# Optimization of an Aircraft Control Surface

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### Abstract

This paper describes the conceptual optimization as performed on an aileron from a typical medium sized aircraft. The goals were to re-design an existing configuration maintaining the overall stiffness and weight whilst reducing the manufacturing cost. A design methodology has been developed to rapidly generate the basic structural configurations to meet given performance requirements. These requirements are either transformed into constraints or an objective function during the optimization process. ANSYS has been used throughout the optimization process starting with a topological optimization study to determine basic internal lay-outs. The internal configuration was then decided concurrently by examining structural and manufacturing constraints. This was followed by parametric optimization carried out on a stepwise fashion to determine firstly the optimum position of internal ribs and spars and finally the optimum skin thickness in each bay. Different initial configurations were studied to determine whether a spar / rib dominated design would be most suitable for the given structure. Additional internal configurations proposed on the basis of minimum assembly/manufacturing cost were quickly analyzed using ANSYS parametric capabilities.

## Introduction

The work presented in this paper was carried out under a collaborative START Grant programme. The partners under this HdH led programme are Hawker de Havilland (HdH), Royal Melbourne Institute of Technology (RMIT), Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) and Hexcel Composites. The goals of this START Grant Program were to develop innovative design and manufacturing technologies for composite control surface structural components that can be used on new passenger aircraft. The total programme cost over 3 years is $2.5 million of which the Australian Government provided the $1million Grant.

Design of control surfaces requires consideration of a number of constraints based on structural performance and manufacturing considerations. Some of those structural requirements are stiffness related such as buckling performance, maximum displacements and aerodynamic smoothness. Usually strength requirements can be met by achieving the required stiffness. From a manufacturing point of view; and for unitized construction; the number of internal mandrels required to produce the control surface can usually yield a relative cost comparison between different structural lay-outs.

Standard design methodology operates on the assumption of an internal configuration at the conceptual design stage followed by analysis. Compliance to structural requirements is subsequently assessed and assumptions can be made as to possible further changes needed to achieve compliance. This iterative process can become quite lengthy and is widely known as “trial and error” methodology. Once the compliance is achieved detail analysis can be completed. The coupling of Topological and Parametric capabilities within ANYS allow for a different methodology to be proposed. This methodology can yield results significantly faster when compared to standard practice. Efficiency ratios of 10:1 (proposed: standard methodology) were achieved in work performed under this task.

## Design Optimization Methodology

Design Optimization methodologies were previously studied by various researchers within organizations with whom Hawker de Havilland collaborates (References 1,2,3). Also more recently other studies (References 4,5 & 6) were published as a result of this and other structural optimization activities.
The Design Optimization Methodology proposed consists in performing topological optimization to determine basic structural lay-out based on critical loading cases. Topological optimization provides an indication of load paths and as a result it indicates where material is mostly needed. A desired material reduction can be achieved while maximising global stiffness (minimising compliance). Its drawback is that results require; in some cases; significant interpretation, thus coarse meshes are not recommended. The interpretation stage can also be aided by the concurrent engineering approach of bringing expert manufacturing knowledge to this critical decision stage. Drawing on this knowledge can provide a number of preferred manufacturing solutions that can then be married to topological results. A number of compromises can then be suggested as internal layouts. Once these suggested internal layouts are agreed to, after trade-off studies, a parametric optimization is carried out to determine the optimum position of the internal ribs and spars. This is considered to be a key advantage of the ANSYS parametric engine as it allows assessment of large design spaces due to its automatic re-meshing capabilities.

A further parametric optimisation is carried out to determine optimum thickness distributions for the different bays. It was found that the stepwise approach to determining internal member positions followed by determination of optimum thicknesses yielded faster results convergence and provided more insight into the structural behaviour of the control surface studied. The importance of a better understanding of the design space and the achievement of a robust design can not be overstated. Whereby the standard methodology might result in an efficient solution for the given conditions, any change in those conditions can result in lengthy re-analysis to assess compliance. This is not the case for the proposed Design Optimization Methodology whereby changes can be quickly implemented and in some cases, given the insight into the structural behaviour of the part, an analysis run might not be at all required. A typical flowchart of this methodology is shown on Figure 1.

