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MULTIDISCIPLINARY OPTIMIZATION OF AIRCRAFT STRUCTURES WITH RESPECT TO STATIC AND DYNAMIC AEROELASTIC REQUIREMENTS

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Abstract

The technical challenges of aircraft design are set to remain at least as difficult in coming years or may become even greater in future. Performance requirements are likely to continue to increase while there is a continuing desire, even for military applications, for a reduced energy footprint. At the same time, particularly in military aircraft design, development times and budgets are decreasing. This calls for more efficient design methods capable of delivering feasible designs fulfilling all design driving requirements more quickly than traditional methods. The latter are based on manually iterating between load case determination at different flight conditions and sizing of the structure to fulfil all necessary design criteria. The new approach at Cassidian has been to take advantage of Multidisciplinary Design Optimization in conceptual and preliminary design phases, integrating the loads calculation discipline for static and dynamic aerodynamic loads into the optimisation process, automatically adjusting the applied loads to the aircraft to modifications in the structural properties.

1. INTRODUCTION

Military aircraft projects, in particular, are facing ever increasing challenges in the shape of reductions in development time and budgets. At the same time, the physical complexities of new aircraft designs are at least equal to existing and previous generations. In particular, the drive to light weight designs and the choice of new materials leads to aircraft structures exhibiting noticeably greater flexibility than previous designs. This leads to a stronger coupling between the aerodynamic loads on the aircraft and the structural displacements in flight.

In order to meet these challenges, Cassidian has identified Multidisciplinary Design Optimization (MDO) in the conceptual and preliminary design phases as a key technology to automate parts of the design process to make the search for feasible optimum compromise designs, that simultaneously fulfil all design driving criteria, more efficient and less labour intensive. This automated design process must integrate the classical disciplines of load calculation for both static and dynamic flight cases on the one hand and structural sizing, the adjustment of the thickness and sizes of individual structural members to achieve a feasible structure, fulfilling all strength and stability requirements, on the other. It must also include a very extensive criteria model covering all aspects necessary to determine the feasibility of the design.

To achieve this aim, Cassidian has in recent years striven to integrate both static and dynamic aerodynamic loads calculation into the in-house structural simulation and optimization tool LAGRANGE. A general description of the tool may be found in Schuhmacher et al. [1]. A significant advantage of this tool is the large selection of criteria models specific to aircraft design available within the programme. Of equal importance are the analytical sensitivities of the structural properties and responses with respect to the design variables which are available in the programme. These have been extended to the load calculation process, enabling efficient, gradient based optimisation of the aircraft structure, automatically taking the dependence of the static and dynamic aerodynamic loads on the structural mass and stiffness properties into account during the optimisation iterations.

2. LOADS AND SIZING DISCIPLINES AND THE DESIGN PROCESS

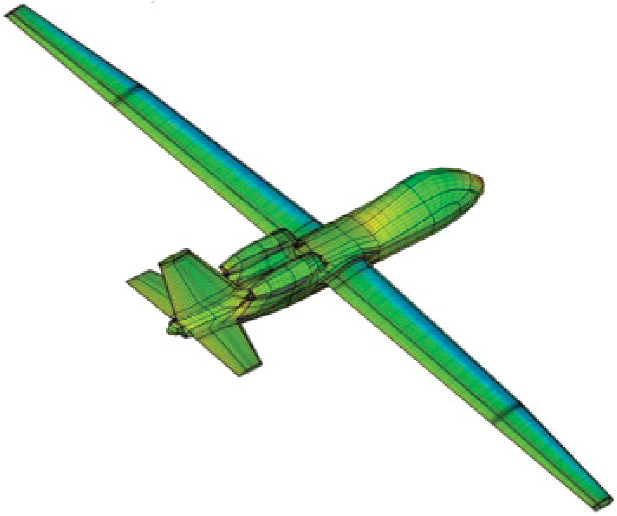

FIG 1. Aerodynamic panel mesh for medium altitude long endurance reconnaissance aircraft.

Traditionally, the aerodynamic loads on the aircraft at several points in the flight envelope are determined using linear aerodynamic panel methods (see e.g. Katz and Plotkin [2]). An example of the computational aerodynamic mesh for an unmanned reconnaissance aircraft can be seen in figure FIG 1..

