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A DASSAULT INDUSTRIAL APPROACH TO AERO-STRUCTURAL OPTIMIZATION

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Abstract: During initial design phase the evaluation of the aircraft’s structural mass for various plan forms is still a challenge. The structural mass has to be minimized while sustaining loads and satisfying various aeroelastic constraints. These constraints could be avoiding flutter phenomena in the flight envelope or guarantying static aeroelastic characteristics such as aileron efficiency. This paper describes an industrial method developed at Dassault Aviation to perform this aero-structural optimization. This fully automatic process can compute the optimized structural weights of several configurations.

Combining this with aerodynamic performance data for each configuration, it becomes a powerful tool to drive the design of new aircraft.

First the global outline of the process will be presented. Then the elementary blocs of the process will be briefly described; finite element modelling, aerodynamic and load computation and finally optimization strategy. Finally two applications will be shown to demonstrate the relevance of the project.

The first example is that of a flutter optimization done during the development of a new Falcon jet. The flutter optimization is shown to be an efficient tool to minimize structural reinforcement for flutter and thus improve global aircraft performance.

The second application is a study using the complete process to determine the effect of the winglet’s height on aircraft mass. The optimized mass of the wing, with respect to both flutter and loads, is calculated for three different winglet heights. The aim is to demonstrate the potential of the process to drive aircraft design and find an optimal shape with respect to both aerodynamic performance and aircraft mass.

1 INTRODUCTION

In order to draw an optimal external shape of a new aircraft, it is essential to be able to evaluate performances with respect to different geometrical parameters. For example aerodynamic performance is routinely integrated in the preliminary design phase and can be evaluated rapidly for many different shapes. Another crucial performance to evaluate is the structural mass of the aircraft. This is still a challenge to assess during preliminary design of the aircraft because it is the sum of all the structural elements, each having been optimized with respect to different criteria.

During the design phase that structure is the result of iterations between different departments and is highly optimized with respect to multiple criteria such as structural sizing criteria and aeroelastic constraints (flutter, static aeroelastic characteristics).

Thus, to properly estimate the final structural mass for a given set of geometrical parameters several optimizations are needed. In order to speed up the process various simplifications are assumed and will be detailed.

This paper presents the methodology developed at Dassault Aviation to estimate rapidly and as precisely as possible the mass of a given configuration by performing automatic aero-structural optimizations. The iterations of the optimization are done automatically allowing one operator to study numerous aircraft configurations rapidly.

The process developed is highly modular and relies on a number of blocs which perform a number of different tasks such as the creation of the reduced order models, aerodynamic computations, aeroelastic computations or structural sizing. These blocs are part of the Elfini$^©$ software suite, developed internally at Dassault Aviation, which allows for fully automated and efficient transfers between blocs. This stat-of-the-art computational tool is also fully integrated with Catia V6$^©$ and Microsoft Excel$^©$ for modelling as well as pre- and post-processing. This mastery and continuous development of these tools are essential for the development of the automated process.

Each of these blocs has been fully parameterized so the same process can be used to study many different parameter variations during preliminary studies. Based on the same tools and process it is also possible to perform more accurate computations once more refined finite element models are available.

As a result the process can be used not only during the preliminary design phase to evaluate the effect of different parameters on the mass but also during the design phase to perform structural or flutter optimizations.

First the optimization method will be presented showing the different steps of each iteration. Then the individual blocs will be further detailed and finally two applications will be shown:

- Flutter optimization of a new Falcon jet
- Study of the effect of winglet height on the wing structural mass

Finally the conclusions of the study will be drawn.

2 OPTIMIZATION PROCESS

In order to optimize aircraft structures two main phenomena must be taken into account to guaranty the aircraft's performance and structural integrity throughout the flight envelope:

- Aeroelastic loads resulting from flight manoeuvres or turbulence
- Aeroelastic constraints such as avoiding dynamic aeroelastic instabilities or static aeroelastic characteristics

The structural loads that arise during manoeuvres or turbulence result in structural sizing criteria such as traction, buckling or fatigue for metallic parts and traction / compression after impact for composite parts. These criteria must be met to ensure structural integrity.

Dynamic aeroelastic instabilities are also phenomena which must not occur in the flight envelop of an aircraft. A minimal flutter speed, under which these instabilities must not occur, is defined taking into account margins defined by the certification authorities. Minimal static aeroelastic characteristics are defined to ensure the aircraft's handling qualities for example minimal aileron efficiency.

Satisfying these two kinds of criteria (mechanical and aeroelastic) as well as the technological constraints while minimizing weight is at the heart of aircraft structural design.

2.1 Global process

Figure 1 presents the global optimization process. Using the tools developed at Dassault Aviation a process pilot has been developed to automatically perform the sizing loops. First the Finite Element Model (FEM), aerodynamic mesh and the structural grid (see 2.3) must be created based on a predefined geometry. Next the process applies either the initial properties or the properties from the last iteration of the sizing loop on the FEM.

