AIRCRAFT LOADS PREDICTION USING ENHANCED SIMULATION

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Abstract

The ALPES research project is an EC FP7 Marie Curie EID Training Network which ran from 2013 to 2017. The partners in the project were the University of Bristol, Siemens Industry Software and Airbus Operations Ltd. The aim of the network was to improve the prediction accuracy and efficiency of the loads experienced by an aircraft in-flight and on the ground. In total 5 PhD researchers worked on three challenges of aircraft load prediction: aeroelastic modelling methods for non-linear and active structures, fast and accurate prediction aerodynamic loads and the uncertainty quantification of aircraft loads during the design. This paper presents an overview of the results achieved.

1 Introduction

1.1 Motivation

Aircraft are designed for optimum operations, for instance the cruise conditions in civil aviation. Regulatory bodies require that the aircraft is strong enough to withstand extreme loads experienced during the entire flight envelope from take-off via cruise and turbulence conditions till landing. An important step in aircraft certification is the determination of the loads acting on the aircraft and its components. These loads are determined by rules laid out by the aviation authorities, and are different for each aircraft project, hence re-determined for each new type of aircraft. Aircraft designers need to consider the total range of static and dynamic loads resulting from flight manoeuvres (equilibrium / steady and dynamic), gust / turbulence encounters, and ground manoeuvres due to landing, braking, turning, etc. These load cases are responsible for the critical design loads acting on the aircraft structure and hence strongly influence the aircraft structural design and sizing, and hence weight. Determination of these loads involves consideration of elastic, inertia and aerodynamic effects and the solution of the dynamic responses. Inaccurate or wrongly predicted loads for the different flight conditions could lead to unsafe design, or at least unnecessary weight gains, increased fuel consumption and lower competitiveness for the aircraft manufacturer.

Some of the main challenges for future aircraft design are defined by the initiatives ACARE 2020 [1] and Flightpath-2050, Europe's Vision for Aviation [2]. A key aspect will be the reduction of the impact of aviation on citizens and the environment, in particular reducing noise (with 65%) and greenhouse gas emissions (with 75% for CO_2 and with 90% for NO_x) regardless of increasing traffic growth by 2050. For the purpose of meeting these objectives, reduction of aircraft weight is an important enabler.

One key element to achieve that is by introducing composites for meeting lightweight and fuel consumption objectives for parts that also need to have a superb mechanical performance. For instance, the Boeing 787 Dreamliner comprises 50% of composites, and 25% of other lightweight materials [5]. Also, in the next generation Airbus A350 XWB [6], more than 50 per cent is made of composites, with carbon fibre fuselage and wings. Another key element is the reduction of critical design loads that an aircraft experiences. This saving will enable reducing the required size of the internal structure, thus leading to a reduction in structural weight and thus improved overall performance. These load reductions can be obtained through better (component) designs, or the inclusion of passive and active loads alleviation approaches.

1.2 ALPES Research Project

The Aircraft Loads Prediction Using Enhanced Simulation (ALPES) research project is an EC FP7 Marie Curie European Industrial Doctorate Training Network which ran from 1 October 2013 to 30 September 2017. The partners in the project are the University of Bristol and Siemens Industry Software, with Airbus Operations Ltd as an Associate Partner. The aim of the network has been to improve the prediction accuracy and efficiency of the loads experienced by an aircraft in-flight and on the ground. The ALPES network involved five Early Stage Researchers (ESRs) who also registered for PhDs, combining a novel research programme with a highly industrially focused training schedule, including placements at Airbus. The ESRs have either been based for 18 months of their employment in Bristol, UK and then spent another 18 months at Siemens PLM Software in Leuven, Belgium or vice versa. The 5 PhD programmes have interacted together throughout the project duration which can be grouped in 3 fields:

- Novel Aeroelastic modelling methods for nonlinear and active structures
- Fast and accurate aerodynamic loads for transonic Mach numbers
- Uncertainty quantification of aircraft uncorrelated loads and landing gear shimmy

