz. This response which included coexisting bi-stable solutions, is typical of a clamped beam with nonlinear membrane stiffness. Calculation of the system first natural frequency based on simple beam theory gave a bad prediction of 64 MHz. This mismatch was qualitatively explained by the authors via differential contraction of the beam and substrate which could cause the beam to be under tension. While the additional axial force would increase the predicted natural frequency, there was no attempt to compare the measured results with those of a more complex beam-string theory or to identify the governing mechanisms responsible for the nonlinear phenomena.

Thus, we present a comprehensive nonlinear beam-string boundary-value problem which consistently incorporates the geometric nonlinearity with the nonlinear contributions of both magnetomotive excitation and viscoelastic damping. Asymptotic and numerical results reveal that a comprehensive quasi-continuum approach enables bridging the gap between theory and measurements and further reveal the importance of instabilities leading to spatial periodic and aperiodic whirling nanowire dynamics that are well known in large scale systems [2]. The derivation, solution and validation of theoretical quasi-continuum based dynamical systems for nanoelectromechanical devices is essential for the development of very-high-frequency nanoelectromechanical systems (NEMS) which can exhibit complex and perhaps chaotic dynamics [3], particularly as atomistic and even molecular based multi-body numerics, are so computationally intensive that they are not yet practical alternatives.

- [1] Husain, A. et al., Appl. Phys. Lett., 83, 1240-1242, 2003.
- [2] Leamy M.J., Gottlieb O., J. Sound and Vib. 236, 683-703, 2000.
- [3] Scheible D.V., Erbe, A., Blick R.H., Appl. Phys. Lett., 81, 1884-1886, 2002.

# **MINI-SYMPOSIUM 20**

## Nonlinear Dynamics and Control of Vehicle Systems

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#### ID of Contribution: 20 - 036

## INFLUENCE OF WHEEL/RAIL CONTACT GEOMETRY ON THE BEHAVIOUR OF A RAILWAY VEHICLE AT STABILITY LIMIT

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Stability assessment plays an important role in railway vehicle dynamics. Bogie stability possesses safety relevance, as the evolving high lateral forces between wheel and rail could cause track shifting which in turn could lead to derailment.

Stability behaviour is highly sensitive to the non-linear conditions of wheel/rail contact. The paper analyses the nonlinearity of the contact geometry wheelset/track and its influence on the behaviour at the bogie stability limit. Several possible methods for non-linear stability analysis are presented [1]. The simulations are carried out in the simulation tool Simpack with a completely non-linear model of a four-car articulated vehicle. Irrespective of the method applied it can be demonstrated that, at the stability limit, either a limit cycle with a large amplitude manifests itself abruptly, or a limit cycle with very small amplitude develops first, whereby the amplitude then only slowly accumulates with increasing speed. This behaviour also demonstrates itself in the different forms of the bifurcation diagrams.

The differing behaviour at the stability limit will be analysed in conjunction to the linearised parameters of the wheel/rail contact. The so-called equivalent conicity and the linearisation peculiarities of the contact geometry wheelset/track will be annotated. The equivalent conicity can attain various progressions in the function of amplitude. Whereas the conicity at the wheel flange contact achieves high values in any case, the progression within the gauge clearance demonstrates either an increasing or decreasing form. In the investigated examples regularity was observed as follows: at contact geometry with increasing conicity in the lateral amplitude range of up to approx. 3 mm, an abrupt limit cycle with large amplitude occurs at the stability limit. Conversely, the contact geometry with decreasing conicity in the lateral amplitude range of up to approx. 3 mm leads to a limit cycle with a minor amplitude which only accumulates slowly at an increasing speed. Should the equivalent conicity for the individual amplitudes be carried out and the linear critical speed for the linearisation parameters be calculated, we achieve similar values to those demonstrated in the bifurcation diagram.

The linearisation of the wheel/rail contact geometry indicates the behaviour to be anticipated at the stability limit. Both the form of conicity reliance on the lateral amplitude as well as the behaviour of the vehicle at the stability limit is dependent on the wheel and rail geometry. These correlations will be commented in more detail in the paper as well as being illustrated in examples.

The analysis of the contact geometry wheelset/track may not only serve as input for the linearised calculation, but also imply behaviour at the stability limit, thereby enabling a better understanding of the non-linear calculations and measuring results.

#### References:

 Polach, O., Vetter, A.: Methods for running stability prediction and their sensitivity to wheel/rail contact geometry. Extended abstracts of the 6th International Conference on Railway Bogies and Running Gears, Budapest, 13-16 Sept., 2004, pp. 62-64

#### ID of Contribution: 20 - 123

## NONLINEAR STABILIZATION CONTROL OF THE HUNTING MOTION BY USING NONLINEAR FEEDBACK

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Railway wheelset experiences the problem of hunting motion above a critical speed, which is known a flutter-type self excited oscillation. It is clarified that Hopf bifurcation is produce at the critical point and the nonlinear characteristic is subcritical. Therefore, the stability of the wheelset depends on the magnitude of disturbance . Even if the running speed is below the critical speed which is obtained from the eigenvalue analysis (linear theory), the hunting motion can be produced. In his research, we propose a control strategy base on nonlinear feedback so that the occurrence of the hunting motion can be avoided regardless of the magnitude of disturbance. We consider a simple model of wheelset. Taking into account the cubic nonlinearity of the contact force, we express the equations of motion governing the lateral and yawing motion of the wheelset. We perform reduction to obtain lower dimension system by using center manifold theory and normal form method. Then the nonlinearity of the Hopf bifurcation at the critical speed is characterized by the coefficient of cubic term of the normal form and the bifurcation results in subcritical one.

To realize the stable system even in the case when the disturbance is large, we change the sign of the cubic term to change the subcritical into supercritical by using nonlinear feedback whose gain is design on the center manifold. As a result, stable wheelset is realized.

Furthermore, we conduct experiments by a simple apparatus. The validity of the theoretically proposed control method is confirmed.

#### ID of Contribution: 20 - 144

## **MECHANISMS TO GENERATE BRAKE SQUEAL**

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Due to increased interest of car customers in comfort features, brake squeal has become a major concern to brakesuppliers. Even though this problem has extensively been studied with various analytical and experimental methods, there is still no complete theory covering all properties of brake squeal, and hence no solution is found to develop a silent brake from an early design stage.

This paper intends to grow understanding of the phenomenon of brake squeal that is caused by friction induced vibrations. Basic mechanism being capable to lead to instability, which stands for squeal generation, are: i) A friction characteristic decreasing with increasing relative velocity; ii) nonconservative restoring forces; iii) fluctuating normal forces, and iv) deformation of the brake disc due to mechanical load. In nonlinear vibration theory, unstable system behaviour can result in a stick-slip vibration, which is treated as a stable limit cycle of a self-excited vibration system. These mechanisms can all be studied using principle models with few degrees of freedom [1].

Regarding the deformation of the disc, a mechanism has been found which describes the coupling of in-plane vibrations caused by friction forces and out-of-plane-vibrations that are leading to sound radiation. This mechanism is strongly

ENOC-2005, Eindhoven, the Netherlands

connected to the effect of fluctuating normal forces, as the pressure in the friction contact varies with the thickness of the brake disc. In the present paper, this phenomenon is investigated using a model of a disc clamped on both sides by springs representing the brake pads. An eigenvalue analysis has been performed to specify the stability boundary of the system. The influence of system parameters like stiffness of the connected springs, geometry of the disc and the coefficient of friction on the system stability is determined by sensitivity analyses.

Further, a multi body system of a brake model has been developed which incorporates several squeal generating mechanisms mentioned above. The influence of each mechanism can be examined separately. A measured friction characteristic is integrated into the system and nonconservative restoring forces, which are identified by an unsymmetrical stiffness matrix of the system, lead to mode coupling. Again a sensitivity analysis was carried out to determine system stability. These analyses conclude in parameter sets which assure stable system behaviour.

References:

[1] Popp, K., Rudolph, M., Kröger, M., Lindner, M., 2002, Mechanisms to Generate and to Avoid Friction Induced Vibrations, VDI-Berichte, 1736, VDI-Verlag Düsseldorf, 1-15.

ID of Contribution: 20 - 150

## NONLINEAR VIBRATIONS OF MOTORCYCLES FORCED BY REGULAR ROAD ROUGHNESS

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In extensive prior work, a virtual motorcycle has been developed. The machine has a very wide range of validity, due to the inclusion of an elaborate tyre force model, suspension and steering limit stops, large excursion kinematics etc. [1]. Firstly, the model is used to show the amplitude dependence of wobble oscillations in a case when the machine design allows unstable motions. Secondly, regular road undulation forcing is applied to the machine and examples of sub-harmonic and super-harmonic responses are shown. Time-frequency signal processing of steer angle and yaw rate histories are used to analyse and clarify the time histories themselves. Some fundamental considerations associated with time-frequency signal processing are exposed. Thirdly, knowledge of nonlinear systems behaviour from low-order systems is used to anticipate those running conditions under which internal and combination resonance vibrations may be expected to occur in the case of the motorcycle. A search procedure for such running conditions is devised, based on solving for trim states over speed and lean angle variations and using the trim state data to solve for small-perturbation stability characteristics. The search is successful when lightly damped modes, having integer frequency relationships, are found. Simulations are set up to correspond to the successful search conditions. Internal and combination resonances oscillatory behaviour. Again time-frequency analysis is used as an aid to understanding the behaviour [2].

The results are placed in a practical context, with a view particularly to revealing to what extent the behaviour contributes to real-life oscillation problems and to what extent it reveals design considerations for the avoidance of problem running circumstances.

- [1] Sharp, R. S., Evangelou, S. and Limebeer, D. J. N., Advances in the modelling of motorcycle dynamics, Multibody System Dynamics, in press.
- [2] Shaeri, A. Theoretical analysis of forced nonlinear oscillations in motorcycles, Imperial College Doctoral Thesis, 2004.

#### ID of Contribution: 20 - 254

## A RIGID BODY ON A SKATE: ANOTHER DEVICE THAT CANNOT STAND STILL BUT BALANCES WHILE MOVING

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Passive mechanical systems that are dynamically stable in statically unstable configurations include tops, a passive bicycle[1], a skateboard with a rigid rider[2], a polygon rolling downhill (in 2D and in 3D), and some simple models of walking[3]. These systems gain their stability by a mixture of having fast-spinning parts, dissipation, having nonholonomic kinematic constraints, having intermittent contact, and having linkages that connect internal degrees of freedom.

The purpose of this work is to find stability of a statically unstable configuration with the fewest number of these features. We study a single three-dimensional rigid body supported by a single-point skate contact on a level plane. Thus there is no dissipation, no fast-spinning parts, no intermittent contact, and no internal linkages and internal degrees of freedom. This system is conservative but non-Hamiltonian because of the nonholonomic skate constraint. The only way to achieve stability is through adjusting the mass distribution.

Using linearized stability analyses and fully nonlinear numerical simulations, we investigate whether such a body can have asymptotically stable motions (in some variables). This system can be thought of as a model of an ice skater on a single ice skate or of a person riding a massless monocycle. Of interest is the possible role of mass distribution for the qualitative dynamics of, say, vehicles, robot, and prosthetic limb designs.

References:

- [1] R. S. Hand, Masters thesis, Cornell University, Ithaca, NY, 1988.
- [2] M. Hubbard, J. Appl. Mech. 46, 931 (1979).
- [3] M. J. Coleman, M. Garcia, K. Mombaur, and A. Ruina. Prediction of stable walking for a toy that cannot stand. Phys. Rev. E, 64(2):22901(3), 2001.

ID of Contribution: 20 - 316

## OPTIMAL AND ROBUST DAMPING CONTROL FOR SEMI-ACTIVE VEHICLE SUSPENSION

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The paper focusses on optimal control issues arising in semi-active vehicle suspension motivated by the application of continuously controllable ERF-shock absorbers. Optimality of the damping control is measured by an objective consisting of a weighted sum of criteria related to safety and comfort which depend on the state variables of the vehicle dynamics model.

In the case of linear objectives and linear quarter or half car dynamics models the well-known linear quadratic regulators can be computed. However, to account for maximum robustness with respect to unknown perturbations, e.g., by the ground, linear robust-optimal H-infinity controllers are investigated which can be computed iteratively.

The linear H-infinity controller can be viewed as the solution of a linear dynamic zero-sum differential game. Thus, a nonlinear H-infinity controller can be obtained in principle as the solution of a nonlinear zero-sum dynamic game problem. Such a problem formulation enables to consider nonlinear vehicle dynamics as well as nonlinear objectives and constraints. A computational method is discussed which computes approximations of robust-optimal trajectories for nonlinear damping control. The method is based on a reformulation of the dynamic game and the application of a control and state parameterization approach in combination with sparse nonlinear programming methods.

Numerical results for the different approaches and their validation by software-in-the-loop simulation using a full motor vehicle dynamics model will be presented and discussed.

ID of Contribution: 20 - 386

## MULTI-OBJECTIVE OPTIMISATION OF VEHICLE MODELS WITH PASSIVE AND SEMI-ACTIVE SUSPENSIONS

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A methodology is presented for optimising the suspension damping and stiffness parameters of vehicle models, subjected to stochastic road excitation. Quarter-car models are first examined. Such models are commonly employed in many areas of the automotive industry. This is mostly due to their simplicity and the qualitatively correct information they provide, especially for ride studies. Also, information extracted from such simple models provides quite frequently a firm basis for more exhaustive, accurate and comprehensive studies with more involved dynamical car models. First, models involving passive damping with constant or dual rate characteristics are considered. Then, models where the damping coefficient of the suspension is selected so that the resulting system approximates the performance of an active suspension system with sky-hook damping are also examined. For all these models, appropriate methodologies are first employed for obtaining the second moment characteristics of motions resulting from roads with random profile. This information is next utilized in the definition of a composite vehicle performance index, which is optimised to yield representative numerical results for the most important suspension parameters. Next, results obtained by applying a suitable multi-objective optimization methodology are also presented in the form of classical Pareto fronts. The study is completed by presenting results obtained from complicated vehicle models. The equations of motion of these models are derived by applying the method of finite elements. Since the resulting number of degrees of freedom is quite large (in the order of a million), appropriate component mode synthesis techniques are first applied. This reduces drastically the dimension of the original system without affecting the accuracy of the calculations within a preselected forcing frequency range.

ID of Contribution: 20 - 420

## DYNAMIC ANALYSIS OF A RAILWAY VEHICLE IN REAL CONDITIONS USING A NEW WHEEL-RAIL CONTACT MODEL

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The dynamic analysis of railway vehicles requires a detailed characterization of the track geometry. In this work, a methodology to create three-dimensional track models, including the perturbations resulting from the track irregularities, is implemented using an appropriate track geometry parameterization. A formulation to parameterize the geometries of the wheel and rail surfaces is also used. The guidance of railway vehicles is determined by a complex

interaction between the wheels and rails. Here, a contact model is proposed to compute the contact forces that are generated in the wheel-rail interface. A new formulation for the identification of the coordinates of the contact points between wheel and rail surfaces, even for the most general three dimensional motion of the wheelset algorithm associated is proposed to support the contact model. This formulation also allows the study of lead and lag flange contact scenarios, which are fundamental for the analysis of potential derailments or for the study of the dynamic behavior in the presence of switches. Furthermore, due to the application of an efficient parameterization procedure this new formulation can be used for any kind of rail or wheel profiles, new or worn, and still be efficient from the computational point of view, without requiring the use of lookup tables. An elastic force model to calculate the normal contact force in the wheel-rail interface is implemented in order to account for the dissipation of energy during contact. The tangential creep forces and moments in the wheel-rail contact area are evaluated using alternatively the Kalker linear theory, the Heuristic nonlinear model or the Polach formulation. The computational tool proposed here is applied to the study of the ML95 trailer vehicle, which is operated by the Lisbon subway company for transportation of passengers. The multibody model of the vehicle is built and its performance is studied in real operation conditions. For this purpose, the existing track between the metro stations of Anjos and Arroios, of the Lisbon subway network, with experimentally measured track irregularities, is considered for the track model assemblage. The accuracy and suitability of the computational tool is demonstrated through the comparison of the dynamic analysis results against those obtained by experimental testing and by the commercial code ADAMS/Rail.

# **MINI-SYMPOSIUM 21**

## Asymptotic Methods in Nonlinear Dynamics

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## COMPLEX DYNAMICS OF A LINEAR OSCILLATOR WITH A NONLINEAR ATTACHMENT

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We study the dynamics of a two-degree-of-freedom (DOF) nonlinear system consisting of a linear oscillator with an essentially nonlinear attachment. We consider first the undamped system and perform a numerical study based on nonsmooth transformations to determine its periodic solutions in a frequency - energy plot. It is found that there is a sequence of periodic solutions bifurcating or emanating from the main backbone curve of the plot. We then study analytically the periodic orbits of the undamped system using a complexification / averaging technique in order to determine the frequency contents of the various branches of solutions, and to understand the types of oscillation performed by the system at the different regimes of the motion. The transient responses of the weakly damped system are then examined, and numerical wavelet transforms are used to study the time evolutions of their harmonic components. We show that the structure of periodic orbits of the undamped system modes in the damped transient motion (more details on this can be found in [1]). In addition, there is the possibility of strong passive energy transfer (energy pumping) [2] from the linear oscillator to the nonlinear attachment if certain periodic orbits of the undamped dynamics are excited by the initial conditions. This is studied in more detail in [3].

References:

- [1] Complicated Dynamics of a Linear Oscillator with a Light, Essentially Nonlinear Attachment, Y. Sup Lee, G. Kerschen, A.F. Vakakis, P.N. Panagopoulos, L.A. Bergman, D.M. McFarland. Physica D (under review).
- [2] Energy 'Pumping' in Nonlinear Mechanical Oscillators II: Resonance Capture 2001. A.F.Vakakis, O.Gendelman. Journal of Applied Mechanics Vol. 68, No. 1, pp. 42-48.
- [3] Irreversible Passive Energy Transfer in Coupled Oscillators with Essential Nonlinearity, G. Kerschen, Y. Sup Lee, A.F. Vakakis, D.M. McFarland, L.A. Bergman. SIAM Journal on Applied Mathematics (under review).

