AEROELASTIC CHALLENGES IN THE AIRCRAFT DESIGN PROCESS

Huub Timmermans

Netherlands Aerospace Centre (NLR)

Anthony Fokkerweg 2

1059CM Amsterdam

`Huub.Timmermans@nlr.nl`

Bimo Prananta

Netherlands Aerospace Centre (NLR)

Anthony Fokkerweg 2

1059CM Amsterdam

`Bimo.Prananta@nlr.nl`

Abstract. Aeroelastic effects influence the aircraft design process at many points. One of the most important constraints within the design process of flexible aircraft is to avoid aeroelastic instability for all combinations of speed and altitude encompassed by the flight envelope. This constraint affects both the structural design and the aerodynamic design, impacting the calculated aircraft performance. Aeroelastic effects also include the estimation of initial design loads used as input in order to size the components and are therefore critical for the aircraft design process. However, during initial design stages, not all parameters that are required to perform correct loads or aeroelastic instability analyses are available. This lack of information on the aeroelastic effects imposes technical and financial risks both for the suppliers as well as the Original Equipment Manufacturer (OEM). It is therefore of significant importance to understand the aeroelastic behaviour of the aircraft concept during all design phases and to avoid major changes in the detailed design phase which bring along additional costs. This holds true both for the design of next generation aircraft concepts, for example strut-braced wings with increased wing's slenderness, as well as newly designed conventional aircraft components. The latter is often a major challenge for tier one and two suppliers that do not have an overview of the total aircraft system which is needed to understand the aeroelastic behaviour. Their component optimization process affects the aeroelastic behaviour of the entire aircraft system and is therefore critical when included in the overall design. This paper discusses a methodology developed by the Netherlands Aerospace Centre (NLR) to estimate design loads and access the aeroelastic instability on aerodynamic aircraft components with different levels of fidelity and different turnaround times. This methodology mitigates the risk of 'invalid' designs and large changes in the next design phases and thereby avoids large modifications and additional costs.

Keywords. Aeroelasticity, Aircraft Design, Flutter, Loads

1 Introduction

The interaction between the inertial, elastic and aerodynamic forces, known as aeroelasticity, influences the aircraft design process at various points in the development process. To perform aeroelastic analyses, including loads and aeroelastic stability limits, a (simplified) model of the full aircraft is required.

In order to prevent 'invalid' designs in the next design phases and thereby avoiding large modifications and additional costs, the NLR has worked on a methodology for fast aeroelastic

modelling and loads/flutter analyses. This methodology allows for an estimation of design loads on aerodynamic aircraft components, including control surfaces, with little available input typical for a proposal or conceptual design stage.

This paper starts with the process of an initial conceptual aeroelastic design. An aeroelastic model of the aircraft is both required for next generation aircraft concepts, for example strut-braced wings with increased wing's slenderness, as well as new designed conventional aircraft components. To generate this initial aircraft model use is made of the NLR methodology AMLoad. This initial model can subsequently be updated when more detailed information is available from higher fidelity tools or experiments. The second part of this paper shows typical applications of aeroelasticity in the various aircraft design processes.

2   Conceptual aeroelastic designs

To start the aeroelastic simulations, use is made of simplified (uncorrected) aeroelastic models using beam structures to represent the structural properties in combination with panel method aerodynamics. The goal of these models is to quickly asses various points within the design space that are considered during the conceptual analyses phase. These conceptual aircraft models provide the engineer a quick overview of the aeroelastic behaviour of conventional and unconventional configurations. One of the unconventional configurations currently under assessment by ONERA and NASA/Boeing is the strut-braced wing making using of an increased aspect ratio [1] [2] , see Figure 1.a. The long and slender wings used in these configurations are more susceptible to flutter than conventional wings, which makes aeroelastic calculations an important aspect to take into account during the conceptual design phase. Figure 1.b shows a simplified aeroelastic model of a strut-braced wing configuration which is used in a Multi-Disciplinary Optimization (MDO) process study [3] .