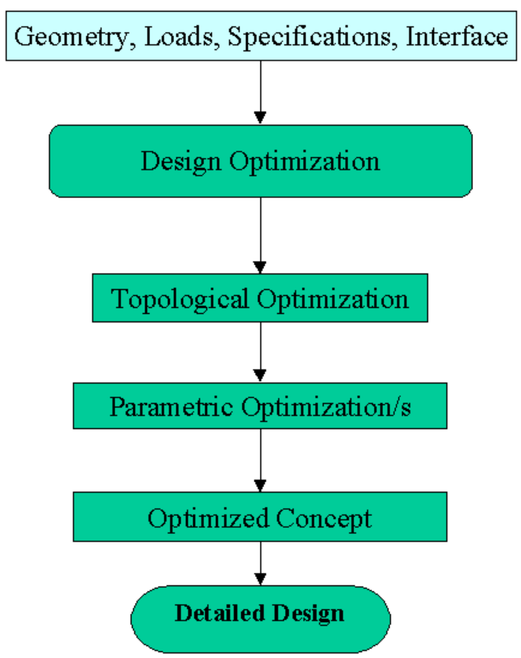


**Figure 1 - Typical Design Optimization Methodology Flowchart**

# Geometry, Load Case and Material Properties

The aileron studied had an average chord of 20 in., an average span of 150 in. and the front spar depth was approximately 4 in.

## Load Distribution

The single load case applied is shown in Figure 2. The load case applied is best represented by a triangular distribution with its peak at the aileron's hinge line tapering to zero at the tab hinge line. Airloads were applied evenly (50/50) on both upper and lower skins. Tab loads were resolved to five (5) tab hinge locations. Constraints and enforced displacements were applied to aileron hinge locations. Enforced displacements were imposed at all hinge positions to simulate wing bending.

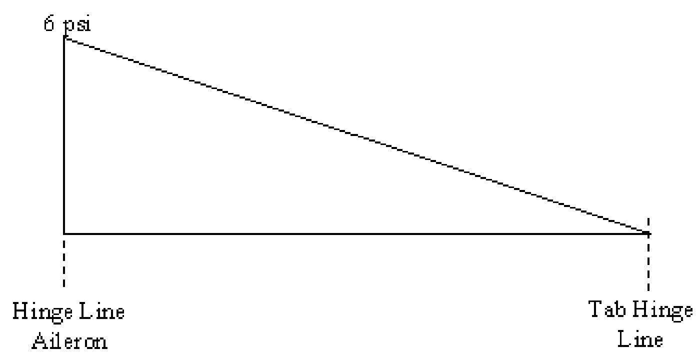


**Figure 2 - Pressure distribution**

## Material Properties

Lamina and Laminate properties employed in the FEA analysis of the aileron are shown on Tables 1 & 2 respectively. Laminate properties are based on a quasi-isotropic lay-up of 12 plies.

**Table 1:** Lamina properties Original Material and New Material

| | Original Material | G926/M18 |
|---|---|---|
| E11 (MPa) | 5.78E+04 | 7.00E+04 |
| E22 (MPa) | 5.78E+04 | 7.00E+04 |
| G12 (MPa) | 3.10E+03 | 3.90E+03 |
| $\upsilon 12$ | 0.03 | 0.04 |

**Table 2:** Laminate properties Original Material and New Material

| | Original Material | New Material |
|---|---|---|
| E11 (MPa) | 4.09E+04 | 4.96E+04 |
| E22 (MPa) | 4.09E+04 | 4.96E+04 |
| G12 (MPa) | 1.56E+04 | 1.88E+04 |
| $\upsilon_{12}$ | 0.313 | 0.32 |

These laminate properties were assumed to be of isotropic nature for the purposes of the optimization run.