ID of Contribution: 21 - 037

## CONSTRUCTION OF HOMO- AND HETEROCLINIC TRAJECTORIES IN DYNAMICAL SYSTEMS BY USING THE PADÉ APPROXIMANTS

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A formation of homo- or heteroclinic trajectories (HT) is a criterion of the chaos onset in dynamical systems [1 et al.]. Note that for a construction of HT it is necessary to determine some important parameters, in particular, initial values of the solutions. In most cases authors of last and recent publications on the HT construction make use of the well-known Melnikov condition [1 et al.] which gives us a single equation for a determination of all unknown parameters. As a result, the separatrix trajectories of the corresponding autonomous equations have to be utilized. A problem of effective analytic approximation of HT in non-autonomous systems is not solved up to now. Here a new approach for the HT construction in dynamical systems is proposed. Pade' approximants (PA) and quasi-Pade' approximants (QPA) which contain powers of some parameter and exponential functions are used for a representation both the HT trajectory in

ENOC-2005, Eindhoven, the Netherlands

phase space, and the corresponding time solution. Note that the phase trajectory can be obtained, if the original equation is multiplied by a derivative of unknown variable and then integrate along the trajectory within limits from the initial time to infinity.

The necessary condition of the PA or QPA convergence used earlier in theory of the non-linear normal vibration modes [2] is the following: a sequence of determinants of linear algebraic systems to obtain coefficients of the PA or QPA tends to zero if an order of the approximants tends to infinity. Besides, it is possible to utilize the convergence condition to determine some unknown parameters in local expansions. The convergence condition as well conditions at infinity made possible to solve the boundary-value problem formulated for the HT and evaluate initial values with admissible precision.

The proposed procedure leads to a system of nonlinear algebraic equations to obtain unknown parameters of HT, which is solved by using the Newton method. For the HT construction it is not necessary to use the HT zero approximation. Concrete results on the HT construction were obtained for the following dynamical systems: the nonautonomous Duffing equation, a self-oscillating system with cubic nonlinearity, a parametrically excited nonlinear pendulum, a system with a discontinuous friction characteristic, a system containing an essential nonlinear absorber with three equilibrium positions, under periodical external force. Checking numerical calculations of the HT with initial amplitude values obtained from the algebraic equations show an acceptable precision of the proposed analytical approximations. Moreover, boundaries of the chaotic behaviour regions are obtained.

References:

- [1] Guckenheimer J, Holmes P. Nonlinear oscillations, dynamical systems and bifurcations of vector fields. New York: Springer-Verlag; 1993.
- [2] Vakakis AF, Manevich LI, Mikhlin YuV, Pilipchuk VN, Zevin AA. Normal modes and localization in nonlinear systems. New York: Wiley; 1996.
- [3] Y.V. Mikhlin, G.V. Manucharyan. Construction of homoclinic and heteroclinic trajectories in mechanical systems with several equilibrium positions. Chaos, Solitons and Fractals 16 (2003), 299-309.

ID of Contribution: 21 - 039

## **QUENCHING OF RELAXATION OSCILLATIONS**

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Stable normal mode oscillations can be undesirable and one of the possibilities for quenching these vibrations is by embedding the oscillator in an autoparametric system. In the case of normal mode vibration generated by a relaxation oscillator we have slow and fast motion which requires us to use low-frequency tuning of the coupled oscillator. The appropriate characteristics of the coupled oscillator are derived by analyzing the corresponding slow manifold. This is illustrated for the Van der Pol relaxation oscillator where we obtain, after embedding in an autoparametric system, a 3-dimensional slow manifold in 4-dimensional phase space. The asymptotic analysis is supplemented by numerical experiments which shows the efficiency of quenching but also suggests the presence of chaotic attractors for various parameter values.

References:

[1] F. Verhulst and Abadi: Autoparametric resonance of relaxation oscillations, to be publ. in ZAMMM, 2005.

303

## ASYMPTOTIC METHODS IN NONLINEAR PROBLEMS OF VIBRATION ABSORPTION AND LOCALIZATION OF ENERGY

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Concept of nonlinear normal modes and asymptotic methods are used to study vibrations of elastic structure attached with a single-DOF nonlinear absorber. Three types of absorbers are considered: an essentially nonlinear oscillator, a snap-through truss and a vibro-impact oscillator.

Dynamics of the system, containing the single-DOF linear oscillator and the essentially nonlinear absorber with a small mass, are studied by the nonlinear normal vibration modes (NNMs) theory [1,3]. In the NNM all position coordinates can be analytically expressed by any one of them. If the localized NNM is stable, and the non-localized one is unstable, the system energy is concentrated in the absorber, and the elastic vibrations absorption takes place. The NNMs trajectories in the system configurational space are determined as power series by a small parameter .

To analyze a stability of the NNMs the algebraization by Ince is used, when a new independent variable associated with the solution is introduced. The obtained results are the following: the non-localized NNM is situated in the instability region for large vibration amplitudes; the localized one is stable for almost all values of the system parameters.

Absorption of the elastic oscillations by means of the shallow snap-through truss is studied. The NNMs, close to one of the stable equilibrium positions, and the snap-through motions are studied. If the snap-through truss has significant vibration amplitudes and the linear oscillator has small amplitudes, and if such motions are stable, it guarantees the vibration absorption.

Small curvature of the NNM is used to analyze their stability. One of the new coordinate which is ortogonal to the trajectory rectilinear approximation defines an orbital stability of the NNM. The variational equation is studied by the multiple scales method.

The forced resonances and its stability are analyzed in such systems. Oscillations close to one of the stable equilibrium position are investigated. Stability of such motions are analyzed by the multiple scales method. In the instability regions the oscillation amplitudes increase and the absorber is fallen into the snap-through motions. The NNMs approach shows that the forced snap-through motions exist in wide range of the forcing frequency, so, the quenching of the forced oscillations takes place.

Analysis of NNMs is realized for the two-DOF system containing the vibro-impact oscillator as absorber. A non-smooth transformation by Pilipchuk is used here.

- [1] Vakakis A., Manevitch L., Mikhlin Yu., Pilipchuk V. and Zevin A. Normal modes and localization in nonlinear systems. New-York: Wiley, 1996.
- [2] Avramov K. and Mikhlin Yu. Snap-through truss as a vibration absorber. Journal of Vibration and Control, 2004, 10 (2), 291-308.
- [3] Mikhlin Yu. and Reshetnikova S. Dynamical interaction of an elastic system and essentially nonlinear absorber. Journal of Sound and Vibration (in press).

## DISCRETE HIGH-FREQUENCY BREATHERS IN ZIGZAG CHAIN

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In spite of growing interest to study of localized nonlinear oscillatory excitations, almost all studies in this field are devoted to straight chains. The reason is that even the simplest realistic models of strongly anisotropic systems turn out to be substantially more complicated than commonly considered one-dimensional models.

We present analytical and numerical study of discrete breathers identified as localized deformations of zigzag chain. It is shown that such breathers can exist in vicinity as well as inside the optic frequency zone and can propagate along the chain with subsonic velocities.

The commonly studied breathers in attenuation zone can be, in principle, linearly stable [1]. However, as it was shown in [2], their nonlinear interaction with extended modes leads to finite times of life in realistic models of nonlinear system. Therefore, in such models there is not qualitative difference between the breathers in attenuation and propagation bands, if naturally they can exist in propagation band at all. From other side, the finite time of life does not mean that such breathers are not physical importance. They can be manifested in different physical properties [3] and their instability relative to interaction with phonons leads to non-monotonous dependence of breathers' contribution with increasing the temperature [2].

To check the validity of assumptions made in the analytical study, we have undertaken a numerical treatment of the breathers' existence as well as their stability in free motions and under collisions. It is shown, using Molecular Dynamics procedure, that initial conditions corresponding to breathers actually lead for all predicted cases to formation of breather-like localized excitations with predicted parameters. They can be both standing and propagating along the chain. These excitations are highly stable and preserve both the form and velocity under collisions.

We integrated also numerically Langevin equations for the zigzag chain to study interaction of breathers with thermal excitations. It turned out that stability of optic breathers with respect to thermal excitations is sufficient to provide their noticeable role in physical processes.

So, the optic breathers, which are localized coupled longitudinal-transversal nonlinear excitations, can exist in zigzag chain. Although approximate analytical solution for breathers has been obtained using a model of isolated chain, we confirmed numerically not only validity of such a model but revealed also that the parameters of breathers change unnoticeably if taking into account interchain interaction. The reason is a weakness of interchain interaction in comparison to intrachain one. Such a weakness is especially clear for optic excitations. The breathers in the system of coupled chains demonstrated stability to collisions and large enough times of life.

- [1] S. Aubry, Physica D, 103, 201 (1997).
- [2] A. V. Savin and L. I. Manevitch, Phys.Rev. B, 67, 144302 (2003).
- [3] L. I. Manevitch, Polymer Science C, 4 (2), 117 (2001).

#### ID of Contribution: 21 - 075

## ANALYTICAL PREDICTION OF CHAOS IN ROTATED FROUDE PENDULUM

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We are aimed to illustrate how the classical Melnikov's technique can be extended to analyse even complex lumped mechanical systems including non-smooth behaviour like those with Coulomb like friction. As an example serves a rotated Froude pendulum harmonically excited. It is assumed that in a place of pendulum fixation the Coulomb friction occurs and that the pendulum pivot rotates with a constant velocity.

The classical Melnikov's technique is used to predict chaotic behaviour in our one-degree-of-freedom mechanical system. The obtained results are verified by numerical experiments. The expected chaotic thresholds are drawn in the control parameter planes. In what follows for one fixed value of the first control parameter the associated critical value of the second control parameter is computed owing to its prediction given by the homoclinic bifurcation condition. Then numerical experiment is carried out using the first control parameter. A range of changes of the bifurcation parameter includes the predicted value of the second parameter owing to the applied Melnikov's method. The numerical verification relies on finding a value of the bifurcation parameter when the homoclinic bifurcation occurs, and on its comparison with the value predicted analytically. In addition, phase portraits and Poincaré maps are used for identification of chaos.

It has been shown that owing to application of the Melnikov's technique, the critical values of the parameter associated with the homoclinic bifurcation have been analytically predicted properly since they have been also identified by the numerical computations. Owing to existence in the non-perturbed system four homoclinic orbits (in the case of relatively high rotating velocity) four analytical chaos criterions have been also computed. The carried out numerical analysis fully coincides with the predicted bifurcations region separated by a periodic window.

References:

- [1] J. Awrejcewicz, M. M. Holicke, Melnikov's Method and Stick-Slip Chaotic Oscillations in Very Weekly Forced Mechanical systems, International Journal of Bifurcation and Chaos, 9(3), 1999, 505-518.
- [2] J. Awrejcewicz, D. Sendkowski, How to predict stick-slip chaos in R4, Physics Letters A, 330, 2004, 371-376.

ID of Contribution: 21 - 079

## EXTERNAL AND INTERNAL RESONANCES IN PARAMETRIC AND SELF- EXCITED SYSTEM WITH LIMITED POWER

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Interactions between vibrations originated by different sources can lead to very interesting phenomena [1]. Particularly, interactions between self- and parametrically excited vibrations produce quasi-periodic motion, but near some resonance regions, the synchronisation of the system frequency is observed as periodic oscillations. If the vibrating model is additionally forced by a harmonic force then, inside the main parametric resonance, new solutions can appear. In such a case, even five coexisting steady states of vibrations are possible. This phenomenon has been observed for one and two degrees of freedom models [1], [2]. Moreover, increase of the parametric excitation transits the system from regular motion to chaos or hyperchaos.

If the system is forced by an energy source with limited power then, due to additional coupling, new dynamic effects appear. Very often, papers devoted to many degrees of freedom systems concern a case when their natural frequencies are incommensurable numbers. Dynamics of the nonlinear system can change radically if its free frequencies ratio is a natural number (internal resonance) [3]. Due to the strong vibration modes interaction, the nature of motion can be

ENOC-2005, Eindhoven, the Netherlands

different. In practical applications, for instance in machining dynamics, this kind of resonance is called 'mode coupling chatter'.

Interactions analysis between parametrically and self-excited vibrations, under the internal resonance condition in the neighbourhood of synchronisation areas, is the main purpose of this paper. Besides, influence of the limited energy source on the safe passage through the resonance region and possible transition of the system to chaotic motion, forced by ideal and non-ideal energy source is investigated as well.

The analysis of the regular motion has been carried out by application of approximate analytical methods. The problem of ideal system has been solved by the asymptotic multiple time scale method, whilst non-ideal problem by Krylov-Bogolubov-Mitropolski method. Transition of the system to chaotic motion has been carried out numerically.

Obtained results show that the synchronisation phenomenon for ideal and non-ideal system differs. Limited power supply causes local decreasing of the amplitude in the synchronisation area and moreover, also decreasing of the excitation frequency. This result shows that for some sets of the system parameter the safe transition through the resonance region can be made difficult due to not enough power supply. Under the internal resonance condition apart from trivial, semi trivial (one-mode) solutions, also non-trivial two mode solutions are possible. Behaviour of the system, approaching to chaotic vibration regimes, under the internal resonance condition changes, comparing to its counterpart without such an assumption.

References:

- [1] Warminski, J., Regular and Chaotic Vibrations of Self- and Parametrically Excited Systems with Ideal and Non-Ideal Energy Sources, (in Polish)., Techn. Univ. of Lublin Publ., Lublin, Poland, 2001.
- [2] Szabelski, K. and Warminski, J., Vibrations of a Non-Linear Self-Excited System with Two Degrees of Freedom under External and Parametric Excitation, Journal of Nonlinear Dynamics, 14 (1997) 23-36.
- [3] Bajkowski, J. and Szemplinska-Stupnicka, W., Internal Resonances Effects Simulation Versus Analytical Methods Results, Journal of Sound and Vibration, 104,2, (1986), 259-275.

ID of Contribution: 21 - 085

## INTERACTION OF SUBHARMONIC AND 1:1 INTERNAL RESONANCES IN 2DOF CUBIC SYMMETRIC SYSTEMS

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Many technical systems, in particular, thin-walled bodies of revolution, have equal or close eigenfrequencies for at least two natural modes, i.e., they are systems with a 1:1 internal resonance. The closeness of eigenfrequencies can essentially influence their nonlinear dynamic behavior under external excitation.

In this presentation the interaction of a 1:1 internal resonance with subharmonic external resonance under harmonic excitation in 2DOF cubic symmetric systems is investigated. This problem for a system consisting of two oscillators with equal eigenfrequencies, having cubic nonlinear coupling, was considered in [1], and some qualitative and quantitative results have been obtained.

Equations of motion are written for the case when generalized displacements are principal coordinates (the linear link between the variables is absent), an external force (of O(1)) is applied to the first degree of freedom, damping coefficients have the order of a small parameter e. The closeness of the eigenfrequencies is specified by a detuning parameter. The second detuning parameter characterizes the difference between the external force excitation frequency and the tripled eigenfrequency for the first degree of freedom.

A complex representation of equations of motion is used to lower the order of differential equations and to simplify the subsequent employing the multiple scales method.

Equations of modulation of the amplitudes and frequencies are obtained, and steady-state solutions of these equations are studied. The behavior of undamped systems is investigated. Alongside with one-mode subharmonic oscillations ('uncoupled' mode) there can exist two-mode subharmonic oscillations ('coupled' subharmonic modes) with

A detailed parametric analysis is carried out. The number of the coupled normal modes, conditions of their existence, frequency response curves and their stability are studied for exact and inexact internal resonances.

#### References:

[1] Vakakis A.F. (1992), Fundamental and Subharmonic Resonances in a System with a 1:1 Internal Resonance, Nonlinear Dynamics, 3, pp. 123-143.

#### ID of Contribution: 21 - 092

## **MODELING AND ROBUST CONTROL OF SMART FLEXIBLE BEAMS**

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The design of intelligent structures requires modelling and simulation techniques to analyze their dynamical behaviour. The phenomenon of piezoelectric materials to transform mechanical energy into electrical energy and vice versa is widely used for monitoring and controlling the structural response. The choice of the control technique is important in ensuring suitable functioning of the structures under required conditions. The main goal of control design is to be built a system that will work in the real environment that may change with time or operating conditions may vary. The work aims are to present design and analysis of active vibration control of externally excited smart structures in presence of uncertainties.

A composite beam laminated with piezoelectric sensors and actuators and subjected to external loads is considered in this paper. First, mechanical modelling of the structure and the subsequent finite element approximation, which is based on Hamilton's principle are presented. Furthermore, the problem of active control is studied. Structured uncertainties addressed to the main physical parameters (mass, damper and stiffness) are introduced to reflect the errors between the model and the reality. The model of the uncertain system is presented in a linear fractional transformation (LFT) framework. The underlying concept within control theory to ensure proper operating of a system in realistic situation is feedback. An active negative feedback control algorithm that couples the direct and converse piezoelectric effects is employed to actively regulate the dynamic response of the beam. This paper considers a practical robust controller design methodology, which is based on recent theoretical results on  $H_2$  and  $H_{\infty}$  control theory. The resulting optimization problem is, in general, nonconvex and admits several local minima. A suboptimal controller is used for numerical modelling. High robust performance and robust stability are achieved. The numerical simulations corroborate that the proposed technique is particularly suited to vibration control problems in flexible structures as smart beams show significant vibration suppression of a laminated beam subjected to different loadings.

- Foutsitzi, G, Marinova, D. G., Hadjigeorgiou, E., and Stavroulakis, G. E. Robust H<sub>2</sub> vibration control of beams with piezoelectric sensors and actuators. Proc. of Int. Conf. on Physics and Control, (St. Petersburg Russia, 20-22 August 2003), v. 1, 157-162.
- [2] Zhou, K. Essentials of robust control. Upper Saddle River, NJ: Prentice-Hall, 1998.

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## DYNAMICS OF A NONLINEAR OSCILLATOR IN CONSIDERATION OF NON-SYMMETRIC COULOMB DRY FRICTION

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In [1] is the motion of two mass points connected by a linear spring discussed. It is supposed that this linear oscillator is under the action of a small non-symmetric Coulomb dry friction force, i.e., the friction force is assumed to change in magnitude depending on the direction of motion. Excitation is carried out by the action of small internal harmonic forces. This oscillator is a mathematical model of a worm-like motion. One recognizes a conversion of periodically internally driven oscillations into a change of external position (undulatory locomotion) in the locomotion of worms.

In this paper, we consider the motion of a system of two equal mass points along a straight line under the action of a small non-symmetric Coulomb dry friction force. The mass points are connected by a non-linear spring with cubical non-linearity. Excitation is carried out in two ways: due to the action of a small internal periodical force and due to a small periodically change of stiffness (a parametric resonance). Such effect arises for example, if the spring, made by a magnetizable elastic material, is under the influence of an external magnetic field [2].

We introduce the system of equations near to the main resonance for the case of a small internal periodic force, and near to the main demultiplication resonance for the case of a parametric resonance. After transforming the system into standard form [3] we apply the procedure of averaging.