2 The Aircraft Design Engineering Process

2.1 Overview

The aircraft structural design engineering process consists of 4 main steps, as shown in Figure 1

- Design: a CAD model of the general design of the internal layout together with external shape is prepared. The structural elements are specified such as the spars, the ribs and stringers.
- Loads: In parallel to the previous step, the integrated and differentiate loads flight and ground loads for static and dynamic loads cases are computed. As this can exceed more than 1 million cases, a simplified aeroelastic model is used, usual a structural stick model coupled with a DLM aerodynamic model. The structural properties that are used are based on estimates as the detailed design of the aircraft is not known yet
- GFEM: Based on the CAD from the first step, a detailed FEM of the complete aircraft is prepared, called the Global FEM or GFEM. Subsequently, the worst cases of the loads performed during the loads analysis are applied to the GFEM to identify the loads on structural elements.
- Stress: The structural elements are now sized in detail using empirical methods of standard elements and detailed finite element models for complex elements. After this step, the structural properties and weight are accurately known. The loads analysis then has to be repeated with new estimates of the structural properties and the load loop process shown in Figure 2 is repeated until convergence is reached.

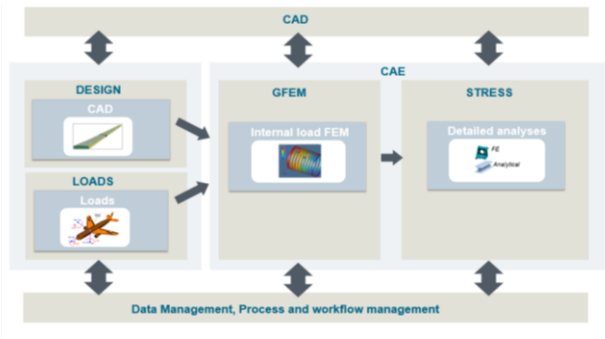

Figure 1 Aircraft structural engineering process

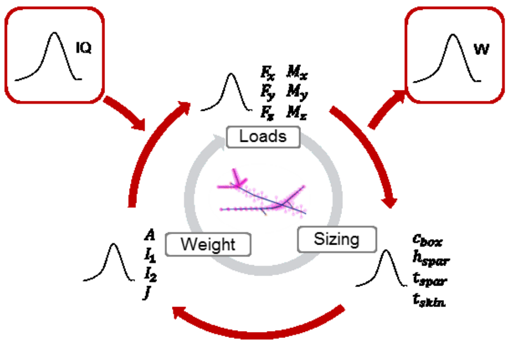

Figure 2. Loads Loops Showing Uncertainty

2.3 Aircraft Loads Prediction

The aim of the loads analysis is to identify the maximum internal structural loads or "interesting quantities" (IQs) in cross sections of the wing and fuselage. These quantities also known as the integrated loads because with respect to a certain cross section, the internal loads in that cross-section corresponds to the sum or integration of the all the external loads and inertia loads on one side of the that cross-section. Every cross-section has multiple IQs that impact on the required size of the structure, for example wing torque and the wing vertical bending moment.

However, the maximum of the IQs, say in response to a gust input, does usually not occur at the same time instant. Not only would it be too conservative to consider all of the maximum IQs together during the structural sizing, stress computations need to be made considering in 2D or 3D, and thus it is usual to include the so-called MAST loads (moment, axial, shear and torque). Therefore, time-correlated loads, shown in Figure 3 are used from which an overall bounding envelope can be derived to give so-called "Potato plots", as shown in Figure 4. From these plots, maximum load combinations can be identified. This approach provides the input to the Global FEM analysis.

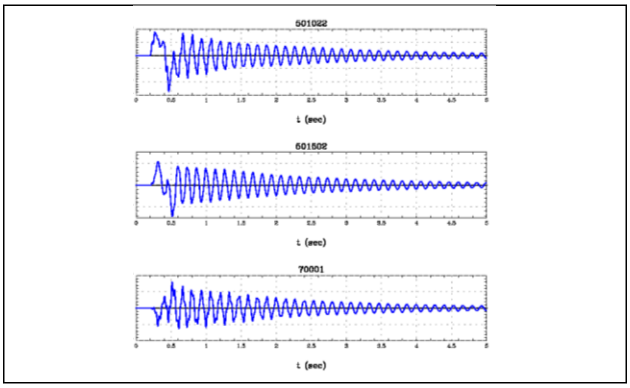

Figure 3 Typical Moment, Shear and Torque Histories.