In short, these methods solve for the unknown velocity potential for the fluid flow around the aircraft. In order for the governing equations to be applicable, the flow must be incompressible, inviscid and irrotational. These assumptions are met at subsonic speeds in the turbulent flow outside the boundary layer at the immediate surface of the aircraft. Using the Prandtl-Glauert correction for compressibility effects, the potential flow models can be used up to Mach numbers of approximately 0.5.

The surface of the aircraft is discretised into a finite number of panels and a previously selected type of singularity of unknown strength distributed onto each panel. At the collocation point of each panel the kinematic boundary condition of the flow must be fulfilled, i.e. at this point the flow must be tangential to the aerodynamic panel. For the assumed type of singularity of each panel, the velocity at each collocation point induced by a unit strength of each panels singularity can be calculated based purely on the geometry of the panel model. This results in a matrix of influence coefficients which when multiplied with a vector of singularity strengths results in the downwash at each collocation point.

Applying the boundary conditions in the form of the known free-stream properties of the flow, results in a set of linear equations with the singularity strengths at each panel as the unknowns. Solving for these enables determination of the disturbance potential and, therefore, fluid velocity at any given point at or around the aircraft and subsequently the aerodynamic pressures can be calculated using Bernoulli's equation.

The main advantage of linear potential theory aerodynamics for the loads discipline, obviously apart from the good agreement between the theory and measurements of aerodynamic pressure in the applicable flow regimes, is the availability of the aerodynamic influence coefficients. As these depend only on the geometry of the non displaced aerodynamic mesh itself, the influence coefficient matrices can be determined once at the beginning of the simulation and then kept constant. Determining new singularity strengths and subsequently velocity and pressure distributions for a new displaced shape of the aircraft, new angle of attack or setting of control surfaces or different flight conditions, becomes simply a matter of solving the system of equations for a new right hand side with a coefficient matrix which has already been factored or inverted, thus reducing to a renewed forward - backward substitution or simply a matrix vector multiplication, the determination of the new velocity field and aerodynamic pressures.

Having determined the aerodynamic pressures for a given flight condition, the pressure acting on each aerodynamic panel may be multiplied with its area resulting in the aerodynamic force. Using a separate coupling model between the aerodynamic panel model and the structural finite element model, the aerodynamic loads can be applied to the structure and the resulting displacements fed back to the aerodynamic mesh to represent the true in flight shape of the aircraft with the corresponding influence on the aerodynamic loads.

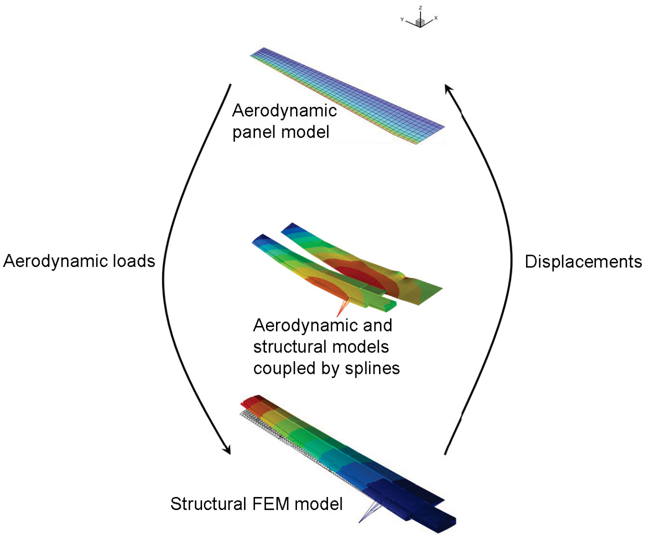

FIG 2. Aeroelastic interaction between structural displacements and aerodynamic loads necessitating the coupling of structural and aerodynamic models.

The structural sizing discipline consists of determining the correct structural sizes for each part of the aircraft to fulfil all relevant criteria for each design driving load case. In other words, the thicknesses of individual plies, the dimensions of stringers and frames, fibre orientations, etc. etc. must be determined such that each individual part of the airframe fulfils all relevant requirements with respect to maximum stresses, strains and stability for each design critical load case.

