Adaptive Stiffness Structures for Air Vehicle Drag Reduction

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ABSTRACT

The development of several adaptive internal structures concepts is described that are aimed towards enabling adaptive static aeroelastic shape control of an aircraft wing in flight. It is shown how changes in the position, orientation and stiffness of the internal wing structure can be used to change the bending and torsion stiffness properties of a wing, and hence to control the aerodynamic performance, in particular the lift and drag characteristics. Two approaches that implement the adaptive internal structures technology are described, based upon the rotation and chordwise translation of the spars. Following the description of conceptual studies to illustrate the concepts, the design, manufacture and testing of two wind tunnel models is described. The experimental results were found to show good agreement with static and dynamic aeroelastic behaviour predictions from Finite Element models. The feasibility of implementing the adaptive internal structures approach on full-size aircraft is discussed.

1.0 INTRODUCTION

Since the beginning of powered flight, aeroelastic phenomena have had a significant influence upon aircraft structural design. In particular, as many prototype aircraft have been destroyed due to the occurrence of either flutter or divergence, it has been accepted that aircraft lifting surfaces have to be built to be stiff, and therefore heavy, enough so that neither phenomenon occurs within the desired flight envelope. Indeed, the most common "fix" to deal with flutter problems that might arise within aircraft development programmes is to add extra mass to the structure. This requirement has been termed the "aeroelastic penalty"[1].

Civil and military aircraft are designed to have optimal aerodynamic characteristics (maximum lift/drag ratio) at one point and fuel condition in the entire flight envelope. However, the fuel loading and distribution changes continuously throughout the flight, and aircraft often have to fly at non-optimal flight conditions due to air traffic control restrictions. The consequent sub-optimal performance has more significance for commercial aircraft as they are more flexible than military aircraft and also have fuel efficiency as a performance parameter of far greater importance. There is also much recent interest in High Altitude Long Endurance (HALE) aircraft which are designed to fly for several days at a time and have a greater proportional of fuel to take-off weight than other aircraft, the resulting changes in the aeroelastic shape throughout the flight can be substantial. Fuel efficiency is becoming increasingly important for civil and HALE aircraft, and any approach that enables better aerodynamic performance throughout a flight needs to be investigated and developed.

In recent years there has been a growing interest in the development of aircraft structures that allow aeroelastic deflections to be used in a beneficial manner and to enhance aerodynamic performance[1,2]. For instance, the Active Flexble Wing[3], Active Aeroelastic Wing[4-6] programs investigated the use of using leading and trailing edge control surfaces to control the wing shape. The Morphing Program[7] developed a

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number of active aeroelastic concepts based upon smart materials and structures. In Europe, the 3AS (Active Aeroelastic Aircraft Structures) research program[8] also developed and demonstrated various active aeroelastic concepts, primarily in the areas of adaptive attachments, three surface aeroelastic aircraft and novel aeroelastic leading edge and wing tip devices. The Variable Stiffness Spar (VSS) approach[9,10] demonstrated the use of rotating spars for roll control.

The concept of adapting the shape of an aircraft in flight has been given the generic title of morphing, however, the activity can be divided clearly into two different categories[11]:

- *Planform morphing* – where the aircraft planform is changed. Recent work[11] has investigated the use of telescopic, deployable and variable sweepback wings using a range of mechanical and pneumatic devices. One of the main drivers behind the use of this technology is the capability of changing mission mid-flight, e.g the development of UCAVs that are able to loiter with high aspect ratio wings, but can then change their aspect ratio as they change to an attack role. Other examples have included the use of telescopic wings for roll control. Of course, there are many examples of military aircraft that have flown for many years with variable sweep wings.

- *Performance morphing* – where the lifting surface planform remains the same but the aerodynamic shape (and hence performance) can be changed either through adjustments in the twist and bending behaviour along the wingspan, or changes in the camber and/or the leading and trailing edge shapes. Such a capability could be used to maintain the best possible lift-drag ratio throughout the flight however, there is also the possibility of implementing roll-control (analogous to the Wright Brother's "wing-warping") which has gained some significance recently with the interest in control-surface-free UAVs in order to improve observability characteristics.

