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Aircraft Loads Prediction Using Enhanced Simulation

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An overview of the technical work performed as part of the EC FP7 Marie Curie European Industrial Doctorate Training Network ALPES (Aircraft Loads Prediction using Enhanced Simulations) is given. A review of the industrially focused studies in the areas of: improved modelling for combined high load events, Reduced Order Modelling approaches, efficient and accurate gust loads modelling, worst case predictions and uncertainty quantification of gust, manoeuvre and landing loads is described. A number of technical advances suitable for application to industrial scale problems have been made.

I. Overview

ALPES is an EC FP7 Marie Curie European Industrial Doctorate Training Network which runs from 1 October 2013 to 30 September 2017. The aim of the network is to improve the prediction accuracy and efficiency of the loads experienced by an aircraft in-flight and on the ground. The ALPES network involves five Early Stage Researchers (ESRs) who are also registered for PhDs, combining a novel research programme with a highly industrially focused training schedule, including placements at Airbus in the UK and/or France. The programme contributes towards two key aspects of the ACARE2020 and FLIGHTPATH2050 initiatives, with the technologies developed helping towards:

- Environmentally friendly aircraft designs
- Faster design and certification process

The main aims of the ALPES ITN are:

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- To develop novel methods and procedures to improve the accuracy and efficiency of aircraft loads predictions
- To provide an industrially focused training regime for the researchers so that they can move directly into the European aerospace industry
- To assess the methods developed in ALPES on industrial scale models, working with engineers in industry
- To transfer the technical developments made in ALPES into industry

The partners in the project are the University of Bristol (UoB) and Siemens Industry Software NV (SISW), with Airbus Operations Ltd an Associate Partner, as shown in table 1. The ESRs are either based for 18 months of their employment in Bristol, UK and then spend another 18 months at SISW in Leuven, or vice versa. The ESRs are also planned to spend time on placements at Airbus, and in the first year all of them spent a two week introductory placement with the Flight Physics department at Airbus UK in Filton, Bristol.

Full Partners	**Short Name**	**Sector**	**Country**
University of Bristol	UoB	Academia	UK
Siemens Industry Software NV	SISW	Industry	Belgium
Associate Partner			
Airbus Operations Ltd	Airbus	Industry	UK

Table 1. Partners in the ALPES project.

II. ALPES Early Stage Researchers

During the course of the first year of the project, five high quality ESRs were recruited, pictured in Figure 1. In order to provide a balance to the supervision, three of the ESRs started at the University of Bristol (UoB) whereas the others were initially placed at SISW.

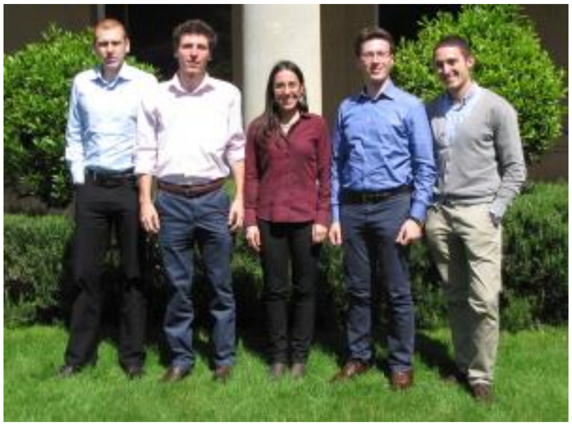


Figure 1. The ALPES Researchers

Each ESR in the ALPES ITN has followed one of the following technical areas supervised by a mix of academic and industrial engineers from the project partners:

- Andrea Castrichini – J E Cooper, M Lowenberg, Y Lemmens
  Improved modelling of landing, manoeuvre and gust loads for combined high load events
- Adrien Poncet-Montages – D Jones, A Gaitonde, Y Lemmens
  Reduced Order Modelling approaches for landing, manoeuvres and gust loads
- Carmine Valente - A Gaitonde, D Jones, Y Lemmens
  Development of efficient and accurate gust loads modelling techniques combining high and low fidelity methods
- M Castellani – J E Cooper, M Lowenberg, Y Lemmens

Development of improved approaches to determine worst case predictions of gust, manoeuvre and landing loads

- Irene Tartaruga – J E Cooper, M Lowenberg, P Sartor, Y Lemmens
  Development of methods for uncertainty quantification of landing, gust and manoeuvre loads

The 5 PhD programmes interact together as shown in figure 2, and this interaction has been maintained and is increasing as the project develops. Both ESRs 4 and 5 have been involved in some modelling aspects relating to highly flexible wings and undercarriages respectively.