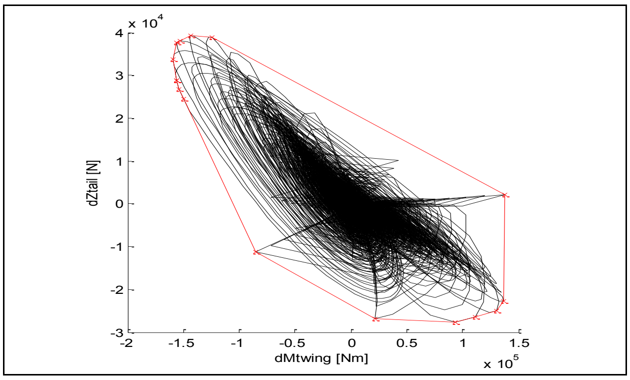

Figure 4. "Potato Plot" From Envelope of Correlated Loads

In aircraft loads, one can distinguish ground loads and flight loads. The flight loads refer to steady, gust and manoeuvre loads. The state of the art is to use (1) Nastran aero-elastic solutions for flight loads, at different flight and load conditions often with a corrected DLM model for higher Mach numbers; or to use (2) in-house codes. The in-house codes typically comprise the use of separate structural and aerodynamic models. The aerodynamic model is validated using wind tunnel tests and flight tests, possibly in the form of look-up tables at different flight conditions. A variety of different tools are used, depending on the aircraft manufacturer and even the aircraft program. For trim and manoeuvre loads, the correct static aerodynamic loads are important and the load changes for gusts and manoeuvres are then added to the static results. Although the DLM with corrections is still the main tool for loads, there is an increasing move towards the inclusion of higher fidelity CFD based aerodynamic tools.

The ground loads refer to taxiing and landing phenomena, and are generally evaluated with in-house tools or multi-body simulation packages. Often for landing cases, the simulation is simplified so that there are no aerodynamic for gravity forces included. The obtained impact loads on landing are superimposed with the trimmed 1g flight loads. Of course, this excludes any effects of the deformation of the aircraft due to the impact loads on the aerodynamic loads. However, only the peak loads at the moment of touch-down are of interest and at the moment the inclusion of the wing deformations is still very limited.

2.3 Current and New Challenges

A current evolution in aircraft structural design is the trend to look at alternative aircraft structures, such as high-aspect-ratio wings, blended wing body designs and load alleviation devices. A limitation is that in-house codes are typically not very well suited for the design of alternative aircraft structures, as they contain historical data and knowledge that is largely based on aircrafts that are made as a rigid tube with wings. This results in a current demand of new more general loads prediction methods and tools that can account for non-linear and active structures, for example based on computational fluid dynamics (CFD). However, the aircraft loads prediction process requires a vast amount of computation, with many flight cases (altitude and speed), load cases (e.g. gust length, landing speed) and aircraft conditions (e.g. mass, COG position) that need to be evaluated on each aircraft design iteration. The aircraft manufacturer may need to perform 100s of thousands of load case evaluations for each design iteration. Hence there is also a need for fast and accurate methods, in particular to predict aerodynamic loads. Moreover, the aircraft design process is an iterative process as explained previously. Consequently, the inclusion of uncertainty into the design process is a large concern. Therefore, methods to quantify and minimise the effects of these uncertainties are also needed.

These three research challenges have been investigated in the ALPES research project and are reported in the references cited at the end of this paper.