Part of the 3AS research programme, as described in this paper, was devoted towards the performance morphing category, and investigated the use of changes in the internal aerospace structure in order to control the static aeroelastic bending and twisting behaviour of a number of simple wings. Other work has examined the use of smart materials (e.g. piezo and shape memory alloys) to achieve this goal[7,12] however, there is still a lot of work and material development required in order to develop the considerable forces required to twist and bend (and maintain that deflection) a wing during flight.

In this paper, the Adaptive Internal Structures concept for control of the wing static aeroelastic shape in-flight is introduced and illustrated with two different approaches: changing the chord-wise position of the spars, and rotating the spars. The design, manufacture and testing of several adaptive aeroelastic wind tunnel models based on the two concepts is described. Comparisons are made with the results obtained from Finite Element simulations. Finally, the feasibility of applying the Adaptive Internal Structures concept to full-size aircraft is discussed.

2.0 ADAPTIVE INTERNAL STRUCTURES

The key idea exploited in the Adaptive Internal Structures approach is to use the aerodynamic forces acting upon the wing to provide the forces and moments to bend and twist the wing, rather than trying to apply the forces via some form of actuator. Consider the schematic of the wing shown in Figure 1, with the lift acting at the aerodynamic centre on the quarter chord. By changing the position of the shear centre of the wing, the bending moment, and hence the amount of twist, will also change. It is envisaged that a far smaller amount of energy is required to adjust the structure compared to that required to twist the wing and to maintain the shape.

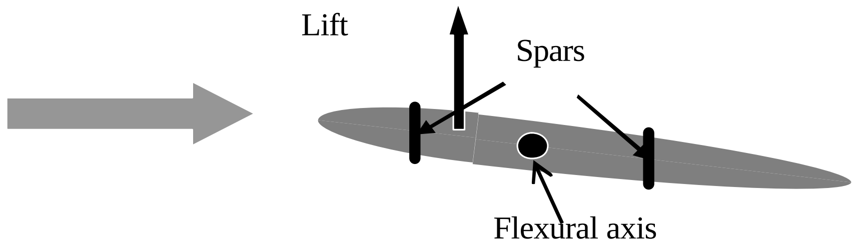

Figure 1. Effect of Position and Orientation of the Spars on the Flexural Axis Position.

Such an approach is very attractive for adaptive aeroelastic concepts, where the lifting surface deflections could be adjusted gradually throughout the flight to maintain an optimal aerodynamic performance. The concept could also be applied for roll control and gust or manoeuvre load alleviation, however, there would be a far greater requirement in these cases for the structural stiffness to change rapidly. The actual application, and how the adaptive internal structure concept was applied, would have a great influence upon whether the required roll or load alleviation performance could be achieved, and this has been investigated elsewhere.

It is envisaged that the adaptive internal structures concept is not suitable for high frequency applications (e.g. flutter or buffet loads suppression.). It should also be noted that the approach is best applied to the tip end of the lifting surface, where the structural stiffness is less and also the influence upon the aerodynamic forces is greatest. Also, only some elements of the wing internal structure would need to be adaptive.

Reference needs to be made to the Variable Stiffness Spar (VSS) work[10] that investigated and demonstrated[9] the use of rotating spars to provide roll control of a wing and to influence the control effectiveness. Part of the work described in this paper builds upon the VSS research, but is aimed towards changing the wing shape using multiple spars with the goal of improving the lift / drag characteristics.

3.0 CONCEPTUAL MODELLING

Consider the aeroelastic analysis of a simple high aspect ratio rectangular wing in order to demonstrate how the static and dynamic aeroelastic behaviour can be controlled through movement (either translation or rotation) of the spars. As the purpose is to demonstrate the concept, only a rudimentary aeroelastic analysis has been employed. Modified strip theory aerodynamics was implemented along with thin walled structural theory and a Rayleigh-Ritz assumed shapes approach in order to study the static and aeroelastic behaviour of the wing, considering only the wing box itself. Of interest is the variation of the torsion constant, the position of the shear centre, the static twist, and also the effect upon the flutter and divergence speeds in relation to the position or orientation of the spars. All of these parameters can be calculated explicitly using this analytical approach, which is not the case if a FE model were used.