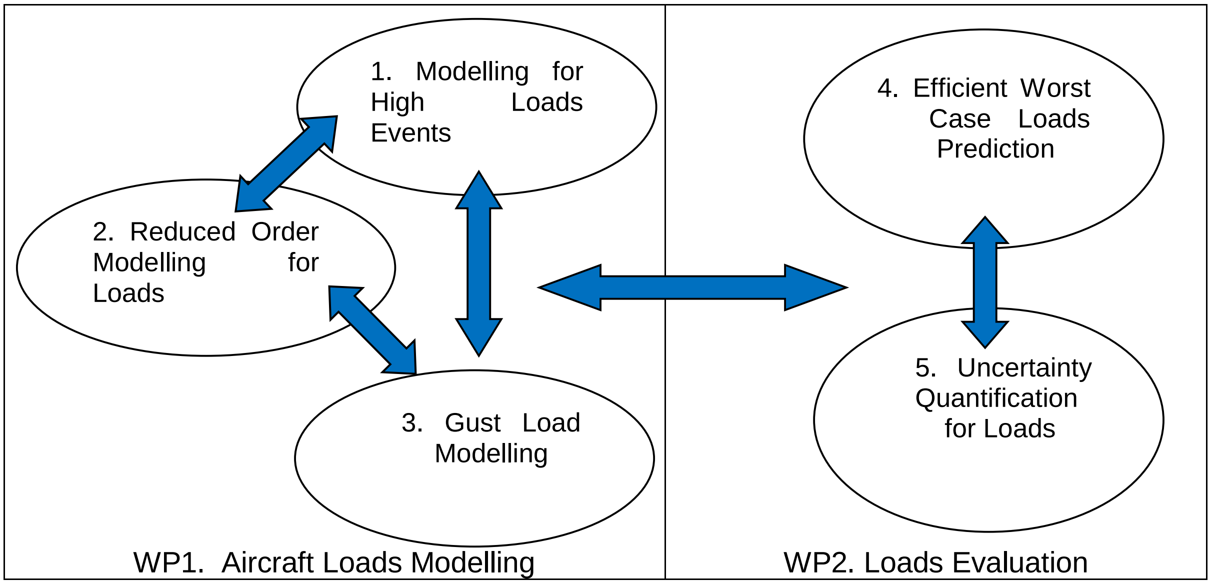


Figure 2. Research WP Structure, Showing Each Project, and Their Interaction

III. Overview of Technical Work

A. Coupling of unsteady Aerodynamic Loads with flexible bodies using Multi-Body Simulation

A methodology has been developed to couple unsteady aerodynamic loads with flexible bodies in multibody simulations[1]. A floating frame of reference was implemented in the Virtual Lab Motion package to enable flexibility in the subcomponents, and then a methodology developed to enable the evaluation of the internal loads distributed throughout the body in the dynamic multibody analysis. This model was then coupled to unsteady aerodynamics using the Roger's Rational Fraction Approximation (RFA) method so that the methodology can be applied in a time domain simulation. These aerodynamic loads were introduced into the multi-body code via the use of a User Defined Force element, applied on the body during the dynamic analysis. A flow chart of the process is shown in figure 6.

The implementation has been validated by comparing the results for the wing root bending moment and tip displacement with Nastran transient aeroelastic analyses for a series of gust lengths of a representative free-free civil jet aircraft aeroelastic model. Good comparisons, see figure 7, were found between a conventional frequency domain FEM based model and the new multi-body approach. Moreover, the use of a multibody simulation software offers the simulation of other manoeuvres such as landing and the use of non-linear and active structures.

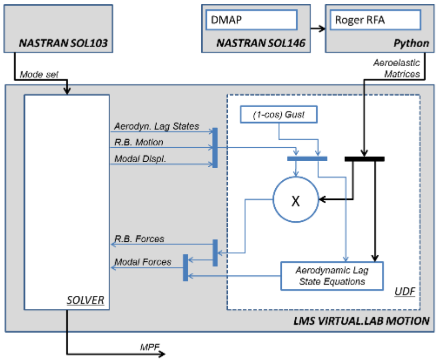
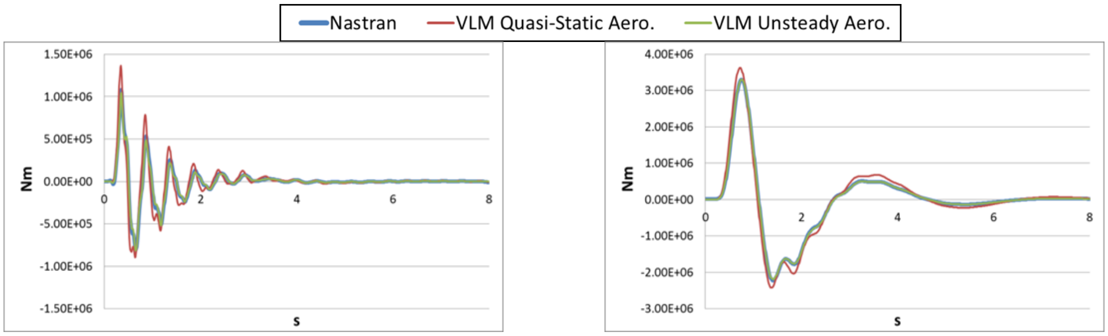


Figure 6. Multi-Body Loads Evaluation Scheme



WRBM (Lg=18 m) ***WRBM (Lg=214 m)***

Figure 7. Comparison of NASTRAN and Multi-Body VLM Gust Response Time Histories

B. Development of a folding wing tip device for gust loads alleviation

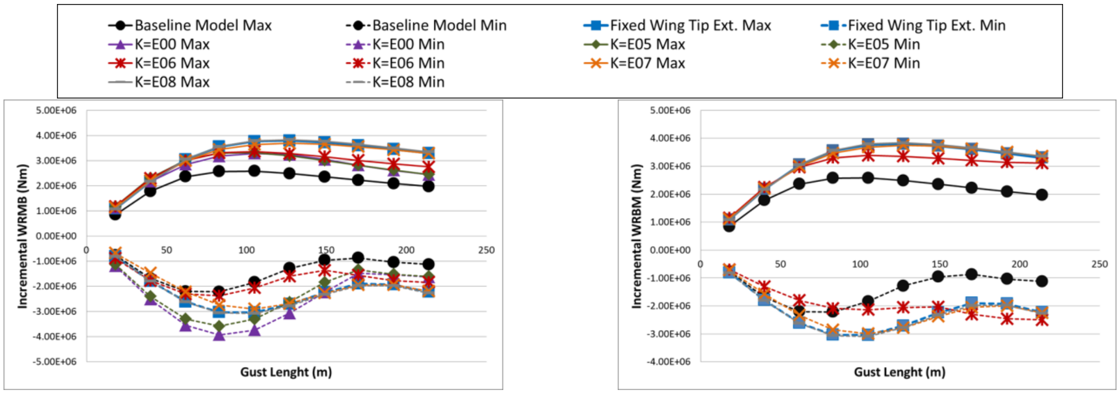
Induced drag can be reduced by increasing the wingspan, but this kind of design solution has well defined limits given by the maximum airport gate size. A possible solution to this problem is the use of folding wings that can be employed on the ground, raising the question as to whether such a folding device could also be used to enable loads reduction on the aircraft during the flight.

Work has been performed[2,3] into using a wing-fold device for loads alleviation on civil jet aircraft configurations. The orientation of the hinge line relative to the direction of travel of the aircraft and the weight of such device are key parameters to enable successful loads alleviation. Figure 8 shows two possible implementations of such device, 0° and 25° outwards from the free stream direction; of particular importance is the case when the hinge line is not along the 0° direction, creating a decrease in the local angle of attack of the wing-tip.