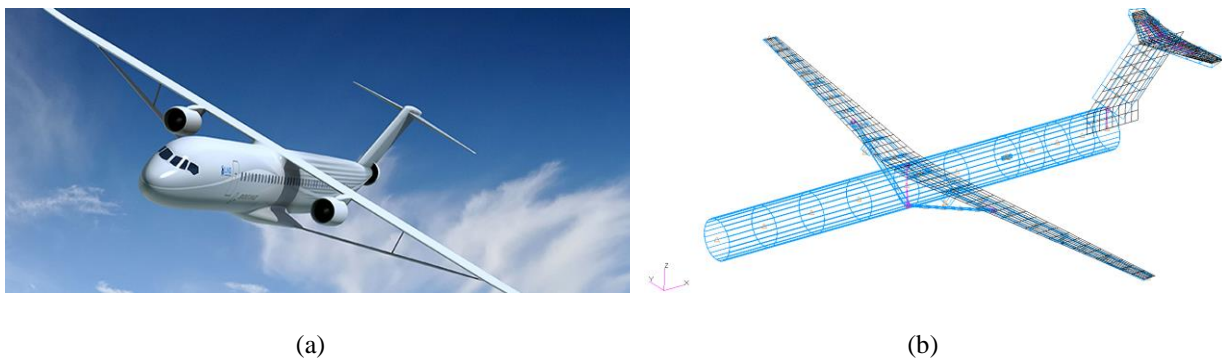(a)   (b)

Figure 1: (a) Example of strut-braced wing aircraft concept developed by Boeing (SUGAR project) [2] , (b) simplified aeroelastic model of a strut-braced wing aircraft concept.

Many load cases should be addressed to have a correct and accurate design validated for the most critical situations (both loads and flutter). In order to estimate and improve the loads assessment for different structural parts of transport aircraft, a methodology for the estimation of the critical design loads is needed. This is a required part of the overall design process, providing the loads in the conceptual or preliminary phase. AMLoad quickly generates

aeroelastic models (as depicted in Figure 1.b) and performs loads/flutter analyses. This provides the designer with more insight in the effect of design changes and thereby mitigates the risk of large modifications in the next design phases. It also increases the knowledge of design changes such that more detailed feedback can be provided to the OEM.

2.1 AMLoad – Methodology for fast aeroelastic modelling

AMLoad is a parametric and interactive, MATLAB and MSC Nastran based tool that can be used for aeroelastic modelling and loads/flutter analyses. It uses a modular environment to create an aeroelastic model of an aircraft configuration. Within the pre-process module this aircraft model is generated based on the geometry, structural properties and possible correction factors. Figure 2 shows the AMLoad flowchart, starting with the pre-processing module. Because of usually little available data, methods are included in this pre-processing module to perform conceptual and preliminary design steps, such as stiffness estimations and aerodynamic properties approximation. In addition, existing data, including an aircraft database and a potentially critical load case database, are made available in this module. Figure 3.a represents the parametric aircraft model as visualized in MATLAB.
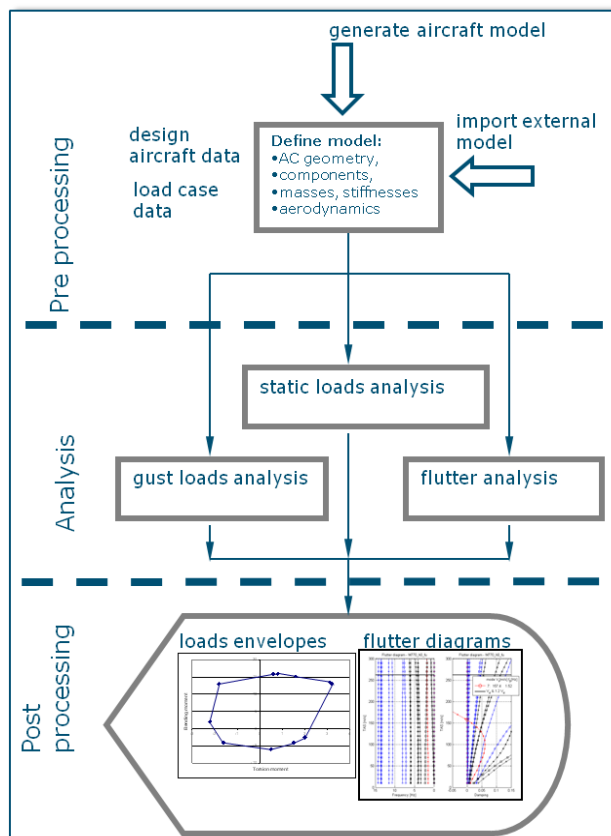

Figure 2: AMLoad process flowchart

In the analysis module, AMLoad creates input files for MSC Nastran using geometrical data and the values of solution specific variables (e.g. gust velocity and trim condition). It includes a parametric generation of aeroelastic beam models using geometric, structural, inertial and damping data, to be particularly suitable for multiple loads sensitivity analyses.