For almost 30 years, sizing of aircraft structures at Cassidian has been supported by the in-house optimization tool LAGRANGE which is under constant development. Using Multidisciplinary Design Optimisation (MDO), the engineering design problem is formulated as a constrained mathematical optimisation problem. The design variables of the optimisation control the structural sizes. The optimisation algorithms available within LAGRANGE seek to minimise the objective function (generally the structural mass) while simultaneously fulfilling all design constraints defined by the user. The so called system equations of the optimisation comprise the structural finite element model and any additional equations and models required to determine the responses of the system as a function of the design variables and the defined loadcases required to evaluate objective and constraints. An extensive criteria model is part of LAGRANGE including various strength and failure criteria for composite materials and metals, buckling of skin and stringers, displacements, velocities and accelerations of parts of the structure, natural frequencies, control surface effectiveness, flutter speed and damping and various manufacturing limitations to enable definition of the relevant design constraints to ensure that feasible designs are returned by the optimiser.

Figure FIG 3. shows a highly simplified traditional aircraft design process highlighting the manual effort in the adjustment of analysis models to changes in structural sizes and thus stiffness and inertial properties of the aircraft and even greater effort due to changes in the aircraft mission and therefore the experienced loads or to the design concept itself.

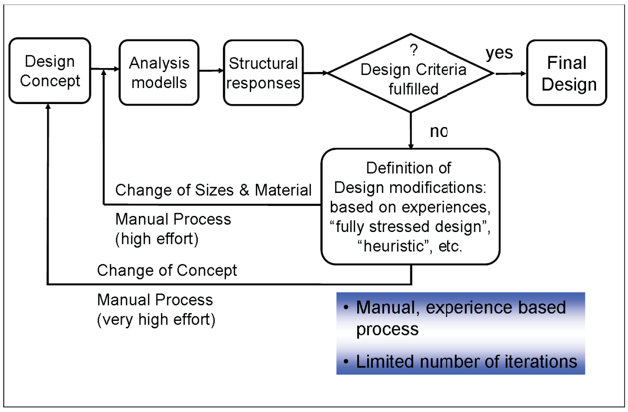

FIG 3. Traditional design process.

FIG 4. highlights the potential of MDO to significantly reduce the costs, effort and engineering resources needed to adapt the design to changing properties of the structure, design missions or requirements.

The optimisation process uses mathematical optimisation criteria to find the optimum compromise design for the given design criteria modifying the design variables defined by the user. The sizing process is thus performed automatically by the computer.

For greater changes in the design mission or the design concept itself, the optimisation models may need to be updated but a search for a new optimum design for the new critical load cases is fast based on knowledge gained from previous runs.

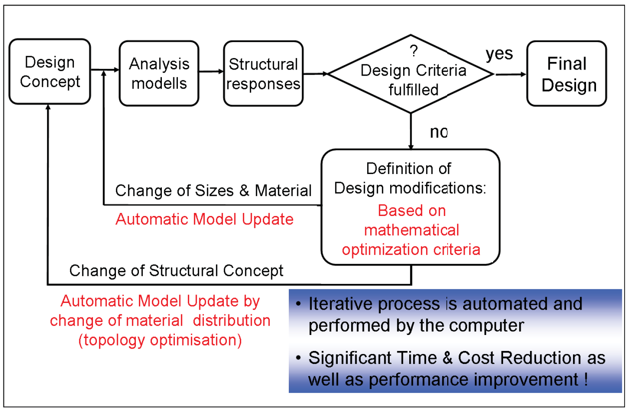

FIG 4. MDO supported design process.

The design loads on the aircraft are not only affected by the definition of the design mission, the load envelope or detailing of the design driving load cases after more accurate simulation, measurements or flight tests etc. but are also affected by the changes made by the optimisation process itself to the structure. Changes to the structural sizes change both the stiffness and inertial properties of the aircraft with subsequent effect on the trimming of the aircraft for static manoeuvres, its dynamic response to external transient loads such as gusts and its in-flight shape.

There is, therefore, a direct coupling between the structural sizing discipline and the load calculation discipline. In the traditional aircraft design process this coupling manifests itself as a manual iteration loop (load loop) between the two relevant parts of the design team which can often be costly and time consuming.