## Analysis

Topological and Parametric Optimization was conducted using ANSYS v 5.6. The combined Air Load and Sympathetic bending case employed for all finite element analysis runs is referred to in the Geometry, Load Case and Material Properties section. The finite element model employed in the analysis is depicted in Figure 3. The re-design activities consisted on achieving similar stiffness characteristics to the original aileron while reducing the manufacturing cost. The original aileron is produced with honeycomb stiffened panels whereas the re-design intends to replace these panels with a unitised co-cured structure consisting of solid composite panels with ribs and spars.

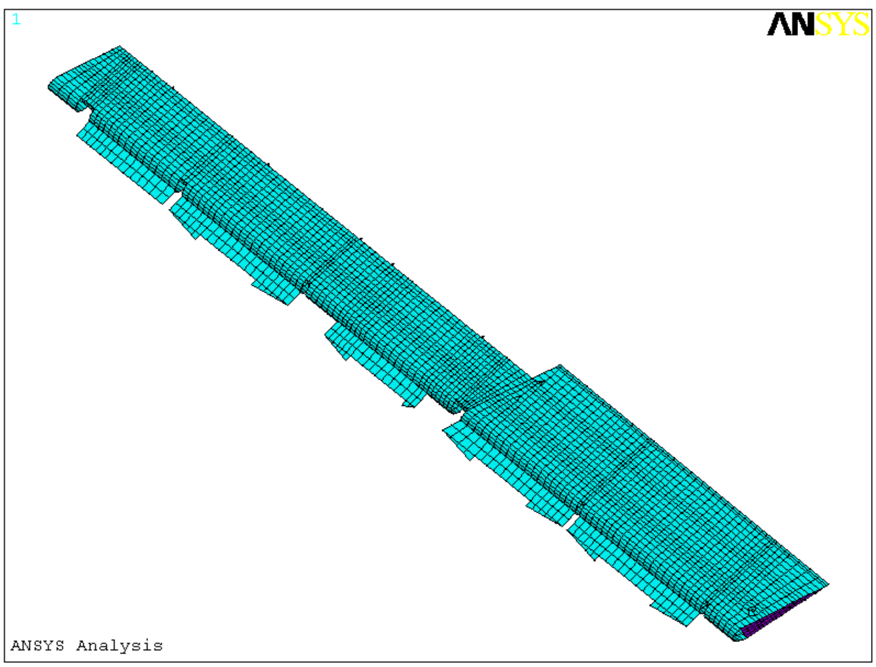


**Figure 3 - Finite Element Model**

### *Topological Optimization*

This is usually referred to as "layout" optimization. The goal is to achieve a "maximum stiffness" design while reducing the material needed. The objective function in this case is to minimize the energy of structural compliance while satisfying a volume constraint. The design variables in this case are the pseudo-densities of each finite element. For the aileron the volume reduction was set at 50%. The value chosen for the reduction is a trade-off between time to solve and increased structural definition. That is the larger the volume reduction chosen, the more definite the load path will appear and vice-versa. The aileron was fully populated with internal ribs and spars so as to employ the results to define the members that would be most efficient in transferring the load from the hinges into the torsion box. SHELL 93 elements were employed for the topological studies. All internal members were assigned equivalent thicknesses so as to avoid any bias. Hinges and closing ribs were specified as non-optimized regions by identifying those elements as TYPE 2 elements. After completing the run, the pseudo-densities were plotted and discussed with people whose manufacturing expertise aided in assessing cost implications of choosing the different possible designs. The plot showing the pseudo-densities yielded by the topological optimization study are shown in Figure 4. Although decisions made at this stage are very significant as they can skew the design one way or another, ANSYS parametric capabilities allow for the inclusion of internal members whose efficiency is questionable. This is achieved by planning ahead all possible combinations that are to be studied and creating the areas representing these members without meshing them.  Therefore the subsequent inclusion of these members in future optimization runs is achieved by simply modifying a few lines on the input files.