The simplified Finite Element Model (FEM) (Figure 3.b) is coupled to an aerodynamic model capable of calculating both steady and unsteady aerodynamic loads (Figure 3.c). Splining techniques are used to transfer the aerodynamic forces and moments at aerodynamic boxes to structural grid point.

(a)

(b)   (c)
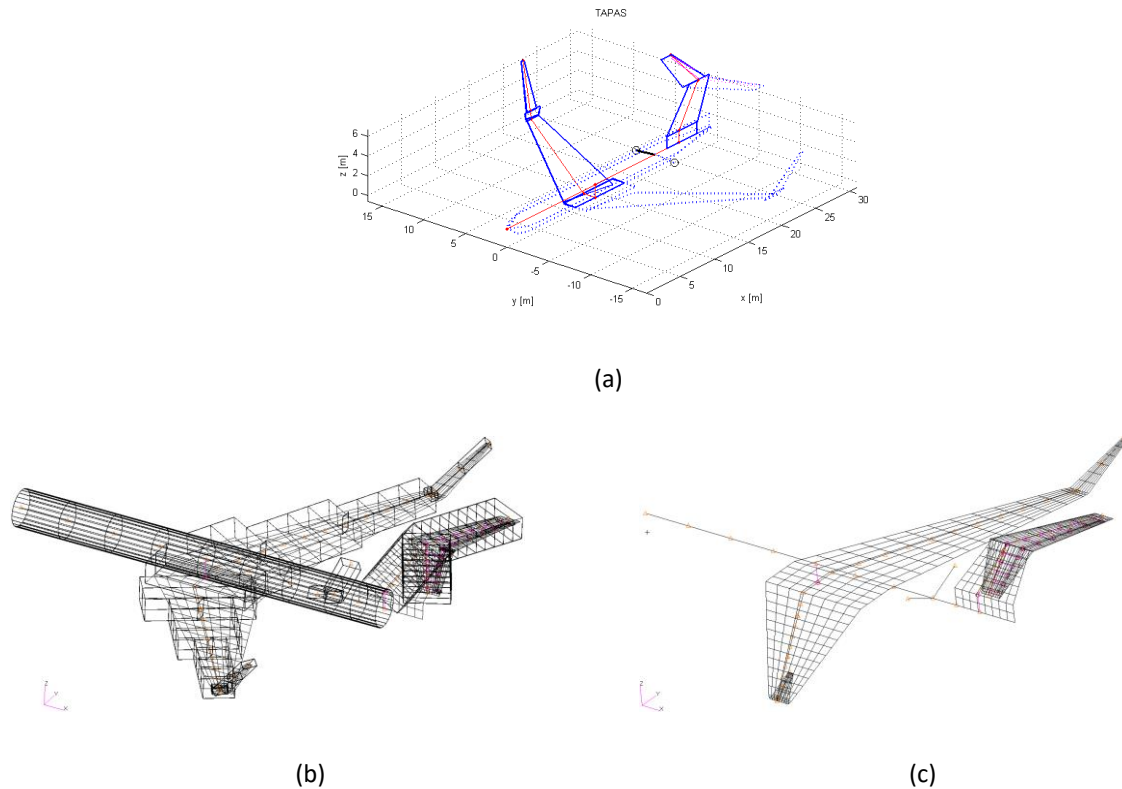
Figure 3: Parametric description of aircraft model inside AMLoad's modular environment (a) Simplified FE model including stiffness and mass information (b), Aerodynamic panel model to estimate steady and unsteady aerodynamic loads (c).

Computations include trimmed conditions (steady flight, steady turn) together with dynamic load cases (gust analysis, abrupt manoeuvres) and flutter analyses. The obtained loads from the MSC Nastran results are fed back to AMLoad for the post-processing module in which loads envelope and flutter diagrams can be generated (Figure 2).

2.2   AMLoad - Loads analyses

Loads from the loads analyses using an aeroelastic model are provided in user specified load sections. This allows the user to obtain loads on specified locations for all structural elements, e.g. loads at the rib locations of a horizontal tail. The load sections are integrated into the computation via the Sectional Load Extraction Matrix (SLEM).

Load extraction for an aircraft component consists of summation of the loads generated in grid points of that component in the aeroelastic model. It also includes loads on sub-components connected to the component (for instance, the loads on the elevator are added to those of the horizontal tail at the connection points). The integration is obtained by creating the SLEM and applying the SLEM to all grid points. The SLEM is a two-dimensional matrix of which each row corresponds to an output load in a section (6 loads and bending moments: Fx, Fy, Fz, Mx, My, Mz in a section, hence number of rows = number of sections x 6) and each column corresponds to an input load in a node (number of input loads = 6 x number of nodes). The matrix is composed such that the grid point loads contributing to a sectional load are multiplied with a nonzero element, whereas all other loads are multiplied with a zero element.

