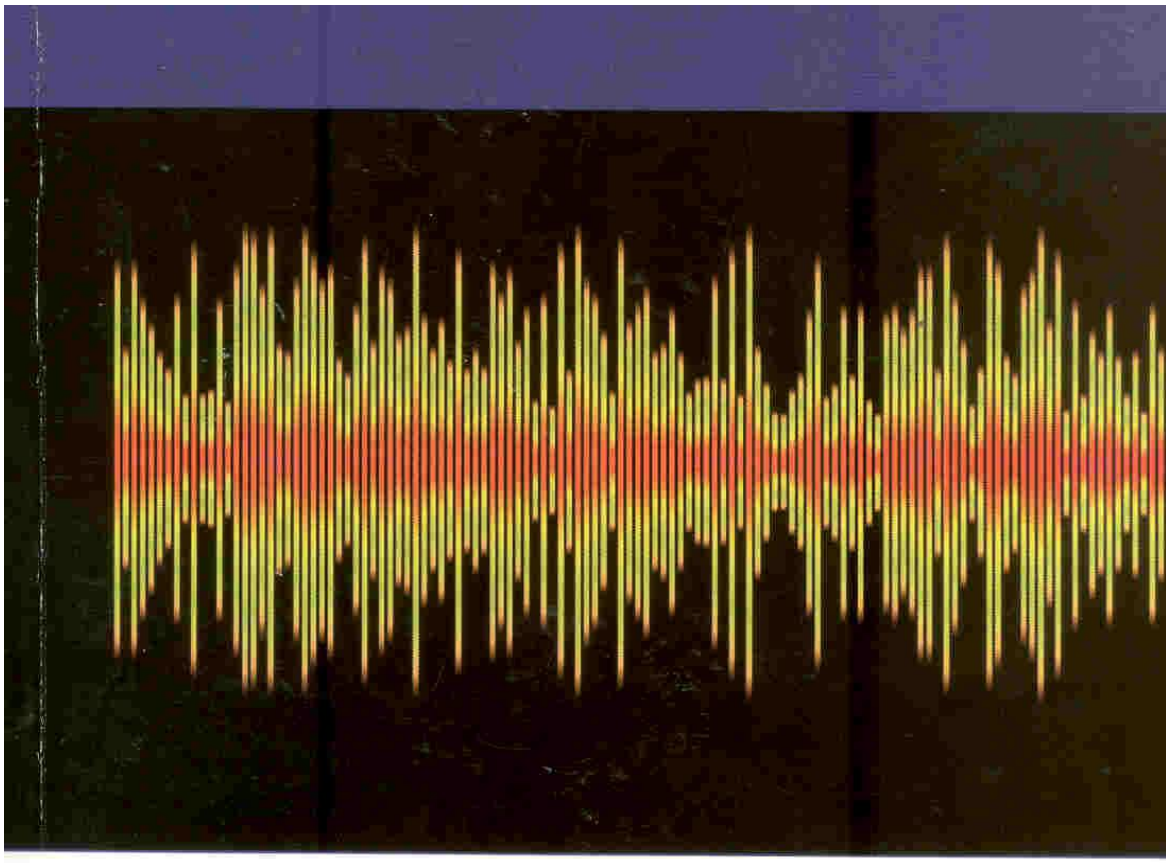

A.K.M. Nurul Amin
Anayet Patwari

Resonance Effect in Chatter Formation in Metal Cutting

A New Chatter Theory Based on Chip Serration Instability and System Response for Prediction of Chatter in End Milling

LAP LAMBERT Academic Publishing

A.K.M. Nurul Amin
Anayet Patwari

Resonance Effect in Chatter Formation in Metal Cutting

A New Chatter Theory Based on Chip Serration Instability and System Response for Prediction of Chatter in End Milling

LAP LAMBERT Academic Publishing

Impressum/Imprint (nur für Deutschland/only for Germany)
Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.
Alle in diesem Buch genannten Marken und Produktnamen unterliegen warenzeichen-, marken- oder patentrechtlichem Schutz bzw. sind Warenzeichen oder eingetragene Warenzeichen der jeweiligen Inhaber. Die Wiedergabe von Marken, Produktnamen, Gebrauchsnamen, Handelsnamen, Warenbezeichnungen u.s.w. in diesem Werk berechtigt auch ohne besondere Kennzeichnung nicht zu der Annahme, dass solche Namen im Sinne der Warenzeichen- und Markenschutzgesetzgebung als frei zu betrachten wären und daher von jedermann benutzt werden dürften.