Schematics of the proposed concepts are shown in Figures 2 and 3. In the first, the simple rectangular wing box is made up of three identical uniform spars. The outer two spars remain in the same position, whereas the middle spar can be moved anywhere within the wing box. By moving the chord-wise position of the central spar, it is possible to change the torsional stiffness and also the position of the local shear centre, but the bending stiffness remains constant. In the second approach, the spars are able to rotate, thereby changing their bending stiffness in both vertical and horizontal directions as well as the torsional stiffness and shear centre position. In both cases, changing the wing section bending and torsional stiffness characteristics leads to changes in aeroelastic twist and bending.

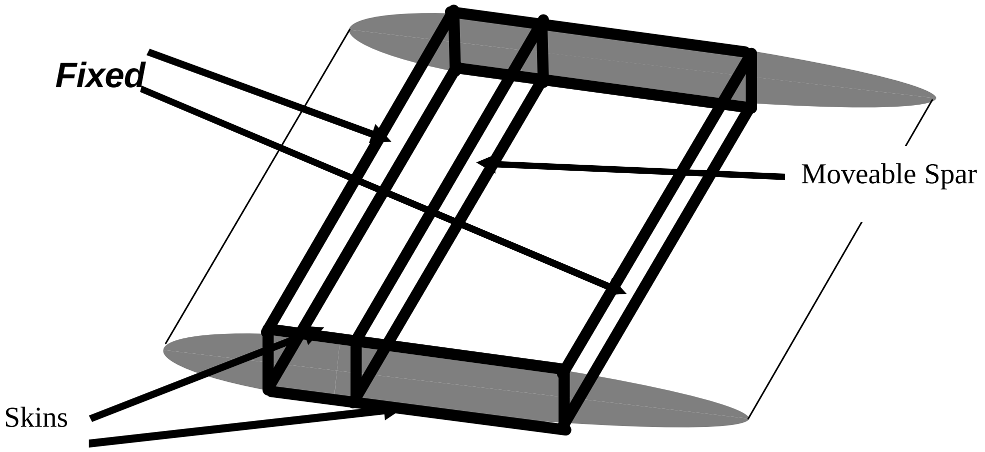

Figure 2. Rectangular Wing Box with Movable Central Spar

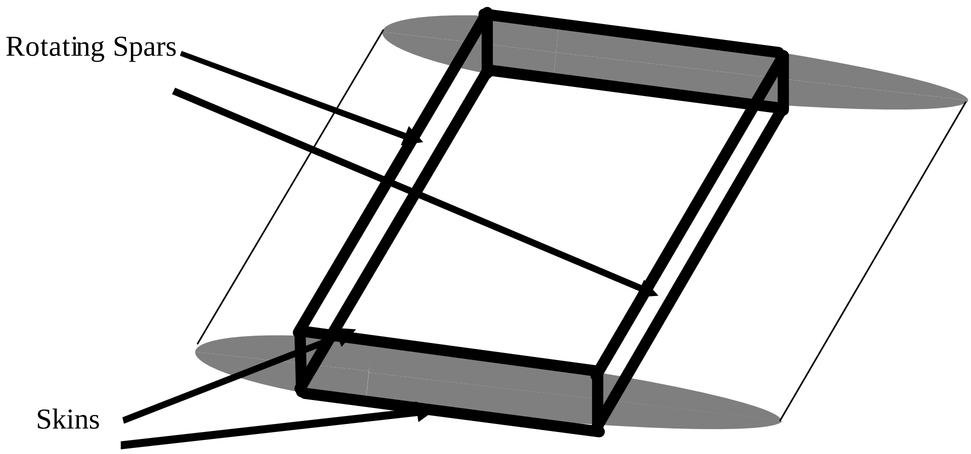

Figure 3. Rectangular Wing Box with Rotating Leading and Trailing Edge Spars

Figure 4 shows the changes in the torsion constant, shear centre position, wing tip twist, flutter and divergence speeds with respect to the position of the middle spar for the moving spar concept. All the results have been normalised with respect to the values found with the spar in the central position. These results demonstrate how the aeroelastic twist can be controlled, simply by moving the spar. However, the twist is not simply a linear relation of the spar position as although the torsion constant and shear centre position have the expected symmetric behaviour with the maximum value occurring when the spar is placed at the central position, the aerodynamic moment is related to the distance of the shear centre from the aerodynamic centre at the quarter chord.

