ALPES (Aircraft Loads Prediction using Enhanced Simulation)

Marie Curie ITN (Initial Training Network)

Mid-Term Report

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15th May 2015

Summary

This report reviews the progress made in the first 21 months of the ALPES (Aircraft Loads Prediction using Enhanced Simulation) Marie Curie ITN between the period 1st October 2013 to 16 June 2015. Details of the recruitment of ESRs (Early Stage Researchers), their projects, placements and training are given, along with information about the management of the project. Finally, an overview of the future direction and activities of the ALPES ITN is discussed.

Contents

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 will contribute 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:

- 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 methodologies 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. Note that since the start of the project, LMS International has now become part of Siemens. 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.

ALPES Early Stage Researchers

During the course of the first year of the project, five high quality ESRs were recruited; they are listed in Table 2 and 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. The timeline for the ESR placements and the major training events are shown in Table 3.

ESR No.	**Name**	**Nationality**	**Start date**	**Initial position**
1	Andrea Castrichini	Italian	1st Oct 2013	SISW
2	Adrien Poncet-Montages	French	3rd Feb 2014	UoB
3	Carmine Valente	Italian	1st May 2014	UoB
4	Michele Castellani	Italian	1st May 2014	SISW
5	Irene Tartaruga	Italian	1st March 2014	UoB

Table 2. ALPES ESRs

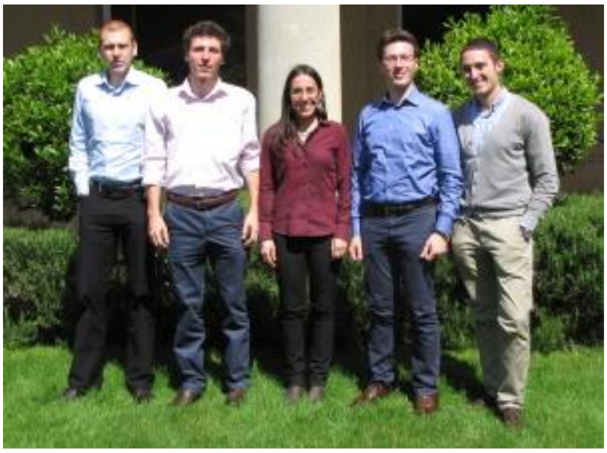


Figure 1. The ALPES Researchers

Table 3. ALPES PROJECT – ESR TIMELINE

	2013			2014												2015												2016												2017								
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
Andrea Castrichini									W	A		I G	B	D		S					M																											
A. Poncet-Montanges									W	A		G		D F							M																											
Irene Tartaruga									W	A		G	B	D F		S					M																											
Carmine Valente									W	A		G		D F							M																											
Michele Castellani									W	A		G I	E	D F							M																											

University of Bristol

SISW

2 Week Placement at Airbus

A	Introduction to Aircraft Aeroelasticity and Loads	W	1st ALPES WORKSHOP	E	EASN Workshop
D	Dipart Meeting	G	GVT Masterclass	S	SCITECH Conf
F	Nonlinear Aeroelasticity of Flexible Aircraft Workshop	I	ISMA Conf	B	4th Int AC Structures Conf
M	Midtem Meeting				

PhD Programmes

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

1. Andrea Castrichini – J E Cooper, M Lowenberg, Y Lemmens
   Improved modelling of landing, manoeuvre and gust loads for combined high load events
2. Adrien Poncet-Montages – D Jones, A Gaitonde, Y Lemmens
   Reduced Order Modelling approaches for landing, manoeuvres and gust loads
3. Carmine Valente - A Gaitonde, D Jones, Y Lemmens
   Development of efficient and accurate gust loads modelling techniques combining high and low fidelity methods
4. M Castellani – J E Cooper, M Lowenberg, Y Lemmens
   Development of improved approaches to determine worst case predictions of gust, manoeuvre and landing loads
5. 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.

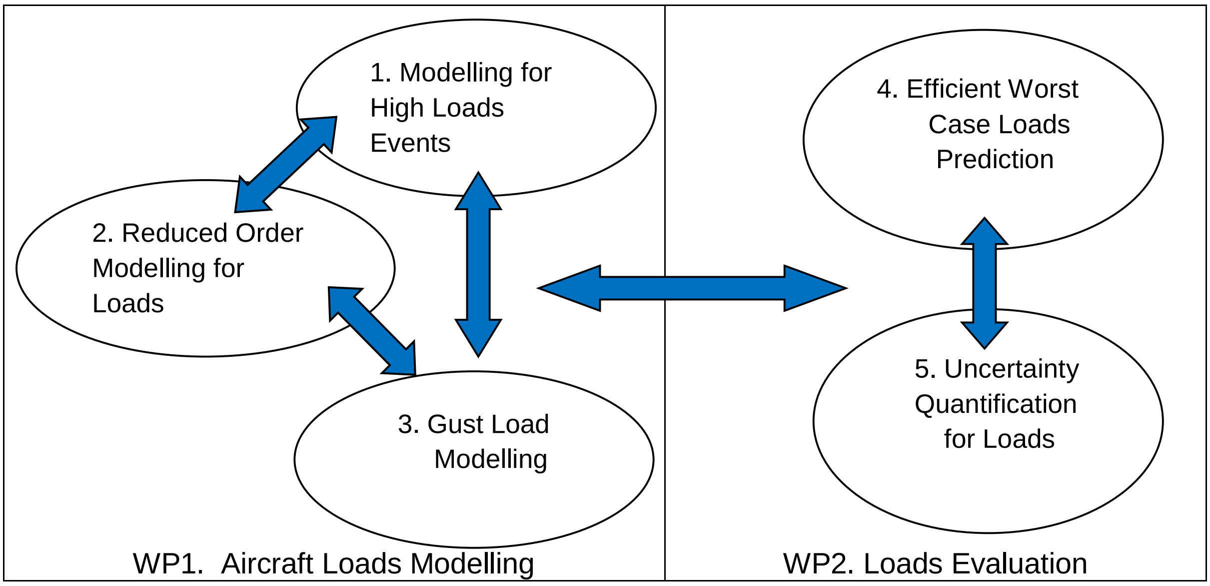


Figure 2. Research WP Structure, Showing Each Project, and Their Interaction

Supervisory and Management Team

The supervisory and management team for ALPES is shown in Table 4, with the lead investigators being Jonathan Cooper from the University of Bristol and Yves Lemmens from Siemens; other staff involved in the technical supervision are also shown. The ALPES project is administered by Sarah Hassall at UoB and Els Tops at Siemens.