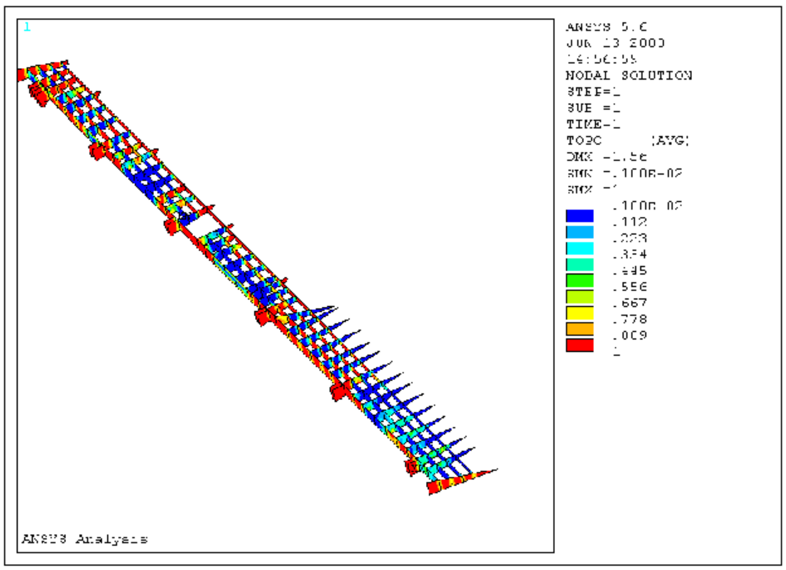


**Figure 4 - Pseudo-densities Plot**

Once the suggested internal layout is agreed to, a parametric optimization is carried out to determine the optimum position of the internal ribs and spars. The layout chosen based on input from the structural analysis and on manufacturing experience (cost) is shown in Figure 5. The configuration depicts a front spar, one mid spar and a rear spar. The rear spar was initially considered to be continuous (full span). However it was later noted that no buckling modes were present in this area. The mid-spar is discontinuous due to cut-outs on the centre area of the aileron to allow for the tab actuator. Although two mid spars seem to be required based on topological results, it was decided to employ one thicker mid spar to minimise manufacturing costs. Ribs were extended from most hinges up to mid spar. This is mostly based on topological results and it provides the added advantage of minimising mandrel counts for a unitised aileron.

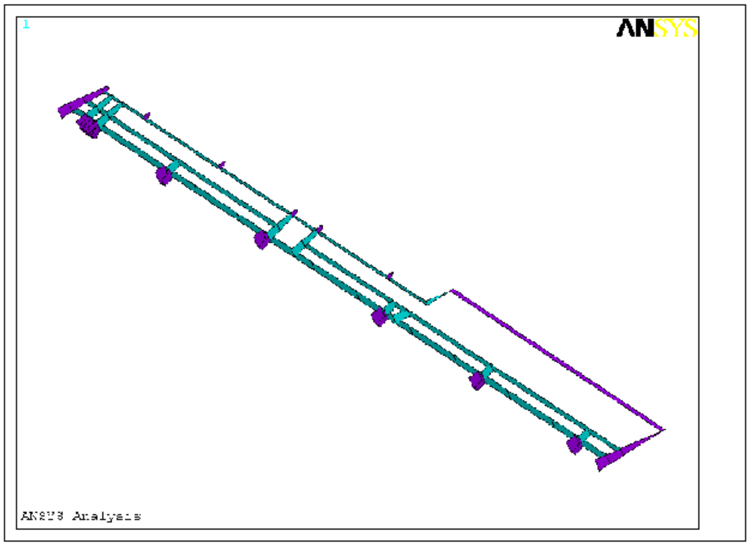


**Figure 5 - Internal Lay-out**

## *Parametric Optimization*

SHELL 63 elements were employed throughout the parametric optimization studies. The design objective pursued throughout the parametric optimization was to minimize buckling (maximise 1st Mode Eigenvalue). In the first instance the position of the mid-spar was chosen as the single design variable. It is important to note that the overall aileron geometry and load pick-up locations (Outer Mould Line (OML), hinge and tab hinge locations, structure forward of front spar) could not be modified as the aileron needed to interface with existing structure and also due to aeroelastic issues. A plot of the 1st Eigenvalue previous to the first parametric optimization run and a fringe plot depicting out of plane displacement are shown on Figures 6 & 7. Convergence was achieved very rapidly after only 6 iterations resulting in an increase in 1st Mode Eigenvalue of approximately 25%. This increase in Eigenvalue was achieved by modifying the mid spar position by only 0.6 inches. A plot showing the optimization history is shown in Figure 8. The weight changes during this optimization run are negligible since the skin thickness for all bays are equal, thus the weight change is given by the change in mid spar height only.