We are interested in an approximately steady motion of an oscillator as a single whole, therefore we are looking for a solution with a constant "on the average" velocity. For that purpose we analyse the position and stability of some special points on a phase cylinder. In presence of internal excitation and non-symmetric Coulomb dry friction a motion of the oscillator with a constant "on the average" velocity is possible. The algebraic equation for this constant velocity is found.

For different parameters of the model there exist at most three regimes of motion with a constant velocity, but only one of them is stable. In the case of a parametric resonance there are no stable motion schemes. The obtained theoretical results can be used for the design of worm-like moving robots.

- [1] Zimmermann K., Zeidis I., Steigenberger J., Pivovarov M.: An Approach to Worm-Like Motion. 21-st International Congress of Theoretical and Applied Mechanics, Warsaw, Poland, August 15-21, Abstracts Book, p.371, 2004.
- [2] Turkov V.A.: Deformation of an elastic composite involving a magnetic fluid. J. Magnetism and Magnetic Materials, v. 252, p. 156-158, 2002.
- [3] Arnold V.I., Kozlov V.V., Neishtadt A.I.: Mathematical Aspects of Classical and Celestial Mechanics. Springer Verlag, 1997.

## DEGENERATE BIFURCATION SCENARIOS IN THE DYNAMICS OF COUPLED OSCILLATORS WITH SYMMETRIC NONLINEARITIES

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We study the degenerate bifurcations of the nonlinear normal modes (NNMs) of an unforced system consisting of a linear oscillator weakly coupled to an essentially nonlinear one [1,2]. Both the potential of the oscillator and of the coupling spring are adopted to be even-power polynomials with nonnegative coefficients. By defining the coupling parameter, the dynamics of this system at the zero limit and for the case of finite coupling is investigated. Bifurcation scenarios of the nonlinear normal modes are revealed. The degeneracy in the dynamics is manifested by a 'bifurcation from infinity' where a saddle - node bifurcation point is generated at high energies, as perturbation of a state of infinite energy.

Another (nondegenerate) saddle - node bifurcation points (at least one point) are generated in the vicinity of the point of exact 1:1 internal resonance between the linear and nonlinear oscillators. The above bifurcations form multiple - branch structure with few stable and unstable branches. This structure may disappear (for certain choices of the oscillator and coupling potentials) by mechanism of successive cusp catastrophes with growth of the coupling parameter.

The above analytical findings are verified by means of direct numerical simulation (conservative Poincaré sections). For particular case of pure cubic nonlinearity of the oscillator and the coupling spring good agreement between quantitative analytical predictions and numerical results is observed.

References:

- [1] O.V.Gendelman, L.I.Manevitch, A.F.Vakakis and L.Bergman, "A Degenerate Bifurcation Structure in the Dynamics of Coupled Oscillators with Essential Stiffness Nonlinearities", Nonlinear Dynamics, 33, 2003, 1-10
- [2] Vakakis, A. F., Manevitch, L. I., Mikhlin, Yu. V., Pilipchuk, V. N., and Zevin, A. A., Normal Modes and Localization in Nonlinear Systems, Wiley Interscience, New York, 1996.

ID of Contribution: 21 - 174

## MODELLING OF INELASTIC IMPACTS WITH THE HELP OF SMOOTH FUNCTIONS

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There exist two well - known essentially nonlinear models for approximate description of the elastic impacts with the help of smooth functions [1]: even - power potential for two - sided impact and inverse - power potential for one - sided impact. It is demonstrated that both models may be generalized to describe the case of inelastic impact with velocity - independent recovery coefficient less than unity. The modification is achieved by adding to each of the model equations another strongly nonlinear dissipative term. Condition of velocity independence leads to unique choice of this term for each model; both resulting equations turn out to be completely integrable despite being non - Hamiltonian. The uniqueness and integrability are proved by means of Lie algebras [2].

Use of modified models for problems in higher dimensions is demonstrated by numeric examples. The results may be generalized for complex potentials used in dynamic models of atomic force microscopy.

- [1] L.I. Manevitch, Yu. V. Mihlin, V.N. Pilipchuk, Normal Vibrations Method for Essentially Nonlinear Systems, Nauka, Moscow, 1989
- [2] P. Olver, Applications of Lie Groups to Differential Equations, Springer Verlag, 2000

#### ID of Contribution: 21 - 179

## TORUS BREAKDOWN AND CHAOTIC BEHAVIOUR IN A SMOOTH AUTONOMOUS SYSTEM

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We study in this paper a 4-d system of coupled oscillators. First, we give a brief description of the flow around the critical points. Then, using the normal form method of averaging, we establish the existence of a periodic solution. This solution undergoes, far beyond the reach of the normal form, a number of bifurcations. We therefore use the software package CONTENT to study these bifurcations. We found that the cycle undergoes a Neimark-Sacker bifurcation, yielding T2 torus. This torus is studied in detail. We establish that, after becoming resonant, the torus breaks down through one period doubling. By numerically following the changes in the involved manifolds, we show, through plots of the poincare section, exactly how this breakdown takes place. This is one of the known scenarios of torus breakdown described by Shilnikov. A cascade of period doublings is also detected within the 1:6 resonance tongue. The strange attractor emerging after the breakdown is as well studied in detail. Also other regimes present in this system are described in detail. Despite its simple form in terms of the differential equations, this system reveals to have very rich and complicated dynamics.

References:

- T. Bakri, R. Nabergoj, A. Tondl, F. Verhulst, Parametric excitation in non-linear dynamics, Int. Journal of Nonlinear Mechanics Vol 39 (2004) 311-329.
- [2] V.S. Afraimovich, L.P. Shilnikov, Invariant Two-Dimensional Tori, Their Breakdown and Stochasticity, Amer. Math. Soc. Transl. (2) Vol 149, 1991.
- [3] Y.A. Kuznetsov, Elements of Applied Bifurcation Theory, 2nd Edition, Springer, New York, 1995.
- [4] F. Verhulst, Nonlinear Differential Equations and Dynamical Systems, Springer, Berlin, Heidelberg, 1996.
- [5] J.A. Sanders, F. Verhulst, Averaging Methods in Nonlinear Dynamical Systems, Springer, New York, 1985.
- [6] D. Ruelle, Elements of differentiable Dynamics and Bifurcation Theory, Academic Press, New York, 1989.

ID of Contribution: 21 - 189

#### STABILIZATION OF PULSES BY COMPETING INSTABILITY MECHANISMS

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The Ginzburg-Landau equation is essential for understanding the dynamics of patterns in a wide variety of physical contexts. It governs the evolution of small instabilities near criticality. It is well known that the Ginzburg-Landau equation has various unstable solitary pulse solutions. Nevertheless, some of these a priori unstable solutions, such as several types of homoclinic pulses, seem to be observable, and thus stable (see [1] and the references therein). This would be in contradiction to the weakly nonlinear stability theory if the observed "patterns" are really governed by the Ginzburg-Landau equation. However, this kind of patterns is observed in systems with two competing instability mechanisms, one with a complex amplitude A that is associated to the Ginzburg-Landau equation and one with a (real) diffusive mode B [1]. The patterns are then described by a Ginzburg-Landau equation coupled to a diffusion equation. This type of interacting instability mechanisms occur naturally in fluid mechanics, bio-chemical systems, geophysical morphodynamics, etc. (see [1]).

From the point of view of analysis, the most feasible setting is that of a mode B that diffuses slowly and is linearly damped. Using methods from geometric singular perturbation theory, it can be shown that the unstable pulse solutions of the uncoupled Ginzburg-Landau equation in that case indeed persist as solutions of the full coupled system. Moreover, a combination of the Evans function approach with (singular) asymptotic methods can be employed to show

ENOC-2005, Eindhoven, the Netherlands

that the effect of the slow diffusion may stabilize the unstable Ginzburg-Landau pulse. However, this diffusive "control mechanism" is quite subtle. The coupling to the B equation has a leading order influence on the eigenvalues of the associated linearized stability problem, but it is necessary to take into account some of the higher-order nonlinearities in the governing (modulation) equation to impose a stabilizing (Hopf) bifurcation on the pulse [1].

The theory as developed so far does not apply to systems in which the mode associated to B is neutrally (un)stable. A priori, this might be seen as a degeneration, however in many of the systems with interacting instability mechanisms, the diffusive mode B indeed is not linearly damped (or driven), but is only marginally (un)stable. This neutral behavior is often due to a (natural) symmetry in the underlying system [1].

The neutral character of the diffusive equation has several non-trivial effects on the structure of the Ginzburg-Landau pulses. For instance, the decay of the pulses becomes algebraic instead of exponential. This important class of patterns has only very recently become the subject of research. Nevertheless, novel methods can be developed by which the stability of these pulses -- and thus the stabilizing effect of competing instability mechanisms -- can be investigated.

#### **References:**

[1] A. Doelman, G. Hek and N. Valkhoff. Stabilization by slow diffusion in a real Ginzburg-Landau system. J. Nonlinear Sci. 14 237-278, 2004.

#### ID of Contribution: 21 - 212

## SHORT WAVELENGTH DYNAMICS OF THE SYSTEM OF NONLINEAR OSCILLATORS COUPLED BY BEAM

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Localized nonlinear normal modes (or breathers) in different oscillatory chains is a subject of growing interest in modern Nonlinear Dynamics [1]. As a rule, the papers in this field, relating to Mechanics, deal with free chains of oscillators coupled by weightless springs. The main goal of our work is to analyse the effects of bending rigidity and static as well as periodic external forces both on existence of the breathers and their stability.

We present analytical and numerical study of short wavelength breathers in unloaded chains of asymmetric nonlinear oscillators coupled by stretched weightless beam. The study is focused on modulations of the nonlinear normal mode with shortest wavelength. A small parameter is introduced as ratio of distance between the particles in the chain and characteristic wavelength of modulation. It is shown that in main asymptotic approach the problem can be reduced to Nonlinear Schrodinger Equation (NSE). Breathers (envelope solitons) are localized oscillating solutions of this equation. We reveal the stability and high mobility of such solutions in their numerical study based on integrating of exact discrete equations of motion.

We present also analytical and numerical study of short wavelength breathers in chains of oscillators loaded by periodic force at free end. We show that the initial equations of motion can be transformed to the form typical for nonlinear unloaded chains. Then we obtain an analytical representation of localized excitation which can be standing or propagating breather. The conditions of the breathers existence were formulated. We found dependence of breather parameters on amplitude and frequency of external force. Numerical simulations confirmed the analytical results. We observed breathers with frequencies in attenuation zones of the system.

#### References:

 Aubry S. Breathers in nonlinar lattices: existence, linear stability and quantization. Physica D 1997; v. 103: pp. 201-250.

#### ID of Contribution: 21 - 214

## HIGH-ORDER VARIATIONAL CALCULATION FOR PERIODIC ORBITS

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Following Ref. [1], we develop a convergent variational perturbation theory for periodic orbits of nonlinear dynamical systems. An optimization with respect to artifically introduced variational parameters allows to convert divergent weak-coupling series for periodic orbits into convergent strong-coupling series. The power of the theory is illustrated by applying it to the frequency and the time-periodic solution of the Duffing oscillator. In both cases we obtain an exponentially fast convergence.

References:

[1] A. Pelster, H. Kleinert, and M. Schanz: Phys. Rev. E 67, 016604 (2003).

#### ID of Contribution: 21 - 220

#### **BIFURCATION OF A SHAFT WITH MASSIVE DISC AND GYROSCOPIC EFFECT**

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The paper is concerned with transverse stability analysis of a flexible rotating shaft supported as a cantilever beam carrying a massive disc and subjected to a tip-concentrated follower load. Such systems work as turbine or compressor rotors and a working medium going thru the blades creates the axial follower load. This leads to generate the tension or compression load in the shafts. The follower load and internal damping in rotation cause dynamic flutter-type bifurcation with two mechanisms of instability and two types of flutter (sub-critical, post-critical), different in physical nature. It is important that the two mechanisms interact producing complicated and unexpected stability regions in the space of rotation speed and follower load.

This paper presents analysis of discrete-continuous system including gyroscopic effect, using boundary conditions as constraint equation between cantilever beam and massive disc. Attention is focused on the influence of the gyroscopic effect on the stability domain and on the near-critical behaviour defined by the second bifurcation coefficient occurring in the Hopf bifurcation theory [1], under interaction of high-speed rotation and tip-concentrated follower load. The present analysis is more precise than analyses in previous research using cantilever beam functions as basic shape functions in discretisation procedures [2]. Transverse shear effect is neglected and the external damping is assumed as linear. The internal damping is described by the Kelvin-Voigt model. The nonlinearity is of geometric type. In similar systems the rotary inertia as well as the gyroscopic effect is usually neglected. However, taking into account results of [3] one can expect that in some regions of parameters, especially in slightly internally dissipative shafts the gyroscopic effect can considerably change the boundaries of the stability domain and the near-critical behaviour.

The massive disc strongly influences the critical rotation speed and the flutter amplitude evolution in the neighbourhood of critical rotation.

An interesting phenomenon observed in analysis is the movement of "fast" and "slow" eigenvalues on the complex plane. It is possible that two eigenvalues with different speeds at the same time intersect the imaginary axis of the complex plane. This leads to bifurcation with four critical eigenvalues.

References:

- [1] Iooss, G., Joseph, D.D., 1980, Elementary Stability and Bifurcation Theory, Springer Verlag, N.Y.
- [2] Kurnik, W., 1994, Stability and Bifurcation Analysis of a Non-linear Transversally Loaded Rotating Shaft, Nonlinear Dynamics, 5, No. 1, 39-52.
- [3] Kurnik, W., Weronko, J., 2003, Optimisation of a flexible cantilever rotor with intermediate support, 5<sup>th</sup> EUROMECH Solid Mechanics Conference, Thessaloniki GREECE, Book Of Abstract, p. 155.

ID of Contribution: 21 - 243

### TORSIONAL OSCILLATIONS IN SYSTEMS WITH COMBINED DRY FRICTION

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It is considered systems with combined dry friction consist of the spring-supported torsion shaft one end of that are bearing to the infinite moving belt. Developed early a principal new model of combined dry friction is applied to modeling the correlations between torsion torque and the kinematical conditions in the contact area of the shaft and belt. Model is based on the replacement of exact integral expressions of the force components and torque by corresponded Pade approximations. This technique significantly simplify problem of the combined dry friction modeling since allows to escape the calculations of double integrals over the area of contact. As distinct from existing models, using of Pade approximations permit to correctly describe correlations between forced and kinematics conditions on the all speed range of the angle and sliding velocities. Cases of circle form of area of contact are investigated in details with the aid of the model of the first and the second order (the order of model is the order of corresponded Pade approximation). The Krilov-Bogolubov method of averaging is used to investigate of equation of motion. Possibility of arising of the self-sustained oscillations is investigated in assumption that the amplitude of oscillations is small. It is shown that partial-linear Pade approximation of combined dry friction based on the Pade approximations can be regarded as a rheological model, then the system under consideration can be used for experimental determination of the model coefficients.

References:

- [1] Zhuravlev, V.Ph. (1998). The model of dry friction in the problem of the rolling of rigid bodies. J.Appl.Math.Mekh.. Vol.62, No.5, pp.762-767.
- [2] Zhuravlev, V.Ph., Kireenkov, A.A. (2005). Pade expansions in problem on two-dimensional Coulomb's friction. Izvt.RAN, MTT[Mechanics of Solids]. No. 2, pp.3-13.

ID of Contribution: 21 - 268

#### NONLINEAR VIBRATIONS OF A MEMBRANE

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Nonlinear free in-plane vibrations of a rectangular plate are studied. The developed asymptotic procedure is based on the introduction of three small parameters. Firstly, the nonlinearity is assumed to be small. Then the solution of zeroorder (linear) boundary value problem is sought in the form of asymptotic expansions with respect to the ratio of stiffness characteristics [1]. In the case of internal resonances the vibration modes occur to be coupled via an infinite system of nonlinear algebraic equations. The approach of artificial small parameter [2] is proposed to solve this system. As the results, approximate analytical expressions for the amplitude-frequency characteristics are derived. Obtained asymptotic solutions are partially verified by comparison with some numerical data.

- [1] Andrianov I.V., Danishevs'kyy V.V., Awrejcewicz J. (2005) An artificial small perturbation parameter and nonlinear plate vibrations. Journal of Sound and Vibrations, to appear.
- [2] Andrianov I.V., Danishevs'kyy V.V. (2002) Asymptotic approach for non-linear periodical vibrations of continuous structures. Journal of Sound and Vibrations 249 (3), 465-481.

ID of Contribution: 21 - 300

## ASYMPTOTIC-BASED DERIVATION OF DISCONTINUITY MAPS FOR NONSMOOTH BIFURCATION ANALYSIS

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In this paper we will discuss a methodology based on a combination of Taylor series expansion and asymptotics for the analysis and classification of bifurcations in nonsmooth dynamical systems. Specifically, the derivation will be discussed of so-called discontinuity maps recently presented in the literature [1], [2], that can be used to construct analytically the system Poincaré map close to a C-bifurcation. This occurs whenever an invariant set interacts nontrivially with the system discontinuity boundaries; for example a limit cycle grazing tangentially the hyperplane between two different phase space regions associated to different system functional forms.

We will discuss, the derivation of this mappings, showing how asymptotic methods can play a role for the derivation of the discontinuity mapping and hence its composition with the affine transformation describing the rest of the orbit of interest. Conditions will be given based on the resulting maps to classify the dynamical scenarios observed close to this bifurcation points. The study will be detailed to the study of degenerate sliding bifurcations; a novel class of codimension-two phenomena recently presented in the literature [3].

References:

- H. Dankowicz, A. B. Nordmark, On the Origin and Bifurcations of Stick-Slip Oscillations. Physica D 136 (2000) 280-302, 1999
- [2] M. di Bernardo, C.J. Budd, A.R. Champneys, Normal From Maps for Grazing Bifurcations in n-Dimensional Piecewise-Smooth Dynamical Systems. Physica D 160 (2001) 222-254, 1999.
- [3] P. Kowalczyk, M. di Bernardo, Degenerate Sliding Bifurcations, submitted to Physica D, 2004

**ID of Contribution: 21 - 327** 

## **RELAXATIONS OSCILLATIONS IN THE NEARLY INVISCID FARADAY SYSTEM**

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The amplitude equations for nearly inviscid Faraday waves couple to a streaming flow driven by oscillatory viscous boundary layers at the rigid walls and the free surface produced by the waves, satisfying a Navier-Stokes-like equation. The streaming flow is driven most efficiently by mixed mode oscillations created in secondary bifurcations from standing waves, and these occur already at small amplitude in containers that are almost symmetric. Among the new dynamical behavior that results is a variety of relaxation oscillations involving abrupt transitions between periodic and quasiperiodic oscillations and associated canards. In some cases the first nontrivial state of the system is characterized by complex time-dependence. These phenomena are characteristic of both almost circular and almost square containers. The origin of relaxation oscillations in this class of systems will be explained and the results related to experiments.