Due to the nature of the ITN, the ALPES project and the ESRs need to be managed not only from a project viewpoint, but also must have adequate supervisory provision in order to meet the requirements of the University of Bristol with whom all are registered for PhDs. Each ESR has at least two university supervisors and one from Siemens. The supervision and management is shared between UoB and Siemens thereby ensuring that the ESRs have day to day supervision.

Regular contact is maintained between the ESRs and the University, Siemens and Airbus staff, via a series of weekly Webex and telecom meetings. These meetings are either for the management team, or involve the ESRs as well.

University of Bristol	**Role in ALPES Project**
Jonathan Cooper	Coordinator, PhD supervisor
Ann Gaitonde	PhD supervisor
Sarah Hassall	Administrator
Dorian Jones	PhD supervisor
Mark Lowenberg	PhD supervisor
Pia Sartor	PhD supervisor
Siemens	
Yves Lemmens	Co-Investigator, PhD supervisor
Jens de Boor	PhD supervisor
Els Tops	Administrator
Airbus	
Tom Wilson	Loads and Aeroelastics Engineer
Simon Coggin	Loads and Aeroelastics Engineer

Table 4. Staff Involved in the ALPES ITN

ESR Training

The ESRs all undertake a series of training courses that aimed at developing both their technical and transferable skills. The initial activities/training courses were aimed at developing the ESRs' skills, through activities aimed at reinforcing their technical capabilities and transferable skills, but now that the ESRs have been in post for over a year most of the activities involve participation in technical conferences.

Each ESR has a programme of training activities aligned with their PhD project and personal development plan as shown in figure 3. The aim has been is to align the PCDP with the global training plan, complemented with dedicated individual training activities for individual or selected ESRs.

Figure 3 Career Development Plan for the ESRs

As can be seen in Table 5 there has been a significant amount of training undertaken during the first 18 months of the ALPES project. Of particular note were the following activities attended by all of the ESRs:

- the two week placement at Airbus Filton, based in the Flight Physics Department and spending that time gaining an understanding of the loads and aeroelasticity process in an industrial setting
- the five day short course on "Introduction to Aircraft Aeroelasticity and Loads" held at the University of Bristol
- a three day master class on Ground Vibration Testing held in Belgium by Siemens in conjunction with KU Leuven.
- 1st ALPES workshop
- A two-day course on "Nonlinear Aeroelasticity of Very Flexible Aircraft" presented by Carlos Cesnik of University of Michigan, held in Bristol in November 2014.

However, it can also be seen that there were numerous other activities that the ESRs participated in.

First ALPES Review Meeting - 5 – 6 June 2014

The First Annual Review meeting for the ALPES Project was held at Engineers' House in Bristol on the 5 and 6 June 2014. It was the first chance for the group to meet up since the recruitment of all 5 PhD/Researchers and was attended by the University of Bristol academic staff working on the project as well as the researchers themselves and delegates from LMS/Siemens and Airbus. Figure 4 shows a photo of the participants of the workshop.

The meeting began with an overview of the project which was presented by the Project Coordinator, Professor Jonathan Cooper.

The five ALPES researchers then gave presentations on their individual PhD projects – giving an outline of the project including some ideas for the future direction of their research, as well as an overview of work completed so far. The presentations were excellent and provoked some extremely interesting and fruitful discussion amongst the industrial and academic members of the project.

Following an interesting and informative day of presentations and discussion, the conference dinner was held at Goldbrick House on Park Street, Bristol.

The second day of the Annual Meeting was an opportunity for the researchers to meet to discuss their projects, whilst the industrial and academic partners attended the Management Committee Meeting.

Figure 4. Attendees of the First ALPES Review Meeting

TECHNICAL SKILLS TRAINING					
Main Training Events and Conferences	Andrea Castrichini	Carmine Valente	Michele Castellani	Irene Tartaruga	Adrien Poncet Montanges
Compulsory Scientific Courses					
Airbus initial 2 week placement	x	x	x	x	x
Practical Modal Analysis	x				
Numerical simulation of multi-body systems	x	x	x		
Introduction to Aircraft Aeroelasticity and Loads	x	x	x	x	x
Optional Scientific Courses					
Ground Vibration Testing (GVT) Master Class	x	x	x	x	x
-Experimental NVH (2 days 30/06 and 01/07)	x				
Course on Detection, Modeling and Identification of Nonlinearities in Engineering Structures (Sept 18-19 2014)	x		x		
Introduction to Python - 30/09/2014		x		x	
Workshop on Nonlinear Aeroelasticity of Very Flexible Aircraft Nov 2014		x	x	x	x
Introduction to Fortran - 28/10/2014				x	
Numerically Solving Partial Differential Equations using Linear Algebra Libraries - 11/11/2014				x	
Introduction to HPC - 28/01/2015		x		x	
Scientific Conferences					
DIPART (Dec 2013)	x				
DIPART (Nov 2014)	x	x	x	x	x
LMS Aerospace Conference - Oct 2013, ...	x				
ISMA-ISAAC International Conference on Noise and Vibration Engineering (15-17/09/2014)	x		x		
4th EASN International Workshop on Flight Physics and Aircraft Design			x	x	
4th Aircraft Structural Design Conference – Belfast, October 2014	x			x	
Scitech Conference - Orlando, January 2015	x			x	
Siemens Aerospace Conference - Mar 2015, ...	x		x		
UNCECOMP 2015 - 1st International Conference on Uncertainty Quantification in Computational Sciences and Engineering 25-27 May 2015, Crete				x	
TRANSFERABLE SKILLS TRAINING					
Main Training Events and Conferences	Andrea Castrichini	Carmine Valente	Michele Castellani	Irene Targaruga	Adrien Poncet-Montanges
Compulsory Trasferable Skills Training					
Managing your PhD		x		x	x
Presenting your research at meetings, seminars and conferences in internationally diverse contexts (levels 1 & 2)		x		x	
Industrial R&D: IPR aspects and entrepreneurship				x	
An introduction to managing research data - 19/11/2014				x	
Presentation skills	x		x		
STT PGRs Lab Demonstrating		x			x
Project Management Course	x				
PG mentors for the third year project IXP (11/2014 - 03/2015)				x	
ALPES 1st Workshop	x	x	x	x	x
Internal presentation of activities at LMS April 2014	x				
Intermediate French Course - B2 - Level 4	x				
Uncertainty in Computer Models, 28-30 July 2014				x	
Dynamics and Control Group Seminar - 1 October 2014				x	
Parallel Programming Workshop Jan 2015		x			
Quality Papers: Getting your paper published in your target journal - Feb 2015		x			