(a) 0° hinge (b) 25° hinge

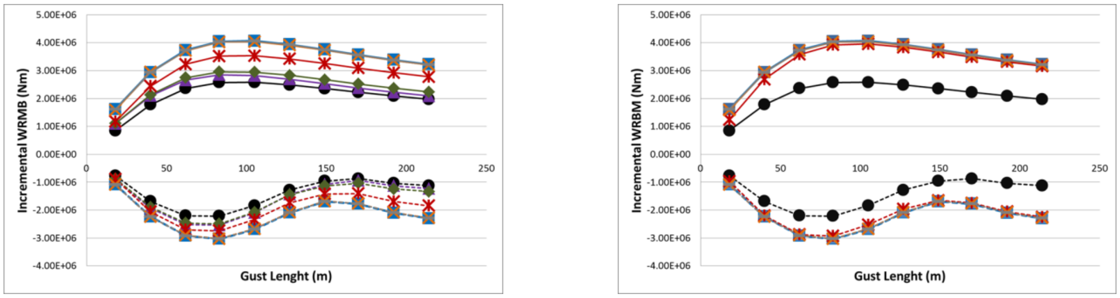
Figure 8. Hinge Orientations

Different structural configurations of a civil aircraft aeroelastic model including: varying the hinge direction, wing-tip weight and linear spring stiffness were considered for static and dynamic gust loads. As seen in fig 9, significant reductions in the resulting static and dynamic loads were achieved with a small hinge stiffness, reduced wing-tip weight and a swept hinge.



(a) 943 Kg wing-tip model, 25° hinge

(b) 943 Kg wing-tip model, 0° hinge



(c) 100 Kg wing-tip model, 25° hinge

(d) 100 Kg wing-tip model, 0° hinge

Figure 9. Wing Bending Moment Envelopes

Further work has extended the concept to consider the use of a nonlinear spring at the hinge incorporating a negative stiffness element in the spring[4].

C. Reduced order aeroelastic modelling

This research investigates the accuracy of reduced order aerodynamic models of the flight loads of a manoeuvring aircraft constructed from limited CFD simulation. The university has developed considerable experience in the construction of reduced order models of unsteady aerodynamic systems that can be coupled with modal structural models to form accurate and efficient aeroelastic solutions. The main scope of this research is the further development of these models for high angles of attack and large control surface deflection where nonlinear viscous effects become important.

Main parts of the research workplan have been split into:

- Creation of reduced order models of the structure that account for control surface deflection and rigid body motion. This stage will be carried out with the partners while in industry.
- The development of reduced order models based on the assumptions of local dynamic linearity about a nonlinear mean flow solution.
- Development of nonlinear aerodynamic models initially based on a nonlinear quasi-static plus dynamically linear assumptions will be investigated.

The development of the initial reduced order model is the largest part of the project and the focus for the first year's research. The main highlight of this part of the research is the development of a new reduced order modelling technique that takes linear frequency domain solutions of the CFD system and produces time domain reduced order models with guaranteed stability[5,6]. The algorithm chosen is similar to the Eigensystem Realization Algorithm but constructed in the discrete frequency domain, using a bilinear transformation to move to the continuous frequency domain where the frequency responses are constructed using the aerospace standard CFD code Tau. A singular value decomposition is performed to identify the dominant modes of the frequency response. This method is particularly interesting as system matrices are not required, only the frequency responses.

The discrete frequency response is given by a uniformly spaced set of points between 0 and π, that is transformed to an equivalent continuous frequencies using the Bi-Linear transform such that

$$\widehat{\omega}_k = \frac{k\,\pi}{N}, \mathrm{k} \in [0\,,\mathrm{N}] \qquad \rightarrow \qquad \omega_k = \frac{2}{T}\tan\frac{\omega_k}{2}$$

The state space system found in the discrete domain $(\hat{A}_r, \hat{B}_r, \hat{C}_r\ \widehat{D}_r)$ is transformed into a continuous system ($A_r, B_r, C_r\ D_r)$ using the relations:

$$A_r = \frac{2}{T}\,(I_r + \hat{A}_r)^{-1}\,(I_r - \hat{A}_r) \qquad B_r = \frac{2}{\sqrt{T}}(I_r + \hat{A}_r)^{-1}\,\hat{B}_r$$

$$C_r = \frac{2}{\sqrt{T}}\,\hat{C}_r\,(I_r + \hat{A}_r)^{-1} \qquad D_r = \widehat{D}_r - \hat{C}_r\,(I_r + \hat{A}_r)^{-1}$$

The Hankel matrix is constructed from the inverse discrete Fourier transform of the discrete frequency response. After reducing the Hankel matrix to the required size, r, by removing the smallest singular values and associated vectors, the remaining vectors are used to construct the discrete $\hat{A}_r$ & $\hat{C}_r$ via comparison with the controllability matrix. Once found the discrete $\hat{A}_r$ & $\hat{C}_r$ matrices are found by solving a linear minimisation problem.

The method developed provides a guarantee of stability and a balanced reduction as the number of test points is increased. The testing of the method has been carried out using a pitching supercritical aerofoil, NLR7301, at transonic conditions with a shock wave at the semi-chord position. Some typical results are detailed below

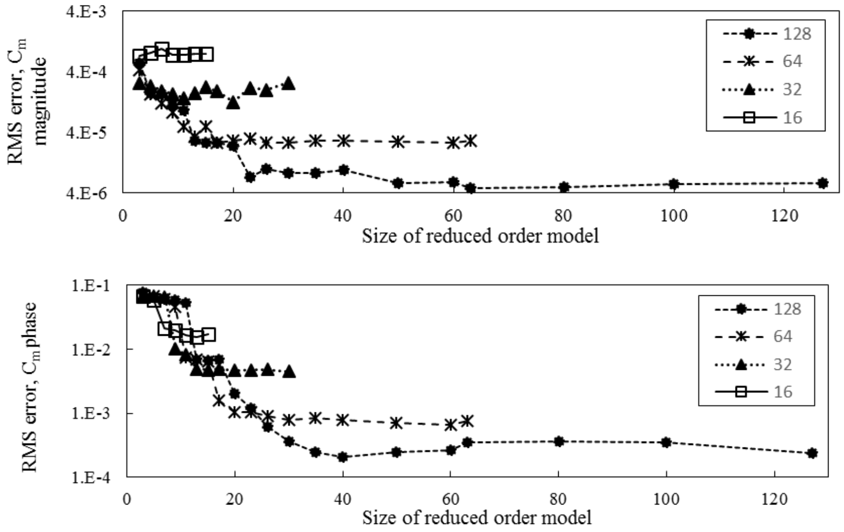


Figure 10: RMS error in c_m, phase and magnitude vs ROM size

RMS error in phase & magnitude of moment coefficient against 256 LFD test points is shown. The error is plotted against model size for a range of numbers of frequency responses used for construction. The error is dominated by high frequency terms and the next stage of research will develop a more suitable error measure. Below is the comparison of lift coefficient phase & magnitude against non-dimensional frequency for the LFD and the ROM (of sizes 9 & 23) constructed using 32 frequency solutions.