#### References:

[1] M. Higuera, J.M. Vega and E. Knobloch, Coupled amplitude-streaming flow equations for nearly inviscid Faraday waves in small aspect ratio containers, J. Nonlinear Sci. 12, 505-551 (2002).

ENOC-2005, Eindhoven, the Netherlands

ID of Contribution: 21 - 358

## ON THE WEAKLY NONLINEAR DYNAMICS OF STRINGS, BEAMS AND RECTANGULAR PLATES

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Since 1970 initial-boundary value problems for weakly nonlinear wave equations have been studied intensively. Several asymptotic approaches (such as multiple time-scales methods, averaging methods, and so on) have been developed to investigate these types of problems. Since 1990 also initial-boundary value problems for weakly nonlinear beam or plate equations obtained a lot of attention. In this lecture a short historical overview will be given, and some recent developments will be discussed. In particular the dynamics of an inclined stretched string will be considered. This string is assumed to be suspended between a fixed support and a vibrating support. Also aspects of boundary damping for 1-D wave equations and for vertical beams will be considered. Finally some remarks will be made on the wind-induced oscillations of flexible structures such as beams and plates.

References:

- [1] G.J. Boertjens and W.T. van Horssen, An asymptotic theory for a weakly nonlinear beam with a quadratic perturbation, SIAM J. Appl. Math., 60, no. 2, 2000, p 602-632.
- [2] Darmawijoyo, W.T.van Horssen and Ph.Clement, On a Rayleigh wave equation with boundary damping, Nonlinear Dynamics 33,no.4,2003,p 399-429.
- [3] M.A.Zarubinskaya and W.T.van Horssen, On the free vibrations of a rectangular plate with two opposite sides simply supported and the other sides attached to linear springs, Journal of Sound and Vibration 278, no.5, 2004, p 1081-1093.

ID of Contribution: 21 - 389

## ON ASPECTS OF BOUNDARY DAMPING FOR VERTICAL BEAMS WITH AND WITHOUT TIP-MASS

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In recent years more and more tall buildings were built. For tall buildings, or high rise buildings, dampers, active or passive, are used to dissipate the energy of the vibrations of the building. Some damping mechanisms give rise to a heavy mass at the top of the building. In this report we will consider beams with and without such tip-masses.

In this report we consider vertical cantilevered beams (that is, beams which are fixed at one side and free at the other side). Tall buildings and elevator cables can be modelled by vertical beams, bridges can be modelled by horizontal beams. Vertical and horizontal cantilevered beams can be described by initial-boundary value problems that describe the displacements of the beams. The initial-boundary value problems for both beams are almost the same. Due to gravity the vertical beam has extra terms in the homogeneous part of the partial differential equation and in the boundary conditions.

We consider passive boundary damping at the free end of the beam. The damping mechanisms we consider are a velocity damper and a tuned mass damper (TMD).

In the case of a velocity damper we study in this report the displacement of a vertical beam (with and without a tipmass), which are subjected to wind-forces. To construct approximations of the displacement functions a two-timescales perturbation method is used. Formal approximations of the solutions of the initial-boundary value problems are constructed and the type of damping has been determined. We compare the damping of the vertical beam to the damping of the horizontal beam. For the beam without tip-mass the vertical beam and the horizontal beam will be damped uniformly. In the case of a beam with tip-mass we have strong damping. The extra term due to gravity will not significantly change the damping rates of the oscillation modes.

For the tuned mass damper(TMD) we show that the displacement of the beam will be damped uniformly if we neglect the extra term due to gravity.

#### ID of Contribution: 21 - 411

## NECESSARY AND SUFFICIENT CONDITIONS OF ABSOLUTE STABILITY OF TWO-DIMENSIONAL TIME-VARYING SYSTEMS

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Method of Lyapunov functions is effective method of stability analysis in control theory. Well-known circle criterion of absolute stability for time-varying nonlinearities was proved with applications of Lyapunov functions from the class of quadratic forms. But circle criterion is only sufficient condition of absolute stability.

Another method - method of two-dimensional comparison systems - allow us to obtain effective necessary and sufficient conditions of absolute stability of two-dimensional systems with time-varying nonlinearities.

A significant direction in the framework of the comparison principle consists of the exploitation of differential inequalities. Fundamental results in differential inequalities were obtained by E. Kamke and S.A. Chaplygin. Method of two-dimensional comparison systems, which proceeds from Kamke-Chaplygin principle, is method of monotone rotation of the vector field. We apply this method here for solution of the problem of absolute stability for two-dimensional time-varying nonlinear systems.

#### ID of Contribution: 21 - 413

## SINGULAR PERTURBATION ANALYSIS OF ENERGY CONTROL SYSTEMS

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Control of system energy is an important problem having different applications to control of mechanical and electromechanical systems, particularly to control of oscillatory modes. A general approach to energy control based on speed-gradient method was proposed in [1] and later extended to control of several invariants of a nonlinear system [2,3]. For control of complex nonlinear systems an important problem is dealing with an unmodeled dynamics, particularly with singularly perturbed systems. It is well known that unmodeled dynamics may not only prevent from achieving the control goal, but also cause unboundedness of control system trajectories.

Conditions for stability of singularly perturbed speed-gradient based control systems were proposed in [4]. These conditions are well suited for adaptive control systems where stability with respect to only a part of variables may be observed. However, the conditions of [4] are not fulfilled for energy control problems, since (A) the energy-based Lyapunov function is not radially unbounded and (B) an unperturbed systems possess weaker stability properties, namely, partial stability with respect to a function rather than stability with respect to a part of variables.

In this paper the results of [4] are extended to encompass the problems of speed-gradient based energy control of singularly perturbed Hamiltonian systems. General stability results for singularly perturbed nonlinear systems are given which allow to deal with energy control of Hamiltonian systems with and without dissipation. Application to controlled synchronization of two coupled pendulums is presented for two cases:

- (A) taking into account flexibility of pendulums;
- (B) taking into account inertia of the coupling link is studied.

In both cases comparison between asymptotic theoretical accuracy bounds and computer simulation results is performed.

References:

- [1] Fradkov, A.L. (1996). Swinging control of nonlinear oscillations. Intern. J. Control. V. 64, No 6.
- [2] Fradkov, A.L. and A.Yu. Pogromsky (1998). Introduction to control of oscillations and chaos. World Scientific Pub. Co, Singapore.
- [3] Shiriaev A.S. and A.L. Fradkov (2001). Stabilization of invariant sets for nonlinear systems with application to control of oscillations. Intern. J. of Robust and Nonlinear Control. V. 11, pp. 215–240.
- [4] Fradkov, A.L. (1987) Adaptive control of singularly perturbed systems. Autom. and Rem. Control, N 7.

#### ID of Contribution: 21 - 439

#### MULTIFREQUENCY FORCED VIBRATIONS OF THIN ELASTIC SHELL

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This paper gives an asymptotic approximation of solutions for multifrequency vibrations of a thin elastic shell with positive constant Gauss's curvatures and finite deformations. The shell is simply supported along rectangular boundaries. The shell is under the action of a multifrequency force with two, tree and four frequencies, whose values are constant or slowly changeable with respect to time in a resonant range of the first, second, third and fourth own frequency of the basic shell free linear vibrations in their own normal harmonics. Using Krilov-Bogolyubov-Mitropolskiy's asymptotic method, both the solutions in the first approximation and the system of nonlinear coupled differential equations for the corresponding number of excited amplitudes and phases, are derived. By means of this asymptotic approximation of differential equations for the analysis of energy transfer between modes is also performed.

- [1] Hedrih (Stevanovic), K., (1985), Multifrequency forced vibrations of thin elastic shells with a positive Gauss' curvature and finite deformations, Theoretical and Applied Mechanics, 11, Beograd 1985, pp. 51-58.
- [2] Katica Stevanovic (Hedrih), Application of the Asymptotic Method for study of the Elastic Bodies Nonlinear Oscillations - Energetic Analysis of the Elastic Bodies Oscillatory Motions, Doctoral Ph. D Dissertation, (in Serbian), Mašinski fakultet, Niš, 1975., p. 331. Supervision: Prof. dr. Ing. Math Danilo P. Raškovic (Yugoslavia) i akademik Yuriy Alekseevich Mitropolskiy (Ukraine).

## **MINI-SYMPOSIUM 22**

## Nonlinear Dynamics of Distributed-Parameter Systems

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Prof. Balakumar Balachandran College Park, MD, USA University of Maryland Email: balab@eng.umd.edu shown that the transient dynamics of resonance capture can be reduced to a set of two 'slow flow' amplitude and phase modulation equations. The analytical results are in agreement with direct numerical simulations.

ID of Contribution: 22 - 044

## MODAL INTERACTIONS IN CYLINDRICAL SHALLOW SHELLS

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In several applications, shells can experience large amplitude, geometrically non-linear vibrations under the action of external forces. In order to characterise the shells' non-linear dynamic behaviour, it is important to define their response to harmonic excitations in the frequency range of interest. The large amplitude oscillations of shells are represented by differential equations with quadratic and cubic non-linearities, due to the combined effects of the surface curvature and of the large displacements. Moreover, transverse excitations of shells can cause buckling phenomena. Therefore, one expects quite interesting dynamics in this problem.

Shell structures vibrating with large displacements can be accurately modelled by finite element methods. The pversion, hierarchical finite element method (HFEM), in which better approximations are achieved by adding higher order shape functions to the model, without altering the FE mesh, requires a reduced number of degrees of freedom for accuracy [1]. This is a very important property, since the solution of the equations of motion at each excitation frequency is carried out by iterative methods, with a regular update of the non-linear matrices.

In this work, the p-version, hierarchical finite element method [1] is employed to investigate the large amplitude motions of isotropic, linear elastic, shallow shells. Reissner-Mindlin's model, where it is assumed that the transverse shear deformation is constant along the cross section, is used to derive the element. Equating the sum of the virtual works of all forces - including the inertia forces - to zero, and assuming stiffness proportional damping, the equations of motion are derived.

Algorithms based on the shooting [2] and Newton methods or on Newmark's scheme [3] are used to solve the finite element equations of motion. The shooting method is able to describe periodic motions with any number of harmonics and gives as a by-product the monodromy matrix, from which the stability of the solutions is defined. Newmark's method allows one to define non-periodic motions.

In the numerical applications, codimension one bifurcations are found. By inspecting the shapes assumed by the shell along each vibration period, it is shown that coupled mode oscillations occur. Particularly in this case, unstable and quite far from harmonic motions may appear. This phenomenon occurs frequently for excitation frequencies close to the non-linear natural frequencies, where large oscillations emerge.

- [1] P. Ribeiro, "A hierarchical finite element for geometrically non-linear vibration of doubly curved, moderately thick isotropic shallow shells," International Journal for Numerical Methods in Engineering, 56 (5), 715-738, 2003.
- [2] A. H. Nayfeh, B. Balachandram, "Applied Nonlinear Dynamics: Analytical, Computational, and Experimental Methods". John Wiley and Sons, New York, 1995.
- [3] M. Petyt, "Introduction to Finite Element Vibration Analysis". Cambridge University Press, Cambridge, 1990.

#### ID of Contribution: 22 - 120

## DROP-SHOCK STABILITY OF A THIN SHALLOW ARCH; CONSIDERING THE EFFECTS OF VARIATIONS IN SHAPE

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Thin-walled structures are encountered in a wide variety of applications, such as for example aircraft fuselages, civil engineering structures and in micro-electro-mechanical systems (MEMS). If such a thin-walled structure is initially curved and is loaded above some critical magnitude, the structure may buckle such that the curvature suddenly reverses. The analysis of structures liable to buckling under static loading is a well established topic in engineering science. However, thin-walled structures are often subjected not only to a static load but also to a distinct dynamic load, such as for example harmonic forcing or drop/impact loading. The resistance of structures liable to buckling, to withstand time-depended loading is often addressed as dynamic stability of these structures. The corresponding failure mode shows a correspondence with static buckling and is often addressed as dynamic buckling. Generally, dynamic buckling is related to a large increase in the response resulting from a small increase in some load parameter [1]. However, still no rigorous criterion exists for the loss of dynamic stability of structures. In the past many studies where already performed concerning the dynamic stability of thin-walled structures [2]. However, design strategies for such structures under dynamic loading are still lacking.

As a first step in deriving such a design guide here a group of thin shallow arches subjected to a half-sine drop-shock pulse is considered. All arches have the same principle dimensions like width, height and cross-sectional area but differ in shape. The arch shape is continuously varied by a single shape-factor constant, and, is thus not restricted to specific shapes like a sinusoidal and circular curves. In order to be able to study the influence of small geometric imperfections, additionally a single geometric imperfection in the form of a first harmonic asymmetry, is taken into account. Prior to the dynamic analyses, the quasi-static behaviour of the arch is studied, using numerical path-following techniques. In these analyses, the quasi-static response of the arch under constant acceleration load is considered for various arch shapes. Moreover, the influence of small geometric imperfections is illustrated and the results are compared with FEM results. The dynamic response of the arches under drop-shock loading is studied by solving the regarding equations of motion numerically. In this analysis the influence of the arch shape, pulse-duration, level of damping and small geometric imperfections is illustrated. The main results are firstly that the critical drop-shock level can be significantly increased by optimizing the arch shape and secondly, a small geometric imperfection alters the critical drop shock level in a much less fatal manner under dynamic loading as encountered in the quasi-static analysis but has, however, significant influence on the amplitudes of the vibrations prior to buckling.

- [1] Budiansky, B. and J.W. Hutchinson (1964). Dynamic buckling of imperfection-sensitive structures. Proc. of the 11th Int. Congress of Applied Mechanics. Berlin. pp. 421–446.
- [2] Simitses, G.J. (1990). Dynamic stability of suddenly loaded structures. Springer-Verlag. New York.
## NEW RESULTS IN STEADY-STATE ANALYSIS OF A TRANSVERSALLY EXCITED, BUCKLED BEAM

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In engineering practice many examples can be found in which the nonlinear dynamic behaviour of buckled structures is of importance, e.g. in Micro-Electro-Mechanical Systems, in large stroke actuators for optical systems, in suspension systems of off-road vehicles or optical measuring systems, or in a buckled fuselage's skin.

In this paper the steady-state behaviour of a transversally excited, buckled beam is investigated. The beam is simply supported and is free to displace axially on one side. In the initial configuration the beam is in a buckled state by presence of a static axial compressive force, which just exceeds the buckling force. Subsequently, it is loaded dynamically in transversal direction by a harmonic, prescribed displacement of the supports. An overview of papers with similar research interest can be found in Emam and Nayfeh (2004). The current paper distinguishes itself from other papers by: the model used (a.o. kinematic relations, boundary conditions, modeling of damping), new analysis results, parameter studies, and a comparison of results from semi-analytical models with results from Finite Element analyses.

First the modeling of the beam will be briefly discussed. The uniaxial kinematic model of Li (1997) is used as a starting point neglecting transversal contraction. Then the so-called Elastica kinematic model is derived by applying the Euler-Bernoulli hypothesis on the uniaxial model.

Comparison of a Finite Element solution of the stable static post-buckling path with a solution calculated using Elastica kinematics and the perturbation method based on Koiter's theory shows that the latter approach may be used as a convenient alternative in static initial post-buckling analysis.

For dynamic buckling analysis the pde (derived using Hamilton's principle and Elastica kinematics) is transformed into a (set of) ode('s) using Galerkin discretization based on the lowest buckling mode(s). The steady-state behaviour of the resulting single and multi-dof semi-analytical models is analyzed and compared. Periodic solutions are calculated by solving Two-Point Boundary Value Problems using a finite difference method. Amplitude-frequency plots are calculated with a path following technique. Local stability and bifurcation analysis is carried out using Floquet theory. Dynamically interesting areas (bifurcation points, routes to chaos, snap-through regions) are analyzed using phase space and Poincaré plots. Also the influence of some parameters on the amplitude-frequency response is investigated.

Finally some of the results mentioned above are compared with results obtained with expensive Finite Element calculations. From this, it can be concluded, that the described semi-analytical approach is very useful for fast evaluation of the nonlinear dynamics of buckled beam systems.

References:

- [1] Emam, S.A., Nayfeh, A.H., 'On the Nonlinear Dynamics of a Buckled Beam Subjected to a Primary-Resonance Excitation', Nonlinear Dynamics, vol. 35, pp. 1-17, 2004.
- [2] Li, M., 'The Finite Deformation Theory for Beam, Plate and Shell, Part I. The Two-Dimensional Beam Theory', Computational Methods in Applied Mechanics and Engineering, vol. 146, pp. 53-63, 1997.

## **CHAOTIC VIBRATIONS OF BEAMS, PLATES AND SHELLS**

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In this work a unified theory of chaotic vibrations of beams, plates and shells is proposed. Mathematical models of multilayer systems for different kinematic models of Kirchhoff-Love, Timoshenko and generalized Timoshenko layers are constructed. In what follows geometrical nonlinearities (T. von Kármán equations match deformations and stresses), physical nonlinearities (nonlinear Hook's law), as well as factors of discontinuities between layers are taken (mathematical model as well as the algorithm of computation of unknown contact zone between layers after lack of their contact is given, and various models of linear and nonlinear damping are studied. The mentioned mathematical models are obtained owing to 3D theory and the Hamilton variation approach. In order to solve the obtained PDEs, a finite difference method, both Bubnov-Galerkin and Ritz approaches in higher approximations are applied. Finally the problem is reduced to ODEs solved via Runge-Kutta methods. This choice of reduction of PDEs to ODEs, and then application of various Runge-Kutta routines is motivated by highly accurate detection, observation and control of chaos exhibited by multidimensional objects like plates and shells.

Owing to proposed mathematical and numerical models, complex vibrations of homogeneous and non-homogeneous plates and shells with an arbitrary geometry (spherical, cylindrical, conical, shallow, rectangular and sector ones) can be studied. The following numerical indicators are applied: signals, phase and modal por-traits, power spectra, FFT, wavelet transformation, Poincaré maps and Lyapunov's exponents.