Table 4. Scientific and Transferable Skill Training during the First Year of ALPES

Management

The original proposal for the ALPES project defined a management structure shown on the left hand side of figure 5 and it can be seen that this involved a number of different boards and committees. It was soon realised once the project had started, that due to the relatively small number of people involved in ALPES that the same personnel would have to attend all of the meetings. Consequently, the management structure shown on the right hand side of figure 5 was adopted, with two main teams – the first involving the PhD supervisors and the Associate Partners as a management team, and the second that consisted of the same people but now with all the ESRs included as well. This revised structure has been found to work very well.

Meetings of the ALPES management team have been held on a regular basis either using telecoms or, when possible, face to face. It has been found that it has been useful to run meetings that include the ESRs, and to get them to give a short presentation of their progress, as well as meetings where only the supervisors, administrators and (when possible) Associate Partner representatives attend. Through such regular meetings it is possible to maintain an overview of the entire project, to monitor the progress of individual ESRs and to enable interactions between the various parts of ALPES.

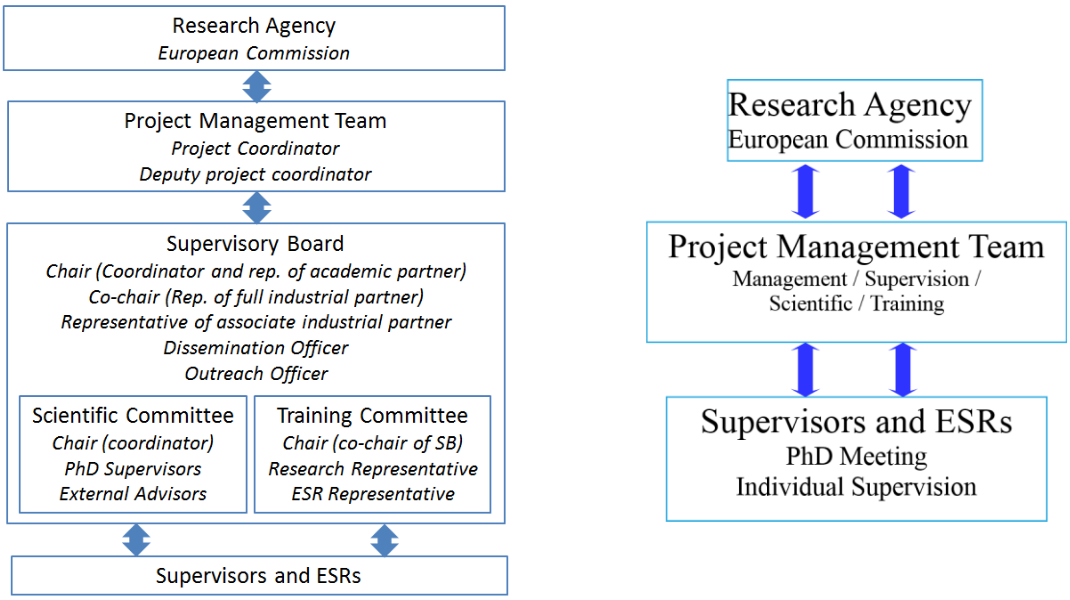


Figure 5. Original (L) and Actual(r) Management Structure

Each of the ESRs holds regular meetings with their supervisors, including telecoms with supervisors who are based at the other partner. The Associate Partner (Airbus) is also made aware of the progress of the individual ESRs; this has already resulted in a significant interaction with Irene Tartaruga's project, and it is hoped that she will spend some more time at Airbus Flight Physics in the 2ND quarter of 2015 applying some of the methodologies that have been developed. Further industrial interaction is underway and placements are being planned for the other ESRs.

Management Committee Meetings:-

21 Oct 2013	UoB - Kick Off Meeting
14-15 Nov 2013	Siemens, Leuven (J Cooper and S Hassall from UoB visit)
11 Feb 2014	Telecom
20 Feb 2014	UoB
18 Mar 2014	UoB
06 June 2014	UoB
05 Feb 2015	UoB
22 Apr 2015	UoB

Networking and Transfer of Knowledge

There is regular contact between ESRs on a daily basis and in addition there is a formal structure of monthly ESR Webex Meetings which are primarily run by and for the ESRs but with attendance and interaction from the Supervisors. The following is a list of the meetings over the past months:-

Regular PhD Webex Meetings - ESRs and Supervisors:-

15 May 2014
14 Aug 2014
11 Sept 2014
17 Oct 2014
6 Nov 2014
4 Dec 2014
29 Jan 2015
26 Feb 2015
23 April 2015
21 May 2015

In addition to the formal Project Meeting in June 2014 most of the ALPES group met at ISMA 15-17 September 2014 in Leuven, in Bristol for the "Nonlinear Aeroelasticity of Very Flexible Aircraft" short course in November 2014, and in Bristol again on 21/22 April 2014.