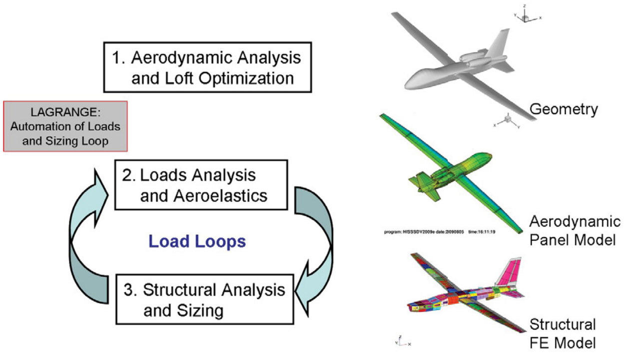

FIG 5. Iterative process (load loops) between the determination of aerodynamic loads (centre, right), structural sizing (bottom, right) and subsequent adjustment of the loads that can be automated by including the loads analysis and structural sizing disciplines in a coupled MDO process.

Recent work at Cassidian has focussed on including the load calculation discipline within the optimisation process in a tightly coupled fashion so that changes to the structural properties are automatically reflected in the aerodynamic loads. This work has been performed both for static manoeuvre loads (trim loads) and dynamic aeroelastic loads (gusts) and has resulted in the extension of the LAGRANGE software to include new loads analysis disciplines and coupling methods as well as significant extensions of the optimisation module.

The optimisation of a full aircraft structure can require the use of up to tens of thousands of design variables and result in several hundred thousand active constraints at the optimum design. For such large scale optimisation problems, the only optimisation methods able to deliver a result in an acceptable time frame are 2. order and use the values and gradients of the objective function and constraints with respect to the design variables. A major advantage of the LAGRANGE software is that for each of the model responses that can be calculated by the software, the analytical sensitivities with respect to the design variables have also been made available, thus facilitating highly efficient large scale optimisation runs. The new analysis routines in LAGRANGE for the static and dynamic aeroelastic responses, therefore, also include new routines for the analytical sensitivity of the relevant aircraft responses to evaluate the gradients of the design constraints.

3. STATIC AND TRIM LOADS

For static flight manoeuvres, the user defines a flight condition consisting of a load factor, i.e. acceleration of the vehicle in magnitude and direction as well as the attitude (angle of attack and sideslip) at which the aircraft is to fly and the control surfaces which are to be used to trim the aircraft for this flight condition.

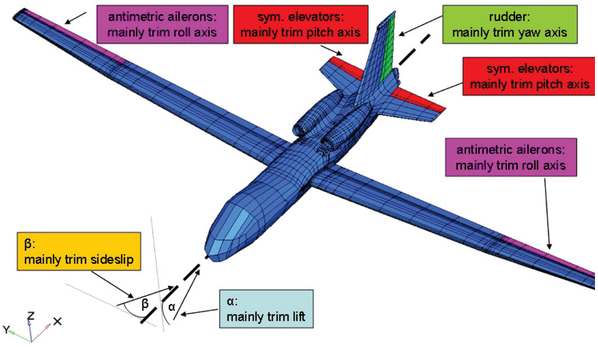

FIG 6. Trim variables; angle of attack, α, sideslip, β, and control surface deflections that must be adjusted to fly the predefined static manoeuvre.

The design variables of the optimisation problem are, therefore, augmented by the trim variables, i.e. the angle of attack or sideslip of the aircraft and the deflections of each control surface. Additional constraints are also added to the traditional structural criteria. At the trimmed flight condition the aircraft must generate lift equal to the current weight and the total moment about the centre of gravity must be zero consistent with trimmed flight. These additional design variables and constraints are added to the optimisation model and become a part of the optimisation problem.

The static aeroelastic forces depend on the trim variables, which determine the free-stream properties of the flow directly, and the displaced shape of the aerodynamic mesh influencing the kinematic boundary condition on each panel. A constant interpolation matrix transforms the elastic structural displacements to the aerodynamic mesh and the aerodynamic forces to the structural model.