New scenarios to chaos are illustrated and discussed in our investigated conservative and dissipative mechanical objects.

ID of Contribution: 22 - 244

## GEAR TEETH IMPACT DYNAMICS IN MANUAL TRANSMISSIONS PROMOTING IDLE RATTLE

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Gear rattle is a major concern in the automotive industry, particularly for high output power-to-weight ratio diesel engines. It is characterised by repetitive impacts of the unladen gear teeth and it mainly manifests in manual transmissions. The term rattle is used in an onomatopoeic context by the quality of radiated noise. It is a worrying factor for the automotive industry, as it is increasingly regarded as a source of annoyance by the customers with serious warranty implications.

The reported research on this phenomenon has involved theoretical and experimental studies, using analytical models and experiments for their verification (Rivin 2000). The use of palliative methods has been proposed (Fujimoto and Kizuka 2003, Rivin 2000). Emphasis has been mainly placed on the inertial dynamics of the problem.

Three types of rattle have been identified, according to vehicle operating conditions: idle rattle, when clutch is engaged and the transmission is in neutral; creep rattle, when one of the gears is selected, the clutch is engaged and the engine speed is around 1200-2000 rpm and over-run rattle, when no gear is selected, clutch is disengaged and engine speed lies between 1400-4000 rpm.

In this paper, an analytical model of automotive gear train system is presented for idle rattle conditions, using a multiphysics framework. The proposed approach integrates inertial system dynamics, the structural behaviour of each component and the impact conditions for every individual pair of teeth. The model predicts the meshing cycle gear forces, assuming elastodynamic characteristics and incorporates the hydrodynamic reaction in combined rolling and squeeze film motion in the impact zone of meshing pairs. This is a highly nonlinear behaviour, even more so than the localised Hertzian type impact. Conditions leading to the appearance and reinforcement of idle gear rattle are thus investigated.

Generally, by increasing the accuracy of a theoretical simulation, the amount of computer calculations increases exponentially. Lubrication and dynamic models were devised to describe the physical phenomena starting from the basic principles with an acceptable analysis time limit. The impact conditions are calculated, considering localized contacts as under indle rattle condition lightly loaded impacts, nevertheless of highly non-linear characteristics occur.

In order to account for the continuous interaction between physical phenomena, which are transient in nature, the entire set of differential equations has been solved, using a time marching integration method. This method ensures the accuracy of the solution as well as the acceptable speed and memory storage levels. The main rattle frequencies and corresponding modes are identified and a parametric study investigates the influence of major gear design parameters.

References:

- [1] Rivin, E., (2000),"Analysis and Reduction of Rattling in Power Transmission Systems", SAE Technical paper 2000-01-0032.
- [2] Fujimoto, T., and Kizuka, T., (2003b), "Audible Noise Simulation –an Attempt to Predict Idling Rattle in Manual Transmissions", SAE Technical Paper 2003-01-0674.
- [3] H. Rahnejat (1985), "Computational modelling of problems in contact dynamics", J. Engng. Analy., Vol.2

ID of Contribution: 22 - 252

## **BIFURCATIONS OF GYROSCOPIC SYSTEMS NEAR A 0:1 RESONANCE**

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We study the local and global bifurcation behavior of autonomous and nonautonomous gyroscopic systems near a 0:1 resonance. As an example, we study the bifurcations of a rotating shaft, focusing on the lightly damped, nearly symmetric autonomous case, and the parametrically excited, subharmonic resonance case. One goal of the analysis is to understand how energy may be transferred from the high frequency mode to the low frequency mode in these gyroscopic systems. Regions where energy transfer may occur from high to low frequency modes are identified. Finally, using recently developed bifurcation methods, in the subharmonic resonance case we detect the presence of orbits which are homoclinic to certain invariant sets. In the dissipative case, we are able to identify conditions under which a generalized Silnikov orbit would exist. In certain parameter regions, we prove that such orbits exist which are homoclinic to fixed points on the slow manifold, leading to chaotic dynamics in the system. These orbits provide the mechanism by which energy transfer between modes may occur.

## A GEOMETRICALLY NONLINEAR FINITE ELEMENT FOR TRANSIENT ANALYSIS OF PIEZOLAMINATED SHELLS

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Weight reduction is one of the main stream philosophies of modern engineering. It leads to optimal production and operation costs. Unfortunately, light weight structures are, due to their low internal damping, susceptible to structural vibrations, which can lead to a decrease of the efficiency or even to their destruction.

Possibilities to overcome this problem can be found numerously in passive damping methods, which, in most cases, contradict the request of weight reduction. Next to the well established semi-active methods, in which the properties of passive elements are altered optimally during operation, active approaches seem to be the most promising alternatives. In order to construct such active structures, smart materials are integrated which act as sensors as well as actuators. One of the most commonly used smart materials is the piezoceramic.

In literature, numerical investigations of smart structures can be found mainly dealing with small vibrations. This paper deals with the transient numerical investigation of piezolaminated composite shell structures in the geometrically nonlinear range. The developed finite element is based on the moderate rotation theory of Schmidt et al. [1]. Further, a total-Lagrangian approach is applied, and the displacement field (according to the Reissner-Mindlin hypothesis) as well as the electric potential is assumed to vary linearly through the thickness.

After an introduction of the underlying theories and assumptions, the finite element is applied to several numerical results. The paper is closed with a final discussion.

References:

[1] R. Schmidt, J.N. Reddy, A Refined Small Strain and Moderate Rotation Theory of Elastic Anistropic Shells, Journal of Applied Mechanics, 55, 611-617, 1988.

ID of Contribution: 22 - 271

## ENHANCED DAMPING OF A BEAM STRUCTURE BY PARAMETRIC EXCITATION

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It is well known that a time-periodic force acting on a beam structure can create different dynamic effects, depending on the direction of the force and the direction of the dominant resulting motion. In case that the force acts in the direction of the beam axis, time-dependent stiffness and damping terms may appear in the governing differential equations of the beam lateral (bending) motion. Frequently such systems are classified as parametrically excited systems (PE-Systems) [1].

PE-Systems have been studied extensively in the past because of the interesting phenomena which are observed in such systems, for example parametric resonances. If the frequency of a harmonic parameter variation (i.e. PE) coincides or is close to twice the natural frequency of the system a parametric resonance with (in the linear case) unbounded amplitudes will occur. Interestingly, this phenomenon may also occur for combinations of two or more natural frequencies and is known as "parametric combination resonance". In the past, almost all investigations were focused on

those cases, where combination resonances appeared to be resonant. The non-resonant cases did not seem to be interesting and have not been investigated in detail, see [2] for example.

Several years ago it was discovered by Tondl [3], that a non-resonant parametric combination resonance exhibits interesting properties that have not been investigated so far. Basically additional damping is provided for the system by the parametric excitation at this frequency. In first studies this effect was used to stabilize self-excited low-dof systems by means of the additional damping created by the PE.

This paper considers a one-dimensional continuous system, a cantilever beam with an axial force at the free end of the beam. By a harmonic time-modulation of the axial force a parametric excitation is created. Adjusting the frequency of the modulation at an appropriate frequency value the transversal free vibrations of the cantilever beam can be damped at a higher rate compared to the conventional beam.

A FE-model is used to discretize the continuous system. By means of Floquet theory the time-varying system is investigated. The eigenvalues of the state transition matrix are calculated after one period of the parametric excitation and are used to quantify the amount of damping which is present in the system. Calculations of time series of the beam deflection by numerical simulation supplement the results.

It is demonstrated that the structural damping which is present in the system can be enhanced considerably by introducing a time-periodic force in axial direction at the tip of the beam structure. Numerical studies show how the modal damping of various bending modes of the beam are affected by the parametric excitation.

- [1] Nayfeh, A. : Nonlinear Interactions. Wiley, 2000.
- [2] Chen C.-C. and Yeh M.-K.: Parametric instability of a cantilevered column under periodic loads in the direction of the tangency coefficient. JSV 183(2), 1995.
- [3] Tondl, A.: To the quenching of self-excited vibrations. Acta Technica CSAV 43, 1998.

ID of Contribution: 22 - 299

## **DYNAMIC BEHAVIOR OF BUCKLED PLATES**

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Both analytic and finite element investigations are performed for the various static and dynamic aspects of snap phenomena of rectangular plates heated deeply into their post-buckling regime. We are especially interested in the robustness of stable equilibria - where co-existing equilibria exist and where 'mode jumping' occurs. Characterized by strong geometrical nonlinearity, the secondary bifurcation point of the thermally loaded plate with fixed in-plane boundary conditions occurs far beyond the primary buckling point and the resulting jump behavior cannot be predicted correctly without sufficient assumed modes. Stationary bifurcation analysis indicates that while the post-buckling deflection before mode jumping is composed of pure symmetric modes, additional pure antisymmetric modes will appear after the occurrence of the snapping, and they play the role of destabilizing the equilibrium. Furthermore, by monitoring natural frequencies and mode shapes, we find that a mode shifting phenomenon (the exchanging of vibration modes) exists in the primary post-buckling regime.

By introducing a linear temperature sweep scheme, a transient analysis is performed to capture the snapping phenomenon dynamically. Comparison between the analytic and finite element method results shows good agreement. Finally some forced vibration is examined within the region of hysteresis, and a limited amount of experimental data is presented.

## SHALLOW VERSUS NON-SHALLOW CABLES: LINEAR AND NONLINEAR VIBRATION PERFORMANCE

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Cables are used in a variety of engineering applications such as in suspension bridges, transmission lines, moorings in ocean engineering or in aerospace applications such as in deployable structures. Cables are successfully employed because they can be relatively easily engineered and are light-weight structures. However, they do possess limitations due to the lack of out-of-plane stiffness and very light damping that make them often prone to large-amplitude vibrations. In most engineering applications, cables are shallow in their static equilibrium configurations and are usually constrained at both ends. Nonetheless, it is also true that in some applications or loss of tension are responsible of their curvature increase. This can be the case with cables used in transmission lines which undergo icing with a significant weight increase.

Most of the theoretical and experimental investigations have been carried out for shallow cables whereby the condensation of the longitudinal dynamics holds. This mechanical model has been employed to investigate linear vibrations as well as the nonlinear responses arising from primary and autoparametric resonances (Lee and Perkins, 1995; Rega et al., 1999; Srinil et al., 2003) or the prediction of the onset of galloping.

Clearly, it is of interest to compute and appreciate the differences in the prediction of linear as well as nonlinear dynamics when the cables become nonshallow. Using the geometrically exact cable theory, accurate mechanical models of nonshallow prestressed cables are discussed. The mechanical model considers the most generale case of inclined cable. The cable is first assumed to undergo a static displacement from a reference configuration to a nonlinear static equilibrium configuration due to its own weight and the added ice. Then, the cable undergoes a dynamic deformation process due to external primary-resonance loads. To start with the simplest configuration, the cable supports are considered at the same level. The equations of motion are first linearized around the nonlinear static equilibrium configuration; variations of the natural frequencies and mode shapes with the cable elasto-geometric parameter are investigated. To this end, the condensed shallow cable model and the nonshallow model are both employed and their differences are discussed. The responses to primary resonances are constructed via a direct perturbation treatment and the nonlinear features of these responses are explored for shallow and nonhallow configurations.

References:

- [1] Lee, C. L. and Perkins, N. C., Experimental investigation of isolated and simultaneous internal resonances in suspended cables, Journal of Vibrations and Acoustics 117, 385-391, 1995.
- [2] Rega, G., Lacarbonara, W., Nayfeh, A. H., and Chin, C.M., Multiple resonances in suspended cables: direct versus reduced-order models, International Journal of Non-Linear Mechanics 34, 901-924, 1999.
- [3] Srinil, N., Rega, G., and Chucheepsakul, S., Large amplitude three-dimensional free vibrations of inclined sagged elastic cables, Nonlinear Dynamics 33, 129-154, 2003.

## CHARACTERIZING THE SPATIO-TEMPORAL COMPLEXITY OF FORCED VIBRATIONS OF NONLINEAR PLANAR RODS

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Geometrically exact models of nonlinear rods are very interesting dynamical systems since they can be considered to be prototypes for infinite coupled systems involving multi-fields. Efficient finite element algorithms have been developed to compute accurately the dynamics of these systems [1]. These algorithms can be used to compute systematically the qualitative dynamics as attractor diagrams of the unloaded configuration for specified forcing. For example, transversely forced planar rods possess regular and chaotic attractors at various levels of forcing amplitudes and frequencies. Since the displacement and rotation fields in a nonlinear rod are coupled nonlinearly (geometrically exact coupling), we expect that the spatio-temporal complexity of attractors to be quite involved. The dimensionality of an attractor can be determined by a certain number of Proper Orthogonal Decomposition modes [2]. In this work, we apply the method of Proper Orthogonal Decomposition (POD) for multi-field dynamics [3] to characterize various regular and chaotic attractors (steady state forced vibrations) of planar straight rods. We perform POD on the high resolution finite element dynamics. For various boundary conditions, we force these systems harmonically in the transverse direction. The important quantity characterizing an attractor is the distribution, called POD spectrum, of its auto-correlation energy over its POD modes. Here we characterize the complexity of an attractor by comparing the POD of its configuration field to that of its velocity field. We find that, for periodic attractors at low energy level, the POD spectrum of the configuration field is almost identical to that of velocity field. These attractors are dominated by a singe POD mode. The remarkable result is the fact that the amplitudes of the POD modes of the velocity field are almost identical to the time derivatives of the amplitudes of the POD modes of the configuration field. In general, for a given attractor, the shapes of the POD modes of the configuration field are not identical to the shapes of the POD modes of the velocity field. The studied planar rods posses quasi-periodic and chaotic attractors whose POD of the configuration field is not similar to that of the velocity field. It turns out that the comparison of the POD of the configuration field to that of the velocity furnishes criteria to determine when an attractor resides on an invariant manifold of motion. These criteria can be used to decide when the shape of a POD mode is identical to that of normal mode of vibration.

References:

- [1] Sansour, C., and Bednarczyk, H., 1995, "The Cosserat surface as a shell model, theory and finite element formulation," Computer methods in Applied Mechanics and Engineering 120, 1-32.
- [2] Georgiou I.T., Sansour J, 1998, "Analyzing the Finite Element Dynamics of Nonlinear in-plane rods by the method of Proper Orthogonal Decomposition," Computational Mechanics, New Trends and Applications, S. Idelshom, E. Onate and E. Dvorkin (Eds.), CIMNE, Barcelona, Spain.
- [3] Georgiou, I. T., 2004, "On Proper Orthogonal Decompositions for one-dimensional coupled structural dynamics: characterization of coupled vibrations in nonlinear elastic rods," (submitted for publication).

## NONLINEAR NORMAL MODES OF MULTI-MODE MODELS OF INERTIALLY COUPLED ELASTIC STRUCTURES

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Nonlinear normal modes for elastic structures have been studied extensively in the literature. Most studies have been limited however to small nonlinear motions and for structures with geometric nonlinearities. Real and complex invariant manifold techniques as well as the asymptotic method of multiple time scales have been utilized for these studies. In these approaches, it is usually assumed that the nonlinear normal modes are invariant manifolds that pass through the stable equilibrium position of the system and are tangent to the eigenspaces of the linearized system. There do exist examples in multi-degree-of-freedom systems, especially in systems with inertial nonlinearities, where the nonlinear normal modes are not tangent to the linear normal modes. Thus, this work investigates the nonlinear normal modes in elastic structures that contain essential inertial nonlinearities. In this direction, Pesheck et al. [1] studied a simplified rotor blade model (a rotating beam) through Galerkin-based solutions for the nonlinear normal modes, or the invariant manifolds. Their solution methodology is primarily local and numerically based.

Examples of nonlinear structures with inertial nonlinearities include multi-beam structures studied by Balachandran and Nayfeh [2], and Crespo da Silva [3]. While Balachandran and Nayfeh focused attention on the 1:2 internal resonance planar dynamics of a flexible L-shaped beam-mass structure, Crespo da Silva [3] developed a general methodology for obtaining multi-mode models for multi-beam structures in planar motion. His approach utilized a set of finite elements based basis functions to obtain reduced-order models that captured the essential dynamics of the system.

In order to analyze the behavior of complex structures with inertial nonlinearites, and to retain the dependence of system parameters in the multi-mode models, we combine Crespo da Silva's formulation with the Raleigh-Ritz method to obtain parametric reduced models. The nonlinear normal modes for the high fidelity multi-mode models are then studied both by the method of multiple time scales, and by a numerical shooting technique. The latter technique allows for large-amplitude nonlinear normal modes. Thus, bifurcations in the nonlinear normal modes as a function of the amplitude of motion, and the frequencies vary through internal resonance conditions can be investigated.

References:

- [1] Pesheck, E. Pierre, C. and Shaw, S.W., 2001, Accurate reduced-order models for a simple rotor blade model using nonlinear normal modes, Mathematical and Computer Modeling, 33, 1085-1097.
- [2] Balachandran, B. and Nayfeh, A.H., 1900, Nonlinear motions of beam-mass structure, Nonlinear Dynamics, 1, 39-61.
- [4] Crespo da Silva, M. R. M., 1998, A reduced-order analytical model for the nonlinear dynamics of a class of flexible multi-beam structure, International Journal of Solids and Structures, 35 (25), 3299-3315.

#### ID of Contribution: 22 - 331

## NONLINEAR WAVE DYNAMICS OF A 2D GRANULAR MEDIUM

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A two-dimensional model of a granular medium is considered that represents a square lattice consisting of uniform round particles. The particles have both translational and rotational degrees of freedom. Each particle (granule) is supposed to interact directly with eight nearest neighbours in the lattice [1]. The nonlinear governing equations describing propagation and interaction of waves of various types in such a medium have been derived for a cubic potential of elastic interactions between the particles in the discrete and continuum approximations.

The discrete equations are valuable, particularly, for numerical simulation of nonlinear wave processes in granular media. The continuum approximations of the model at issue are convenient for its comparison with known theories of solids.

The continuum equations do not coincide with the classical theory of elasticity due to additional equation for the rotational wave. Such a wave exists when the frequency is larger than a threshold value. Its dispersion properties are similar to dispersion properties of the spin wave in a magnet-elastic medium. From the numerical estimations of the rotational wave velocity in some cubic crystals follows that, as a rule, it is less than the translational wave velocities. When microturns of the particles are absent, the linear parts of the governing equations of the first continuum approximation degenerate into Lame equations for anisotropic medium with the cubic symmetry. In the paraxial approximation of the diffraction theory, evolution of quasi-longitudinal waves is shown to be described by Kadomtsev-Petviashvili equation [2].