ESR Meetings

5-6 June 2014 following the 1st Workshop
14-18 July 2014 during the Aeroelasticity and Loads Course
15-17 September 2014 during the ISMA Conference
13-14 November 2014 during the Very Flexible Aircraft Course in Bristol.
21/22 April 2015 at University of Bristol.

Scientific Results

A short description of the objectives and scientific highlights for each of the ESRs now follows. These section have been kept deliberately short; however, further details can be obtained from their 12 months PhD progress reports, or the relevant publications which are based on their work.

ESR1. Andrea Castrichini

Research Objective - To improve the modelling of landing, manoeuvre and gust loads for combined high load events

Scientific Highlights

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

A methodology has been developed to couple unsteady aerodynamic loads with flexible bodies in multibody simulations. 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.

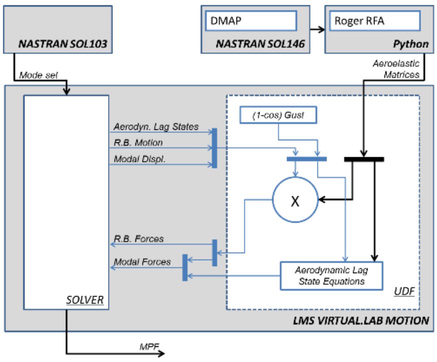


Figure 6. Multi-Body Loads Evaluation Scheme

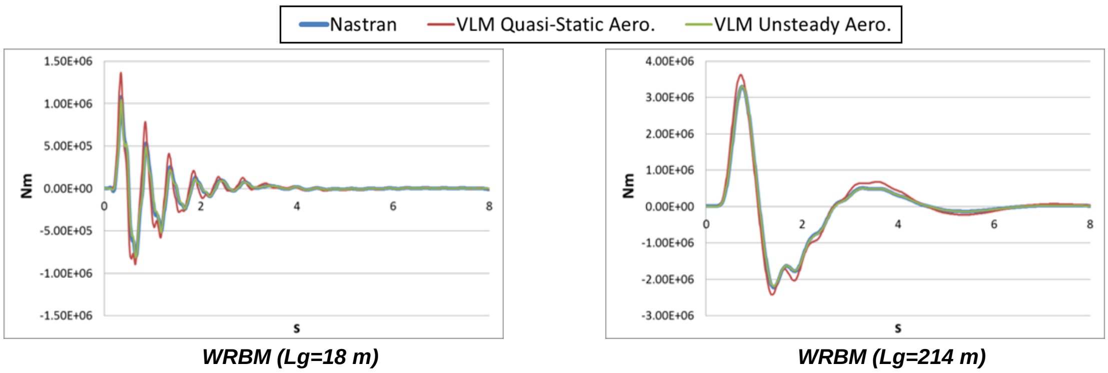
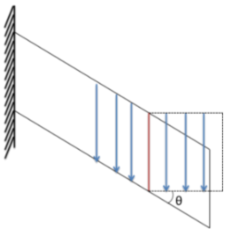


Figure 7. Comparison of NASTRAN and Multi-Body VLM Gust Response Time Histories

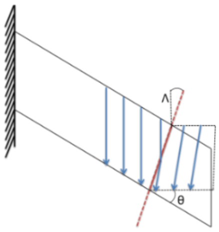
- Development of a folding wing tip device for gust loads alleviation

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 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.



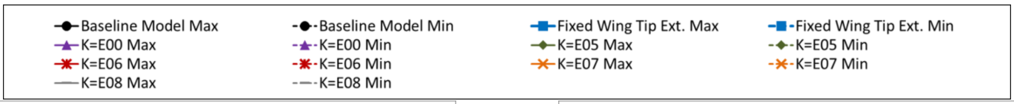
(a) 0° hinge

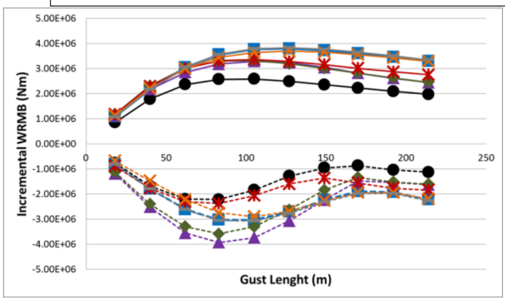


(b) 25° hinge

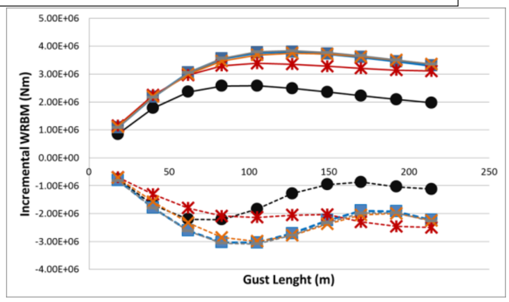
Figure 8. Hinge Orientations

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.