Having determined the flow velocity at each collocation point of the aerodynamic mesh using the precalculated matrix of aerodynamic influence coefficients for the given boundary conditions, resulting from the trim variables and displaced shape, the aerodynamic pressure can be calculated and the coupled equation of motion solved.

The sensitivity analysis in LAGRANGE has been extended to include the effects of the structural variables on the aerodynamic forces via the stiffness and inertia of the structure. Because of the dependency of the structural displacements and aerodynamic loads on each other, the sensitivity analysis is performed iteratively. Details of the static aeroelastic sensitivity analysis may be found in Daoud et al. [3].

4. GUST LOADS

For the dynamic external aeroelastic loads, due to turbulence or gusts, the procedure for the aerodynamic loads calculation is similar to the static loads apart from the choice of a different basic singularity solution (doublets instead of sources) and the fact that the velocity potential is calculated not for the static boundary conditions but for harmonically oscillating boundary conditions. The resulting matrix of aerodynamic influence coefficients is constant as before but now complex valued, reflecting the phase shift between a disturbance on an aerodynamic panel and the subsequent effect on the singularity strength of other panels. In the time domain, this phase shift appears as a time delay between a disturbance and its effect. The matrix of unsteady aerodynamic influence coefficients is inverted completely, resulting in a system of linear equations returning the harmonically varying unsteady pressure difference across each aerodynamic panel due to the harmonically varying downwash on each of the other panels:

$$(1) \quad [AIC]w(\omega) = \Delta C_p(\omega)$$

The determination of the AIC matrices must be performed for each Mach number and reduced frequency, k:

$$(2) \quad k = \frac{\omega c}{2V}$$

required for the analysis separately (c is the wing chord, V the free stream velocity). In LAGRANGE the AIC matrices are determined a priori for a sufficient range of Mach numbers and k values. During the gust response analysis, the aerodynamic forces for intermediate values of (Ma,k) are found by a term by term bicubic spline interpolation of the coefficients of the matrix.

As in the static case, the aerodynamic pressures are multiplied with the area of each aerodynamic panel to obtain the forces and a constant mesh interpolation matrix is used to apply the unsteady aerodynamic forces to the structure and the corresponding displacements of the structure back to the aerodynamic mesh. In addition, a derivative matrix, D, is required to calculate the unsteady boundary condition on each aerodynamic panel from the displaced structural shape. Finally, to improve efficiency, the equation of motion is solved using the normal modes of the structure as generalised coordinates, as this greatly reduces the sizes of the coefficient matrices involved.

Combining all of these constant matrices, the mesh interpolation matrix, G, the boundary condition derivative matrix, D, the matrix of panel areas, S, the unsteady aerodynamic influence coefficient matrix, AIC and finally the matrix of normal modes of the structure, Φ, results in the generalised unsteady aerodynamic forces, Q:

$$(3) \quad [Q] = [\Phi]^T [G]^T [S][AIC(Ma,k)][D][G][\Phi]$$

The generalised aerodynamic forces provide the modal unsteady aerodynamic forces caused by the displacements and deflections of the structure on itself. The rightmost three terms of equation (3) give the downwash or slope of each aerodynamic panel due to unit modal displacements. Multiplication with the AIC matrix in accordance with equation (1) returns the aerodynamic pressures, multiplication with the areas of the aerodynamic panels, S, results in the aerodynamic forces which are applied to the structure and transformed to modal coordinates by the leftmost two terms on the right hand side.

To determine the external gust loads themselves, the rightmost three terms of equation (3) are left out and replaced with the downwash on each aerodynamic panel caused by the gust, defined by its shape and the velocity at which the aircraft is flying.

With the self induced and external unsteady aerodynamic loads available, the modal frequency domain transient equation of motion can be assembled and solved. The analytical sensitivities of the dynamic aeroelastic response with respect to structural sizing variables have been determined and are available in the programme. Details of the sensitivity analysis may be found in Petersson and Baier [4].