The governing equations are structurally similar to equations of the anisotropic Cosserat continuum with centrally symmetric particles. However, the longitudinal wave velocity does not depend on the medium structure in the Cosserat continuum, while such dependence presents in the considered model. The last fact enables to explain, particularly, experimentally observing variations of this wave velocity when size of granules grows [2]. The governing equations of the second (quasicontinuum) approximation contain summands with higher-order derivatives and give explanation to appearance of the longitudinal wave dispersion. The Cosserat theory is unable to explain this effect.

## References:

- [1] Pavlov I.S. Nonlinear Acoustic Waves in a 2D Granular Medium, Proceedings of the 5th World Congress on Ultrasonics. WCU 2003, Paris, France, 2003, pp. 1315-1318.
- [2] Potapov A.I., Pavlov I.S., Gorshkov K.A., Maugin G.A. Nonlinear interactions of solitary waves in a 2D lattice, Wave Motion, 2001, V.34, N 1, pp. 83-95.

ID of Contribution: 22 - 366

## CAUSES FOR THE SOFTENING PHENOMENON AT VIBRATIONS OF BEAMS UNDERGOING LARGE ROTATION

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Researchers stumble across a problem called "softening" [1] at some computational models of rotating cantilever, which reflects one of the nonlinear effects of interaction between macro- and micro-motions of deformable bodies. On the other hand it is assumed in advance that instability of the beam motion actually can not exist from physical point of view. The reason for this concept is the presumption that the action of the centrifugal forces along the beam length leads to increase of the beam eigenfrequencies, i.e. to stiffening. The general opinion formed was that the ultimate prevailing effect of the simultaneous action of both phenomena is the stiffening [2]. However, there are no data in the existing literature about experiments, which substantiate this thesis.

## Longitudinal Vibration of Beams Undergoing Large Rotation

Ordinary Differential Equations of longitudinal free vibration of a homogeneous beam, turning with a constant angular rate, was derived by a method of the analytical mechanics, based on a direct approach for calculation of the generalized inertial forces for holonomic mechanical systems. It is indicated, at the derivation of the equations that as a contrast to the vibration component of the centrifugal force applied to a point from the beam axis, the rigid body component of the centrifugal force does not lead to point oscillations. The stiffness coefficient at the generalized coordinate in the equation of longitudinal oscillation decreases proportionally to the square of the angular rate of turn. This phenomenon persists on all possible frequencies of oscillation.

Lateral Vibration of Beams Undergoing Large Rotation

Explicit equations of lateral free vibration were derived also for turning of a homogenous pinned-pinned beam. Again, the vibration component of the centrifugal force leads to a decrease of the beam stiffness for all frequencies of the lateral vibration.

Conclusion

The present work clarifies what are the reasons for softening effect at purely longitudinal or lateral vibrations, as well as at their coupling. It is displayed that the effect persists continuously for all possible oscillation frequencies. The results were obtained for a non-linear set-up without simplifying assumptions and/or function approximation. The work shows that the softening phenomenon is a completely real event at large rotation of oscillating beams and is related to the vibration component of the centrifugal force. It is interesting that the effect does not depend either from the amplitude or from the frequency of oscillations and completely disappears when no oscillations are present. Actually, the first eigenfrequency of the vibration represents the critical value of the possible angular rate of large rotation of the beam. No doubt this assertion needs experimental verification.

## References:

- [1] Kane T.R., Ryan, R.R.and Banerjee A.K. Dynamics of a cantilever beam attached to a moving base, J. Guidance, 1987, vol.10, no.2, p. 139-151.
- [2] J. Martines, M. A. Botto and J. Sa Da Costa. Modeling of Flexible Beams for Robotic Manipulators. Multibody System Dynamics, Kluwer Academic Publishers, 7, 2002, p. 79-100.

ID of Contribution: 22 - 378

## COUPLED, LARGE AMPLITUDE VIBRATIONS OF CIRCULAR PLATES SUBJECTED TO THERMAL AND MECHANICAL LOADS

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The consideration of large dynamic and thermal loads on the structures is of great importance for machine design in many modern branches of machine building. The plates are fundamental structural elements and they are widely applied in the technological areas mentioned above. Being thin walled structural elements the plates are often subjected to mechanical and thermal loadings leading to intensive large amplitude vibrations whose consideration is very essential in the design process.

The objectives of the present study are: (i) to develop an efficient and accurate numerical procedure for the large thermoelastic uncoupled and coupled vibrations of circular plates, (ii) to study buckling and post-buckling behaviour of plates at elevated temperatures subjected to harmonic mechanical loading based on the proposed numerical approach, (iii) to study coupled vibrations of the plates subjected to heat and mechanical impacts and to identify the validity of the model when the elevated temperature is accepted instantly distributed uniformly along the plate length and thickness.

The geometrically non-linear version of Mindlin plate theory is used to describe the plate vibrations. The thermal and mechanical loads are applied on the upper surface of the plate. The lower surface and the edge of the plate are subjected to convective heating (cooling).

An iterative procedure based on the pseudo-load mode superposition method and the finite differences method has been developed (see for example [1] and [2]). This approach allows the change of the basis from the nodal spatial displacements to the modal generalized displacement by using a set of vectors based on the "assumed linear system". The nonlinear terms due to large deflections and temperature loads are grouped together with the mechanical loads thus forming the pseudo-load force vector. The coupled ordinary differential equations for the generalized displacement are solved applying an iterative procedure for determining the non-linear pseudo-load force vector. The equation describing the heat propagation (considering the influence of the mechanical field) is discretized by FDM and then an implicit algorithm is applied for its solution. Then a numerical algorithm as applied based on the successive solution of the equations for the mechanical vibrations of the plate and for the heat transfer. The obtained numerical results aim to clarify the validity of the model at which the heat propagation is not considered accepting that the plate gets the elevated temperature instantaneously. This will allow the establishment of appropriate criteria for the use a dynamic coupled thermo-mechanical model dependent on the thickness of the plate and heat impact parameters. The influence of the temperature loading for plate subjected to harmonic mechanical loading with frequencies of excitations close to the frequencies of the free vibrations as well the rise of a nonperiodic and chaotic motion are investigated in detail.

## References:

[1] E. Manoach, Large amplitude vibrations of Timoshenko beams subjected to thermal loading, 8th International Conference Recent Advances on Structural Dynamics. Southampton, England, 2003, paper 39 [2] E. Manoach and P. Ribeiro, Coupled, thermoelastic large amplitude vibrations of Timoshenko beams. Int. Journal of Mechanical Sciences (in press).

ID of Contribution: 22 - 432

## NONLINEAR WARPING AND TORSIONAL ELONGATION IN THE RESPONSE OF CHANNEL SECTION BEAM

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In last years, many paper have been devoted to nonlinear dynamics of 3D beams. In a previous paper [1] the Authors studied a nonlinear one-dimensional model of inextensional, shear undeformable, thin-walled beam with an open cross-section. Nonlinear in-plane and out-of-plane warping and torsional elongation effects were included in the model. By using a generalization of the Vlasov kinematical hypotheses, the nonlinear warping was described in terms of the flexural and torsional curvatures. The displacement field depends on three components only, two transversal translations of the shear center and the torsional rotation. By taking into account the order of magnitude of the various terms, the equations were simplified and the effect of symmetry properties has been also outlined. A discrete form of the equations was derived to study dynamic coupling phenomena in conditions of internal resonance. The results showed that warping and torsional elongation produce notable modifications in the response of the beam to harmonic excitation [1]. Unfortunately this model is very complex and the interpretation of the mechanical behavior of the system is very difficult.

Aim of the present paper is to study more in detail the effects of nonlinear warping and torsional elongation that has been shown to play an important role in the nonlinear response. A preliminary study is developed to determine the different order of the kinematical quantities in a realistic beam, that will be a prototype for an experimental investigation, loaded by a static force at the free end in the direction orthogonal to the symmetry axis. A beam is considered characterized by the following nondimensional parameters : t/h=0.02, b/h=0.5, h/l=0.05, where t is the thickness of the section, b and h are the dimensions of the C cross section, being h orthogonal to the symmetry axis, and 1 the length of the cantilever beam. For this beam the ratio between torsional and flexural curvatures is about forty; this circumstance makes it possible to introduce a great simplification in the model developed in [1].

Through Hamilton principle, under the hypothesis of large torsional curvature and small flexural curvatures, three equations of motion are derived describing dynamics of inextensional and shear undeformable nonlinear 3D beam. An harmonic load is considered acting in the direction orthogonal to the symmetry axis and applied to the free end of the cantilever beam. A Galerkin discretization is performed by introducing the first three eigenfunctions and, by using multiple scale method and amplitude-modulation equations are obtained. Frequency-response and amplitude-load curves are evaluated to characterize the behaviour of the beam and highlight the nonlinear warping and torsional elongation contributions. A numerical investigation using a finite element model including geometrical nonlinearities, is performed to validate the mechanical model and an experimental test is also expected in the next future.

References:

 A. Di Egidio, A. Luongo, F. Vestroni, A nonlinear model for open cross-section thin-walled beams, Part I: Formulation and Part II: Forced motion, Int. J. of Non-Linear Mechanics, 2003, 38(7), 1067-1081 and 1083-1094

## NONLINEAR DYNAMICS AND STABILITY ANALYSIS OF CLAMPED CYLINDRICAL SHELLS SUBJECTED TO AXIAL FLOW

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In 1972, a combined theoretical/experimental study by Païdoussis and Denise [1] gave new impetus to research on the stability of cylindrical shells in contact with subsonic axial flow. The experimental data showed that elastomer shells with clamped ends conveying fluid lose stability by flutter, while the linear theoretical model predicted loss of stability by divergence, followed at slightly higher flow by coupled-mode flutter. More recently, it was realized that the discrepancy between theory and experiment must be addressed by nonlinear theory [2]. A recent nonlinear analysis of simply supported shells conveying fluid [3] predicted loss of stability by divergence, but not followed by flutter. In the present study new experiments were undertaken and a new nonlinear theoretical model for clamped shells was developed to investigate the dynamics further and resolve residual discrepancies between theory and experiment. Applications of fluid structure interaction (FSI) systems may be found in nuclear reactors, space vehicles, aircraft engines, pumps, and in biomechanics (pulmonary passages, veins, etc.).

The aim of the experimental study was twofold: (i) to gather important data on the critical flow velocity for instability, maximum flexural shell displacement, and the evolution of shell frequencies with flow; (ii) to analyze the experimental results and use them to validate the theoretical model. The experimental study involved aluminum and plastic Polyethylene Terephthalate (PET) shells conveying water.

The radial deformation of the shell at the first point of buckling was about 18 times the shell thickness. When slowly decreasing the flow velocity, the shell amplitude was also decreased until the original circular shape was restored This flow-dependent hysteresis shows that the divergence instability is subcritical; i.e., the nonlinear behaviour is of the softening type.

In the theoretical study the nonlinear Donnell shallow shell theory, with structural damping, is used to describe the large-amplitude shell motion. The assumed deflection mode is an expansion of asymmetric (driven and companion modes) and axisymmetric modes. The interaction between the flowing fluid and the shell structure is formulated with linear potential flow theory. The fluid domain is assumed to be a cylindrical flow of infinite extent that is periodically supported by an infinite length shell, allowing for the use of the separation of variables method in the flow solution. The system is discretized using Galerkin's method and the amplitude of the shell response is obtained by the arc-length continuation technique employed in the AUTO software.

The experimental and theoretical results are in excellent qualitative and reasonably good quantitative agreement for the water-plastic shell system. Both the experimental data and the theoretical model show that the shell system in internal flow loses stability by divergence, experiencing a large hysteresis, returning to its original circular shape at much lower flow velocities. Post-divergence flutter was not observed or predicted.

## References:

- M.P. Païdoussis and J.P. Denise: "Flutter of thin cylindrical shells conveying fluid", Journal of Sound and Vibration, 20, 9-26 (1972).
- [2] M.P. Païdoussis: "Fluid Structure Interaction: Slender Structures and Axial Flow", Vol. 2., London: Elsevier Academic Press, 2003.
- [3] M. Amabili, P. Pellicano, and M.P. Païdoussis: "Nonlinear dynamics and stability of circular cylindrical shells containing flowing fluid. Part I: Stability", Journal of Sound and Vibration, 225, 655-699 (1999).

# **MINI-SYMPOSIUM 23**

## Miscellaneous

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## SOME MODELS WITH FRICTION TERM AND HISTORY TERM

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In [1], we established some existence, uniqueness and numerical analysis results for a first order differential inclusion in time with a maximal monotone term. To prove these results we established some uniformly in time estimations for a discrete solution, defined by the implicit Euler numerical scheme. We pass then to the limit as the discrete time step tends to zero. By using Gronwall's Lemma we prove then that the order of convergence of the discrete solution to the solution is equal to 1/2 in the general case and equal to 1 if the maximal monotone term is the subdifferential of the indicatrix function of a closed convex set. Theses results can be applied to some models with finite number of degrees of freedom involving linear springs, dashpot and dry friction elements. This frame can by extended to models with infinite number of degrees of freedom.

In [3], we consider the same frame with a delay term of convolution. The method is similar.

In fact, all theses results can be extended to differential inclusions involving maximal monotone term and a history term. We make some assumptions on smoothness of this history term and we introduce discretization in time. Thus, it is possible to apply the above method to prove existence and uniqueness of the solution of the studied differential inclusion and the convergence of the numerical scheme. Theses results were obtained in [2]. We also give two examples. The first one possesses two degrees of freedom. The history term is a convolution delay term and it is presented with numerical simulations. The second one is an abstract example it permits to study deformation process, with a creep term, for elasto-viscoplastic bodies with a linear hardening.

References:

- [1] Jérôme Bastien and Michelle Schatzman. Numerical precision for differential inclusions with uniqueness. M2AN Math. Model. Numer. Anal., 36(3):427--460, 2002.
- [2] Jérôme Bastien and Claude-Henri Lamarque. Maximal monotone model with history term. Submitted to M2AN. Mathematical Modelling and Numerical Analysis, 2004.
- [3] Claude-Henri Lamarque, Jérôme Bastien, and Matthieu Holland. Maximal monotone model with delay term of convolution. Submitted to Mathematical problems in Engineering, 2004.

ID of Contribution: 23 - 006

## HELICOSEIR AND HELIX AS EXAMPLES OF ROTATING CHAIN PROBLEM

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The problem of determination of the shape of a continuous medium is not a new one and has its own history. For example, the catenary problem (non-rotating chain) and the troposkein problem (rotating chain suspended at two points) belong to this area. The problems arising here often have a simple physical representation but surprisingly complicated equations. Such is the case of the quite interesting problem discussed in this paper and called 'helicoseir', from Greek for 'rotating rope' [1].

We consider a heavy rotating chain with only one fixed top point and without resistance forces, at first. For the first sight, it can be considered as 2D curve in a rotating reference frame. Several dynamical formulations, such as Newton's

ENOC-2005, Eindhoven, the Netherlands

second law, d'Alembert or a variation principle, are considered. They lead to several representations of configuration equations. The simplest equation obtained in [2] still remains very complicated, that is why we solve it numerically using the shooting method. We represent the behaviour of the solutions by the diagram of bifurcation. The main disappointing result of this part is that all the non-trivial equilibrium shapes appear instable using Hamilton-Ostrogradsky principle. However, one can demonstrate that the visual behavior of the real helicoseir is stable.

Obviously, this discrepancy exists because the real shape of the helicoseir is not flat but the chain takes some spatial form. We derived full formulation in the form of system of partial nonlinear differential equations and showed that the 2D equations above are their particular cases. However we found 3D equations very complicated to solve them analytically. Instead, we analyzed them numerically using a large-displacement finite-element approach called the absolute nodal coordinate formulation [3]. The simulation shows that the spatial motion of the helicoseir is stable and looks like self-excited oscillations near the flat instable configurations that were obtained previously. Some examples of bifurcation instability of the spatial motion are presented. Unfortunately, numerical simulation cannot give answers to some interesting theoretical questions, that is why further analytical research of this problem is desirable.

In the paper, we consider 2D and 3D rigid-body models of the helicoseir in the form of multibody pendulums. The results are in a good agreement with the continuous model.

We also consider a more general problem including bending stiffness as well as air resistance forces, when the chain takes a helix-like form. Exact PDE of motion, numerical simulation using finite elements and experimental results are presented as well.

## References:

- [1] Silverman M. P., Strange Wayne, Lipscombe T. C., 'String theory': equilibrium configurations of a helicoseir', in European Journal of Physics 19, 379-387, 1998.
- [2] Dmitrochenko O., Yoo Wan-Suk, Pogorelov D., 'Helicoseir as shape of a rotating chain (I/II): 2D/3D theory and simulation using ANCF', submitted in Multibody System Dynamics Journal in 2004.
- [3] Shabana A. A., Dynamics of Multibody Systems, 2nd Edition, Cambridge University Press, Cambridge, 1998.

#### D of Contribution: 23 - 049

## TIME INTEGRATION OF NONLINEAR EQUATIONS OF MOTION - NUMERICAL INSTABILITY OR NUMERICAL INCONSISTENCY?

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In spite of the versatility of time integration methods in analyzing semi-discretized equations of motion, the resulting responses are inexact. Therefore, to have a successful analysis, convergence should be maintained. In presence of nonlinearity, convergence can not be always maintained for the responses produced by time integration. In the past decades, many researchers have tried to explain the phenomenon and overcome the shortcoming. Among the considerable number of existing researches, one of the most recent studies is carried out by the authors of this abstract, where the mechanism and main reason of the convergence shortcoming (in time integration of nonlinear equations of motion) is explained in detail and from a mathematical point of view. This paper will be a review of this very recent and in-press research. In brief, after introducing sufficient conditions for proper convergence in presence of nonlinearity, it will be explained that in time integration of a nonlinear semi-discretized equation of motion, the inconsistency between the errors induced by time integration and the nonzero residuals of iterative nonlinearity solutions is the main reason of improper convergence. The mechanism of this inconsistency will be explained in detail. Some limiting cases will also be studied, and, after a short review on some other sources of the shortcoming, numerical inconsistency will be introduced as the main source of shortcoming.

#### References:

 T. Belytschko, W. K. Liu, B. Moran, Nonlinear Finite Elements for Continua and Structures, John Wiley & Sons Inc., USA, 2001.