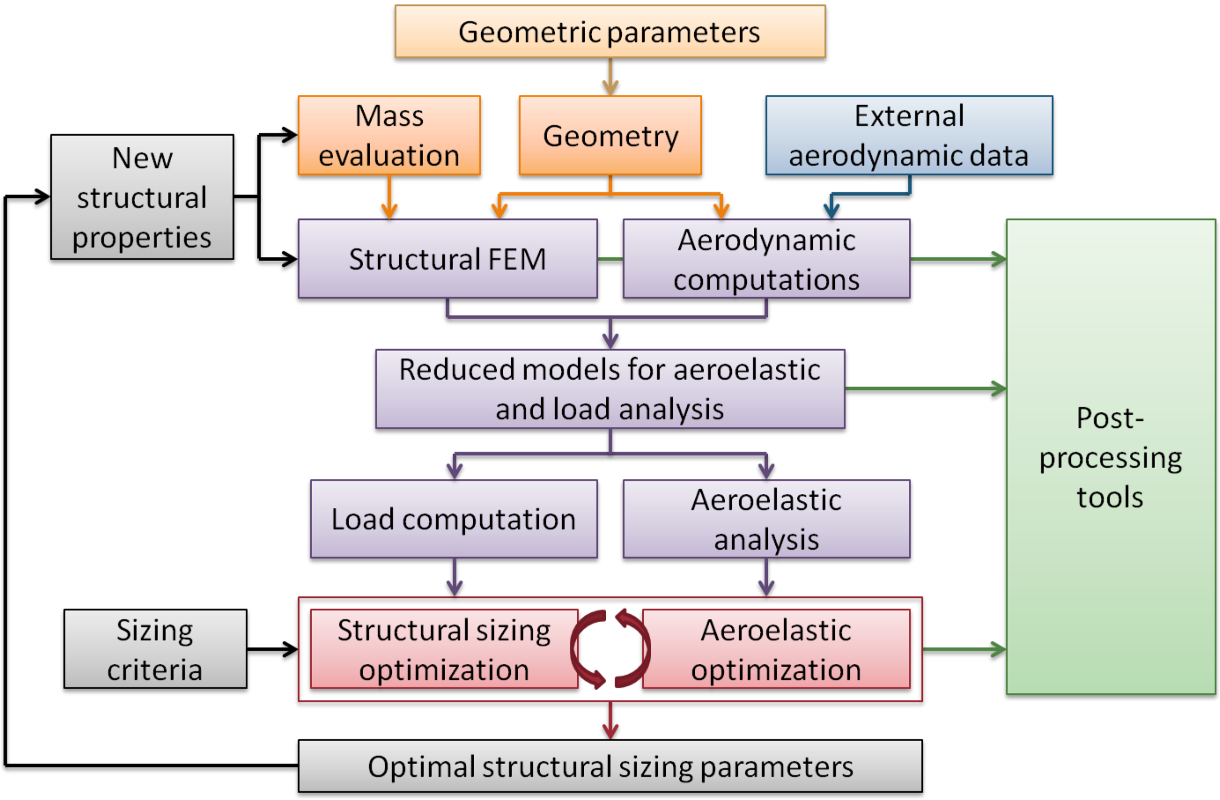


Figure 1 : Global optimization process

The process then builds an aerodynamic database by combining aerodynamic computations with external aerodynamic data, if available. These computations are independent from the structural properties and are reused during the other iterations to reduce computational time.

The reduced order models used for load computations and aeroelastic analyses are computed. Once these models are created, the optimization is performed taking into account both load and aeroelastic constraints. Finally the new optimal properties are exported and the process loops back until convergence is obtained.

During the iterations different results are exported and post-processed in order to control and validate the loops as well as the final result.

Most of these tasks are integrated directly in Elfini© and interact seamlessly with one another. The process is nevertheless capable of calling other programs such as Matlab© or Excel©. This facilitates automatic pre- and post-processing and has allowed the integration of the structural sizing with respect to loads.

2.2 Structural modelling

Structural modelling and meshing is performed using Catia V6©. Using this powerful tool it is possible to create a completely parameterized geometry and automatically update the mesh for each new variation of the geometry. For each configuration the finite element density is preserved since the model is automatically remeshed. Figure 2 shows an example of a parameterized winglet mesh for 3 different heights.

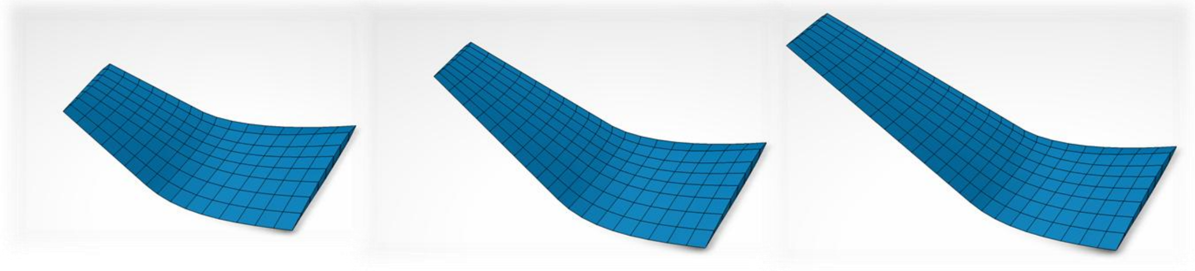


Figure 2 : Example of an automatic mesh based on a winglet with varying height

Once exported from Catia V6© into Elfini© this mesh is fixed and only the properties change with each iteration.

2.3 Aerodynamic modelling

The aerodynamic computations needed to calculate loads and flutter are estimated with the commonly used Doublet Lattice Method (DLM) enriched with mode advanced techniques like Navier-Stokes Computational Fluid Dynamics (CFD). This theoretical unsteady aerodynamic database can be combined with results from wind tunnel experiments ([2]).

The combination of the aerodynamic results is handled by a computational grid. This intermediary grid between the FEM and the aerodynamic mesh has many advantages:

- It reduces the amount of aerodynamic data stored to the level of necessary detail for FEM projection.
- It gathers all the aerodynamic results from different sources
- It allows fast and efficient combination or correction of the results

The transfer from the aerodynamic mesh to the structural model is done directly from the grid.

2.4 Structural sizing with respect to loads

The structural sizing is iterative. Sizing loads are computed and then the corresponding optimal structural properties are found. This is repeated until convergence is achieved. It has been observed that this process converges when applied to metallic wing panels composed of skin and stiffeners.

2.4.1 Sizing loads and flows

To certify an aircraft many manoeuvres and turbulences cases must be considered (more than 10000). They are examined in the entire flight domain and for all the mass configurations. Each of these points represents a load case on the FEM.

Based on general loads, only the envelope load are transferred back from the reduced order models to the FEM. This greatly reduces the number of cases to be transferred and, as a result, the computational cost to do it.

It is then possible to calculate the flow resulting from each of the selected load case and create the flow envelope for each element.

2.4.2 Structural Optimization

The structural sizing determines the optimal properties of the structure with regards to the structural sizing criteria and technological constraints so as to withstand the flows induced by the in-flight manoeuvres. Many criteria can be taken into account, for example for a metallic structure:

- Global buckling
- Local buckling
- Damage tolerance
- Maximal stress before rupture

Technological criteria such as minimal or maximal thickness are also accounted for to respect production processes. For a wing the different sizing criteria are all computed based on “super-stiffeners”. These elements contain a stiffener and part of the skin to either side; an example is shown Figure 3. Given the compressive/tensile stress in each super-stiffener and the criteria to satisfy, the optimization calculates the optimal skin and stiffener properties for the super-stiffener using a gradient method.