3 ALPES Research Overview

3.1 Novel aeroelastic modelling methods for non-linear and active structures

3.1.1 Investigation of a folding wing tip

The first research topic in this field was the investigation of folding wing tips (Figure 5) that could be used in fight to alleviate gust loads [1-11]. Different structural configurations for a civil aircraft aeroelastic model were investigated, including varying the hinge direction, wing-tip weight and linear and non-linear spring stiffness at the hinge, all of which were evaluated for static and dynamic gust loads. For that purpose, linear finite models were developed in Nastran and non-linear multi-body models were developed. For the latter, Simcenter 3D Motion was used and extended with unsteady aerodynamic loads modelling capabilities to enable full aeroelastic analyses on non-linear mechanical systems.

The simulation results in Figure 6 show that for a wing tip that is 25% of the span of the fixed wing, the use of a reduced spring stiffness hinge element can limit the increase of the loads to 4% compared to the baseline wing without the wing tip.

Figure 5. Folding Wing Tip

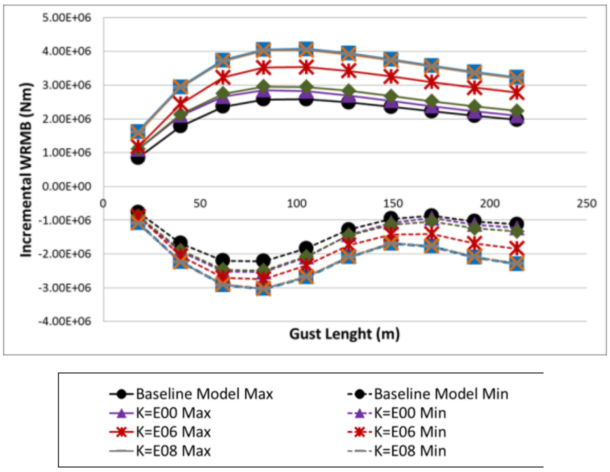

Figure 6. Gust Loads Along Wing with Folding Wing-tip

The studies from the ALPES project have led to much further work on this promising research, including the use of nonlinear spring devices to enhance the gust alleviation properties of the wing – tips.

3.1.2 Model order reduction of aeroelastic models

The second topic that was researched in this field was the development of a model order reduction method of the aeroelastic finite element models based on the Parametric Model Order Reduction (PMOR) method to able to predict the Interesting Quantities (IQs) for a wide range of different load cases that the aircraft is likely to experience in-flight [12-15]. Traditionally, such analysis are performed with linear aeroelastic finite element models, which are extremely time consuming as 100 of thousands loads cases need to be considered. The effectiveness of the developed method was 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 results, as shown in Figure 7 and Figure 8, demonstrate an excellent comparison between the full finite element and reduced order models with a significant saving in computation with the reduced order models. The approach has also been successfully used for prediction of 2D correlated loads plots and also when nonlinearities are present in the system.