5. EXAMPLE: UNMANNED MALE RECONNAISSANCE AIRCRAFT

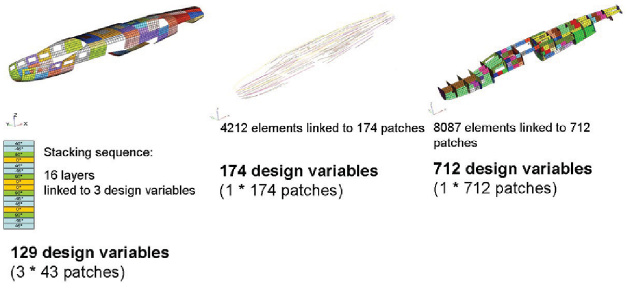

FIG 7. Structural sizing variables for optimisation of MALE UAV fuselage.

The coupled multidisciplinary optimisation process described in the previous sections has been applied at Cassidian during the development of an unmanned Medium Altitude Long Endurance (MALE) reconnaissance aircraft. This section focuses on the sizing of the centre fuselage only, but the entire aircraft hast been designed and optimized according to the methodology described in section 2.

The variable properties of the structure, i.e. the free parameters controlled by the design variables are depicted in figure FIG 7.. For the composite outer skin on the left, three design variables per designed area, or patch, control the thickness of individual bundled ply layers. The cross sectional shape of the stringers is also a design variable as shown in the centre figure as are the thicknesses of the metallic shear walls shown on the right. In addition to the structural design variables 5 trim variables shown in figure FIG 6. were also included for each trim case.

FIG 8. Structural strength criteria model for composite and metallic skins in fuselage optimisation.

The objective of the optimisation is the minimisation of the structural mass. Several load cases were defined, both trimmed flight cases for different mass configurations and flight conditions and static load cases such as ground handling, landing etc.

Completing the picture, the criteria model needed to evaluate the constraints is depicted in figures FIG 8. to FIG 10.. Strength constraints consist of a maximum strain limit for the composite shells and maximum von Mises stress for the metallic shear walls. The outer skin and shear walls also included buckling constraints and column buckling of the stringers was also taken into account.

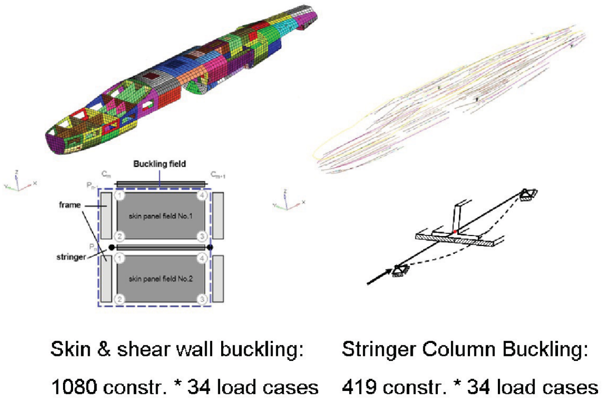

FIG 9. Buckling and stability constraints in skin and stringers of fuselage optimisation.

On top of these strength and stability constraints, the minimum stiffness of the structure was also guaranteed by displacement constraints shown in figure FIG 10. and manufacturing constraints limit the optimiser to designs fulfilling minimum requirements for the manufacturability of, in particular, composite parts.

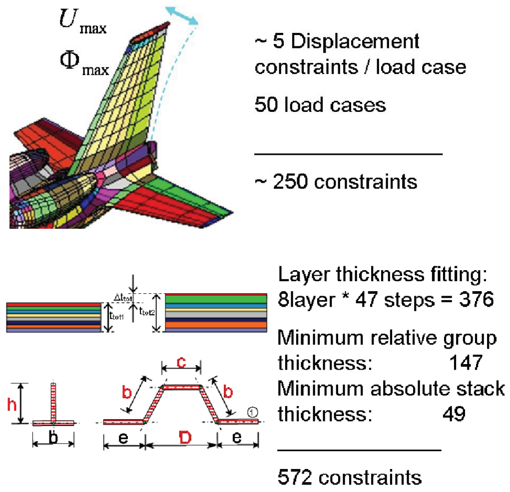

FIG 10. Displacement and manufacturing constraints for fuselage optimisation.