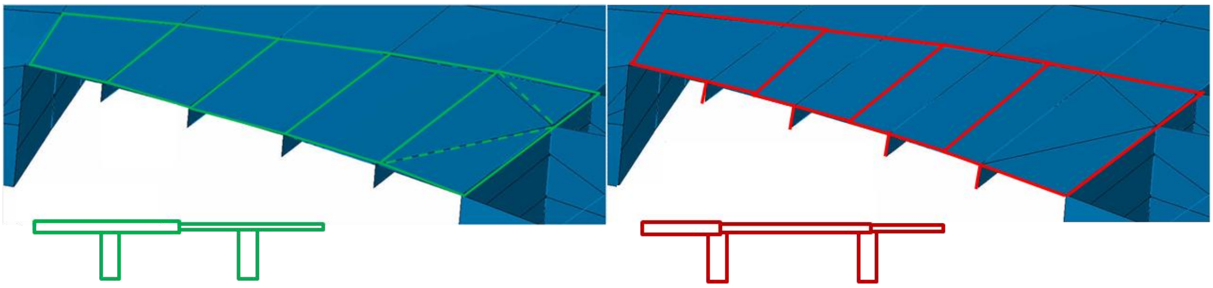


Figure 3 : Finite elements (in green) and corresponding super-stiffeners (in red)

If, as is the case Figure 3, there is only one element between each stiffener a conversion is applied to calculate the compressive/tensile stress in the super-stiffener and to get the final properties of the finite elements once the optimization is complete.

2.5 Aeroelastic optimization

Many different static and dynamic aeroelastic stability constraints can be taken into account for this optimization. Some of the most common are control surface efficiency and flutter constraints.

For example, to ensure that the safety margin for the minimal flutter speed is met it may be necessary to add a flutter reinforcement on the wing tip. This extra skin thickness stiffens the wing torsion mode and adds weight to the wing bending mode increasing the frequency gap between the two modes and increasing the minimal flutter speed.

To calculate this reinforcement and to ensure that this extra weight is minimal an aeroelastic optimization can be performed. The optimization process is completely integrated in the Elfini© software package.

On the FEM the optimization variables are created, these often represent element thickness. Then the reduced order modal basis in computed. The linerized flutter model is created and used to calculate the derivative of flutter speeds with respect to all the optimization variables. Once this derivative and the derivate of the structural mass are known the optimal flutter reinforcement can be determined. Like the structural sizing this process is iterative and must be repeated until convergence.

Given that the reduced models for flutter computations are created from modal bases, each model is associated with the corresponding mass case. These multi-model problems are also handled by Elfini© since it is more efficient to optimize the aeroelastic constraints of several mass cases at once.

In an aeroelastic optimization it is possible to include many different types of constraints at once. For example during a flutter optimization, aileron efficiency can be guaranteed by adding the corresponding constraint to the optimization.

2.6 Strategy for a coupled aeroelastic and structural optimization

To find optimal properties taking into account both the sizing and aeroelastic constraints the two optimizations (see 2.4 and 2.5) must be coupled or at least linked in some way to guaranty that both constraints are satisfied in the most optimal way to ensure the structural mass is minimal.

One method would be to use the all-in-one optimization developed in Elfini© ([3]). However that would require the derivation of the sizing criteria with respect to all the variables. Calculating that term would require a large number of evaluations using finite differences; 400 optimized elements on the wing represent 1200 sizing criteria and 800 variables. The other option to compute that term would be to calculate an analytical derivative directly but that derivative’s existence is not guaranteed. Even then the final system to be resolved could be too large for rapid sizing loops.

So to satisfy both constraints an alternate method was used for this project. The idea is to combine the two optimizations in each loop so both load and aeroelastic constraints are satisfied. The method used in each loop is shown Figure 4.

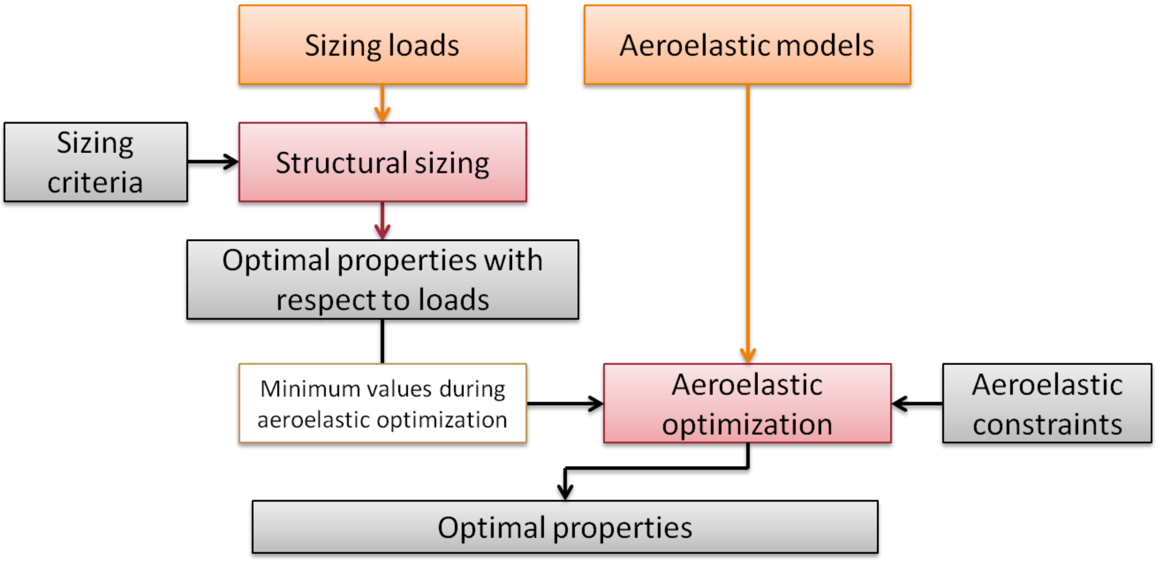


Figure 4 : Coupled aeroelastic and structural optimization process

For every step the sizing loads and the aeroelastic models are established. Then the structural sizing optimization is performed, the result is then used simply as minimal values during the aeroelastic optimization. The resulting model respects both the aeroelastic and the load constraints for that iteration with minimal superfluous mass. This process gives a view of both loads and the aeroelastic constraints during each iteration.

3 APPLICATIONS

Two examples are presented here to demonstrate the capability of Dassault Aviation's process. First an example of a flutter optimization done during the development of a new Falcon jet will be presented. The second application is the study of the effect of winglet height on the wing's structural mass.

3.1 Flutter optimization on a new Falcon jet

During the development of a new Falcon jet various flutter optimizations are done in order to minimize the extra weight added to satisfy the flutter safety margins. By performing the flutter optimizations this early during the design process the flutter reinforcement can be directly integrated in the wing structure providing additional stiffness. Indeed if the flutter constraints were taken into account later in the process only additional mass could be added to the wing thus reducing its effectiveness since no stiffness is added.