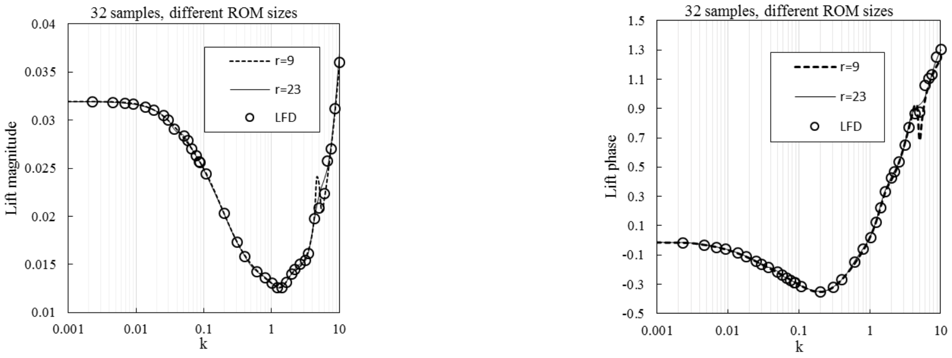


Figure 11: Lift magnitude and phase vs reduced frequency for LFD solution and ROM of size r

D. Efficient and accurate gust loads modelling techniques combining high and low fidelity methods

The current industrial standard for gust loads modelling is to use the Doublet Lattice panel method (DLM) to generate the aerodynamic loads interacting with the flexible aircraft structure. Although this has been the standard approach for nearly 20 years, there are inaccuracies with computations in the transonic regime but it is not yet feasible to perform full CFD aerodynamic computations due to computational limitations. Consequently, the development of techniques to correct the DLM results will lead to gust load predictions that are both fast and accurate. This project will investigate the following aspects:

- Initially the full order aeroelastic gust loads are required to provide the nonlinear solutions for comparison and a basis for estimates of accuracy of the updated models. The viscous Split Velocity Methods (SVM) extends previous work at Bristol that allows the accurate modelling of aircraft gust responses in CFD simulations without the dissipation of the onset gust in the large cells far from the aircraft surface. The creation of this nonlinear baseline model has been the focus of the first year of research.
- The use of CFD data to update vortex lattice models of aircraft gust responses. Initially the Dau-Garner modelling assumptions will be used as a basis for updates. This has the advantage that only steady flight loads of the actual aircraft are needed for the update of the vortex lattice method. A limited subset of unsteady CFD simulations, based on the response of the real aircraft, will be considered.

To create the baseline aeroelastic model a fluid structure interaction environment has been developed. The “ALPESOpenFSI" interface is the name of the interface created using the MSC Software Service Development Kit (SDK) to couple the CFD code TAU and the FEM code MSC-Nastran[7,8]. This interface allows the full order aeroelastic gust responses to be modelled.

The service created is an additional piece of code that can be called inside the Nastran bulk data file, and allows the performance of multi-physics analysis FEM/CFD. The exchange of data between the two codes is realised thanks to pre-built functions which expose the necessary variables that will allow the transfer of information from the structural code. As well as extracting the outputs of the structural solution, the SDK provided with the MSC-Nastran distribution allows the creation of skeletons for the files that contain all the method (function) signatures defining the OpenFSI interface, but without the source code. Most of the activities performed in the first part of this research have been to implement the source code in the skeleton files. The interface for the OpenFSI SCA component is defined in a file (“OpenFSI.idl") which provides the Application Programming Interface (API) for implementing the external code connected to the MSC-Nastran solver. This file is provided with the SDK installation, and can be used to make all the OpenFSI services.

The interface can be used for both static aeroelastic couplings, to allow the trim conditions to be identified, and the unsteady coupling needed for the unsteady aeroelastic gust calculations. Typical results for the static analysis applied for the trim calculation on the FFAST wing are shown below.

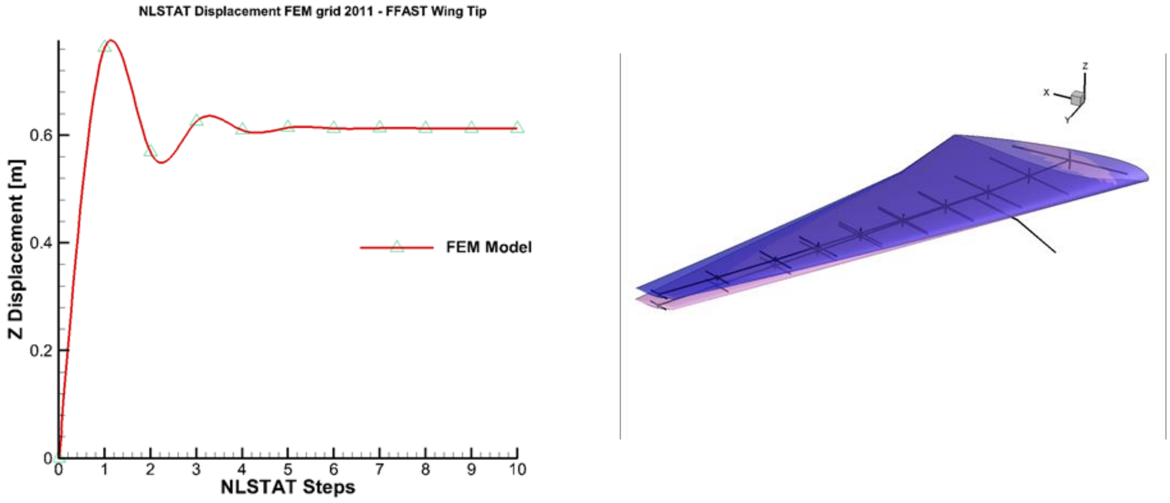


Figure 12: Tip displacement vs number of static aeroelastic evaluations, also shown is the initial and final aerodynamic and structural surfaces for the FFAST wing

The results of the dynamic coupling of the AGARD 445.6 wing with a gust of length 1.7 times the root chord is shown below. The gust is equivalent to a 4 degree change in angle of attack. Also shown are the surface structural and aerodynamic meshes.