The aeroelastic characteristics are dependent upon not just the torsional and bending (constant in this case) stiffness, but also the distance between the flexural axis and the aerodynamic centre. Although the bending stiffness does not change, there is still a coupling between the bending and torsion behaviour in the aeroelastic model. Inspection of the bottom three plots in Figure 4 demonstrates the relative complexity of this behaviour even for such a simple case. As the spar is moved from forwards to aft, the twist of the wing reduces. The flutter speed increases as the spar is moved aft until it reaches a maximum at a position of around 70% and then it reduces. However, the divergence speed can be seen to rise steadily as the middle spar is moved from one side to the other.

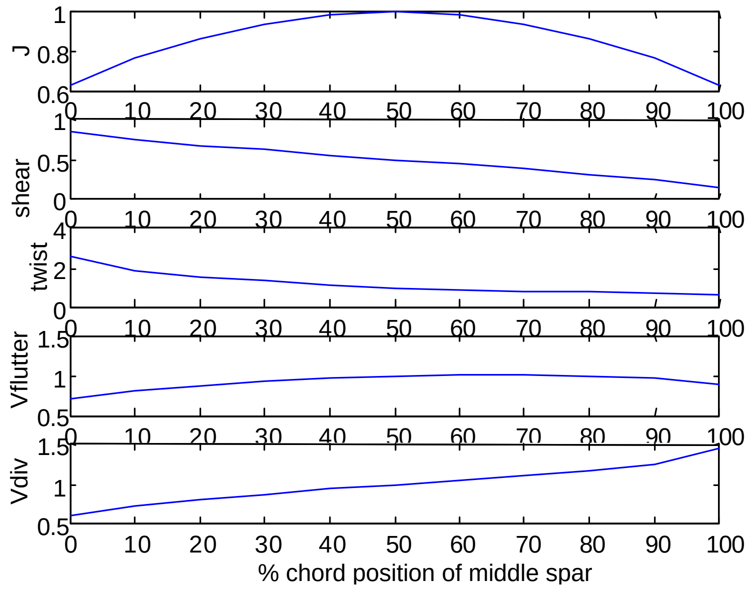

Figure 4. Moving Spar. Normalised Values of Torsion Constant, Shear Centre, Tip Twist, Flutter Speed and Divergence Speed for the Rectangular Wing for Different Positions of the Centre Spar.

The rotating spar concept was modelled in a similar way for a two spar wing box model except that both the leading and trailing edge spars could be rotated between 0^o and 90^o. Figure 5 show the second moment of area calculated for all orientations of both spars, and similar plots can be drawn for the torsion constant, shear centre position, wing tip twist, flutter and divergence speeds. The second moment of area and torsion constant values are directly related to the orientation of the spars and are greater the closer that they are to 90^o. The position of the shear centre depends upon the relative rotation of the spars as it moves towards the stiffest one. As with the first concept, the behaviour of the tip twist, flutter and divergence speeds is not simple to predict for, although a reduced torsional stiffness leads to larger deflections and reduced flutter speeds, the behaviour is complicated by the position of the shear centre relative to the aerodynamic centre.

4.0 DESIGN OF PROTOTYPE DEMONSTRATORS

Having assessed the feasibility of both concepts, a number of prototype demonstrators were designed and constructed via the use of several Finite Element models. Figures 6 and 7 show the wing tunnel models that were designed in order to assess the feasibility of implementing the moving and rotating spar concepts described above. The moving spar model differs slightly from the model described above numerical example in that there were two fixed outer spars and two inner spars whose chord-wise position could be varied. All of the wind tunnel models were rectangular, untapered wings with semi-span 0.775m and chord 0.25m. Being an aeroelastic study, the models were designed to be reasonably flexible and to fit in the test section of one of the low-speed wind tunnels at the University of Manchester.