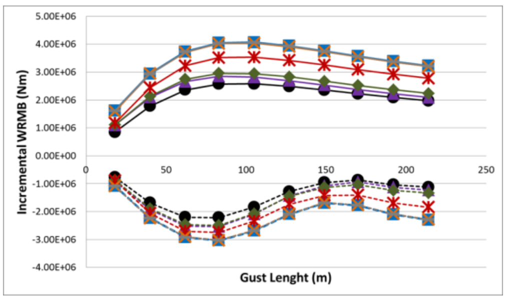




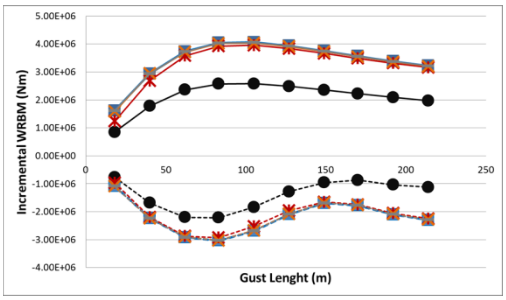
(a) 943 Kg wing-tip model, 25° hinge



(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

ESR 2 Adrien Poncet-Montages

Research Objective - To develop reduced order aeroelastic modelling approaches for landing, manoeuvres and gust loads

Research Highlights
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 years 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. 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.

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

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

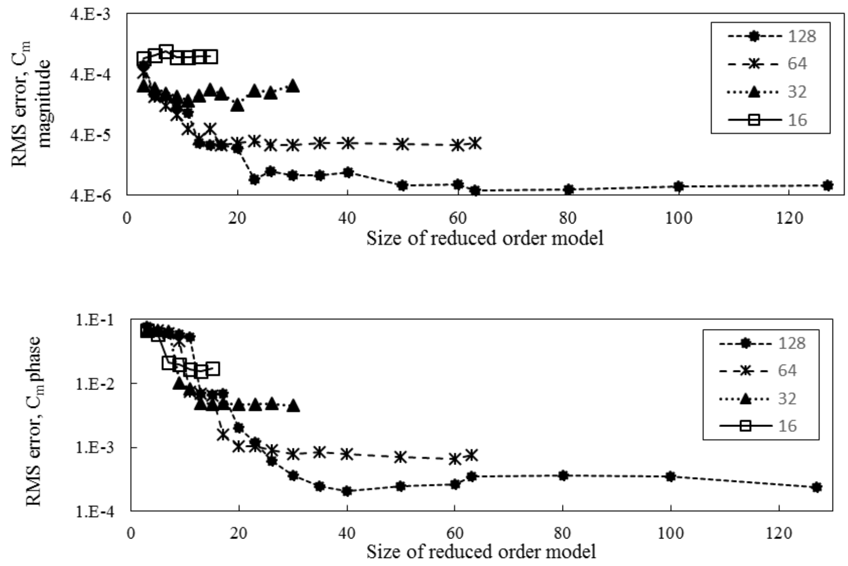


Figure 10: RMS error in c_m, phase and magnitude vs ROM size

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.

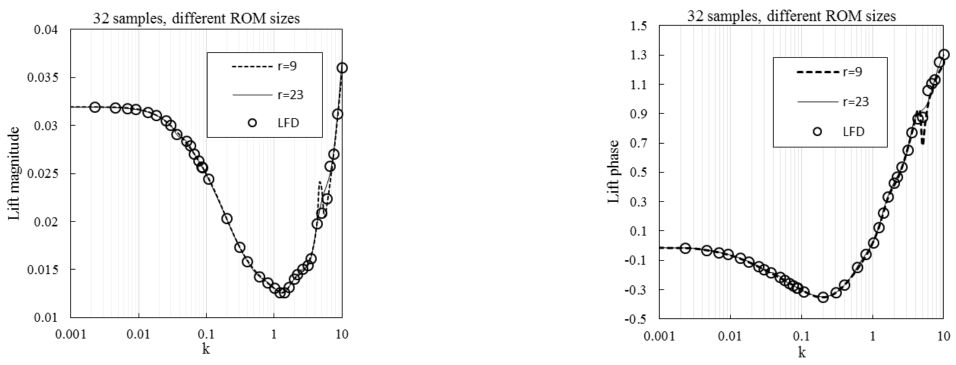


Figure 11: Lift magnitude and phase vs reduced frequency for LFD solution and ROM of size r

ESR3 – Carmine Valente

Research Objective - To development efficient and accurate gust loads modelling techniques combining high and low fidelity methods

Research Highlights

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. 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 aerelastic gust calculations. Typical results for the static analysis applied for the trim calculation on the FFAST wing are shown below.

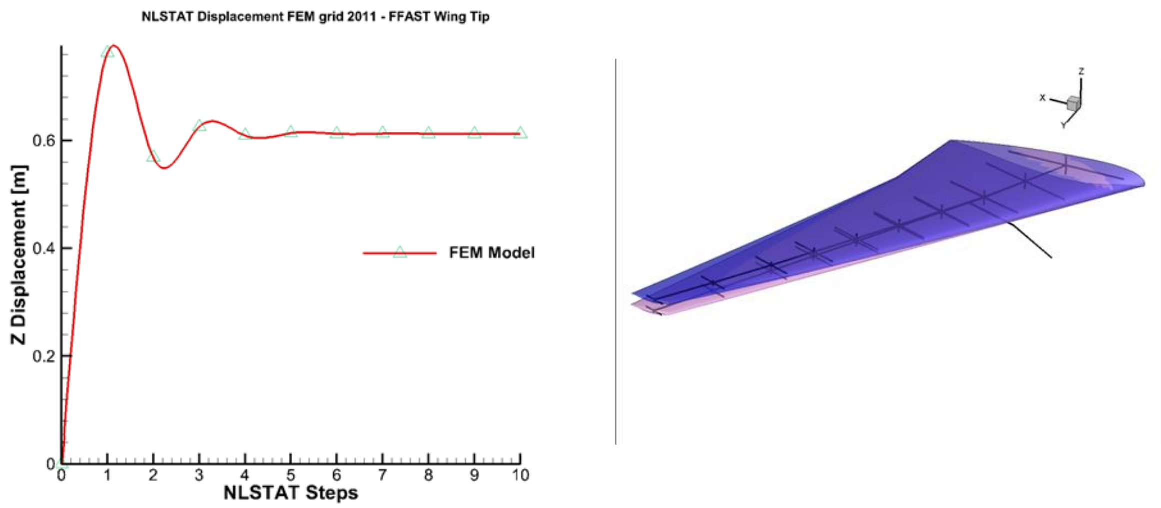


Figure 12: Tip displacement vs number of static aeroelastic evaluations, also shown is the initial and final aerodynamic and structural surfaces for the FFAST wing

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.