The results include, among others, the design loads (aerodynamic, inertia, connection and total loads) which can be used as input for the detailed FE models.

In addition, load envelopes can be generated for certain locations in combination with two degrees of freedom. AMLoad is able to run multiple load analyses in a batch process. This allows running a large number of simulations for various flight and model conditions. The loads can be exported to Microsoft Excel or as CPACS (Common Language for Aircraft Design, [4]) xml-format. CPACS is an XML schema data definition for a complete air transportation system that can be used to connect different analysis tools.

2.3 AMLoad - Flutter

A dangerous form of aeroelastic behaviour is flutter. This dynamic instability is characterised by a positive feedback between the force acting on the body and the resulting deformation. An example is wing bending under influence of the lifting force acting on the structure. Flutter occurs if this beam bending is not damped but increasing in amplitude. This divergence causes the deformations to increase rapidly ultimately resulting in failure of aircraft components.

Flutter predictions are important during different aircraft design phases to avoid an invalid design. AMLoad can be used to perform flutter analyses in a batch process in order to quickly asses various configurations within a design space. Using this batch mode the user is able to perform sensitivity studies, varying design variables, in order to see the effect on the aeroelastic instability. A recent study has been done in which this process has also been implemented in an aircraft optimization routine [3] . Using AMLoad, flutter diagrams can be generated during each run which shows the damping (see Figure 9.a) and frequency as function of velocity.

3 Model corrections

In Chapter 2 a methodology is described to perform fast loads and flutter analyses, with a relatively simplified aircraft model. When more accurate information becomes available from higher fidelity simulations in the following design phases this simplified aeroelastic model is corrected. To be able to perform aeroelastic analyses using relatively low computational efforts, use is made of correction factors on the simplified models rather than coupling the high fidelity structural and aerodynamics analyses. This chapter describes a method to include detailed structural properties from the high fidelity FEM analyses (**3.1**) as well as aerodynamic corrections using Computational Fluid Dynamics (CFD) (**3.2**). This high fidelity data is used to update the model during the design process iteratively using the AMLoad generated aircraft models.

3.1   Structural model

This paragraph describes the method used to extract the structural properties from the Detailed Finite Element Model (DFEM) of the structure and the structural model based on those properties. Figure 4 shows a schematic overview of the procedure to extract the stiffness and mass matrix out of an Abaqus FEA DFEM. The stiffness and mass matrix are extracted by means of Direct Matrix Input at Grid (DMIG) cards which are a standard MSC Nastran format. DMIG cards include the stiffness and mass matrix of the assigned substructure.
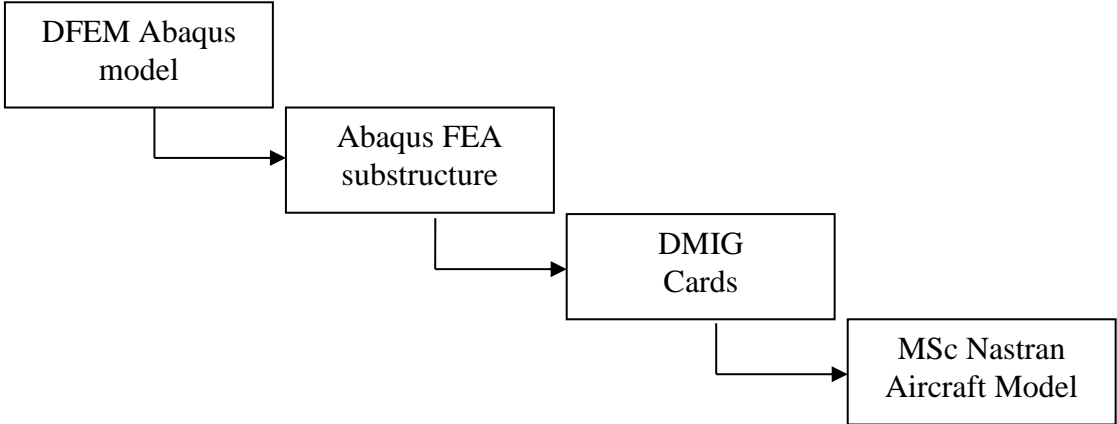