Coverbild: www.ingimage.com

Verlag: LAP LAMBERT Academic Publishing GmbH & Co. KG
Dudweiler Landstr. 99, 66123 Saarbrücken, Deutschland
Telefon +49 681 3720-310, Telefax +49 681 3720-3109
Email: info@lap-publishing.com

Herstellung in Deutschland:
Schaltungsdienst Lange o.H.G., Berlin
Books on Demand GmbH, Norderstedt
Reha GmbH, Saarbrücken
Amazon Distribution GmbH, Leipzig
ISBN: 978-3-8443-0447-3

Imprint (only for USA, GB)
Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.
Any brand names and product names mentioned in this book are subject to trademark, brand or patent protection and are trademarks or registered trademarks of their respective holders. The use of brand names, product names, common names, trade names, product descriptions etc. even without a particular marking in this works is in no way to be construed to mean that such names may be regarded as unrestricted in respect of trademark and brand protection legislation and could thus be used by anyone.

Cover image: www.ingimage.com

Publisher: LAP LAMBERT Academic Publishing GmbH & Co. KG
Dudweiler Landstr. 99, 66123 Saarbrücken, Germany
Phone +49 681 3720-310, Fax +49 681 3720-3109
Email: info@lap-publishing.com

Printed in the U.S.A.
Printed in the U.K. by (see last page)
ISBN: 978-3-8443-0447-3

Copyright © 2011 by the author and LAP LAMBERT Academic Publishing GmbH & Co. KG and licensors
All rights reserved. Saarbrücken 2011

Contents

Chapter 1	**Introduction**	1
Chapter 2	**Existing Understanding on Chatter**	3
	2.1 Existing Chatter Hypothesis and Theories	3
	2.2 Nonlinearities and Complex Dynamics Chatter Model In Metal Cutting	7
	2.3 Stability Analysis of Machining Processes	11
	2.4 Nonlinearity in Chatter Stability	16
	2.5 Previous Work on Modal Analysis	19
Chapter 3	**Chip Formation and its Formative Instability**	23
	3.1 Introduction	24
	3.2 Methods of Study of Chip Formation Mechanism	25
	3.2.1 Application of High Speed Movie Camera	26
	3.2.2 Drop Tool Apparatus	26
	3.2.3 Chip Roots	29
	3.2.4 Analysis of Chips and Frozen Chip Samples	31
	3.2.5 Conventional Shear Plane Model	35
	3.2.6 Shear Zone Concept of Chip Formation	37
	3.2.7 Contact Processes	45
	3.2.8 The Shear Plane Angle and Minimum Energy Theory of Rowe and Spick	46
	3.3 Classification of Chips	49
	3.3.1 Classification of Chips according to Ernst	51
	3.3.2 Classification of Chips according to Loladze	52
	3.3.3 Classification of Chip Proposed by Amin	53
	3.3.4 Mechanism of Formation of Chips With Primary Serrated Teeth Proposed by Various Researchers	65

3.3.4.1 Mechanism of Formation of Chips with Primary Serrated Teeth Proposed by Trent 66
3.3.4.2 Mechanism of Formation of Chips with Primary Serrated Teeth Proposed by Komanduri and Komanduri et al 71
3.3.4.3 Mechanism of Formation of Chips with Primary Serrated Teeth Proposed by Talantov et al and Amin 72
3.3.4.4 Mechanism of Formation of Chips with Primary Serrated Teeth in the Presence of Chatter Proposed by Amin 73
3.3.4.5 Mechanism of Formation of Chips with Primary Serrated Teeth under Non Chatter Condition Proposed by Amin 85
3.3.5 Chips with Secondary serrated teeth 90
3.4 Image Processing Technique for Analysis of Chip Serration 101
3.5 Chip Serration Frequency 103
3.5.1 Method of Chip Serration Frequency Calculation 105

Chapter 4 System Stability and Vibration Monitoring 107
4.1 Overview 107
4.2 Types of Vibrations 108
4.3 Vibration Measurements Techniques during Machining 111
4.3.1 Acquisition and Analysis of Online Vibration 112
4.3.2 Accelerometers 113