The case presented below is an example to show the power of the flutter optimization. This application uses only parts of the process described above since only flutter constraints are taken into account, no loads or sizing criteria are computed during the iterations. The wing structure in this example is metallic.

The complete FEM of the aircraft was used and the flutter speeds from the three most critical mass cases were taken into account:

- Zero Fuel Weight with icing conditions
- Fuel in fuselage and empty wings with icing conditions
- Full fuel with icing conditions

A crucial step to ensure a good optimum is the definition of the optimization variables. Many different properties can be used (material characteristics, thickness...). The real optimization variables are actually coefficients which are applied to the initial value of the property. This way it is easy to define a variable containing many different properties since the final value of each property is the initial value multiplied by the optimal coefficient.

For this example the thickness of the upper and lower skins were modified to arrive at the minimal flutter speed. These variables were chosen because they are the ones who have the most influence on flutter speeds. They play a deciding role for the frequencies of both the wing torsion and wing bending modes. These two modes usually constitute the critical flutter mechanism. The skin thickness is, as a result, the most effective key to controlling flutter speeds.

Since no sizing criteria checks were performed the optimization was not allowed to remove any thickness from the initial model ensuring that the sizing criteria are still satisfied, for the most part.

Figure 5 shows the flutter speeds before and after optimization. On the x-axis are the different mass cases and on the y-axis, the minimal flutter speed for each mass case. The flutter speeds have been normalized with respect to the objective flutter speed.

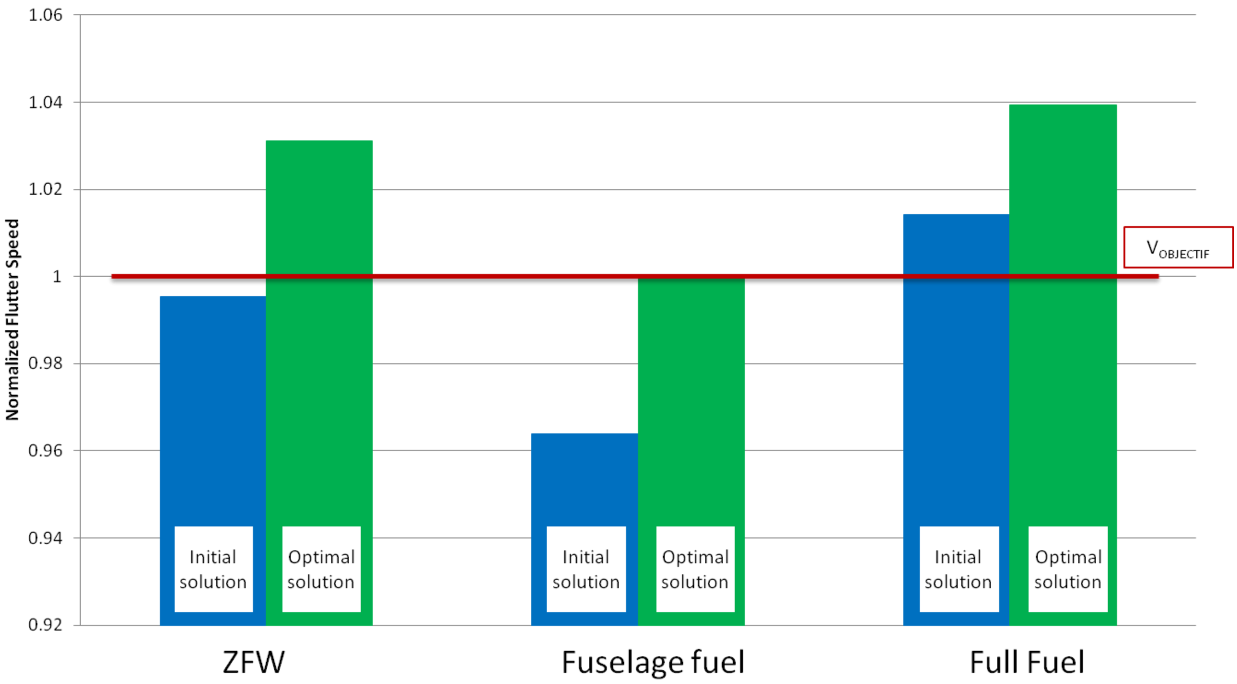


Figure 5 : Flutter speed before and after optimization for 3 mass cases

Flutter curves show the evolution of modal frequencies (top half) and dampening (bottom half) as the true air speed increases. The flutter speeds can be read on these curves as the speeds were a negative dampening appears. Figure 6 gives an example of flutter curves before and after optimization for a given mass case. Before the optimization at least one flutter speed is below the objective speed and after the optimization the first flutter mechanism appears at the objective speed.