Figure 4: Diagram from DFEM to Aeroelastic model using DMIG

The substructure is represented in the aeroelastic MSC Nastran model where the stiffness and mass matrices are assigned to the corresponding nodes (Figure 5). In this way the complex Abaqus DFEM can be represented by a simplified model including the stiffness and mass matrices. Moreover, the effects of static nonlinearities on the stiffness matrix can be included during the export. The subsequent dynamic analysis can be seen as vibration around a nonlinear static state. Effects of large deformation on the aeroelastic behaviour can be taken into account in such analyses. In this study, jig shape is considered during export.
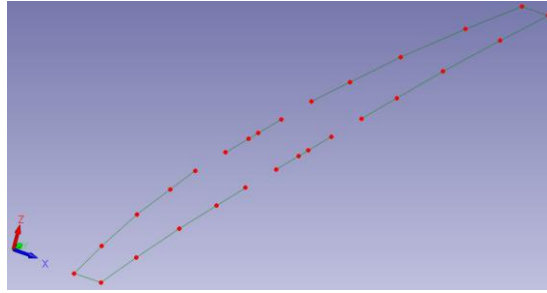
(b)

Figure 5: full span simplified MSC Nastran model including DMIG

To compare the consistency between the Abaqus DFEM and the simplified MSC Nastran model, use is made of the Modal Assurance Criterion (MAC). The MAC value is a statistic indicator to show the consistency between mode shapes. Often the MAC is used to pair mode shapes between theoretical and experimental data. The MAC is bounded between 0% and 100%, with 100% indicating a fully consistent mode. Figure 6.a represents the 2D and 3D MAC matrix for modes 1-15. As can be seen, the elastic modes (mode 7-15), see for example Figure 6.b, correspond 100% indicating fully consistent flexible mode shape pairs between the DFEM and simplified MSC Nastran model. This means the stiffness and mass properties are consistent between the DFEM Abaqus model and simplified MSC Nastran model. The first six modes are Rigid Body Modes (RBM's) which show lower MAC values. The cause of this result is the minor coupling between the RBM's in the MSC Nastran model. This is fixed using a SUPORT command in the model which specifies reference degrees of freedom for rigid body motion [5] . Some higher-frequency modes are not paired due to the complexity of the mode which is not possible to match with a simplified beam model. These higher-frequency modes are not critical for flutter analyses and can therefore be ignored.
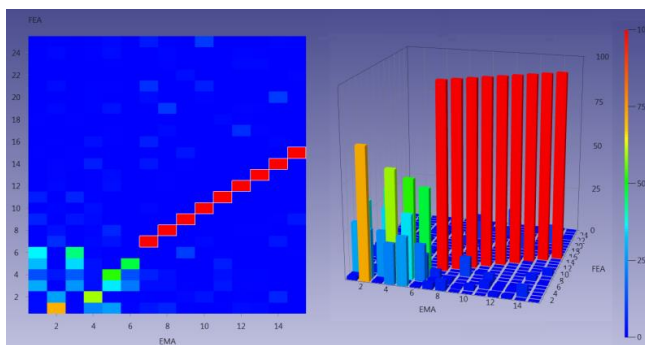
(a)
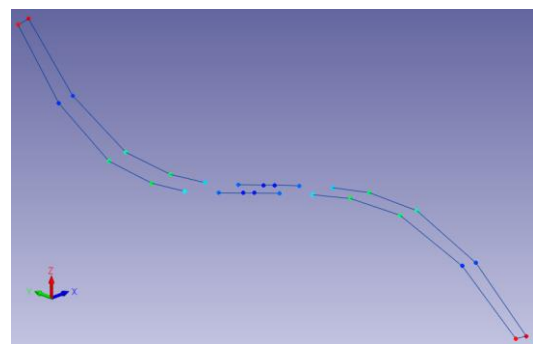
(b)

Figure 6: (a) MAC values DFEM Wing and simplified Nastran model, (b) Second wing bending mode

This method shows that an aeroelastic model can be created with the structural properties derived from a DFEM model. A comparison of mode shapes and frequencies of several components verified that the aeroelastic model and the DFEM model show similar dynamic behaviour.

3.2   Aerodynamic model

With regard to unsteady aerodynamic modelling, linear Doublet-Lattice Method (DLM) is commonly applied during preliminary design. Typical aeroelastic analyses at this stage of design are gust response analysis, flutter stability analysis and loads analysis during unsteady manoeuvres.

DLM is based on linear potential theory, i.e. neglecting nonlinear compressibility effects and viscous effects. Computing time and setup effort of DLM is relatively low, making it most suitable to be applied for design loops where configuration is changing and many analyses have to be performed. However, it is generally known that the use of DLM in an aeroelastic analysis can lead to unrealistic predictions, in terms of either structural loads or flutter speeds. This is especially true for transonic flight conditions. Therefore it is important that a proper correction is applied to the DLM. During the design such correction data can be generated using CFD.