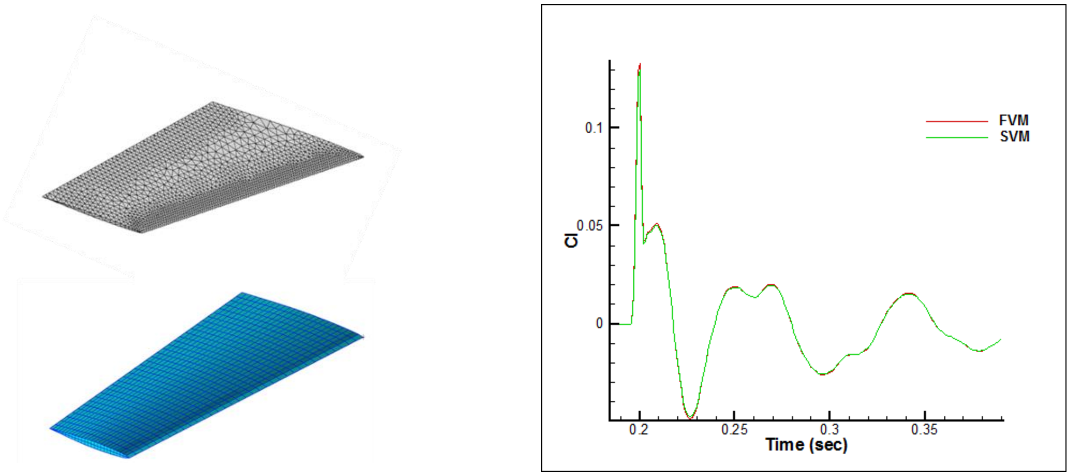


Figure 13: AGARD 445.6 wing, initial structure and aerodynamic surface meshes and the C_l response to a 4º gust.

A significant research effort has also enabled the use of strong coupling and variable time stepping in the Tau CFD code. Flexibility is achieved in the computational solution that was not previously available.

E. Efficient ROM Approach for Loads Prediction

Loads calculations play an important part across much of the design and development of an aircraft, and have an impact upon structural design, aerodynamic characteristics, weight, flight control system design and performance. A typical aircraft loads design process involves monitoring many of so-called Interesting Quantities (IQs) (e.g. bending moments, torques, accelerations etc.) for a wide range of different load cases that the aircraft is likely to experience in-flight and on the ground. Such a process is extremely time consuming and furthermore, has to be repeated every time that there is an update in the aircraft structure.

An approach for rapid loads estimation based on Parametric Model Order Reduction (PMOR) has been developed. It produces a Reduced Order Model (ROM) able to predict IQs time histories for different flight conditions retaining a good accuracy with a significant reduction in computational time. The effectiveness of the developed method is demonstrated by considering loads due to gusts and pitching manoeuvres for an aeroservoelastic model of a generic transport aircraft. The PMOR approach has been extended for aeroelastic systems with concentrated structural non-linearities [9-12].

The aeroelastic response of the aircraft must be solved to compute a large number of IQs under different flight conditions, mass configurations and external excitations to show compliance with the certification requirements. The parameters of the aeroelastic equations of motion are thus, for instance, the flight point, altitude and Mach number. A considerable saving in computational effort is envisaged if, for the thousands of simulations required during an aircraft loads loop, a ROM is used in place of the high dimensional model. The ROM could thus be seen as a physics-based surrogate alternative to data-fit approaches. As the generation of a new ROM at each point of interest in the parameter space is usually impractical, and could even be more computationally expensive than building and evaluating the Full Order Model (FOM) anew, Parametric Model Order Reduction (PMOR) has been introduced to efficiently generate ROMs that preserve the parametric dependency and are accurate over a broad range of parameters, without needing a new reduction at each design point.

The LTI state-space model of the aeroservoelastic system is written as

$$\begin{aligned}\dot{\boldsymbol{x}} &= \boldsymbol{A}(\boldsymbol{p})\boldsymbol{x} + \boldsymbol{B}(\boldsymbol{p})\boldsymbol{u}\\ \boldsymbol{y} &= \boldsymbol{C}(\boldsymbol{p})\boldsymbol{x} + \boldsymbol{D}(\boldsymbol{p})\boldsymbol{u}\end{aligned}$$

where $\boldsymbol{p} \in \mathbb{R}^d$ is a set of parameters on which the state-space matrices arbitrarily depend and N is the order of the model. MOR seeks a low-dimensional approximation of this dynamic system, of order $n_r \ll N$, through a projection-based reduction

$$\begin{aligned}\dot{\boldsymbol{x}}_r &= \boldsymbol{A}_r(\boldsymbol{p})\boldsymbol{x}_r + \boldsymbol{B}_r(\boldsymbol{p})\boldsymbol{u}\\ \boldsymbol{y} &= \boldsymbol{C}_r(\boldsymbol{p})\boldsymbol{x}_r + \boldsymbol{D}(\boldsymbol{p})\boldsymbol{u}\end{aligned}$$

where

$$\boldsymbol{A}_r = (\boldsymbol{W}^T\boldsymbol{V})^{-1}\boldsymbol{W}^T\boldsymbol{A}\boldsymbol{V}, \boldsymbol{B}_r = (\boldsymbol{W}^T\boldsymbol{V})^{-1}\boldsymbol{W}^T\boldsymbol{B}, \boldsymbol{C}_r = \boldsymbol{C}\boldsymbol{V}$$