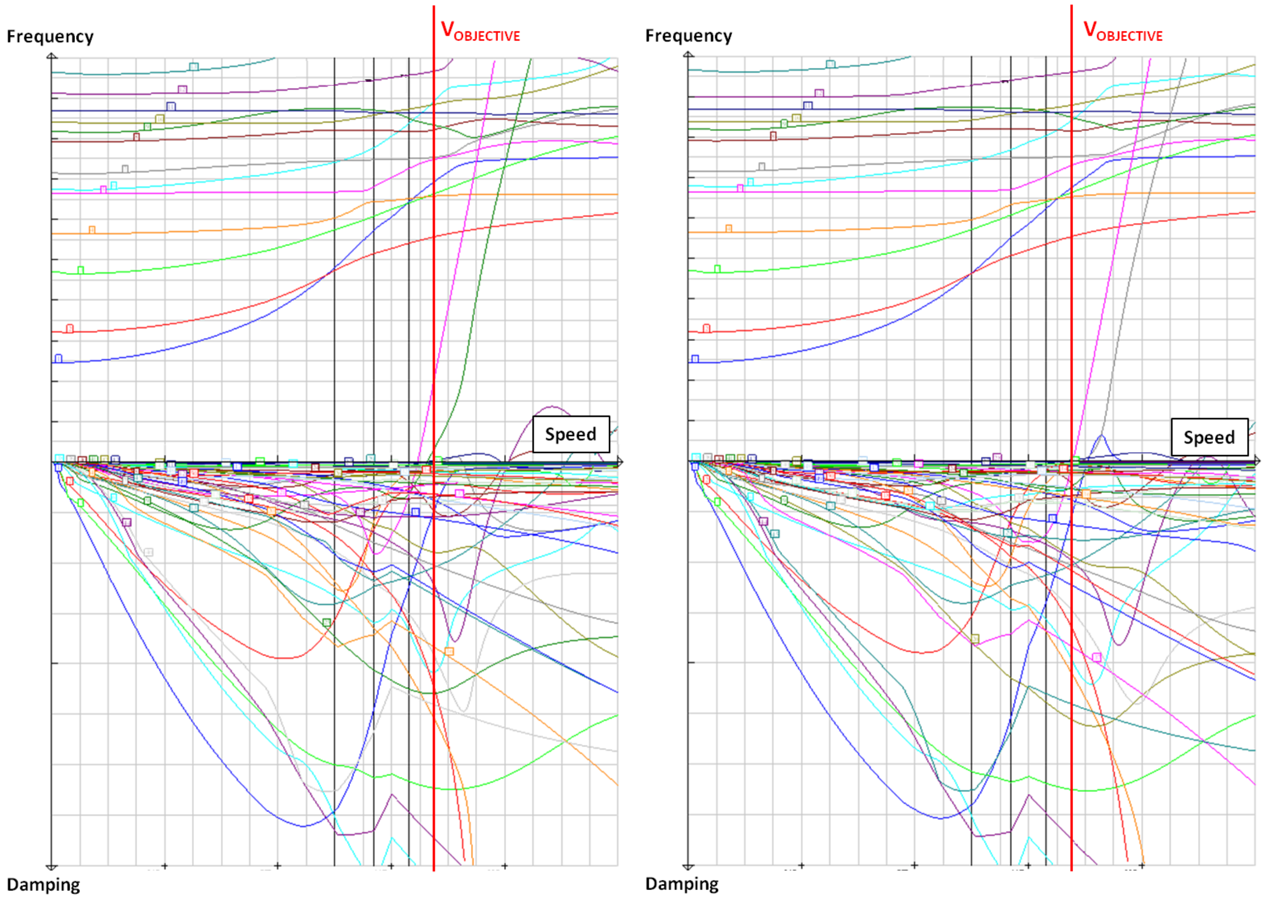


Figure 6 : Flutter curves before (left) and after (right) the flutter optimization for one mass case and altitude

The resulting optimal skin thickness is shown Figure 7. Each row represents the skin elements between two adjacent stiffeners and the columns correspond to the additional cuts done between the ribs. The value in each cell is the normalized thickness added to the corresponding elements.

This optimal solution adds enough mass to the initial wing mass while completely satisfying the minimal flutter speed constraint. As seen on Figure 7 the best place to add thickness is at the wing tip.

This example has shown that the flutter optimization is able to satisfy the flutter constraints imposed while adding mass only where most pertinent.

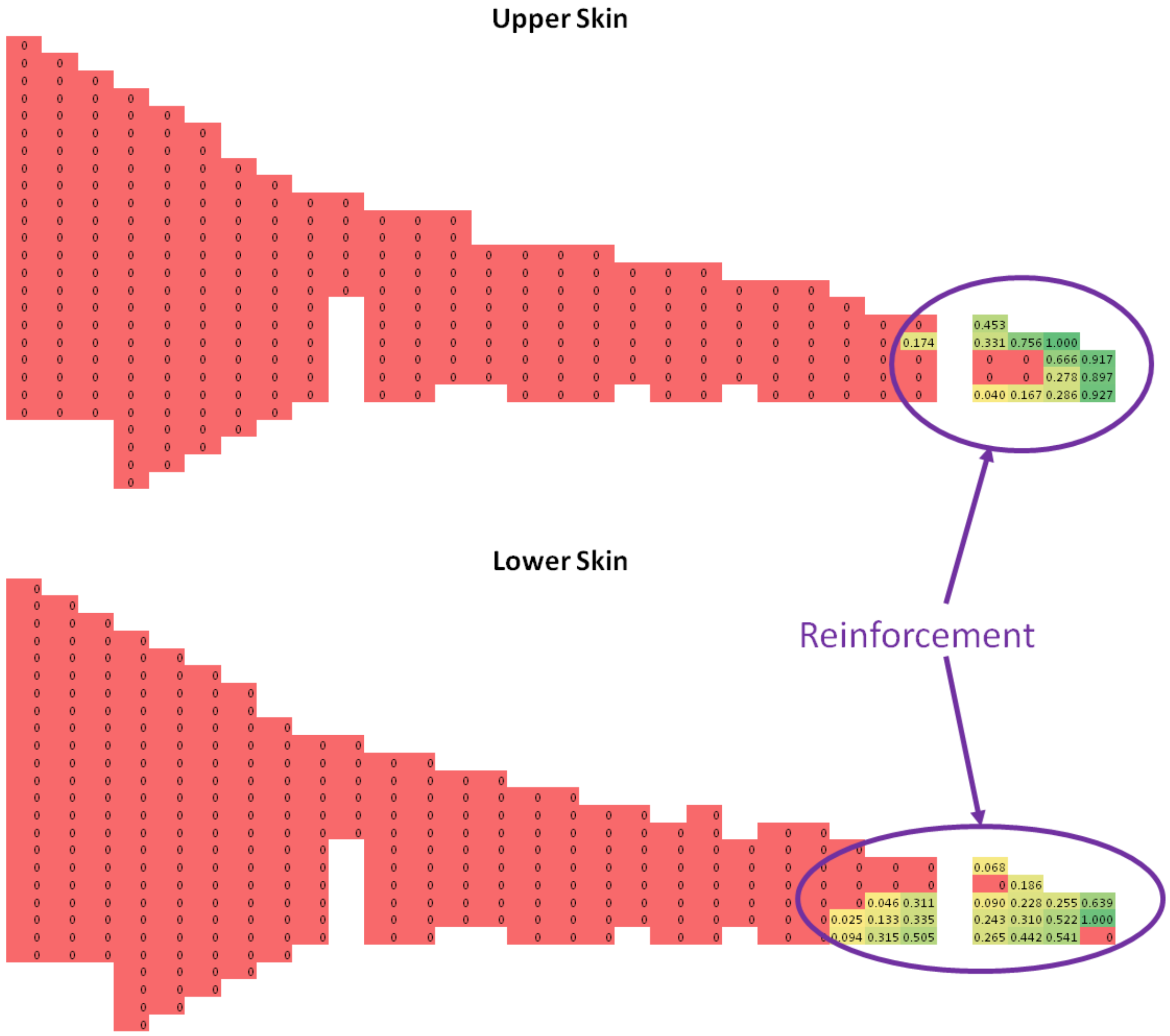


Figure 7 : Normalized added thickness for the flutter reinforcement

3.2 Winglet height variation

3.2.1 Model

The goal of this study is to determine the variation of the optimized structural mass of the aircraft for different winglet heights. At the same time the aerodynamic performance of each winglet shape was evaluated, so provided the exchange rate between drag and mass is known, an optimal winglet height can be determined. Three variations were considered for the study; the original winglet, a winglet 300mm longer and one 600mm longer. Their meshes are shown Figure 2.