## ENOC-2005, Eindhoven, the Netherlands

- [2] A. Soroushian, New Methods to Maintain Responses' Convergence and Control Responses' Errors in the Analysis of Nonlinear Dynamic Models of Structural Systems, PhD Thesis, University of Tehran, 2003.
- [3] Soroushian, P. Wriggers, J. Farjoodi. On practical integration of semi-discretized nonlinear equations of motion. Part 1: reasons for probable instability and improper convergence. Journal of Sound and Vibration (accepted for publication).

## A GRAZING CRITERION FOR A PERIODICALLY FORCED, FRICTION-INDUCED, LINEAR OSCILLATOR

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The criterion for grazing motions in a dry-friction oscillator is obtained from the local theory of non-smooth dynamical systems on the connectable and accessible domains. The generic mappings for such a dry-friction oscillator are also introduced. The sufficient and necessary conditions for grazing at the final points of mappings are expressed. The initial and final switching sets of grazing mapping, varying with system parameters, are illustrated for a better understanding of the grazing parametric characteristics. The initial and grazing, switching manifolds in the switching sets are defined through grazing mappings. Finally, numerical illustrations of grazing motions are very easily carried out with help of the analytical predictions. This paper provides a comprehensive investigation of grazing motions in the dry-friction oscillator for a better understanding of the grazing mechanism of such a discontinuous system. The investigation based on the local singularity theory is more intuitive than the discontinuous mapping techniques.

ID of Contribution: 23 - 182

## **CONTROL OF NONLINEAR MECHANICAL SYSTEMS UNDER UNCERTAINTY**

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A problem of designing a feedback control for mechanical systems of general form is considered. The main objective of the investigation is to develop a feedback control for nonlinear systems with many degrees of freedom, such as multibody systems, robots, etc.

The systems under consideration are governed by Lagrange's equations of the second kind. Both scleronomous and rheonomic systems will be of our concern. In the most general rheonomic case the kinetic energy has the form of a full quadratic polynomial whose coefficients depend on time explicitly. We assume that some coefficients of this quadratic polynomial are unknown and the system is subjected to unknown bounded disturbances. The control forces are assumed to be bounded as well.

The problem is to construct a continuous feedback control law meeting imposed constraint which steers the system to the prescribed terminal state in a finite time.

Major difficulties encountered in investigating the control problem stated are caused by high dimension of the phase space, nonlinearities in equations of motion, the requirement to have a constraint control law in feedback form, uncertainties in the system parameters, uncontrolled external disturbances, and finitude of the time of motion.

Most of the known approaches for constructing such algorithms lead to control laws that are in general discontinuous functions of time. The aim of this study is to design a continuous feedback control which guarantees the desired performance of the system under consideration.

We propose a control which is presented in closed-loop form, meets the imposed constraints, drives the system to a prescribed terminal state in a finite time, and is effective irrespective of the realization of uncertain parameters of the system unless they go outside admissible boundaries.

The proposed algorithm employs a linear feedback control with the gains which are functions of the phase variables and time. The gains increase and tend to infinity as the phase variables tend to zero; nevertheless, the control forces are bounded and meet the imposed constraint.

The approach developed is based on Lyapunov's direct method.

References:

- Piatnitski, Y. S. Decomposition principle in control of mechanical systems. Dokl. akad. nauk SSSR. vol. 300, N 2, pp. 300-303. 1988.
- [2] Chernousko, F. L. Decomposition and suboptimal control in dynamic systems. Applied Mathematics and Mechanics (PMM). vol. 54, N 6, pp. 727-734. 1990.
- [3] Ananievski, I. M. Continuous Feedback Control of Mechanical Systems Subjected to Disturbances. Dokl. Akad. Nauk. vol. 385, N 3, pp. 1 - 5. 2002.

ID of Contribution: 23 - 227

## COMPARISON OF PASSIVE AND ACTIVE ENERGY PUMPING IN MECHANICAL NONLINEAR SYSTEM

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The problem of energy pumping in mechanical systems with two and many degrees of freedom attracts a special attention now [1-2]. Energy pumping is passive, almost irreversible transfer of mechanical energy from the main substructure of the system to the light auxiliary attachment. The prime practical object of this process is removal of excess mechanical energy from the main substructure (for example, a building, an engine etc.) to the light auxiliary substructure where energy dissipates as heat without damage to the main substructure. There are different techniques of energy pumping. However active control approaches [3] were not applied in this field until now. There are several types of control algorithms. It is possible to apply control signal to the main or auxiliary substructure (to put it in another words: to apply external control force to this substructure). This signal depends on the current state of the system. However this type of control actions have essential drawbacks. It is very difficult to compose optimal form of control signal. Practical applications of such algorithms require complicated and expensive control devices. These devices consume considerable energy.

Algorithms of the second type are based on the following principle. It is possible to attach and disconnect component parts of mechanical system: springs, absorbers etc. during its work. Practical applications of such algorithms is simpler and cheaper than applications of algorithms of the first type. In our presentation we propose algorithm of the second type.

In our presentation we describe nonlinear dynamics of essentially non-homogeneous system of coupled oscillators using the technique of multi-scale expansion. The resonant mechanism of passive energy transfer from a massive oscillator into a light auxiliary one provides essential reduction of energy of the massive oscillator. Proposed active control algorithm increases essentially efficiency of energy transfer in comparison with passive control. The important advantage of this algorithm is that it provides a small consumption of energy. It is expedient to use our algorithm in the certain limits of parameters determined in the presentation. This algorithm provides a necessary level of reduction of oscillator amplitude in a wide range of external perturbations.

References:

[1] Gendelman O., 'Transition of Energy to a Nonlinear Localized Mode in a Highly Asymmetric System of Two Oscillators', Nonlinear Dynamics 25 (2001) 237-253.

[2] Manevitch L.I., Gendelman O., Musienko A.I., Vakakis A.F., Bergman L., 'Dynamic Interaction of a Semi-infinite Linear Chain of Coupled Oscillators with a Strongly Nonlinear End Attachment', Physica D, 178 (2003) 1-18.

[3] Fradkov A.L. Cybernetical Physics: Foundations and Examples. Saint-Petersburg: Nauka, 2003 (in Russian).

ID of Contribution: 23 - 248

## INSTABILITY OF A WHIRLING CONDUCTING ROD IN THE PRESENCE OF A MAGNETIC FIELD

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We study instabilities of a conducting elastic rod whirling in a magnetic field by performing a (largely numerical) continuation and bifurcation analysis of the dynamics equations for a geometrically nonlinear rod (a PDE) linearised about a statical solution of interest. Attention is also paid to exact finite-length helical solutions, which require special boundary conditions, for which exact results can be obtained.

The results are relevant for the Short Electrodynamic Tether (SET) prototype of the European Space Agency, which is designed to use the earth's magnetic field, rather than chemical fuel, for thrust and drag. Such a tether is spun about its axis for gyroscopic stability and resists bending and twisting so that the usual approach based on strings, rather than rods, is invalid.

ID of Contribution: 23 - 306

## **GEOMETRIC MECHANICS AND WAKE-BODY INTERACTIONS**

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The development of liftlike forces on solid surfaces through vortex shedding is central to a variety of problems in aquatic and aerial propulsion and steering. Indeed, distinct wake structures like the staircase of vortex rings shed by a swimming dolphin or tuna provide revealing reflections of the propulsive forces resulting from their creation. Tools for the realization of reduced-order models for interactions between controlled bodies and large wake structures presently exist only ad hoc. The development of a formalism for such systems will enable, for example, the development of general nonlinear control methods for biomorphic robotic vehicles.

The mechanical system comprising a deformable body immersed in an incompressible fluid exhibits a finitedimensional symmetry with respect to rigid translations and rotations and an infinite-dimensional symmetry with respect to fluid particle relabeling. If the fluid is inviscid, these symmetries give rise to conservation laws for Kelvin impulse and circulation. The locomotion of a body undergoing controlled deformations in an inviscid fluid has been treated using Lagrangian reduction to realize a finite-dimensional model in the form of a control-affine nonlinear system [1].

Vortex shedding is a fundamentally viscous phenomenon. Classically, however, the development of lift on a translating airfoil has been treated in the context of inviscid flow through the introduction of a Kutta condition to enforce stagnation at the foil's trailing edge. In the context of geometric mechanics, the concept of a Kutta condition can be generalized to a class of group-invariant constraints --- some holonomic, some nonholonomic --- which restrict flow velocities relative to solid surfaces. If a body and fluid are cast as a single reduced Lagrangian system, such constraints couple momentum equations in the sense of [2] which describe the interdependent evolution of body momentum and fluid vorticity.

Liftlike forces derived from the establishment of circulatory flows contribute gyroscopic terms to equations governing body momentum. The rectification of periodic control inputs is a pervasive aspect of biomorphic locomotion, essential

to the notion of gait. In even simple cases, periodic gyroscopic terms can lead to complex trajectories for vehicles subject to external forces [3].

We develop this geometric perspective on fluid-body interactions, focusing on the formulation of problems in planar biomorphic aquatic locomotion in terms of constrained Lagrangian mechanics and nonlinear control. We link this work to current Hamiltonian models for free and controlled interactions between planar bodies and point vortices, and describe parallel experimental research in aquatic robotics.

References:

- [1] Kelly, S. D. The Mechanics and Control of Driftless Swimming. To appear, SIAM Journal on Control and Optimization.
- [2] Bloch, A. M., P. S. Krishnaprasad, J. E. Marsden, and R. M. Murray. Nonholonomic Mechanical Systems with Symmetry. Archive of Rational Mechanics and Analysis, 136, 21--99.
- [3] Kelly, S. D., H. Xiong, and R. B. Hukkeri. Mechanics, Dynamics, and Control of a Single-Input Aquatic Vehicle with Variable Coefficient of Lift. Submitted to IEEE Transactions on Robotics, 2004.

## ID of Contribution: 23 - 342

## VIBRATIONAL DISPLACEMENT, OVERCOMING THE POTENTIAL AND FORCE BARRIERS

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Between the stable states of material systems there are potential and force barriers. We can also state the opposite: the states are stable because there are barriers between them. Many technical and natural processes can be regarded as a transition from one stable state to another or as a change of stable states.

One of the methods of changing the states of a mechanical system, of its displacement from one state to another, is vibration. By vibrational displacement we mean the appearance of the "directed on the average", as a rule, slow change of the state of the system (in particular of motion) under the action of the "non-directed on the average" oscillatory, as a rule, fast action. Examples of the vibrational displacement are the transportation of single bodies and granular materials in the vibrating vessels or trays; the work of the devices, called vibrational transformers of motion and vibro-engines; vibrational driving of piles, of sheet piles, of shells; vibrational separation of granular materials, the motion of vibrational coaches; flight, swimming and crawling of living organisms.

The notion of vibrational displacement was formulated as far back as 1964 by G.Yu.Janelidze and by the author. By now there are several thousand investigations of this effect, both purely theoretical and devoted to numerous technical applications.

The presentation contains but a brief review of those investigations. A detailed review may be a subject matter of a special presentation. The main attention is paid to some new results. In particular we consider the problem of vibrational overcoming of the force and potential barriers when the state of the dynamic system is changing. In that case special attention is given to the investigation of the effect of the hidden motions and hidden degrees of freedom on the processes of vibrational displacement. Models of the motion of the vermicular are also under consideration. It has been shown that the observer who does not notice vibration or the hidden degrees of freedom of the system perceives the behavior of the system as a reduction of the level of the force and energetic barriers between the stable states of equilibrium of the system (the tunnel effect). Such an observer has an illusion that the main laws of mechanics and thermo-dynamics have been violated while the above effects are in good accordance with those laws.

## NONLINEAR DYNAMICS IN THE NOSÉ-HOOVER ENVIRONMENT

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Nowadays Molecular Dynamics is one of the most wide spread methods for modeling and computer simulations of molecular systems. Among the objects of modeling there are such important biological molecules as DNA and peptides, the conformational dynamics of the latter deserves special attention. The important problem is setting the temperature of the system, or to be more general and precise: consideration of the interaction between the system and the medium, characterized by some thermodynamic parameters. In real molecular simulations large systems are considered, it leads to impossibility of setting the interaction directly. For this purpose the simplified models of so called "mechanical thermostats" are often used. The correspondence of distribution functions of the system's characteristics to Gibbs' canonical ensemble could be the criteria of the thermostat efficiency. In fact, the problem of modeling Gibbs' canonical distribution is fundamental for modern statistical physics.

Various thermostat models were introduced in the method of Molecular Dynamics (see [1], and references therein), their efficiency depends on the simulated system. The most widely used models nowadays are the Berendsen and the Nosé-Hoover ones. The dynamics of some systems, confined to the first one was studied in [2]. As the development of the research, described in [3], the dynamics of some special systems was analyzed for the Nosé-Hoover thermostat, using its most widely applied in numerical experiments model, which is realized by introducing nonlinear dissipative terms (nonlinear alternating friction) into the right hand sides of the equations of motion.

It is known that for simple systems (ideal gas) the Nosé-Hoover thermostat doesn't lead to correct, from the point of view of thermodynamics, distribution functions, but it is generally accepted that the situation becomes better with the increase of complexity and dimension of the simulated system.

Employing the method of averaging and direct computer simulations it has been shown that for an ensemble of harmonic oscillators (which is the generalization of a harmonic lattice) for some parameters of the thermostat oscillatory motion around the stationary solution with the frequency, dependent on the values of thermostat parameters, is observed. Or for their larger values one can observe the process of chaotisation. (See [3] for details). For this case also the distribution of energy against degrees of freedom has been obtained numerically, and for some situations the distribution is incorrect.

Besides the resonance effects for the harmonic systems have been studied. In case of parametric excitation of the system, the parametric resonance, resulting in the increase of energy amplitude, can be easily observed. Its conditions were found with the help of Rayleigh's method. And the subject of the very recent research is systems with constraints.

References:

- [1] M.D'Alessandro, A.Tenenbaum, and A.Amadei, J.Physical chemistry B 106, 5050 (2002).
- [2] V.L.Golo, K.V.Shaitan, Biofizika, 47, 611 (2002)
- [3] V.L.Golo, Vl.N.Salnikov, K.V.Shaitan, Phys. Rev. E 70, 046130 (2004)

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## NONLINEAR VIBRATIONS OF A FLUID COUPLED COAXIAL CYLINDRICAL SHELL

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Circular cylindrical tanks are extensively used as fluid storage in industry, municipal water supply constructions and other devices. Such systems are subjected to intensive dynamic loads that might lead to cyclic tensions, stability loss, and other negative effects. That is why the study of the dynamic behavior of fluid in tanks is important in the earthquake-proof design and reliability assessment of fluid storage tanks.

A fluid-structure interaction system of two coaxial circular cylindrical shells with the same height, partially filled with an incompressible inviscid fluid to the same depth in the inner shell and in the outer annular gap between both shells, is under consideration. The outer shell is rigid, the inner is elastic. The shells' bottom is an absolutely rigid plate.

A nonlinear problem of the free vibrations of the given fluid-structure interaction system is considered, taking that its nonlinearity is as a result of big gradients of the shell vibrations. An analysis of the nonlinear vibrations of the system which correspond to some of its natural frequencies has been done.

Usually some simplifying method is used for the solution of nonlinear problems of the dynamics of the fluid-structure interaction systems - the forms of the "dry" natural vibrations of the shell (without fluid) are taken as basis functions for the elastic shell with fluid and only one or two forms are considered. Such method could lead to essential mistakes in many cases for the determination of the nonlinear dynamic characteristics of the corresponding system.

Here the displacement of the elastic shell is expressed directly through the forms of its vibrations, which were found taking into account its interaction with fluids [1]. Analogously the deformations of the free surfaces of the fluids in the inner shell and in the annular gap between the shells are presented, using the vibration forms of these surfaces, which were found taking into attention the interaction between the fluids and the elastic shell [1].

Applying the Bubnov-Galerkin method to the differential equation about the elastic shell displacement, some nonlinear system is obtained with coefficients, depending on the physical and geometrical parameters of the fluid-structure interaction system. Its investigation is made, following [2] and applying the method of Bogolubov [3].

#### References:

- Gavrilova, E. (2004) A Study of the Vibration of Fluid Coupled Coaxial Cylindrical Shell. Fluid Mechanics and Its Application, IUTAM Symposium on Integrated Modeling of Fully Coupled Fluid Structure Interactions Using Analysis, Computations and Experiments, Editors: H. Benaroya and T. Wei, Kluwer Academic Publishers, 363-374.
- [2] Kubenko, V. D., P. S. Kovalchuk, N. P. Podchasov 1989 Nonlinear Vibrations of Cylindrical Shells, Kiev, Visha skola. (in Russian)
- [3] Bogolubov, N. N., Yu. A. Mitropolskii 1974 Asymptotic Methods in Theory of Nonlinear Oscillations, Moscow, Nauka. (in Russian)

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## CHARACTERIZATION OF DYNAMIC BEHAVIOR OF THE LAYER-SUBSTRATE SYSTEM THROUGH MD SIMULATION

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Coatings increase the tool life significantly by directly increasing wear resistance or improving contact conditions. Cutting processes, in which coated tools and Minimal Quantity Lubrication are adopted, were believed as promising alternatives to conventional wet-machining processes that are currently criticized for their environmental impacts of cutting fluids. However, the typical failure of coated tools, such as, crack and delamination always unexpectedly introduce uncertainty to the machining process. Strong variations in tool life were observed due to unpredictable tool failures. Intensive attention was drawn to understand the nonlinear effects in the layer-substrate systems with the primary aim of improve the reliability of machining processes with coated tools. The static composite properties of the coating-substrate system have been widely investigated through nano-indentation, scratch test, pin-on-disc experiments, XRD. To characterize the fatigue and creep behaviors of the coating-substrate systems, multi-impact tests were conducted accompanying with the static FEM analysis of the critical working stress on basis of critical impact loads obtained from the tests. Unfortunately such static or post-failure phenomenological studies provided insufficient information for the dynamic behaviors of layer-substrate system to understand the cracking and delaminating in the coated tools. The advent of the supercomputer and the development of the FEM theory open a new way allowing scientists to study the dynamic behaviors, failure mechanisms through FEM simulations, but the lack of mechanical

ENOC-2005, Eindhoven, the Netherlands

## 346

properties of the interface and the isotropic approximation of local properties sometimes limit or even paralyze intensive application of the method. The intrinsic residual stress, introduced from the coating process and tool fabricating processes, as a result of film lattice mismatch with the substrate, can significantly influence the residual stress nature and magnitude, and accordingly the dynamic behavior of the layer-substrate systems depending on the coating techniques.