Balanced truncation is chosen to compute the ROB. This is one of the most common techniques employed in the control systems field and it has desirable properties such as stability preservation of the reduced models, an H_∞ error bound and the dimension of the ROM can be easily chosen by observing the decay of the Hankel singular values of the state-space system in balanced form. The idea behind PMOR is the generation of the ROB at few selected sampling points $\hat{\boldsymbol{p}}_i$ in the parameter domain and then several approaches are possible for constructing a Parametric Reduced Order Model (PROM) at all the other points of interest. The resulting PMOR framework is followed:

- Generation of the n_p local ROMs at the sampling points $\hat{\boldsymbol{p}}_i$, $i = 1 \dots n_p$
- Congruence transformation of the locally reduced state-space matrices
- Elementwise interpolation of the locally reduced state-space matrices to the validation points $\bar{\boldsymbol{p}}$
- Time simulation of the resulting interpolated ROM

Figure 14 shows simulated responses to a gust for an aeroelastic aircraft model and it can be seen that there is an excellent comparison between the full and reduced order models with a significant saving in computation in the ROM case. The approach has also been successfully used for prediction of 2D correlated loads plots and also when nonlinearities are present in the system.

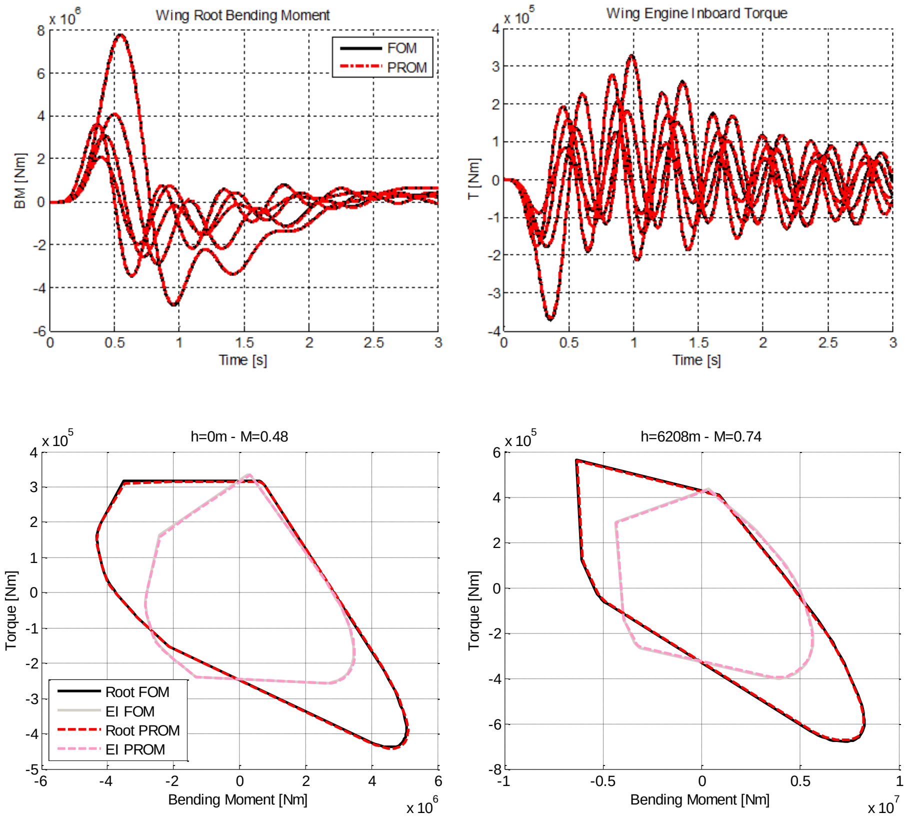


Figure 14. Comparison of IQ Time Histories and Correlated Loads Boundaries between full and reduced order models

F. Nonlinear Aeroelastic Response of Highly Flexible Wings

Several procedures for the nonlinear static aeroelastic analysis of high aspect ratio wing aircraft subject to geometric nonlinearities have been developed[13]. In particular, two approaches are based on the nonlinear Finite Element Method and on multibody dynamics using linear aerodynamics have been investigated. The static aeroelastic results in terms of wing integrated loads at various trim conditions for a very flexible aircraft test case have been computed and compared to results obtained using a purely linear analysis.

The static flight loads at various trim conditions were compared for the linear and the two nonlinear methods and the importance of adopting a nonlinear approach demonstrated by the significant differences in the wing integrated loads. As can be seen in figure 15 there are big differences between the nonlinear and linear behaviours. The FEM and multibody methods show an excellent agreement for purely structural problems (static and pre-stressed normal modes). There are, however, more differences in the aeroelastic trim results. The root causes of these differences have been identified in the different assumption for the aerodynamic force orientation and in the treatment of rigid body rotations.

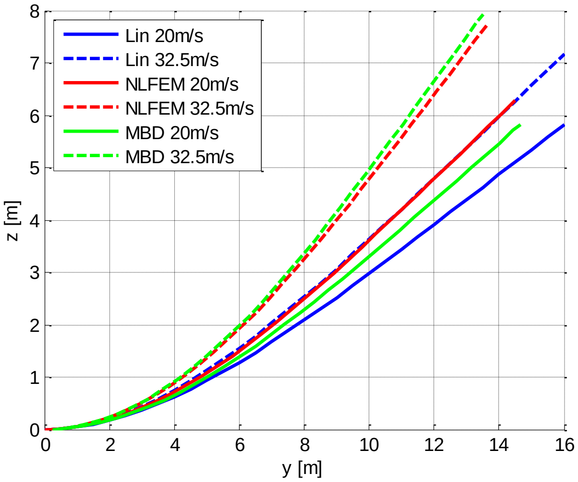


Figure 15. Wing deformed shape at 20m/s and 32.5m/s trim, comparison of linear and nonlinear results.

G. Uncertainty Quantification of Aircraft Correlated Loads

Aircraft structural design is influenced by the static and dynamic loads resulting from flight manoeuvres, gust/turbulence encounters and ground manoeuvres; thus the identification of such loads is crucial for the development and the structural analysis of an aircraft and requires the solution of the aeroelastic dynamic responses. Numerical aeroelastic models are used to predict a large number (1000s) of “Interesting Quantities” (IQs). For aircraft design, the IQs related to the worst case are significant, but their identification implies a significant computational effort. Of particular interest are the so-called correlated loads, where coincident values of pairs of IQs are plotted against each other. A Singular Value Decomposition (SVD) based approach has been developed[14-16] which reduces the computational burden to determine the correlated loads envelopes with little reduction in the accuracy, and also to quantify the effects of uncertainty, for a range of different parameters.