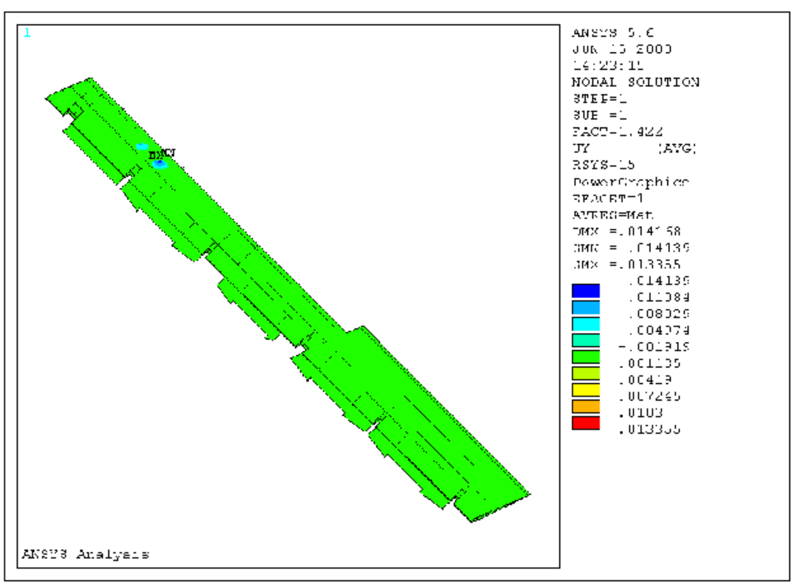


**Figure 6 - 1st Eigenvalue Pre-Optimisation Run**

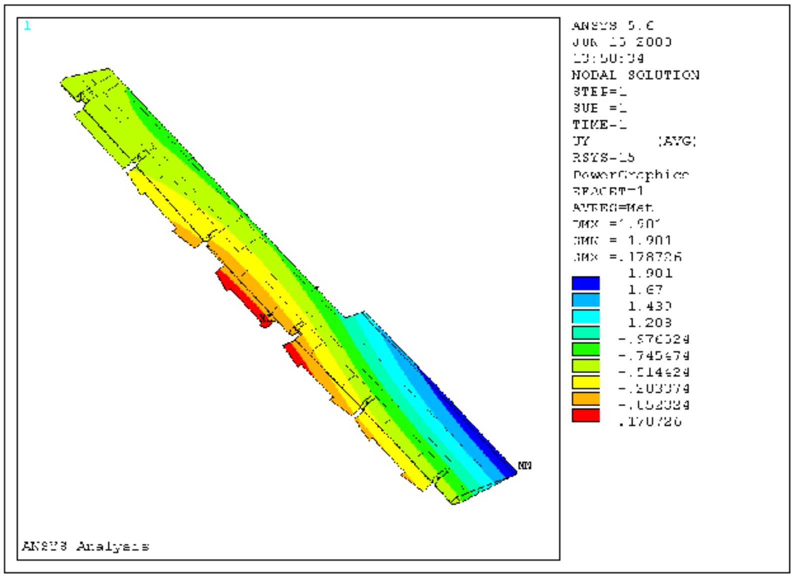


**Figure 7 - Displacement Fringe Plot**

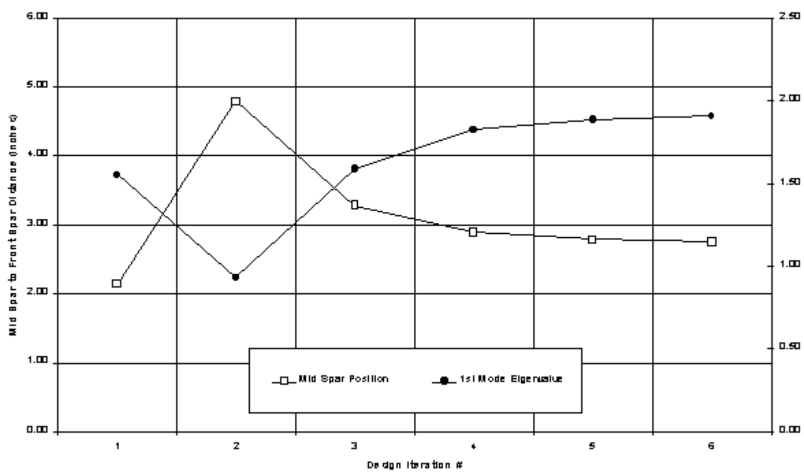


**Figure 8 - Spar Optimization Iteration History**

This study was followed by thickness optimisation whereby an upper and lower constraint was placed on the 1$^{st}$ Mode Eigenvalue (0.8 to 1.0) while the design objective was set as a minimum weight design. In this case the weight was reduced by up to 20 %. A relative wide range had to be placed between upper and lower limits on the 1$^{st}$ Mode Eigenvalue in order to avoid overly constraining the optimization run. The optimization run converged after 8 iterations. The optimization history for this study is shown on Figure 9. An appropriate thickness based on manufacturing constraints (composite ply thickness) was then chosen. The optimum number of plies yielded by the analysis was 4.75 plies of the "New Material" (0.352 mm/ply) and this was rounded up to 5 plies. A plot of the 1$^{st}$ Eigenvalue and a fringe plot depicting out of plane displacement at the completion of the parametric optimization studies and after rounding up to allow for manufacturability are shown on Figures 10 & 11.