In addition to the structural constraints, each trim case contained constraints defining the equilibrium of aerodynamic and inertial forces and zero moments about the centre of gravity. Finally, a constraint on the minimum flutter speed was also included for one mass configuration

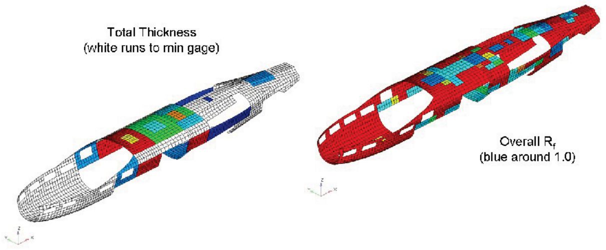

FIG 11. Optimum thickness distribution in outer skin and resulting reserve factors.

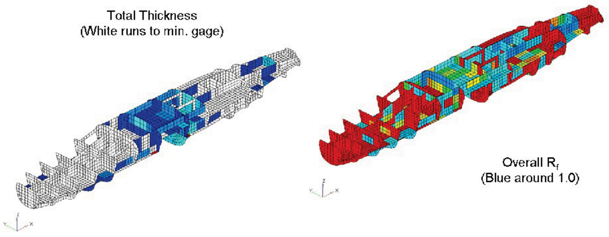

FIG 12. Optimum thickness distribution in shear walls and resulting reserve factors.

The resulting optimum shell thickness distribution of the fuselage and the corresponding reserve factors can be seen in figures FIG 11. and FIG 12.. Notable is the fact that most shells are at or close to their lower gage which indicates further mass saving potential is available. The result of this study was to revise the design concept of the fuselage to take advantage of this potential, showing that MDO can also deliver valuable impulses to the conceptual design phase where the design concept can still be adjusted.

6. EXAMPLE: SWEPT WING

To demonstrate the optimisation capabilities of LAGRANGE with respect to gusts, an example of a swept wing shown in figure FIG 13. is used. The wing consists of three spars, five ribs and the wing skin. Caps of spars and ribs are represented with beam elements. The wing is pinned at the top and bottom of each of its spars. The example is described in greater detail in Petersson [5].

A 1 – cos shaped gust as described in the FAR 25 certification requirements is applied to the wing and the response given sufficient time to die out.

Design variables of the problem were the web thickness of each spar, the thickness of the skin separated into eight patches (four each on upper and lower surface as shown in the figure), thickness of the rib webs and cross sectional areas of rib and spar caps. The objective of the optimisation was the minimisation of the wing root bending moment at the centre spar due to the incremental gust load. Constraints were placed on the maximum bending moment of front and rear spars to avoid simply transferring the load to either of these. No additional strength constraints were included.

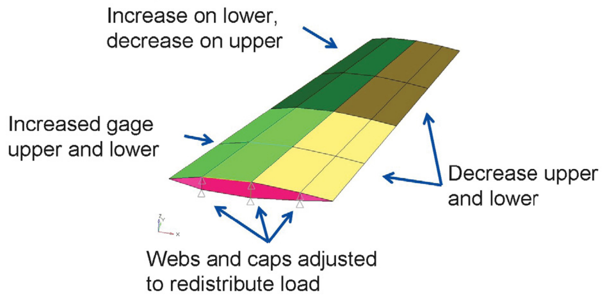

FIG 13. Swept wing pinned at each of its three spar caps at the root subjected to a FAR 1 – cos gust. Annotations indicate changes made by the optimisation to minimise the incremental bending moment at the centre spar root.

It is worth noting, that the structural mass did not enter the definition of the optimisation problem directly. As stated above, the objective was purely the minimisation of the bending moment at the centre spar and not reduction of the structural mass. Theoretically, the optimisation algorithm would, therefore, be free to increase all gages to the maximum without concern for the obvious penalty this has on structural mass. However, as this would lead to a highly stiff structure, the resulting wing root bending moment due to the gust would be greater than for a more flexible structure and is therefore not the result returned by the optimisation.

The incremental wing root bending moment at each of the three spars as a function of time is plotted in figure FIG 14. for the initial design and in FIG 15. after the optimisation. As can be seen in the figures, the bending moment in the centre spar has been reduced significantly (by around 40%). The load has been redistributed to the other two spars (the front spar in particular) but the total peak load is also reduced by around 3%. This is caused by a bending-torsion coupling introduced by the optimisation. Moving the elastic axis forward causes the wing to twist down (in the direction of negative angle of attack) as it bends up, effectively reducing the incremental load due to the gust. This manipulation of the stiffness properties of the structure to utilise the coupling between the aerodynamic forces and the deflection of the structure is called aeroelastic tailoring (see also Shirk et al. [6]).