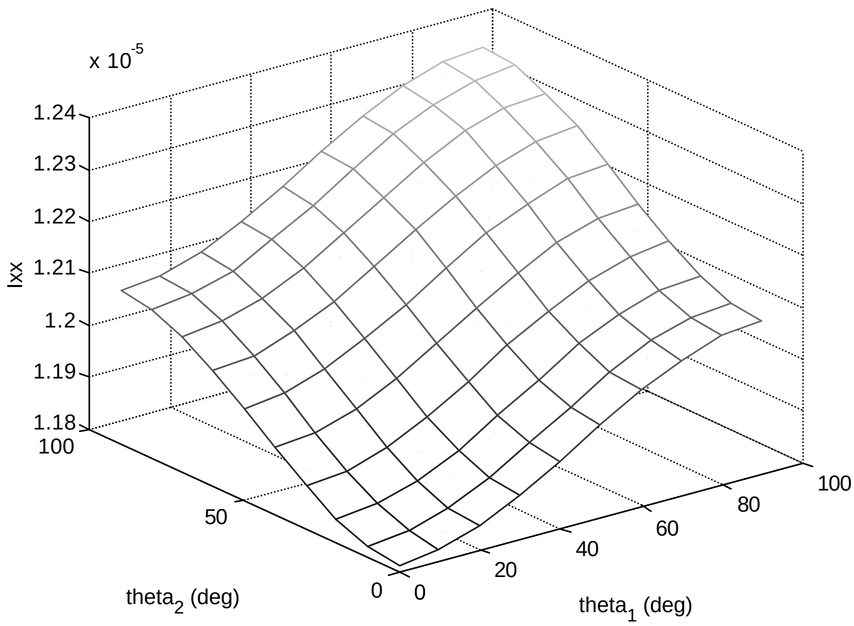

Figure 5. Change of I_{xx} For Different Angles of Front and Rear Spar Rotation

Two versions of the moving spar concept were assessed, one where the position of the moving spars was controlled using a worm-drive driven with an electric motor, and in the other, a pneumatic ram. The main structure (see Figure 6) was constructed of aluminium and comprised of five ribs, two fixed spars positioned horizontally near the leading and trailing edges, and two moveable spars positioned vertically. The moveable spars could translate in the chord-wise direction along the tracks in the ribs. For the purpose of the wind tunnel testing, specially formed balsa blocks were used to form the leading and trailing edges, and a thin polyethylene skin was added to provide the aerodynamic surface.

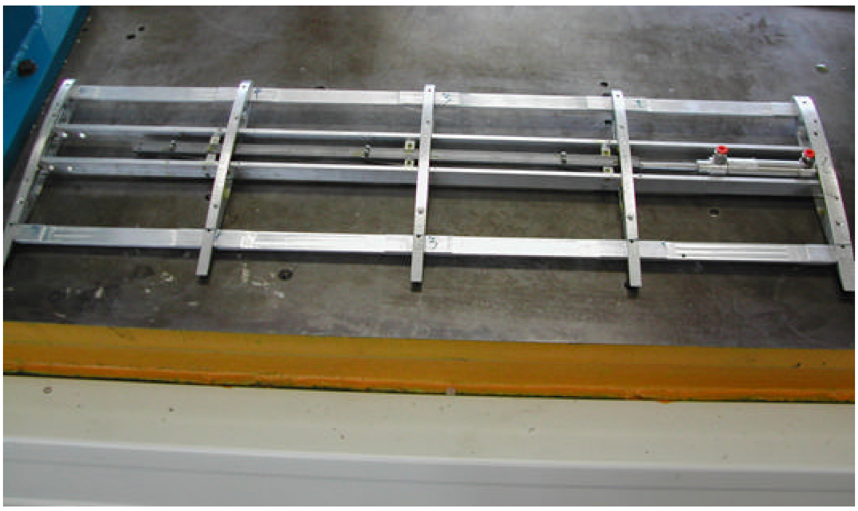

Figure 6. Moving Spar Prototype Wind Tunnel Model.

The orientation of the rotating spars was controlled via four motors positioned at either end of the spars, as seen in Figure 7, and then attached to the ribs. Note that for both of these concepts, and unlike a traditional aircraft wing design, the aerodynamic loads are transmitted from the skins to the ribs and then onto the moving or rotating spars. Care has to be taken to ensure that these load paths are followed and that the moving/rotating spars do carry the load in all possible positions / orientations.