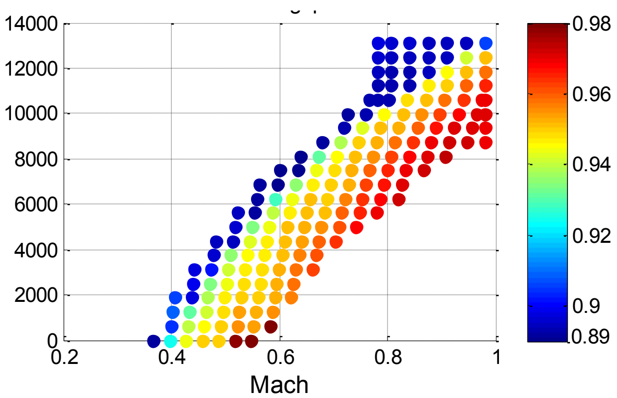

Figure 7. PROM % accuracy of predicting wing bending alleviation at 75% wingspan

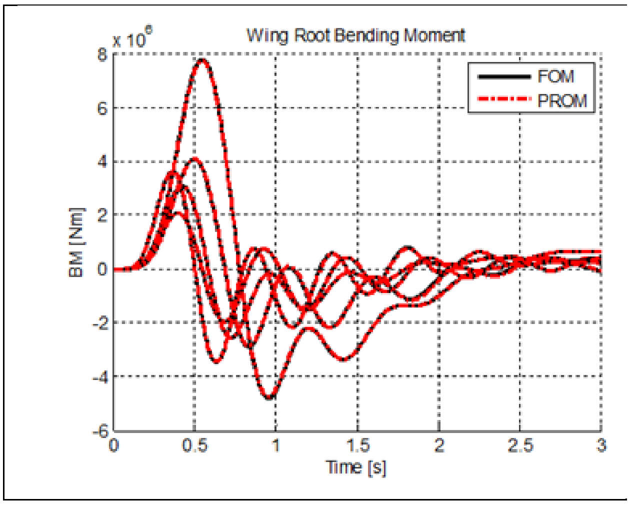

Figure 8. PROM and Full Simulation Gust Response Histories

3.1.3 Non-linear wing modelling methods

Finally, several procedures for the nonlinear static aeroelastic analysis of high aspect ratio wing (HARW) aircraft subject to geometric nonlinearities have been developed [16-18]. In particular, two approaches 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. Figure 9shows big differences between the nonlinear and linear behaviours while the FEM and multibody methods show an excellent agreement for purely structural problems, for example the gust response shown in Figure 10. There are, however, more differences in the aeroelastic trim results because the multi-body approach takes better into account the aerodynamic force orientation and the treatment of rigid body rotations, although it is more difficult to trim the multibody model.

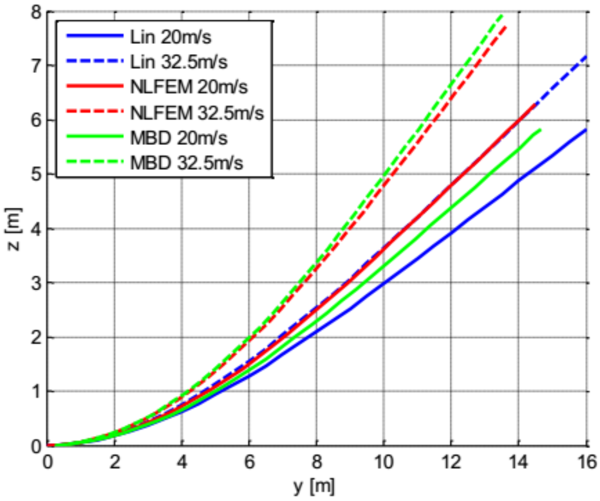

Figure 9. Wing Tip Deflection prediction of HARW

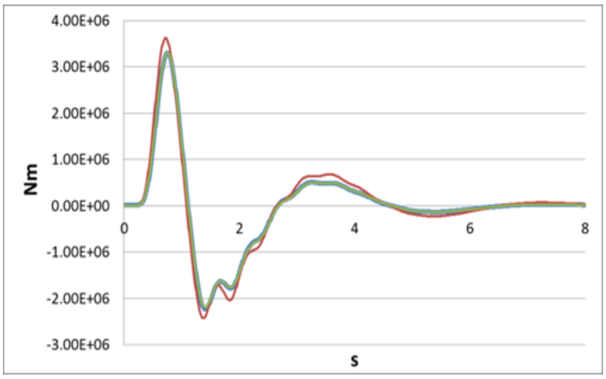

Figure 10. Comparison of NASTRAN and Multi-Body VLM Gust Response Time Histories for 214m gust length

3.2 Fast and accurate aerodynamic loads for transonic Mach numbers

3.2.1 Frequency-domain Model Order Reduction

In the field fast and accurate aerodynamic loads prediction, two topics have been researched. First, a method for the construction of a reduced order model (ROM) in the frequency domain was investigated [19]. The ROM is constructed with input data from CFD analyses for a number of oscillation frequencies of the model. Both unsteady CFD analyses and linearized frequency domain CFD analyses were used. First the method had been demonstrated for 2D aerofoils. Later 3D aircraft models were used that resulted successfully in multiple reduced order models for different strips on the wing (Figure 11), the fuselage and the horizontal plane. The final results showed a good correlation between gust loads predicted by the ROM and CFD results. Especially due to the new linearized frequency domain CFD analyses, a lot of time can be saved for predicting loads.