Key to the approach is the formulation of a matrix containing the IQ time responses to different gust length, structural parameters and flight conditions, as shown in figure 16. This matrix can then be decomposed using the SVD and then can be used to efficiently predict the effect of variations in particular parameters, or indeed to investigate the effects of uncertainty.

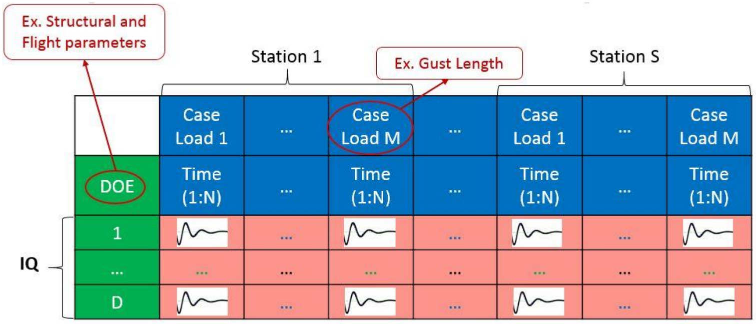


Figure 16 – Format of Data Matrix

Figure 17 shows some example results relating to the response surface of the largest root bending moment due to a family of “1-cosine” gusts for varying engine mass and pylon Young’s modulus, and also the uncertainty bounds for a so-called “potato plot” for variations in mass and Young’s modulus. This results are obtained very efficiently using the SVD approach.

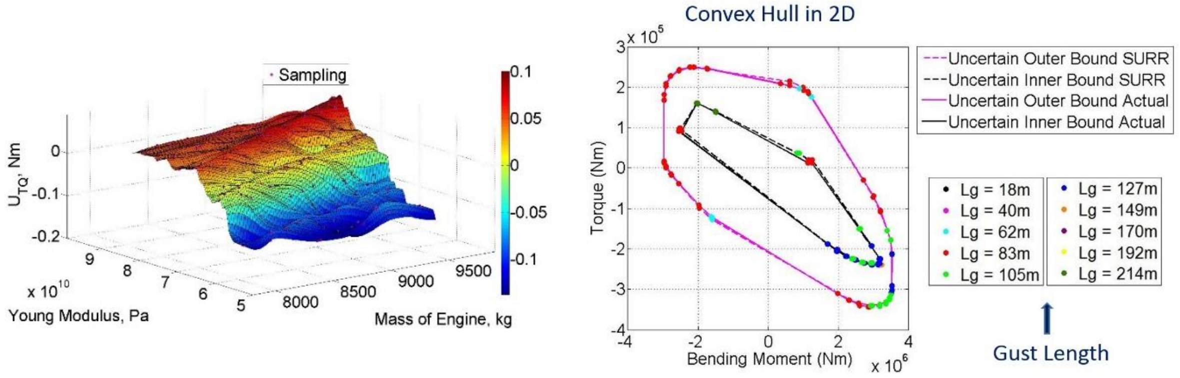


Figure 17. Response Surface and Uncertainty Bounds on Correlated Loads Envelope

H. Sensitivity Analysis and Uncertainty Quantification in the presence of Hopf bifurcations

A new methodology, shown in figure 18, has been developed to perform sensitivity analysis (SA) and uncertainty quantification (UQ) in terms of locus of Hopf bifurcation points in operational parameter. Suitable SA has been accomplished adopting main and total effect indices in order to identify the most influential parameters, which, in the case study, result in being parameters related to the torsional and tyre dynamics (figure 19). Outer bounds for the locus of Hopf bifurcation points (figure 20) have been identified using SVD and also High Order Singular Value Decomposition (HOSVD) and surrogate models to speed up the whole process. The methodology has been demonstrated on a nonlinear analytical landing gear system and the obtained results emphasizes exceptional accuracy and a reduction of almost 95% of the total computation time required by Monte Carlo Simulations.

The aim is to apply the methodology to a multi-body landing gear system, thus a Matlab/Simulink code has been developed to couple the adopted AUTO continuation software to LMS Virtual.Lab Motion software. The Matlab/Simulink code includes also the modelling of a suitable Tyre model and the bifurcation analysis considering the tyre lateral slip has already been successfully performed[16-18].

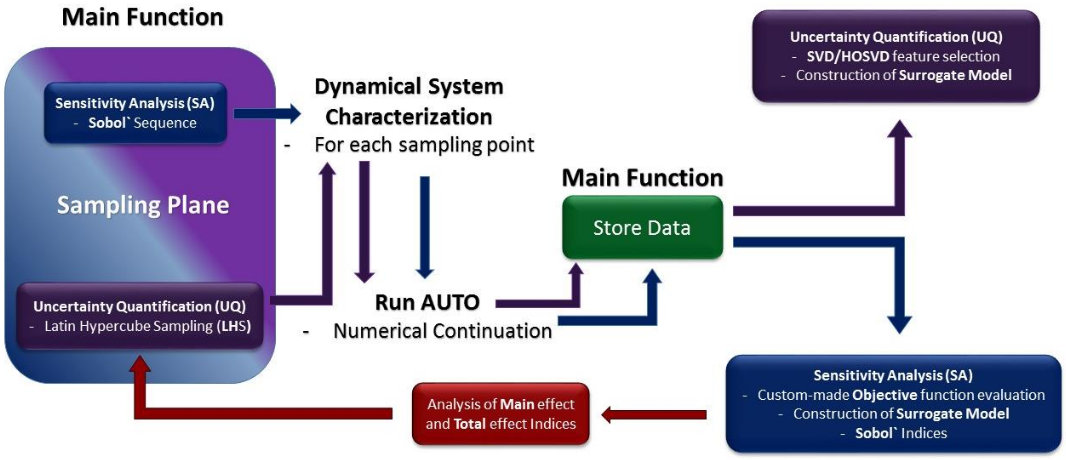


Figure 18. Flow Chart for Coupling of VLM, AUTO and SA/UQ Analysis

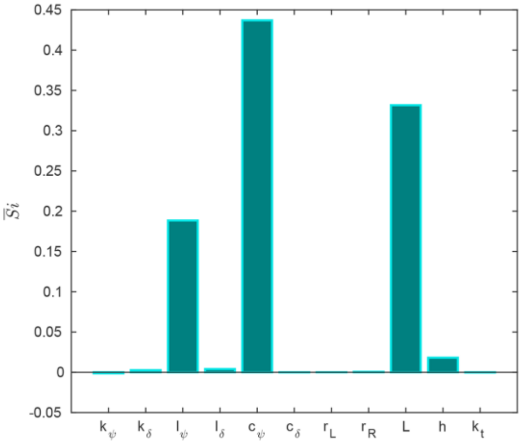


Figure 19. Comparison of the influence of each parameter on the analysed bifurcation branches.