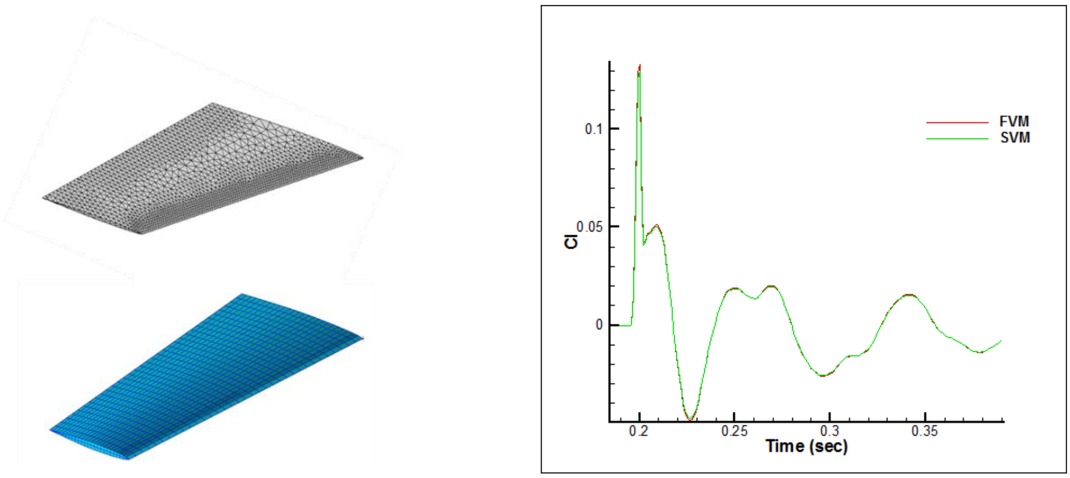


Figure 13: AGARD 445.6 wing, initial structure and aerodynamic surface meshes. Also shown is the C_l response to a 4° gust.

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

ESR4. Michele Castellani

Research Objective - To develop improved approaches to determine worst case predictions of gust, manoeuvre and landing loads

Scientific Highlights

- 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.

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

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

where

$$A_r = (W^T V)^{-1} W^T A V, B_r = (W^T V)^{-1} W^T B, C_r = CV$$

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 following PMOR framework is followed:

1. Generation of the n_p local ROMs at the sampling points $\hat{\boldsymbol{p}}_i$, $i = 1 \dots n_p$
2. Congruence transformation of the locally reduced state-space matrices
3. Elementwise interpolation of the locally reduced state-space matrices to the validation points $\overline{\boldsymbol{p}}$
4. 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.

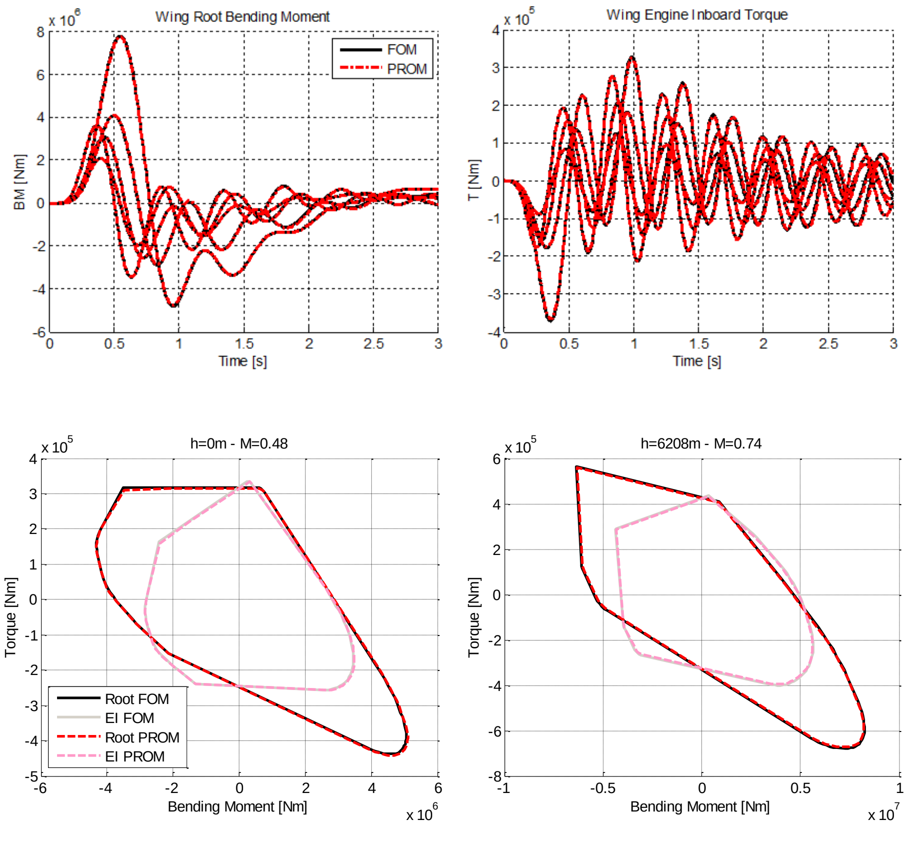


Figure 14. Comparison of IQ Time Histories and Correlated Loads Boundaries between full and reduced order models

ESR5. Irene Tartaruga

Research Objective - To develop methods for the uncertainty quantification of landing, gust and manoeuvre loads

Scientific Highlights

- 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 an 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 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 15. 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.