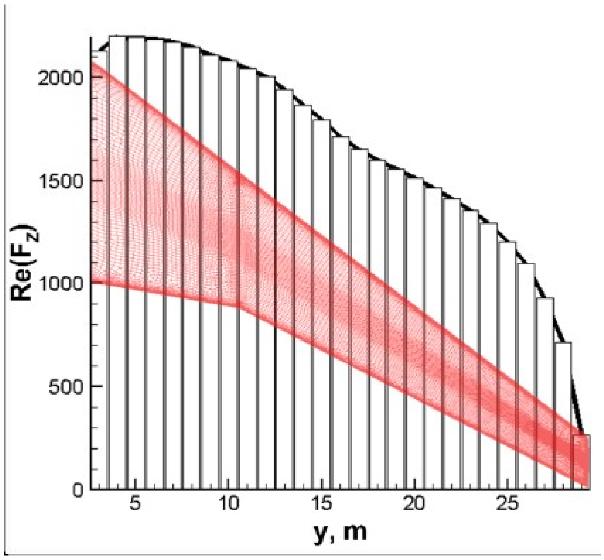

Figure 11. Lift vs wing span predicted by ROM

3.2.2 Unsteady correction of the DLM

The second research topic developed a new methodology to increase the accuracy of gust loads analysis that is based on traditional potential flow models [20-23]. Also in this case, results from linearized frequency domain CFD analysis have been used but now to estimate correction factors necessary to update the Aerodynamic Interference Coefficients matrices. The results for gust loads in the transonic regime, obtained using a corrected doublet-lattice method, were compared to fully coupled CFD/FEM results computed with a Fluid Structure Interaction (FSI) interface. The application of this technique to the wing model in Figure 12, representative of a general single aisle civil aircraft, has shown an excellent agreement to the fully coupled results.

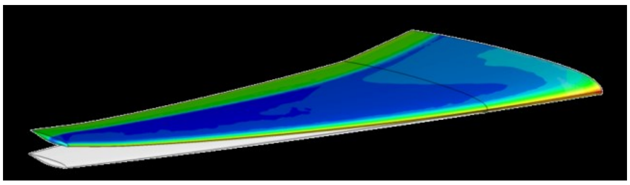

Figure 12. FSI model for DLM correction calculations

3.3 Uncertainty Quantification of aircraft correlated loads and landing gear shimmy

This research first developed a methodology that reduced the computational burden for determining the correlated loads envelopes but with little reduction in the accuracy, and also to quantify the effects of uncertainty, for a range of different parameters [24-30]. Key to the approach is the formulation of a matrix containing the IQ time responses to different gust length, structural parameters and flight conditions. This matrix was decomposed using the Singular Value Decomposition method and then used to efficiently predict the effect of variations in particular parameters, or indeed to investigate the effects of uncertainty. Figure 13 shows how uncertainty bounds on the 2D correlated IQs can be predicted whilst maintaining knowledge of which gust length is causing the extreme cases.

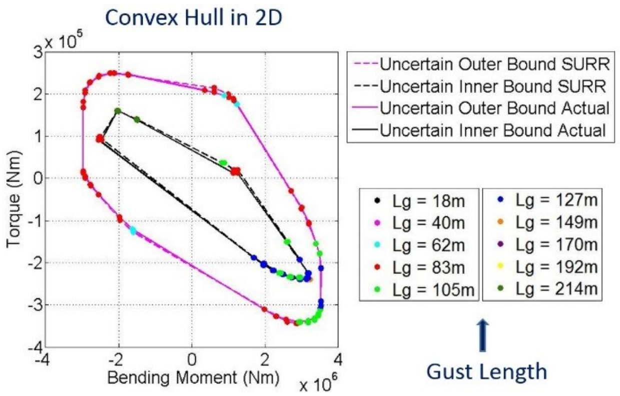

Figure 13. Uncertainty Bounds Envelope of 2D Correlated Gust Loads

Secondly, the methodology was extended to perform sensitivity analysis (SA) and uncertainty quantification (UQ) in terms of locus of Hopf bifurcation points for operational parameters [31-37]. The approach has been demonstrated by coupling the bifurcation and continuation software AUTO to a nonlinear analytical landing gear system in Matlab and to a multi-body landing gear system in Simcenter 3D Motion as shown in Figure 14.