4.3.3 Signal Analysis and Conditioning 114

4.4 Experimental Modal Analysis 115

4.4.1 Experimental Modal Analysis of Vertical Machining Centre 116

4.4.2 Determination of the Natural Frequencies of the System Components 116

4.4.3 Experimental Modal Analysis: Measurement Hardware 117

4.4.4 Experimental Modal Analysis of Responses 118

4.4.5 Operational Modal Analysis 120

4.4.6 Finite E1ement (FE) Analysis 122

Chapter 5 Mechanisms of Chatter Formation 125

5.1 Overview 127

5.2 Investigation of Chatter Formation in Turning and Thread Cutting Operations 127

5.2.1 Analysis of FFT In Turning and Thread Cutting 129

5.2.2 Mechanisms of Formation of Chatter for both the Machining Operations 133

5.3 Conclusions and Summary 138

5.4 Influence of Chip Serration Frequency on Chatter Formation in End Milling 138

5.4.1 Investigation of Chatter Formation in End Milling of Ti6Al4V Alloy 139

5.4.1.1 Investigation of the Effect of Cutting Speed on Chatter Formation 139

5.4.1.2 Effect of Depth of Cut on Chatter Formation for End Milling of Ti6Al4V 148

5.4.1.3 Investigation of the Effect of Feed on Chatter Formation during End Milling of Ti6Al4V 153
5.4.1.4 Effect of Tool Diameter on Chatter Formation for End Milling of Ti6Al4V 159
5.4.1.5 Summary 168
5.4.2 Influence of Chip Serration Frequency and Chatter Frequency in End Milling of Stainless Steel (SS304) 169
5.4.2.1 Chip Morphology of Stainless Steel during End Milling Operations at Constant Feed and Depth of Cut 169
5.4.2.2 FFT Analysis Different Cutting Conditions for End Milling of Stainless Steel 170
5.4.2.3 Relationship between Chip Serration Frequency and Chatter Frequency for End Milling of SS304 172
5.4.3 Influence of Chip Serration Frequency and Chatter Frequency in End Milling of Medium Carbon Steel (AISI 45) 174
5.4.3.1 Chip Morphology of Medium Carbon Steel during End Milling Operations 174
5.4.3.2 FFT Analysis under Various Cutting Conditions 175
5.4.3.3 Relationship between Chip Serration Frequency and Chatter Frequency in End Milling of Medium Carbon Steel 177
5.5 Summary 179

Chapter 6 Models for Prediction of Chip Serration Frequency 181
6.1 Overview 181
6.2 Design of Experiment and Analysis of Data using Response Surface Methodology (RSM) 182

6.2.1 Test for Significance of the Regression Model 185
6.2.2 Test for Significance on Individual Model Coefficients 186
6.2.3 Test for Lack-of-Fit 186
6.2.4 Central Composite Design of RSM 187
6.2.5 Design of Experiment 188
6.2.6 Experimental Design using RSM 189
6.3 Chip Serration (Secondary) Frequency Model 193
6.3.1 Chip Serration (Secondary) Model of Ti6Al4V Alloy 193
6.3.1.1 Coding of the Independent Variables for Machining of Titanium Alloy 194
6.3.1.2 Experimental Design 194
6.3.1.3 Development of Second Order Model using CCD Design 194
6.3.1.4 Analysis of the Results 196
6.3.1.5 Study Chip Shrinkage Effect 203
6.3.1.6 Chip Analysis during End Milling of Titanium Alloy (Ti6Al4V) 204
6.4 Model Summary for Chip Serration (Secondary) Frequency for Different Materials 207

Chapter 7 Mathematical Model for Prediction of Chatter in Metal Cutting 209
7.1 Overview 209
7.2 Formulation of Chatter Model Based on Chip Serration 210
7.2.1 Sequence of Analysis 211
7.2.2 Chatter Model Hypotheses 212
7.2.3 Analysis of the System Components 212
7.2.3.1 Dynamic Characteristics of System Components 215

7.2.4 Analysis of the Cutting Force and its Relation with Chip Serration 216
7.2.4.1 Dynamic Characteristics of the Cutting Process 219
7.2.5 Prediction of Stability Lobes by the Model 219
7.2.6 Model of Chatter Formation Zone Based on Chip Serration 222
7.3 Determination of Model Parameters 223
7.3.1 Determination of Chip Serration Coefficient (C_1) for Different Materials 227
7.3.2 Determination of System Parameters 227
7.4 Verification of the Model 228
7.4.1 Verification of the Unstable Cutting Speed Predicted by the Model 228
7.4.2 Verification of Stability Lobes for Ti6Al4V 229
7.4.3 Verification of Chatter Amplitude Predicted by the Model 231
7.4.4 Summary 233

Bibliography 235