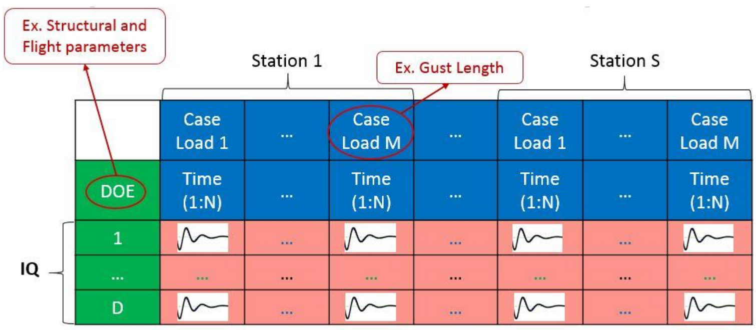


Figure 15 – Format of Data Matrix

Figure 16 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.

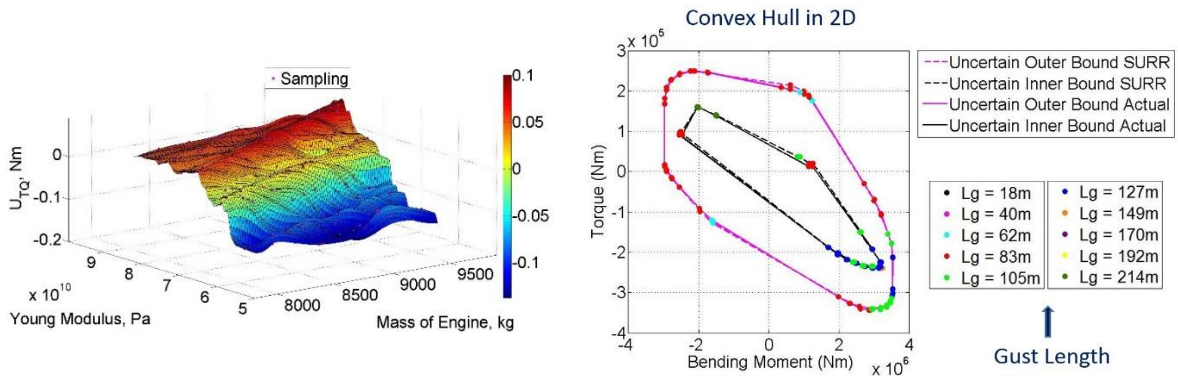


Figure 16. Response Surface and Uncertainty Bounds on Correlated Loads Envelope

- Sensitivity Analysis and Uncertainty Quantification in the presence of Hopf bifurcations

A new methodology, shown in figure 17, 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 18). Outer bounds for the locus of Hopf bifurcation points (figure 19) 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 performed.

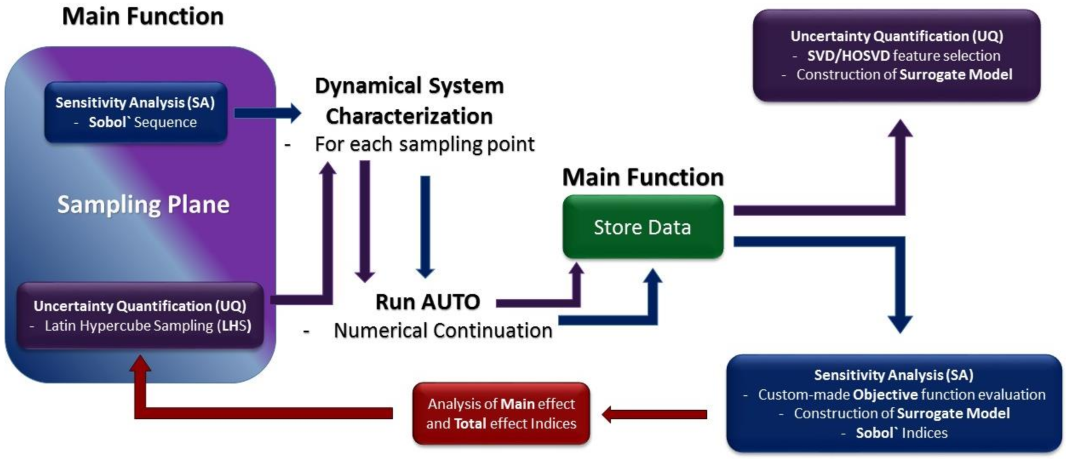


Figure 17. Flow Chart for Coupling of VLM, AUTO and SA/UQ Analysis

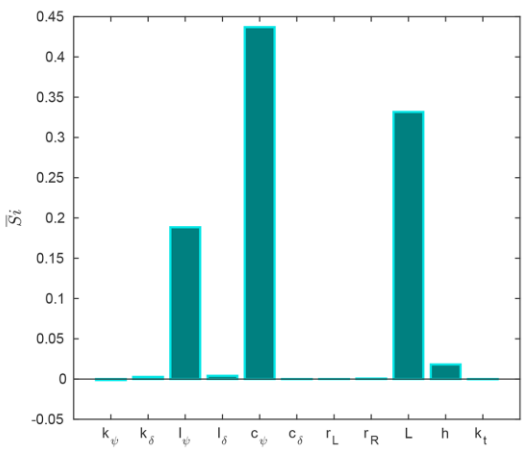


Figure 18. Comparison of the influence of each parameter on the analysed bifurcation branches.

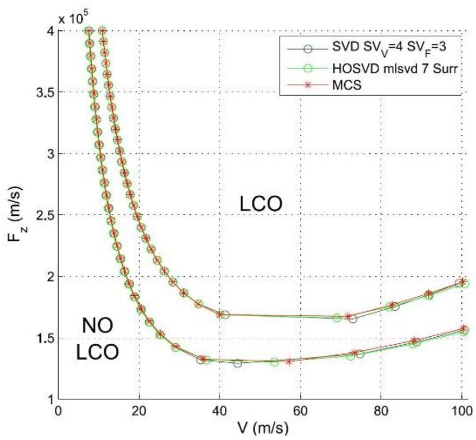


Figure 19. Uncertainty bounds of locus of Hopf bifurcation points.