For flutter analysis, based on experience so far, the most important correction concerns vibration modes with significant trailing edge movement. This includes torsional-type vibration modes, and most importantly trailing edge control surface rotation. At the trailing edge region, the boundary layer is relatively thick, influencing the effectiveness of the aerodynamic shape. This effect becomes even worse when shockwaves exist, thickening the boundary layer, or even causing flow separation behind them. This phenomenon changes the unsteady aerodynamic behaviour and needs to be corrected properly. For this case quasi-steady correction suffices.

Another important situation occurs at the dive Mach number, i.e. low lift coefficient and shockwaves exists both at the upper and lower side of the wing. At this situation, although the magnitude of the generalised aerodynamic force is relatively low, the interaction between upper and lower side shockwave causes significant change in the phase-lag behaviour. This can be the critical condition, in terms of flutter stability which requires correction to the phase lag of the generalised aerodynamic forces.

Once the configuration has been frozen, a more refined computational method can be applied, e.g. with a direct use of CFD.

For gust response analysis, since the flight mechanic response will influence the loads significantly, the CFD correction should provide correct global forces. This is especially true for the lateral-directional modes which are mostly defined by the aerodynamic modelling of the fuselage. DLM modelling for the fuselage is known to be inaccurate. Sometimes it is also appropriate to directly replace the global force, i.e. static and dynamic derivatives, with the results computed using CFD.

4 Applications

In this chapter several applications in which simplified and corrected models have been used to study design aspects are provided as example.

4.1 Multidisciplinary Design Optimization of a Strut-braced wing

Aircraft concepts with large aspect ratio wings have been investigated in the recent past. Using high aspect ratio wings results in a reduction of induced drag. Strut-braced wings are investigated in this respect. The strut reduces the bending loads carried by the wing, which makes it possible to increase the aspect ratio. A risk attached to using large aspect ratio wings is aero-structural instability. Long and slender wings are more susceptible to flutter than conventional wings, which makes aeroelastic calculations an important aspect to take into account during the conceptual design phase. Figure 7 shows the used aeroelastic model of the strut-braced wing during the MDO study together with an illustration of the wing bending mode. Since flutter calculations are relatively time consuming for a conceptual design study, flutter checks are often only performed on the final optimization result [6] [7] [8] . During this conceptual design study, a method is introduced to implement the flutter speed as a constraint in the optimization. Every intermediate result of the optimization is checked for the presence of flutter. The extended Design Structure Matrix (Figure 8) shows the location of the flutter module in the optimization. The design variables define the aircraft model that is investigated; the static calculations mode calculates all forces and moments acting on the aircraft. The flutter analysis module uses this input to determine the flutter speed of the aircraft configuration. The constraint function is defined by comparing the flutter speed with the regulatory constraint of 1.15 times the dive speed.

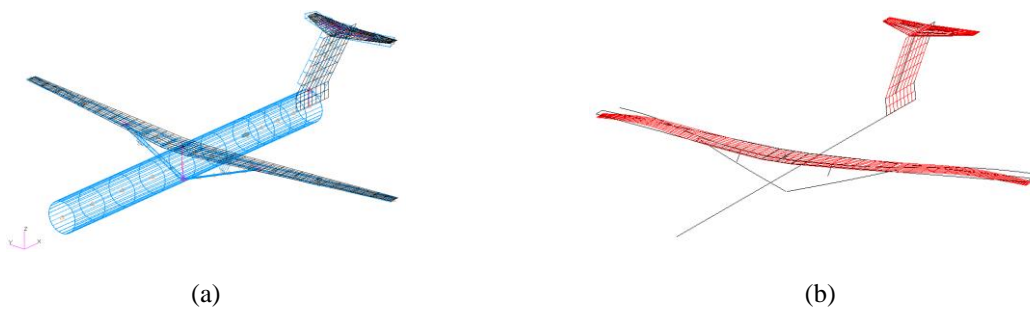(a)   (b)

Figure 7: (a) aeroelastic strut-braced wing model, (b) wing bending mode

During this study, it is investigated whether or not the flutter constraint can be used in a surrogate model, in order to decrease the computational time. After comparison of various surrogate models, the artificial neural network has shown to be the most promising model to predict flutter. However, the switching of different critical flutter modes (non-linear behaviour) proved to complicate the prediction of the flutter speed. The optimizer only has information on the critical flutter mode with the lowest flutter speed, but has no information on the mode itself. The optimizer would be able to track the influence of a geometric variation on every mode separately if these modes could be tracked.