This paper presented a layer-substrate system with Ni coating on Cu substrate, resembling a combination of hard coating on softer substrate. The developed MD program calculates the layer-substrate system properties, both structural and mechanical, while carrying out indentation simulations. The dynamic behavior of was studied through multi-impact test simulation. By introducing normal dynamic workloads on the coating-substrate system, this setup actually allows to study the non-linear dynamic response of the normally loaded systems, such as the chisel edge of drill bit, ball nose end mills etc. The tool forces during impact testing simulation are analyzed both in time and frequency zone, particularly the instantaneous working stresses and structural changes inside of the layer-substrate provide details of the local changes due to the impacting forces which are believed to induce cracks, delamination.

References:

[1] F. Klocke, T. Krieg, Annals of the CIRP, 48(2), 1-11(1999).

- [2] H. K. Tönshoff, A. Mohlfeld, C. Spengler, C. Podolsky, Conference Proceedings the Coatings in Manufacturing Engineering, Thessaloniki, Greece (1999), 1-20.
- [3] E. Brinksmeier, Precision Engineering, 11, 211-224(1989).

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## FLOW-INDUCED OPTIMIZATION OF ARTERIAL NETWORKS FOR NONLINEAR VISCOELASTIC ARTERIAL WALL MODEL

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Time-dependent blood flow in arteries is defined by heart contractions. Geometry of the arterial vasculature plays an important role in pressure-flow relations in the separate vessels and total network. Numerous measurements on the plastic casts of the vasculatures of the inner organs have revealed clear regularity between the diameters of the vessels in the arterial bifurcations (Murray's law) and between the diameters and branching angles. The relations can be explained on the basis of the optimization criterion proposed by C.D. Murray (1926). The developed theory suggests that the arterial vasculatures consist of the optimal tubes which provide blood delivery at minimal total energy costs W of the blood motion through the vessel and construction and maintenance of the vessel wall that are proportional to the volume V of the vessel. For the stationary blood flow in the rigid tube (Hagen-Poiseuille flow) the solution of the optimization problem and the volumetric rate continuity conditions in the bifurcation give Murray's law. It follows that in the optimal tubes the shear stress at the wall is constant. In that way optimal arterial networks can be constructed during the growth and development of the individuals when the shear stress is maintained at a constant level by the mechanoreceptors in the inner layer of the wall. Murray's law is regarded as a general rule for the arterial network construction. Deviation from the law is negligible small for the vasculatures in terms of average values though variations can be significant in separate bifurcations and at pathological conditions.

When flow is time-dependent and the shear stress oscillates, the optimization criterion can be considered as applied to the time-averaged flow parameters. At the same time many phenomena such as non-linear dynamics of the arterial wall, oscillations of the diameter of the vessel, superposition of the propagated pulse wave and the waves which are reflected at each bifurcation of the arterial network are not taken into consideration in different modifications of the Murray model yet. Actually blood flow in arteries is much more complicated process than one is described by Hagen-Poiseuille flow and validity of Murray's law is still discussed in literature.

Here the axisymmetric flow of the incompressible viscous liquid in the nonlinear viscoelastic isotropic thick-walled cylindrical shell is investigated. The Navier-Stokes equations and momentum equations for the shell at given pressure oscillations in the inlet of the tube and the wave reflection conditions in the outlet are considered. The solution of the coupled mechanical problem is obtained numerically in the time domain. The optimization problem when total energy loss reaches its minimum at a given volume of the system V=const is solved. Combined with the pressure and volumetric rate continuity conditions in the bifurcations the solution gives the generalization of Murray's law for the nonlinear viscoelastic arterial wall. The shear stress at the inner surface of the moving wall with time-varying diameter

d(t) is calculated. The results confirm that in the optimal vessel the time-averaged for the period of the heart contraction shear stress is practically independent on the volumetric rate.

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## MODELLING AND SIMULATION OF KINEMATICALLY EXCITED VIBRATION ISOLATION SYSTEMS WITH FRICTION, UNDER RANDOM AND HARMONIC EXCITATION

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An alternative approach to vibration mitigation in vibro-isolation systems (VIS) is to use a friction interface instead of a standard viscous damper. This approach requires consistent analysis using sophisticated mathematical modelling and simulation tools.

The intended paper will deal with kinematically excited single DOF oscillatory systems, using several approaches to friction modelling. A brief overview of the development of various algorithms will be provided. Continuous development of the solver algorithm led to a model with autonomous state equations with logical switching between them, based on thorough limit force analysis and to implementation of the Stribeck's effect. The advantages of modelling the influence of friction in mechanical systems in such a way are presented, especially when time integrated output vibration characteristics are sought, so as the RMS acceleration value, commonly used in describing vibration isolation in vehicle systems. The numerical stability aspect is taken into account, pointing out special problems, such as false saw-tooth-like oscillation and determination of optimal step size. Further comparison with laboratory measurements on a real VIS is provided. The detailed analysis of the real system is based upon the assumption of a range of relative displacement motion constrained by end-stops, which are further represented as a non-linear stiffness. The study of the dissipative capacity of the friction damper in resonance, limited within the admissible linear range of relative displacement due to end-stops influence, enables to forecast risk of undesired oscillatory behaviour. Towards the end of the paper, all models are summarized and compared to each other and to experimental results. The paper concludes with surveying the consequences for possible optimisation and design of VIS with friction dampers.

# **Author – Abstract Index**

Abdo: 17-014: p.241 Abed: 04-442: p.88 Acary: 02-228: p.53; 14-131: p.205 Ackemann: 18-286: p.272 Aeberhard: 02-204: p.52 Agrawal: 11-446: p.183 Ahlborn: 10-263: p.160 Alonso: 10-160: p.158 Alvarado: See Martinez-Alvarado Ambrósio: 03-421: p.72; 05-419: p.98; 20-420: p.297 Ananievski: 23-182: p.341 Andrianov: 21-268: p.313 Avramov: 06-061: p.103 Avrutin: 01-213: p.35 Awrejcewicz: 01-196: p.34; 02-090: p.49; 06-071: p.104; 10-074: p.157; 12-069: p.188; 14-065: p.203; 17-088: p.245; 21-075: p.305; 22-195: p.325 Bajaj: 19-318: p.286; 22-324: p.331 Bakri: 21-179: p.310 Balachandran: 17-156: p.249 Baleanu: 11-022: p.167 Barbosa: 11-106: p.171 Bardella: 18-431: p.275 Bastien: 23-003: p.339 Batako: 02-205: p.52 Baxendale: 04-081: p.80 Belouettar: 15-385: p.218 Bender: 17-145: p.248 Benner: 08-242: p.140 Bernardin: 14-376: p.210 Bernardo, Di: See Di Bernardo Besnard: 18-427: p.274 Beyn: 16-399: p.238 Bielawski: 08-430: p.146 Błachowski: 05-185: p.93 Blekhman: 23-342: p.344 Boukabou: 10-283: p.161 Bourgeot: 01-076: p.26 Breakspear: 07-473: p.129 Broer: 12-058: p.187 Buks: 19-015: p.281 Byrtus: 03-181: p.66 Chang: 01-257: p.38 Chareyron: 01-127: p.28 Chatterjee: 11-438: p.181 Chavez: 07-146: p.125 Chebouba: 05-379: p.97 Chelidze: 06-301: p.112; 09-304: p.151 Chirikov: 22-366: p.332 Choi: 05-320: p.96 Claussen: 08-232: p.138; 10-231: p.160 Coleman: 20-254: p.296 Csernák: 01-258: p.38 Dankowicz: 01-118: p.27; 19-101: p.282 De Schutter: 01-151: p.29 Demenkov: 14-159: p.207 Di Bernardo: 01-302: p.42; 10-303: p.162; 10-305: p.162; 21-300: p.314 Di Egidio: 22-432: p.334 Dick: 19-239: p.283

Dimitriu: 10-288: p.161; 17-292: p.256 Dimnet: 02-414: p.56; 14-415: p.212 Dmitrochenko: 23-006: p.339 Doedel: 15-452: p.219 Domokos: 16-031: p.227 Doris: 01-217: p.36 Dumitrache: 06-207: p.109 Dumont: 14-255: p.208; 14-256: p.209 Dzhanoev: 10-139: p.158 Dzonou: 02-362: p.55 Ecker: 22-271: p.327 Egidio, Di: See Di Egidio Erzgräber: 18-169: p.268 Faassen: 08-109: p.137 Faris: 19-400: p.288 Fey: 22-128: p.324 Fidlin: 02-040: p.48 Fischer: 18-429: p.274 Foerg: 14-461: p.212 Fossas: 01-210: p.35 Fossen: 00-KN1: p.17 Foukzon: 04-012: p.75 Fradkov: 10-412: p.164; 21-413: p.316 Frank: 08-375: p.145 Frémond: 02-449: p.57 Fukuyama: 08-059: p.134 Galhano: 11-042: p.169 García-Ojalvo: 18-148: p.266 Gavrilova: 23-359: p.345 Gendelman: 06-173: p.107; 21-166: p.309; 21-174: p.309 Georgiou: 06-325: p.113; 22-322: p.330 Germay: 08-297: p.143 Glösmann: 06-260: p.110 Gonçalves: 06-052: p.102 Gottlieb: 19-464: p.289 Govaerts: 16-034: p.228 Green: 16-140: p.230; 17-119: p.247 Gross: 07-082: p.123 Halkjær: 05-208: p.94 Haller: 06-219: p.110; 12-216: p.190 Hanßmann: 12-330: p.192 Harrison: 04-236: p.81 Hedrih: 11-428: p.181; 21-439: p.317 Heertjes: 17-027: p.242 Heijden, Van der: See Van der Heijden Hek: 18-045: p.265 Henderson: 16-141: p.230 Henninger: 03-188: p.67 Hijmissen: 21-389: p.315 Hogan: 01-276: p.40 Holmes: 00-OPN: p.17 Holobut: 05-184: p.93 Homburg: 15-287: p.218 Horssen, Van: See Van Horssen Ichtiaroglou: 12-277: p.191 Ikeda: 17-261: p.254 Illing: 08-241: p.140 Ing: 06-468: p.118 Insperger: 08-273: p.141

Iourtchenko: 04-029: p.76 Ishida: 16-097: p.228; 17-448: p.262 Ivanov: 01-416: p.43 Jansen: 06-319: p.112 Järvenpää: 03-309: p.69 Jirsa: 07-368: p.127 Jorba: 15-453: p.219; 16-314: p.237 Kalia: 11-417: p.179 Kanth: 03-158: p.64 Karagiozis: 22-467: p.335 Kedar: 13-116: p.197 Kelly: 23-306: p.343 Keskinen: 04-315: p.82 Kevrekidis: 16-199: p.232 Khayari: 17-114: p.246 Kilner: 07-203: p.125 Kireenkov: 03-246: p.68; 21-243: p.313 Kirillov: 22-002: p.321 Kirsch: 05-011: p.91 Kizilova: 23-380: p.347 Kleinhans: 09-194: p.149 Kliemann: 04-370: p.85 Knobloch: 21-327: p.314 Kokalj: 05-334: p.97 Kossenko: 06-391: p.115 Kovaleva: 04-355: p.84 Kovecses: 03-339: p.70 Krauskopf: 18-183: p.269 Krempl: 11-363: p.177 Krylov: 19-293: p.284 Kuleshov: 03-113: p.62 Kulvietiene: 03-013: p.61 Kuroda: 11-365: p.178; 17-352: p.257 Kuske: 04-016: p.75 Kwasniok: 06-326: p.114; 09-250: p.150 Lacarbonara: 17-441: p.261; 22-310: p.329 Lammen: 14-133: p.206 Lanusse: 11-112: p.172 Laskar: 00-KN2: p.18 Leeuwen: 07-463: p.129 Lefranc: 18-197: p.270 Leger: 01-296: p.41 Leine: 02-030: p.47 Lenci: 01-154: p.31; 19-346: p.287 Lentzen: 22-259: p.327 Leonov: 21-411: p.316 Levi: 00-KN3: p.18 Li: 10-053: p.156; 10-064: p.156; 23-371: p.346 Lippi: 18-349: p.273 Lopez: 01-321: p.42 Luo: 02-121: p.51; 23-122: p.341 Lüssen: See Welge-Lüssen Lust: 16-142: p.231 Maas: 00-KN4: p.19 Machado: 11-041: p.168 Machete: 17-046: p.243 Magnitskii: 10-374: p.163 Mailybaev: 17-351: p.257 Mäkinen: 03-157: p.63 Mallon: 22-120: p.323 Mandel: 18-447: p.275

Manevich: 21-085: p.306 Manevitch: 21-070: p.304 Mann: 17-163: p.250 Manoach: 22-378: p.333 Marco: 13-190: p.198 Marinova: 21-092: p.307 Marjamäki: 03-099: p.61 Markovic: 06-098: p.107 Martinelli: 01-152: p.30 Martinez-Alvarado: 06-077: p.106 Masdemont: 15-455: p.220 Meijaard: 03-176: p.65 Melchior: 11-426: p.180 Mezic: 06-388: p.114 Mihajlović: 17-215: p.252 Mikhlin: 21-037: p.301; 21-047: p.303 Mirasso: 18-132: p.266 Moroz: 06-072: p.105 Musienko: 21-212: p.311; 23-227: p.342 Muth: 14-262: p.210 Naess: 04-060: p.78 Namachchivaya: 04-251: p.81; 04-347: p.84; 08-028: p.133; 22-252: p.326 Natsiavas: 03-407: p.71; 06-406: p.116; 20-386: p.297 Néel: 11-138: p.173; 11-393: p.178 Neishtadt: 12-110: p.189 Neubauer: 20-144: p.294 Neumann: 02-294: p.55 Nigmatullin: 11-329: p.175; 11-364: p.177 Nolte: 07-401: p.128 Noort: 15-457: p.221 Nuij: 17-202: p.251 Oguchi: 08-328: p.144 Ojalvo: See García-Ojalvo Olivar: 01-172: p.32 Onu: 04-130: p.80 Orosz: 08-108: p.136 Ortigueira: 11-091: p.170; 11-445: p.182 Osinga: 15-454: p.220; 16-235: p.233 Osorio: 01-290: p.40 Park: 05-063: p.92 Parker: 01-149: p.28 Parlitz: 09-224: p.149 Pavlov: 01-238: p.37; 22-331: p.331 Payr: 02-234: p.54 Peil: 18-269: p.271 Pellicano: 14-397: p.211; 17-396: p.260 Pernot: 17-193: p.251 Pesquera: 08-171: p.138; 18-170: p.269 Petera: 05-266: p.95 Pfeiffer: 02-018: p.47 Phipps: 16-161: p.231 Pick: 16-382: p.237 Piiroinen: 14-178: p.208 Pogorelov: 03-177: p.66 Polach: 20-036: p.293 Poloskov: 04-066: p.79 Porto: 11-270: p.175 Prants: 12-057: p.187 Pulngern: 17-095: p.246 Pyragas: 08-405: p.145

Ouinn: 07-282: p.126: 19-240: p.284 Ranković: 08-080: p.134 Ribeiro: 22-044: p.322 Rink: 12-200: p.190 Romeo: 12-336: p.193 Ros: 15-032: p.217 Rowley: 16-284: p.235 Ryabov: 02-280: p.54 Sabatier: 11-338: p.176 Saeki: 02-392: p.56 Salas: 10-229: p.159 Salnikov: 23-353: p.345 Samaey: 16-245: p.234 Sartorelli: 17-162: p.249 Sauzin: 13-472: p.200 Scalas: 11-067: p.169; 11-067: p.169 Schanz: 21-214: p.312 Schilder: 16-100: p.229 Schöll: 08-237: p.139 Schutter, De: See De Schutter Schwab: 03-129: p.62 Sciamanna: 18-167: p.267 Seifried: 02-094: p.50 Sharp: 20-150: p.295 Shaw: 06-424: p.117; 19-423: p.288 Shi: 10-048: p.155 Shimizu: 11-444: p.182 Sichermann: 04-055: p.78 Sieber: 08-102: p.135 Simanovskii: 04-033: p.77 Simó: 15-425: p.219 Sinha: 06-469: p.119 Smith: 09-274: p.150 Sofi: 04-323: p.83 Soroushian: 23-049: p.340 Sowers: 04-356: p.85 Spiess: 06-191: p.108 Spinola: 17-395: p.259 Stein: 23-470: p.348 Steindl: 06-443: p.117 Stépán: 00-KN5: p.19 Stryk, Von: See Von Stryk Studer: 14-093: p.204 Tanaka: 02-125: p.51 Tanrıöver: 15-143: p.217 Theodossiades: 22-244: p.325 Thomsen: 00-KN6: p.20 Tiso: 06-278: p.111 Tjahjowidodo: 17-062: p.244; 17-285: p.255

Touzé: 06-007: p.101 Treschev: 13-471: p.199 Tuwankotta: 12-360: p.194 Tylikowski: 04-381: p.86 Vakakis: 17-025: p.241; 21-024: p.301; 22-026: p.321 Valério: 11-155: p.173 Valkhoff: 21-189: p.310 Van de Wouw: 01-021: p.25 Van der Heijden: 23-248: p.343 Van Horssen: 21-358: p.315 Vanderbauwhede: 16-377: p.237 Varoto: 17-221: p.253; 17-249: p.254 Vasta: 04-440: p.87 Veen: 15-458: p.221 Verhulst: 21-039: p.302 Vieiro: 15-459: p.222 Vinagre: 11-230: p.174 Vioque: 16-180: p.232 Virgin: 22-299: p.328 Vitolo: 15-460: p.223 Vladimirsky: 16-308: p.236 Von Stryk: 20-316: p.296 Wachal: 03-295: p.68 Wang: 16-209: p.233; 19-402: p.288 Warminski: 21-079: p.305 Welge-Lüssen: 17-367: p.258 Weronko: 21-220: p.312 Westerlund: 11-404: p.179 Wihstutz: 04-017: p.76 Wilson: 01-267: p.39 Wolfrum: 18-265: p.271 Worden: 06-410: p.116; 14-409: p.212; 17-408: p.261 Wouw, Van de: See Van de Wouw Xu: 07-084: p.124 Yabuno: 17-124: p.247; 20-123: p.294 Yagasaki: 12-311: p.192; 13-312: p.199; 19-307: p.285 Yanchuk: 08-010: p.133 Yapali: 08-281: p.142 Yousefi: 18-466: p.276 Yuan: 08-313: p.143 Yunt: 14-086: p.203 Zahariev: 03-369: p.71 Zaslavsky: 11-354: p.176; 13-078: p.197 Zeidis: 21-105: p.308 Zevin: 12-264: p.191 Zhang: 18-107: p.265 Zhusubaliyev: 01-186: p.33 Zubova: 12-147: p.189



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