The global FEM is based on a preliminary model for a new Falcon jet with a metallic wing structure. The FEM is shown Figure 9. The objective of the study is to optimize the wing panels so only the detailed FEM of the wing was used. In addition to speeding up the analysis, this shows that it is possible to study geometric variations of the wing without a detailed fuselage model.

Since the panels are optimized, their thickness varies after each iteration so it is necessary to redefine their mass at the same time. That is not simply the finite element mass, indeed the mass applied to the wing panel includes a fixed part such as pipes or equipments and a variable part which is the consequence of the difference between the FEM and what is actually created, an example of that difference is shown in red Figure 8. The mass after each iteration is the finite element mass multiplied by coefficients representing the variable mass added to the fixed mass.

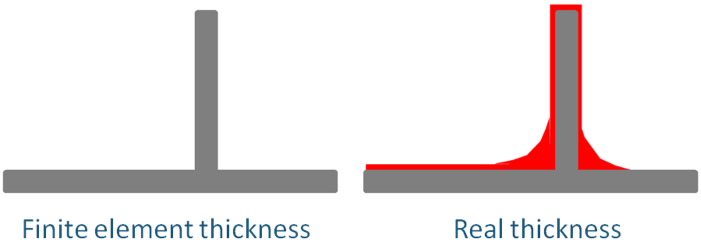


Figure 8 : Difference between finite element mass and real mass

All the computations done during the study were without flaps or slats so only three CFD effect were added to the original database: The initial pressure field around the aircraft ("zero effect"), the effect due to incidence and the effect of aileron deflection. The last two effects are assumed linear and calculated as the difference between the initial field and the field with incidence or aileron deflection.

The aeroelastic studies are performed on a complete model of the aircraft with a simplified fuselage. The Young modulus of the fuselage is adjusted so the fuselage modes don't interact with the wing modes. The aim of the fuselage is to serve as a mass support and to apply the aerodynamic effects of the horizontal control surfaces.

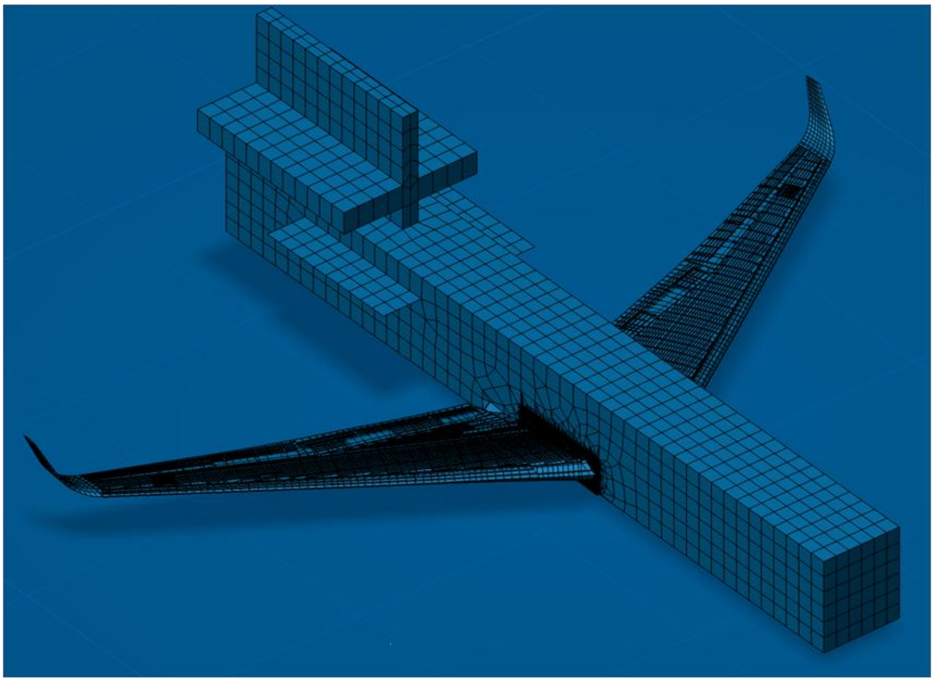


Figure 9 : Mesh for flutter and load computations

The flutter computations are carried out using only the linear DLM results from the aerodynamic database. Tests on a complete Falcon model have shown that the fuselage has a negligible effect on the pure wing flutter mechanism. Four mass cases are considered: empty and full fuel both with and without icing conditions. The flutter analysis is done for an altitude of 20000ft, the most critical.

Once the reduced load basis created a certain number of manoeuvres and turbulence cases must be computed to find the most critical ones. During advanced design phases a huge number of cases are treated, this requires a lot of computational power to justify that only a limited number of cases are critical. So to reduce the computational time, a simplified set of manoeuvres and turbulences were used, they were chosen to recreate as accurately as possible the envelopes of the global forces in the wing (bending moment, torsion moment, and shear force) with as few cases as possible. Three cases were selected.

The simplified envelope only uses the clean wing configuration. The sizing loads are chosen based on this envelope and that of torsion moment and shear force.

3.2.2 Optimization

The optimization strategy used is the coupled one presented in 2.6. First the structural sizing optimization is carried out. The optimization variables for such a metallic wing are the skin thickness and the stiffener thickness. The stiffener height was fixed during this study; however the process is capable of including that variable as well.

The flutter optimization, like the one used in the previous example only optimizes the skin thickness. All the skin elements are optimized with one variable per cell (elements between two adjacent ribs and stiffeners). With the upper and lower skin of one wing that leaves 846 optimization variables. The objective flutter speed is chosen and that speed is imposed gradually during the iterations to ensure a smooth convergence of the flutter optimization.

In addition to the flutter speed constraint each skin element has an lower bound imposed for the thickness variations. The lower bound is defined by the structural sizing.

3.2.3 Results

Only the results from the first winglet height are presented in this article. The complete results including the evolution of wing mass as a function of winglet height were presented at the IFASD 2015 conference.

The initial thickness of the wing panels is a realistic, but arbitrary, sampling without any flutter reinforcement. In order to verify the convergence of the process, 12 iterations were completed. The evolution of the wing mass is represented Figure 10. It has been normalized with respect to the initial mass. The mass corresponds to the finite element mass of one wing with the multiplicative coefficients in order to have the best estimation of the real design mass.