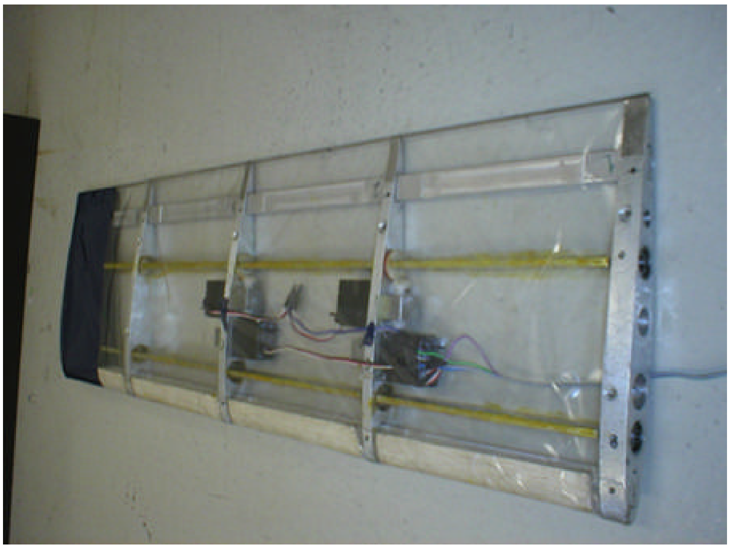

Figure 7. Rotating Spar Model Showing Motors to Control Twist

In order to obtain an initial assessment of the performance of both prototype models, as well as providing comparative data for the FE models (as shown in Figure 8), the prototype models were subjected to static loads and also vibration testing. These initial static loading tests also provided confirmation that the spars could be moved or rotated, as required, whilst carrying a significant static load. Unfortunately the pneumatic ram device had problems maintaining the maximum separation of the moving spars concept at the highest load considered, and therefore this device was consequently abandoned in favour of the worm-drive. It took roughly 0.5 seconds for the spars to rotate from minimum to maximum rotation, whereas the time to achieve minimum to maximum separation of the moving spars was 10 seconds.

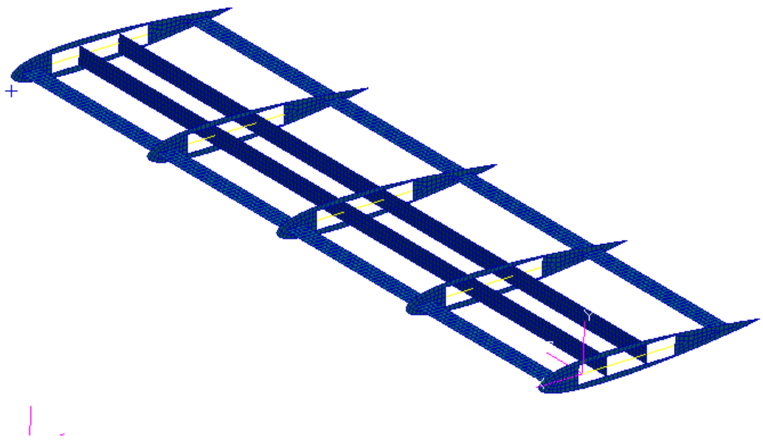

Figure 8. Typical Finite Element Model of Adaptive Internal Structures

5.0 NUMERICAL AEROELASTIC MODELLING

A dynamic aeroelastic analysis was performed using the NASTRAN doublet lattice approach and pk algorithm for both concepts and different spar positions and orientations. From the resulting vg diagrams it was possible to determine whether the initial instability would be divergence or flutter. Figures 9 and 10 show the stability boundary envelopes for each of the two concepts, mostly flutter but there are several instances when divergence is the instability mechanism. These plots also illustrate the variation in the speed at which the instability can occur, in these cases almost a 50% difference between the minimum and maximum value. Whilst the aim of this work on the adaptive internal structures approach is to focus on the static aeroelastic behaviour and aerodynamic performance, it must of course be ensured that flutter and divergence do not occur.

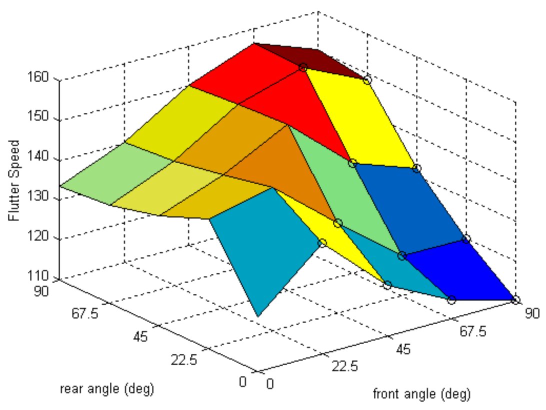

Figure 9 – Flutter and divergence (o) speeds for the rotating spar concept.