Publications

A number of conference papers have been presented/accepted over the past 18 months, many of which have been converted into journal papers which have now been submitted – see figure below for full details. All of the ALPES researchers will aim to have several journal and conference publications by the end of their PhD study.

Author/s	Title	Conference/Journal
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.
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
A. Castrichini, Y. Lemmens, J.E. Cooper	*Unsteady Aerodynamics in Multibody Simulation For Aircraft Loads Prediction*	NAFEMS World Congress 2015 (22-24 June 2015)
A Castrichini, V. Hodigere Siddaramaiah, D Calderon, J.E. Cooper, T Wilson, Y Lemmens	*'Preliminary Investigation of Use of Flexible Folding Wing-Tips for Static and Dynamic Loads Alleviation'*	Aeronautical Journal (submitted)
A Castrichini, V. Hodigere Siddaramaiah, D. E. Calderon J.E. Cooper, T Wilson	*'Nonlinear Folding Wing-Tips for Gust Loads Alleviation'*	AIAA, Journal of Aircraft (submitted)
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
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
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 Island, Greece
I. Tartaruga, J E Cooper, M H Lowenberg, P Sartor, S Coggon, Y Lemmens	*'Prediction and Uncertainty Propagation of Correlated Time-Varying Quantities'*	CEAS Aeronautical Journal (submitted)
I. Tartaruga, P Sartor, J E Cooper, M H Lowenberg, Y Lemmens	*''Sensitivity Analysis and Uncertainty Quantification in the Presence of Hopf Bifurcation'*	SIAM/ASA Journal of Uncertainty Quantification (submitted)
C. Valente , D. Jones, A. Gaitonde, J. E. Cooper Y. Lemmens	*'OpenFSI interface for strongly coupled steady and unsteady aeroelasticity'*	Accepted for IFASD2015

M. Castellani, J. E. Cooper, Y. Lemmens.	*'Parametric Reduced Order Model Approach for Rapid Dynamic Loads Prediction'*	Aerospace Science & Technology (submitted)
M. Castellani, J. E. Cooper, Y. Lemmens	*'Reduced Order Model Approach for Efficient Aircraft Loads Prediction'*	SAE Aerotech Conference 2015
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'*	Accepted for IFASD 2015, Russia
A. Poncet-Montanges, D. Jones, J. E. Cooper, Y. Lemmens	*'Frequency-domain approach for transonic unsteady aerodynamics modelling'*	Accepted for IFASD 2015, Russia

Table 5. Accepted Conference Papers Resulting from ALPES Project and Submitted Journal Papers

Project Website

A website for the ALPES ITN has been set up and can be accessed on

http://www.bristol.ac.uk/aerodynamics-research/alpes/

The website contains details of the organisations making up the network, the people involved and a description of main events that have taken place.

Dissemination and Outreach Activities

A good start has been made to disseminate the scientific outcomes from the ALPES project through conference and journal publications, and also dedicated ALPES sessions at scientific meetings. Activities are being planned in order to enable outreach relating to aerospace engineering to occur, and this will have more emphasis in the second half of the project.

1. The ALPES Project ran a two day course in November 2014 at Engineers' House in Bristol, headed up by Prof Carlos Cesnik of University of Michigan which was attended by more than 40 delegates from industry and academic institutions from throughout Europe as well as the ALPES ESRs. The Workshop received tremendous feedback.

2. A dedicated ALPES session was held at the annual DiPART meeting in November 2014, which is an Airbus organised meeting for researchers in the UK who work in the areas of Aircraft Aeroelasticity and Loads. A similar event is planned for November 2015.

3. A special ALPES Session will be held at the forthcoming SCITECH 2016 Conference when each of the ESRs will present a paper along with an overview of the Project presented by Professor Cooper.

4. Two of the ESRs - Carmine Valente and Adrien Poncet-Montanges - have taught laboratory classes at the University of Bristol, and Irene Tartaruga has acted as Postgraduate Mentor for the Third Year Undergraduate IXP Project.

5. Together with the University of the West of England and the Bristol Natural History Consortium the University of Bristol was awarded a grant by the EC under the Marie-Sklodowska-Curie Programme to do Researchers' Night, an event that will take place on 25th September 2015 and that will mean that during that day from midday to midnight there will be activities happening in Bristol that will aim to bring research closer to the public, show them how it's relevant to their daily life and also break stereotypes about research and researchers. Some of the activities that we are planning include a Research Fair, Short Talks and debates, some science art collaborations and Street Theatre on science topics. The aim is to engage as many people related to the programme as possible and the ALPES ESRs will be participating in this event.

6. The PI for the ALPES Project is currently in discussion with the Outreach & Student Liaison Manager and the Widening Participation and Undergraduate Recruitment Officer at University of Bristol in relation to the organisation of Outreach activities for the Project within local schools – e.g. for the ESRs to visit schools to give talks/presentations to pupils to give a broad overview of the project and some of the work done.

7. 2016 sees the 150th Anniversary of the Royal Aeronautical Society and also the 60th Anniversary of the Aerospace Department at the University of Bristol. As part of this activity, the ESRs will participate in the managing of, and participating in, 3 "Cool Aeronautics" days which are attended by local school children.

Conclusions and Future Plans

The first 18 months of the ALPES ITN have been a great success. All of the required ESR posts have been filled with excellent researchers who have made very promising progress in their PhD studies and also training. Excellent contacts have been developed between the partners including good interaction with Airbus.

In the second half of the project we will aim to consolidate the progress of the ITN, including publication of the research at international conferences and in journals, further interaction with industry and also a programme of Outreach activities.