The first important point to verify is convergence. The total mass reaches a stable value after only a few iterations, at the fifth iteration the mass is within 0.5kg of the value at the last iteration. The variation at the end is less than 0.1kg, so mass convergence is achieved at 0.02%. Likewise the flutter speed variation is less than 0.05% at the last iteration, Figure 11 shows the evolution of the flutter speeds for various mass cases. These have been normalized with respect to the objective flutter speed. It is also worth noting the effectiveness of the linearized flutter models. The objective flutter speed is achieved after only five iterations.

The variations of individual element thickness are less than 1% with most elements less than 0.1%. These higher values are due to an exchange, during the structural sizing, of matter between the stiffener and the skin; a slight variation of the element stress caused the structural sizing process to find a new optimum, however the variation of the element’s mass remains low.

In Figure 12 is shown the initial and final properties of the upper and lower wing panel. Only the skin's thickness is shown. The new flutter reinforcement is clearly visible towards the wing tip for the upper panels. On the lower panel s mass is added to the middle.

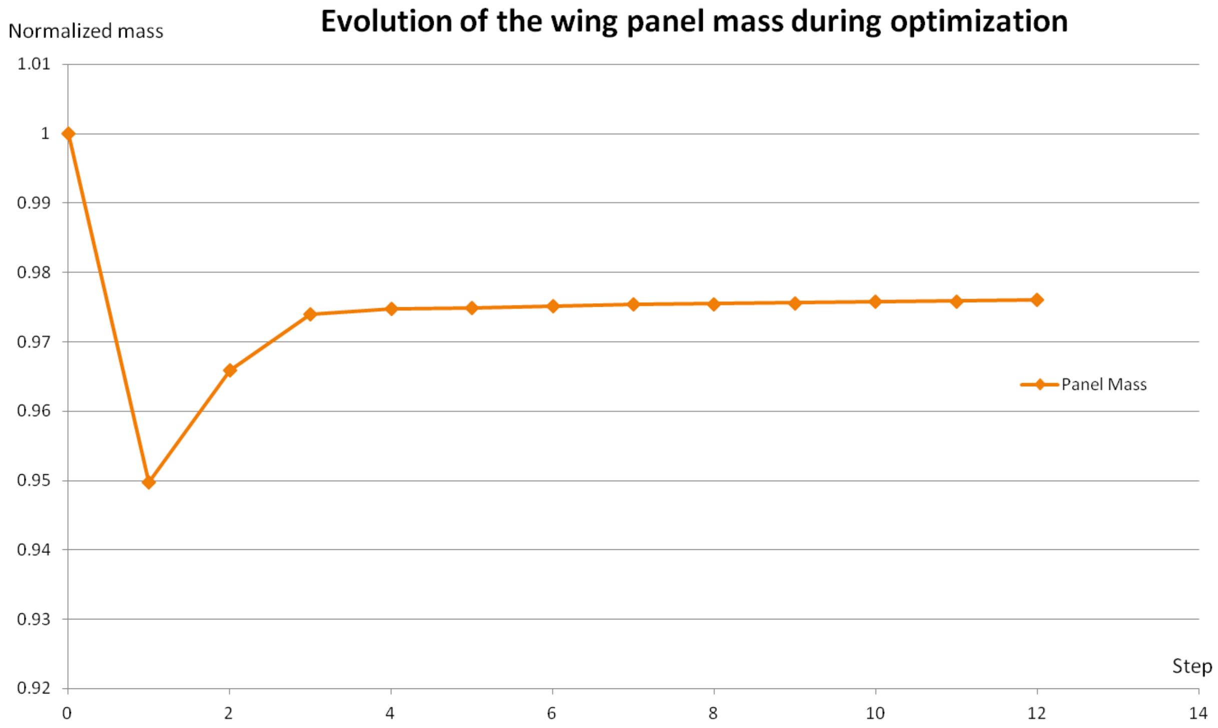


Figure 10 : Wing panel mass for each iteration

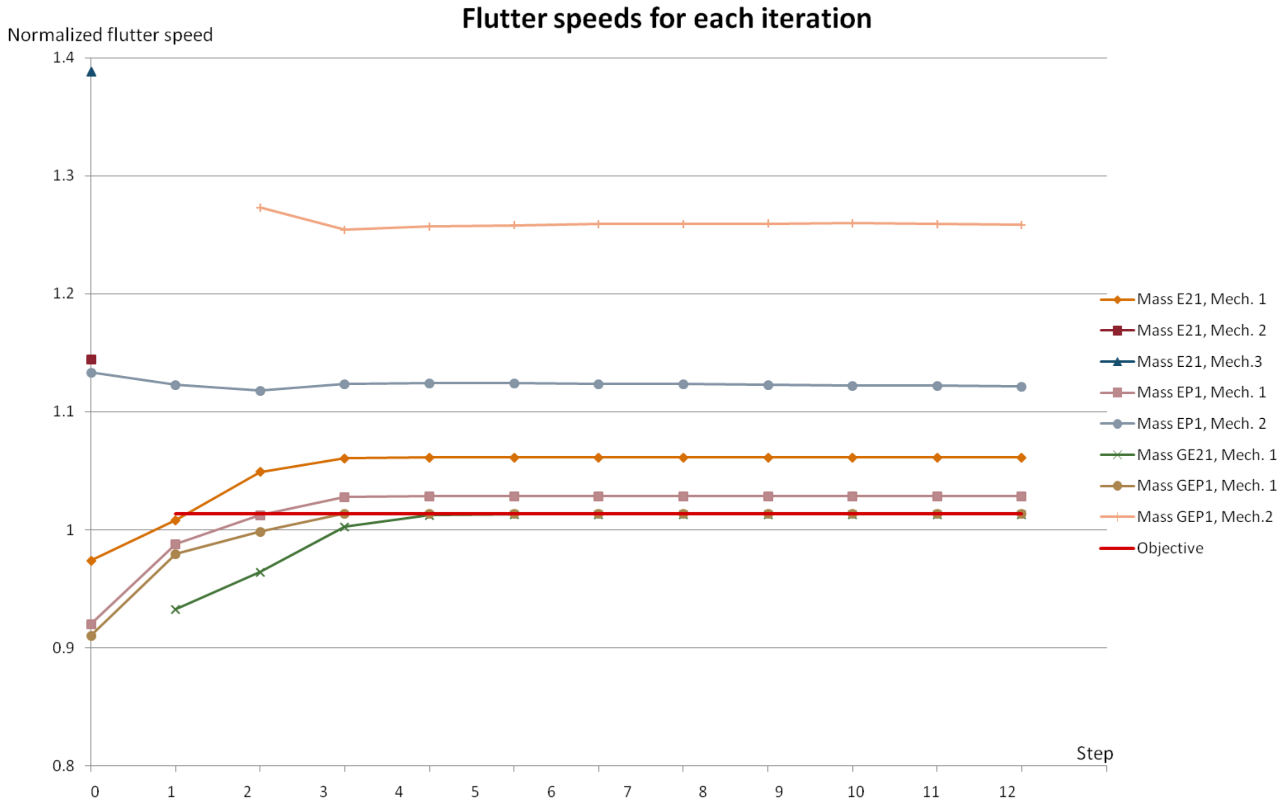
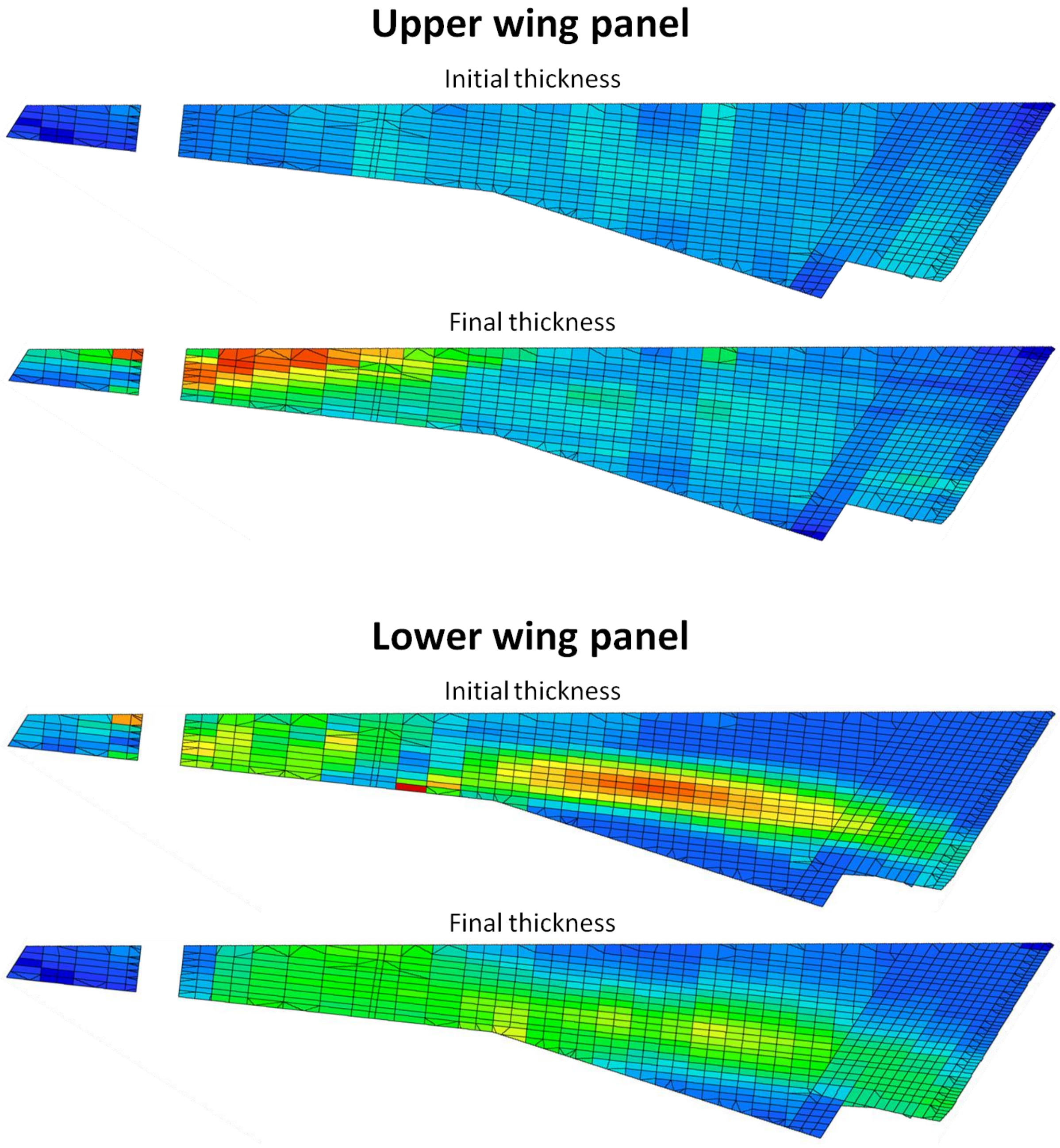


Figure 11 : Flutter Speeds during optimization



Upper wing panel

Initial thickness

Final thickness

Lower wing panel

Initial thickness

Final thickness

Figure 12 : Initial and final thickness of the upper and lower panel

4 CONCLUSION