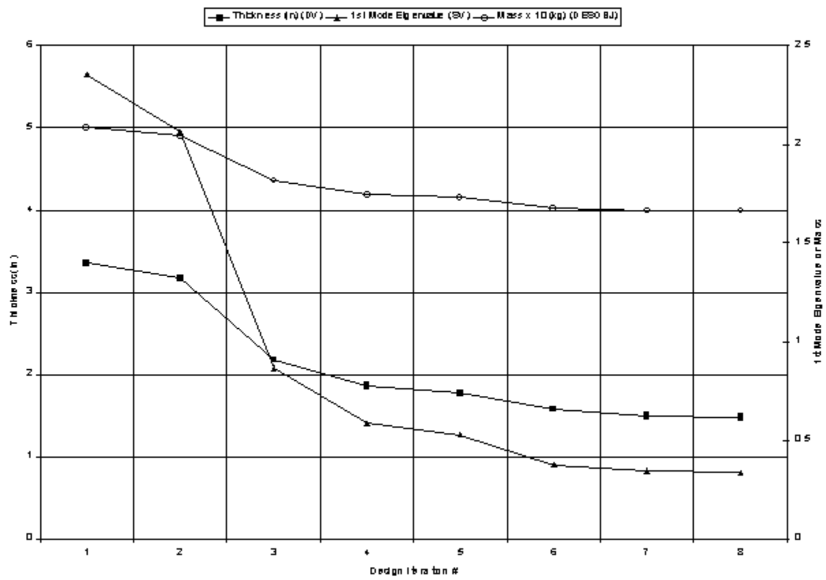


**Figure 9 - Thickness Optimization Iteration History**

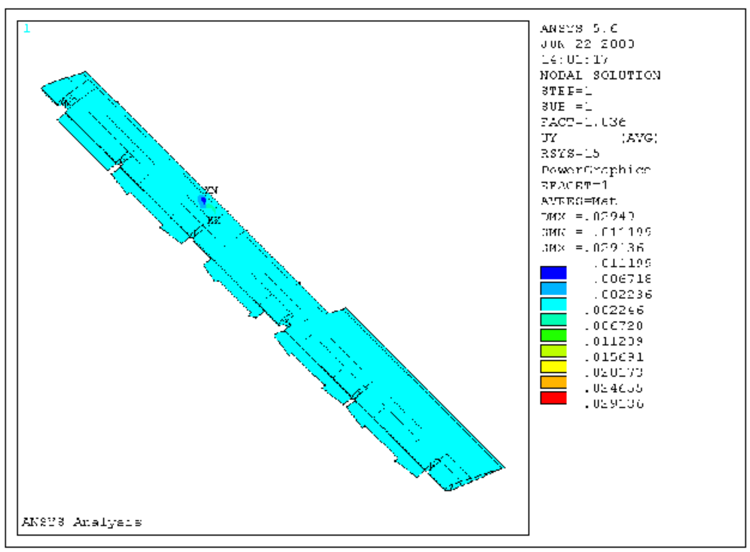


**Figure 10 - 1st Eigenvalue Post-Optimization Run**

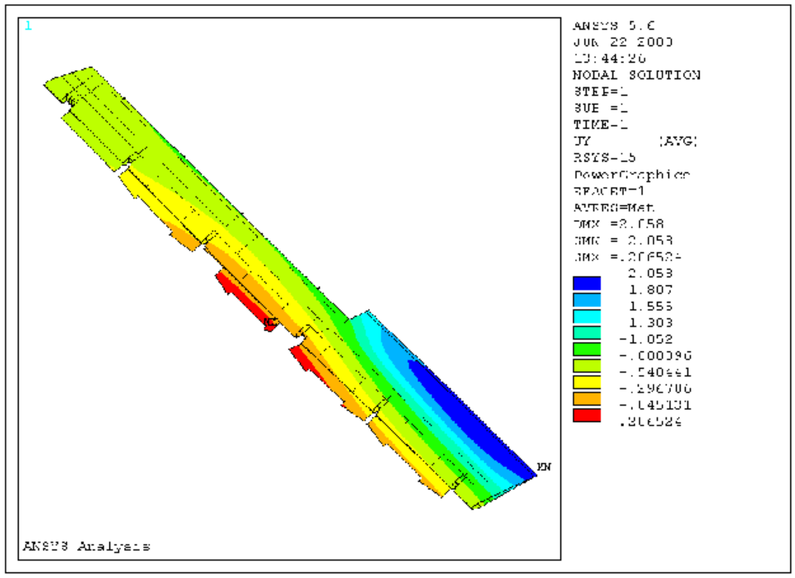


**Figure 11 - Displacement Fringe Plot Post Optimization**

# Analysis Results & Discussion

Aerodynamic smoothness was also checked at the end of the optimization run to ensure all technical requirements were met. This was achieved by fitting a cubic polynomial equation to the out of plane displacements along a critical spanwise location. The cubic polynomial equation represents the