The optimizer then knows the flutter speed of every individual mode. Instead of using the flutter speed as the constraint in the optimization, the damping values of individual modes could then be used. This would allow for more precise predictions of the influence of the geometry variations on the flutter speeds of different modes. Surrogate models can be created for the damping values of every flutter mode separately.
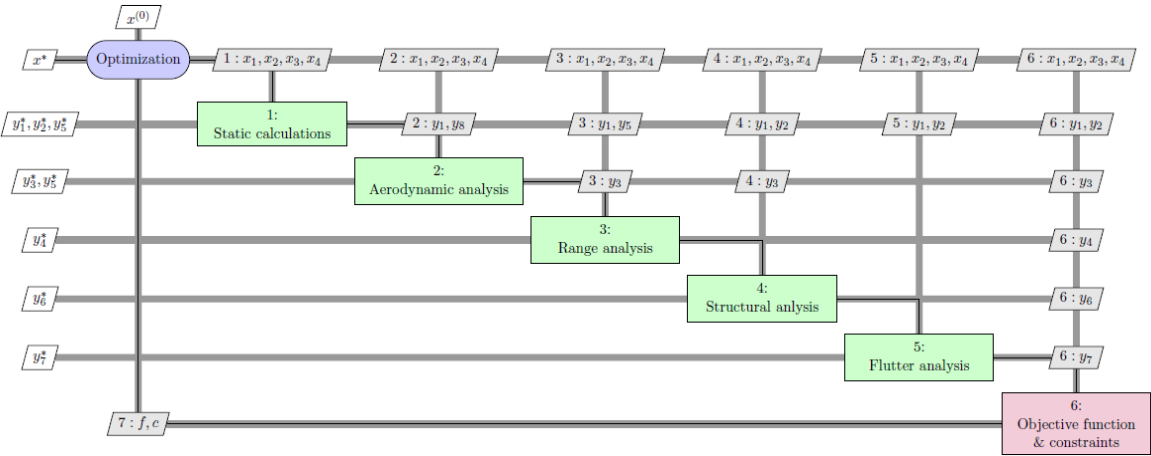

Figure 8: AMLoad modules in an extended Design Structure Matrix used in the MDO study of a strut-braced wing.

4.2   Flutter sensitivity study

Using an existing aircraft model, a flutter sensitivity study has been performed in three different phases. This existing (verified) aircraft model has been corrected due to CFD and wind tunnel tests which is a higher fidelity application compared to the previous study. The aerodynamic correction factors are both applied statically on the aerodynamic boxes for the wing and horizontal tail plane as well as an unsteady (phase angle) transonic flow correction. The phase angle correction was determined based on wind tunnel and theoretical data of two- and three-dimensional unsteady transonic flows, used for validation of 2D and 3D subsonic and transonic unsteady airload analyses. The structural model has been updated based on a Ground Vibration Tests (GVT).

The three different phases narrowed the design space for the aircraft modifications in which the aircraft was free from aeroelastic instability. The aircraft modification affecting the flutter characteristics was an additional mass attached to the wing structure. Due to this modification, one of the certification subjects included flutter. A parameter that has significant influence on the flutter behaviour was the centre of gravity of this additional mass (x_{cg}). Figure 9.a shows a typical flutter diagram (damping versus velocity) obtained from AMLoad for one of the batch analyses. In addition an overview of the most critical modes and normalized flutter velocity, V_F/V_D, is shown for various mass conditions for a total number of 15 analyses.
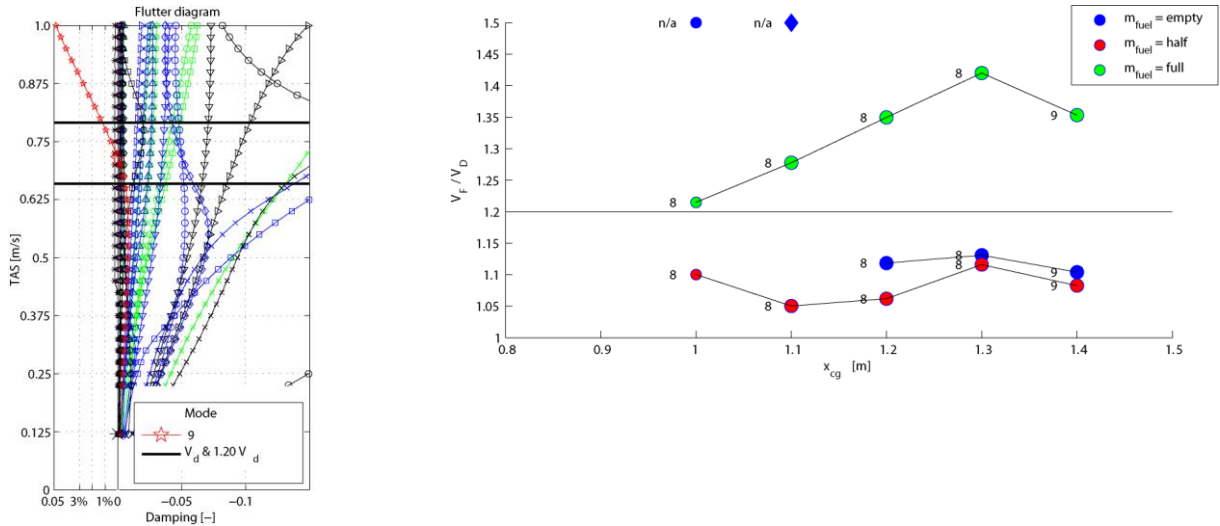
Figure 9: (a) normalized flutter diagram obtained from AMLoad, (b) normalized flutter velocity V_F/V_D results from sensitivity study (15 runs) as function of the mass centre of gravity