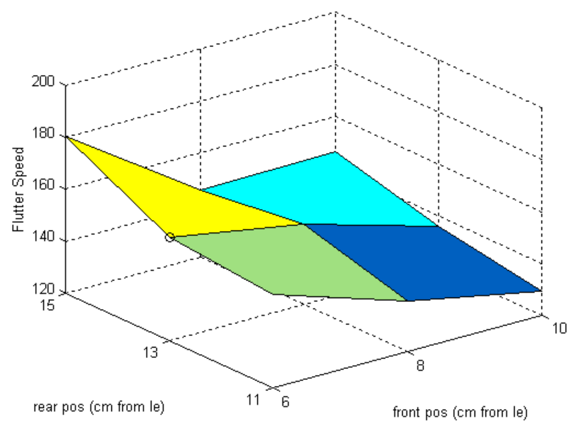

Figure 10 – Flutter and divergence (o) speeds for the Moving Spar concept

The ZAERO software was used to calculate the lift and drag coefficients for both concepts at a range of speeds. The results shown in Figures 11 and 12 are for the 50m/s case and illustrate that even for this simple case, it is feasible to achieve a range of values.

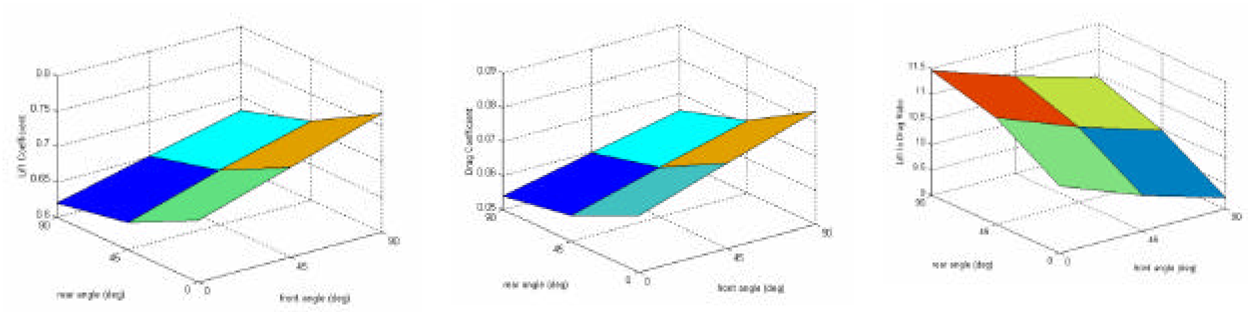

Figure 11. C_L, C_D and C_L/C_D Variation for the Rotating Spar Concept

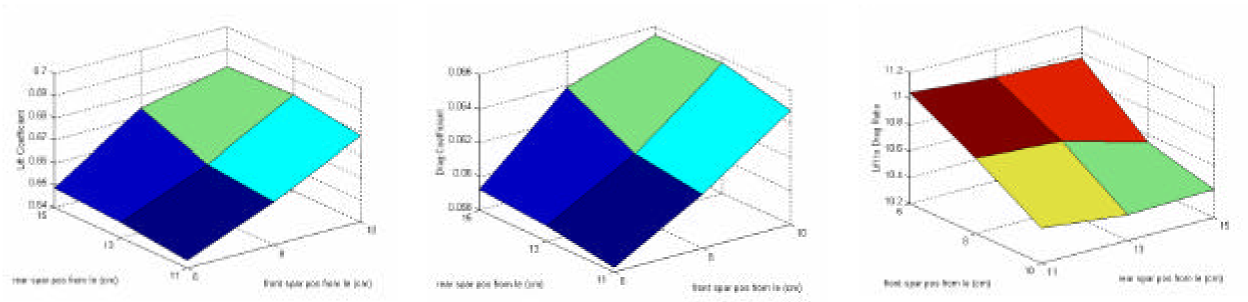

Figure 12. C_L, C_D and C_L/C_D Variation for the Moving Spar Concept

6.0 DRAG MINIMISATION

Aircraft are traditionally designed so that they have the best aerodynamic performance, i.e. optimum lift/drag ratio at some cruise configuration, however as shown in Figure 13, they often fly at different parts of the flight envelope and the fuel loading also varies.