mean outer skin profile. The maximum mean slope can be calculated by dividing the wave amplitude by the half wavelength of the actual skin profile. A plot of the actual and mean skin profiles for slope calculation is shown on Figure 12.

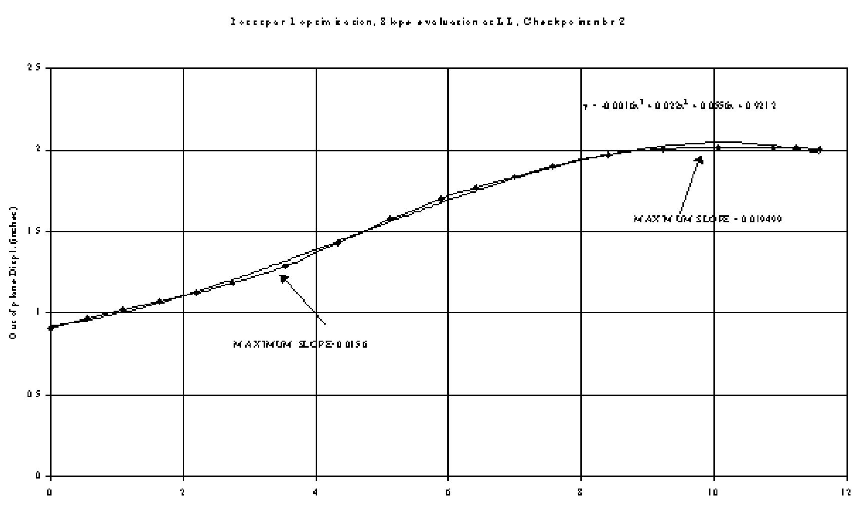


**Figure 12 - Aerodynamic Smoothness Assessment**

Based on the depicted internal structure, two designs were further assessed employing the two chosen materials as per Tables 1 & 2 (Original Material and New Material). The thickness for skins and internal structure of the "New Material" and “Original Material” designs is shown on Table 3.