In these subchapters two applications have been discussed that are analysed with AMLoad which are both in a different design stage. The first application included a conceptual design study using an uncorrected and simplified full aircraft model. The second application shows the use of AMLoad in a more advanced design stage using an existing (corrected) model to perform flutter analyses.

5   Conclusions

This paper has provided an overview of the work done at the NLR in which aeroelastic challenges have been incorporated at various aircraft design stages. A methodology is developed and used at the NLR for fast aeroelastic modelling and loads/flutter analyses. This allows for the generation of an aeroelastic full aircraft model during the design stage, when aircraft information is limited.

The methodology uses relatively simple structural elements (beam model) in combination with panel method aerodynamics to connect both disciplines. Once the design process is more developed and results from higher fidelity tools are available, correction factors can be applied to the simplified model. In addition, the simplified structural component can be replaced using stiffness and mass matrices obtained from the FEM analyses. Corrections concerning aerodynamics are required for the vibration modes and shockwaves around higher Mach numbers.

The methodologies developed at the NLR in combination with MSC Nastran have been used for multiple applications. These examples have demonstrated the added value of AMLoad in different aircraft design phases using the simplified model in the initial phases and corrected models in a more advanced stage. Both examples have shown AMLoad's capabilities to quickly generate aeroelastic models and perform multiple studies. The studies done using AMLoad mitigate the risk of 'invalid' designs and large changes in the next phases and provide the user more insight in the aeroelastic effects of various variable changes in a design space.

Acknowledgment

References

[1] G. Carrier; O. Atinault; S. Dequand; J.-L. Hantrais-Gervois; C. Liauzun; B. Paluch; A.-M. Rodde; C. Toussaint. **Investigation of a strut-braced wing configuration for future commercial transport**. In 28th international congress of the aeronautical sciences, 2012.

[2] T. .J. Allen; B.W. Sexton; M.J. Scott. **Sugar truss braced wing full scale aeroelastic analysis and dynamically scaled wind tunnel model development**. Structures, Structural Dynamics, and Materials Conference, 2015.

[3] A. C. Lambers, **Surrogate based optimization with flutter constraints for aircraft conceptual design**, Delft University of Technology, 2016

[4] B. Nagel, D. Böhnke, V. Gollnick, P. Schmollgruber, A. Rizzi, G. La Rocca, J.J. Alonso , **Communication in Aircraft Design: Can We Establish a Common Language?**, 28th International Congress of the Aeronautical Sciences. Brisbane, Australia, 2012

[5] MSC Software, Aeroelastic Analysis User's Guide, MSc Nastran Version 68, 2013

[6] E. Sulaeman; R.K. Kapania; R.T. Haftka. **Parametric studies of flutter speed in a strut-braced wing**. Structures, Structural Dynamics, and Materials Conference, 2002.

[7] F.H. Gern; A. Ko; E. Sulaeman; J.F. Gundlach; R.K. Kapania; R.T. Haftka. **Multidisciplinary design optimization of a transonic commercial transport with strut-braced wing**. Journal of Aircraft, 38(6):1006{1014, 2001.

[8] M. Bhatia; R.K. Kapania; M. van Hoek; R.T. Haftka. **Structural design of a truss braced wing: potential and challenges**. AIAA Journal, 2147, 2009.