A new methodology to perform coupled aeroelastic and structural optimizations taking into account both sizing and aeroelastic constraints (flutter, static aeroelastic characteristics) has been implemented at Dassault Aviation. This new process is based on the state-of-the-art computational tools developed in-house in Elfini© and Catia V6©. This mastery of all the tools involved has allowed us to create a fully automatic and parameterized procedure which can be applied to study many different variations. The additional benefit of an automatic process is the reduction of error inherent to manual and repetitive operation.

The strategy used for the optimization includes aeroelastic and load calculations which allows for a safer and more efficient optimization since both constraints are followed as the process iterates. After each iteration the structural sizing criteria are met as well as the aeroelastic constraints.

Two applications of the process were put forward; the first one demonstrating the efficiency and capabilities of the flutter optimization performed during the development of a new Falcon jet. The second application was the study of the effect of the winglet's height on the aircraft's structural mass. It has shown the potential of this method to calculate the optimized structural mass of a configuration.

The process is necessarily time efficient in order to be applied during the preliminary design phase of a new Falcon jet. Each iteration takes approximately 3 hours and the mass is converged after only a few iterations so it is possible to study rapidly a number of different configurations. It is thus possible to carry out parametric analyses which have always been a challenge. It's for example possible to calculate the influence of a sizing criterion margin on the final aircraft mass.

The next step in the development of this tool is to include this optimization loop in a larger process which would also contain the definition of the geometric parameters (such as the winglet height in the previous study). That global process would be able to determine automatically the optimal geometry with respect to the total mass or any other structural criteria.

5 ACKNOWLEDGEMENTS

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