A result matrix comparing these two designs against technical requirements is shown on Table 4. Weight calculations assume a monolithic construction, thus includes a weight saving of an estimated 1.2 kg for fasteners employed in the aft box.

The complete process of analysing and optimizing the aileron took only 12 days. A large number of options were studied within this period. This is considered to be a significant improvement when compared to the standard methodology of "trial and error" previously employed. The insight gained throughout the analysis also provides opportunities for future analysis of control surfaces either where redesign is concerned or for new projects.

**Table 3:** New Material and Original Material Ply stack-up for skins and internal structure

| PARAMETRIC OPTIMISATION PARAMETERS | | |
|---|---|---|
| | | |
| New Material Thickness (inches) | Original Material Thickness (inches) | Description |
| | | |
| 0.1247 | 0.1299 | Top & bottom skin leading edge |
| 0.3326 | 0.3291 | Top & bottom skin front spar flange region |
| 0.0416 | 0.0433 | Top skin F/S to Spar #1 |
| 0.0416 | 0.0433 | Top skin Spar #1 to Rear Spar |
| 0.0416 | 0.0433 | Top skin Rear Spar to Trailing edge |
| 0.0416 | 0.0433 | Bottom skin F/S to Spar #1 |
| 0.0416 | 0.0433 | Bottom skin Spar #1 to Rear Spar |
| 0.2079 | 0.2079 | Top skin Rear Spar flange region |
| 0.2079 | 0.2079 | Bottom skin Rear Spar flange region |
| 0.0416 | 0.0433 | Bottom skin Rear Spar to Trailing edge |
| 0.2772 | 0.2858 | F/Spar (between H5 & H4 **only**) |
| 0.1109 | 0.1126 | F/Spar ( except between H5 & H4) |
| 0.1109 | 0.1039 | Spar # 1 |
| 0.0832 | 0.0779 | Rear Spar |
| 0.1247 | 0.1300 | Trailing edge (top & bottom skin joined together) |
| 0.1109 | 0.1039 | Actuator rib |
| 0.0831 | 0.0779 | Remaining ribs |
| 0.0693 | 0.0693 | Ibd/Obd rib |
| 0.0831 | 0.0866 | Top skin cut out region |
| 0.0831 | 0.0866 | Bottom skin cut out region |
| 0.0554 | 0.0520 | Top & Bottom skin between inbd rib & hinge 2 |

**Table 4:** Results Matrix

| | New Material | Original Material |
|---|---|---|
| Eigenvalue at LL | 1.036 | 0.995 |
| Maximum Slope at LL (Aerodynamic Smoothness Requirements) | 0.0195 | 0.0158 |
| Maximum Tip Displacement (inches) | 2.058 | 2.28 |
| Weight Composites (lbs.) | 30.33 | 35.73 |

## Conclusion

This paper addresses the use of a recently created design optimization methodology for an aircraft aileron. The work undertaken proves that even when structures are largely constrained, significant gains can be achieved by optimizing internal layouts of structural components. The 1$^{st}$ Eigenvalue was increased by approximately 23 % while the weight of the composite structure was reduced by 20%. Furthermore, the structural internal configuration derived should significantly reduce the manufacturing costs of the composite torsion box.

The productivity enhancements allowed by this tool can be increased further by the customization of certain parts of the analysis and the post-processing of the results. To this end and as part of the START Grant work, S. Rajbhandari et. al. (Reference 6) have developed GUI interfaces to allow for automatic assessment of aerodynamic smoothness and for the calculation of user defined failure criteria for composite materials and its post-processing.

The methodology here described has been successfully employed in a number of control surfaces such as spoilers, rudders and flaps. The customisation and standardisation of these activities is currently being pursued for future projects.

### *References*


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