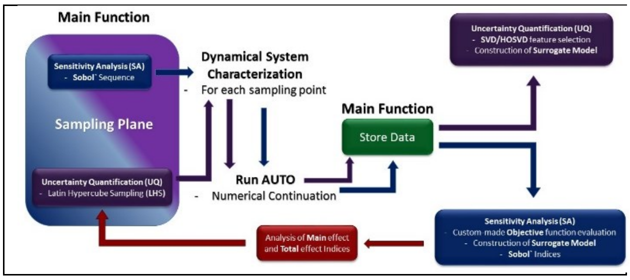

Figure 14. Flow Chart for Coupling of VLM, AUTO and SA/UQ Analysis

The study investigated the onset of “shimmy”, an unsteady oscillation in landing gear that arises from the nonlinearities in the system. Figure 15 shows a plot of the onset velocity of shimmy vs the vertical load acting down on the landing gear. The red line shows the operational trend above which want the bands that include uncertainties in the system parameters to lie. A robust optimum design is achieved using the HOSVD method so that the uncertainty bounds are above the required operational trend. The results emphasize high accuracy whilst achieving a reduction of almost 95% of the total computation time required by Monte Carlo Simulations.

4 Conclusions

The aircraft design process is complex iterative process. Moreover, the current trends in aircraft design is to investigate new aircraft concepts to achieve a step change in efficiency. Current methods for load prediction are not always suitable for these new aircraft concepts. Therefore, the aircraft design process would benefit from methods and tools that can predict aircraft loads faster and more accurately for existing aircraft concepts as well as new concepts or systems. The ALPES research project addressed these challenges and validated the techniques with industrial relevant cases. Future plans include developing these technologies further, applying them to industrial scale problems and integrating them into reliable software tools.

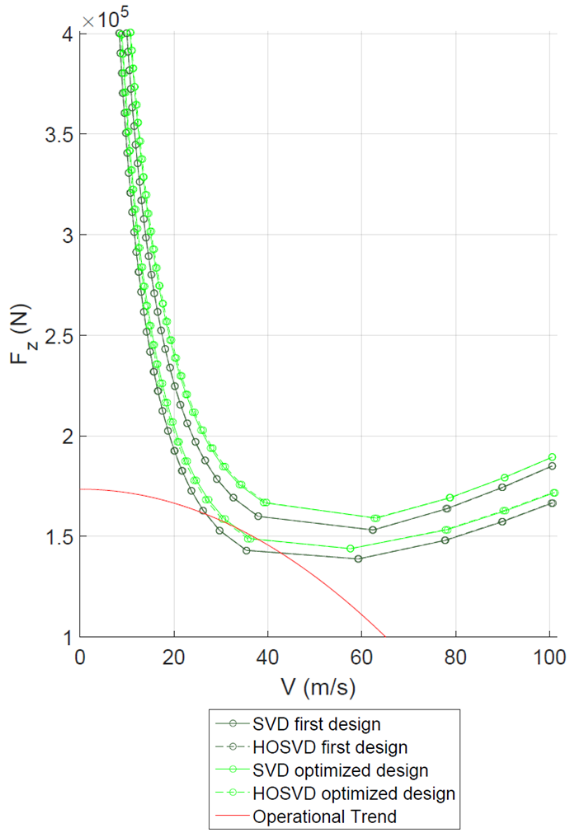

Figure 15. Uncertainty Bounds of LCO Behaviour for Undercarriage (black = deterministic design, green = robust optimised design)

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