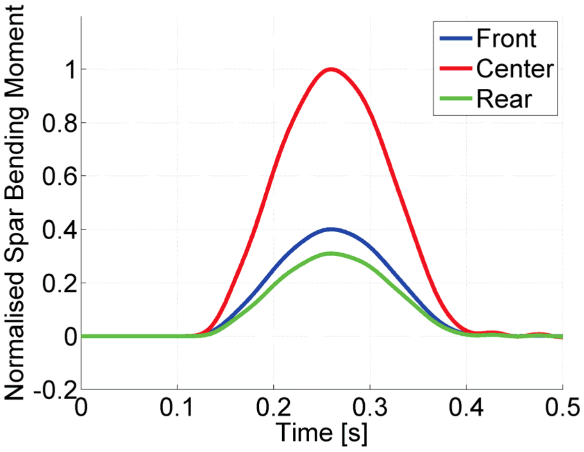

FIG 14. Wing root bending moment as a function of time due to FAR 1 – cos gust for initial design

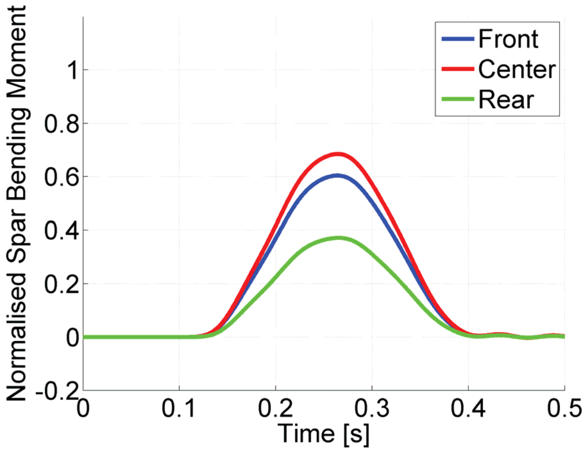

FIG 15. Wing root bending moment as a function of time due to FAR 1 – cos gust for optimised design.

The optimised design of the wing is described in figure FIG 13.. The elastic axis has been brought forward and the stiffness of the wing increased inboard by increasing the thickness of the outer skins forward and inboard and decreasing aft. The thickness of the spar webs and dimensions of the caps have been adjusted to redistribute the bending moment more equally among the spars. The ribs have relatively little influence as would be expected. Interesting is the increase of the outer shell thickness of the forward outer patch on only one side of the wing. As the thickness of the shell on the opposite side was not increased this increase in thickness has relatively little effect on the bending or torsion stiffness of the wing. Indeed, manually increasing the opposing shell thickness leads to an increase in the bending moment at the centre spar. The effect of this one sided thickness increase appears to mostly be to increase the inertia of the wing close to the tip and thus decrease the effect of the gust.

7. CONCLUSIONS

By tightly integrating the loads calculation discipline and the structural sizing discipline in a multidisciplinary optimisation process, dramatic reductions can be made in both development time and cost in the aircraft design process while simultaneously contributing to the increased quality of the final design. MDO increases the amount of information available to the designer in the conceptual and preliminary design phases where freedom to modify the design is still relatively great.

Integration of the loads calculation discipline, both for static and dynamic aeroelastic load cases (i.e. trim and gust loads) directly in the optimisation process is necessary to automate the iterative loops between load calculation and structural sizing. This has been performed in the in-house optimisation tool LAGRANGE enabling both analysis and optimisation of static and dynamic aeroelastic load cases with automatic adjustment of the aerodynamic loads due to changes in structural stiffness and inertia.

Taking advantage of the aerodynamic influence coefficients and the appropriate mesh coupling methods, the analytical sensitivities of the system responses with respect to the design variables have been determined and made available within the programme enabling the use of efficient gradient based optimisation methods for large scale applications. These have included optimisation of whole aircraft with tens of thousands of design variables and hundreds of thousands of constraints.

8. ACKNOWLEDGEMENTS

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