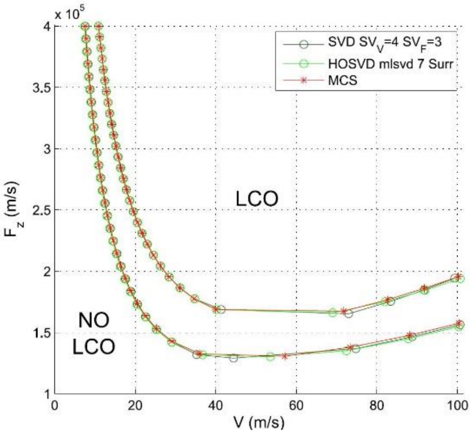


Figure 20. Uncertainty bounds of locus of Hopf bifurcation points.

IV. Conclusions

This paper has given a brief overview of some of the work undertaken as part of the ALPES Marie-Curie Initial Training Network on Aircraft Loads. Some examples of the industrially focussed research undertaken as part of the project have been described. Future plans include developing these technologies further and applying them to industrial scale problems.

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References

[1] A. Castrichini, Y. Lemmens, J.E. Cooper *Unsteady Aerodynamics in Multibody Simulation For Aircraft Loads Prediction* NAFEMS World Congress 2015

[2] A Castrichini, V Siddaramairah, D Calderon, J.E. Cooper, T Wilson, Y Lemmens *Preliminary Investigation of Use of Flexible Folding Wing-Tips for Static and Dynamic Loads Alleviation* 4th RAeS Aircraft Structural Design Conference, Belfast, Oct 2014.

[3] A Castrichini, V. Hodigere Siddaramaiah, D. E. Calderon J.E. Cooper, T Wilson *Nonlinear Folding Wing-Tips for Gust Loads Alleviation* 2nd AIAA SCITECH Conf. Jan 2015

[4] A. Castrichini , J.E. Cooper, T. Wilson, A. Carrella ,Y. Lemmens , "*Nonlinear Negative Stiffness Wing-Tip Spring Device for Gust Loads Alleviation*"   Proc. SCITECH 2016.

[5] A. Poncet-Montanges, D. Jones, J. E. Cooper, Y. Lemmens *'Frequency-domain approach for transonic unsteady aerodynamics modelling'* IFASD 2015

[6] A. Poncet-Montanges, J.E. Cooper, D. Jones, A.L. Gaitonde and Y. Lemmens, "*Frequency Domain Approach for Transonic Unsteady Aerodynamic Modelling*" Proc. SCITECH 2016

[7] C. Valente, D. Jones, A.L. Gaitonde, J. E. Cooper, Y. Lemmens," *Doublet-Lattice Method Correction by Means of Linearised Frequency Domain Solver Analysis*" Proc. SCITECH 2016

[8] C. Valente , D. Jones, A. Gaitonde, J. E. Cooper Y. Lemmens *'OpenFSI interface for strongly coupled steady and unsteady aeroelasticity'* IFASD2015

[9] M. Castellani, J. E. Cooper, Y. Lemmens *‘Reduced Order Model Approach for Efficient Aircraft Loads Prediction’* SAE Aerotech 2015

[10] M. Castellani, J. E. Cooper, Y. Lemmens *‘Parametric Reduced Order Model Approach for Rapid Dynamic Loads Prediction and Simulation of Aeroelastic Systems with Structural Nonlinearities*’ IFASD 2015

[11] M. Castellani, Y. Lemmens and J.E. Cooper, “Parametric reduced-order model approach for simulation and optimization of aeroelastic systems with structural nonlinearities” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,* first published on October 8, 2015 doi:10.1177/0954410015608888

[12] M. Castellani, Y. Lemmens, Y. & J.E. Cooper “Reduced Order Model Approach for Efficient Aircraft Loads Prediction” 2015: To appear in SAE International Journal of Aerospace.

[13] M. Castellani, J.E. Cooper & Y. Lemmens, “*Nonlinear Static Aeroelasticity of High Aspect Ratio Wing Aircraft by FEM and Multibody Approaches*” Proc. SCITECH 2016.

[14] I. Tartaruga, J E Cooper, M H Lowenberg, S Coggon, Y Lemmens *‘Uncertainty Quantification of Correlated Aircraft Loads'* 4th Aircraft Structural Design Conference, Belfast, October 2014

[15] I. Tartaruga, J E Cooper, M H Lowenberg, P Sartor, S Coggon, Y Lemmens *'Efficient Prediction and Uncertainty Propagation of Correlated Loads',* Scitech Conference - Orlando, January 2015

[16] I. Tartaruga , J. E. Cooper, M. H. Lowenberg, P. Sartor, S. Coggon, Y. Lemmens, “Prediction and uncertainty propagation of correlated time-varying quantities using surrogate models” *CEAS Aeronautical Journal* pp 1-14 First online: 22 October 2015

[17] I. Tartaruga, J E Cooper, M H Lowenberg, Y Lemmens *'Evaluation and Uncertainty Quantification of Bifurcation Diagram: Landing Gear, a case study'* UNCECOMP 2015, 1st International Conference on Uncertainty Quantification in Computational Sciences and Engineering 25-27 May 2015, Crete, Greece

[18] I. Tartaruga , M. H. Lowenberg, J. E. Cooper P. Sartor and Y. Lemmens, “*Bifurcation Analysis of a Nose Landing Gear System*” Proc SCITECH 2016