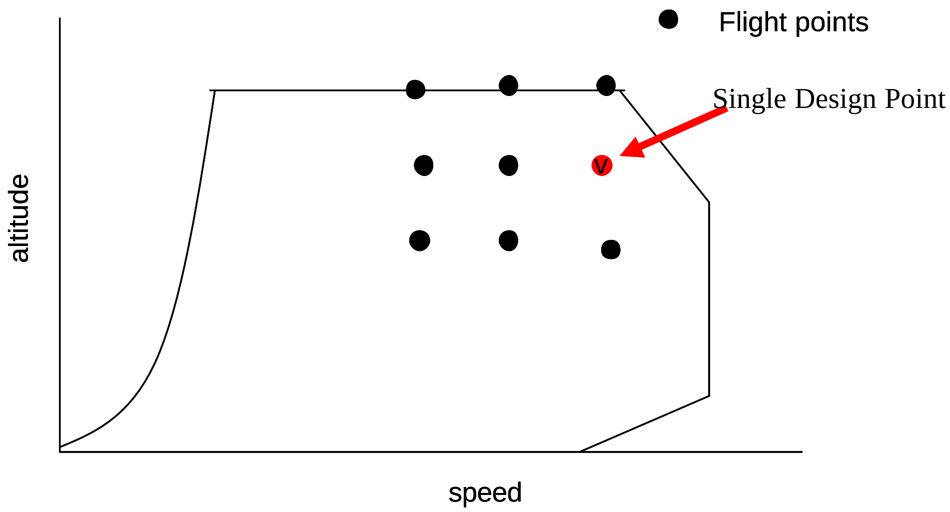

Figure 13. Flight Envelope Showing Optimum Design Point and Sub-Optimal Design Points

This also gives an indication of the how adaptive aeroelastic structures can be used to obtain optimum aerodynamic performance. In order to keep the aircraft flying at the same altitude but at differing speeds, the internal structure needs to be changed in order to give the same lift (allowing for trim considerations) but also minimising the drag. The rotating spar model that was considered was extended so that each of the spar elements between ribs was allowed to rotate between 0 and 90 degrees. Figure 14 shows the different lift and drag coefficients that can obtained at one flight envelope point. It can be seen that there are a range of configurations that give the same lift but different drag values.

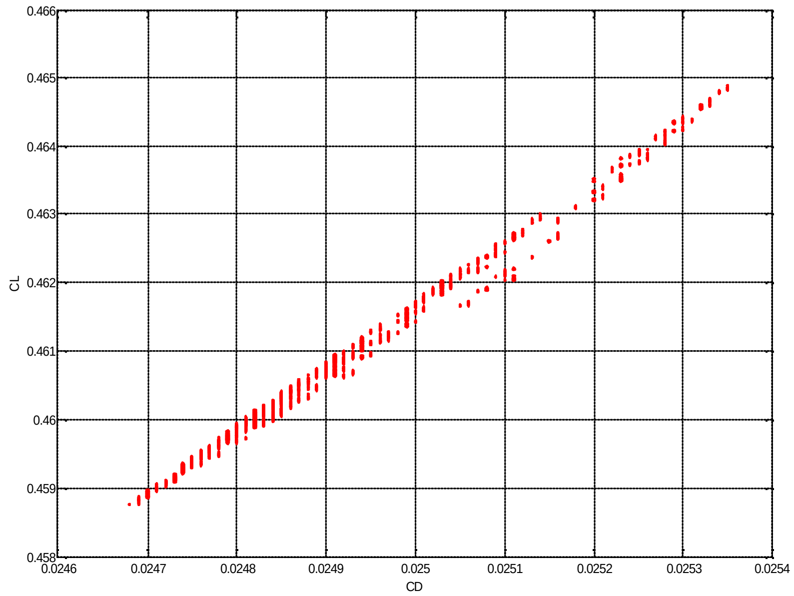

Figure 14. Lift vs. Drag Coefficients for Different Spar Orientations

At each flight point the minimum drag for a given lift value can be determined and the orientation of the spars noted. An optimisation process than then be applied to determine the best spar orientations over the entire flight envelope. Weighting functions can also be introduced that favour movement of the furthest outboard spars, as these will carry less aerodynamic load and will be thinner than the in-board spars, and also the minimum number of spars that need to be altered. Current work is investigating the use of a Genetic Algorithm approach to carry out this optimisation. Initial results show that the greatest effect can be achieved through moving the spars shown in Figure 15.

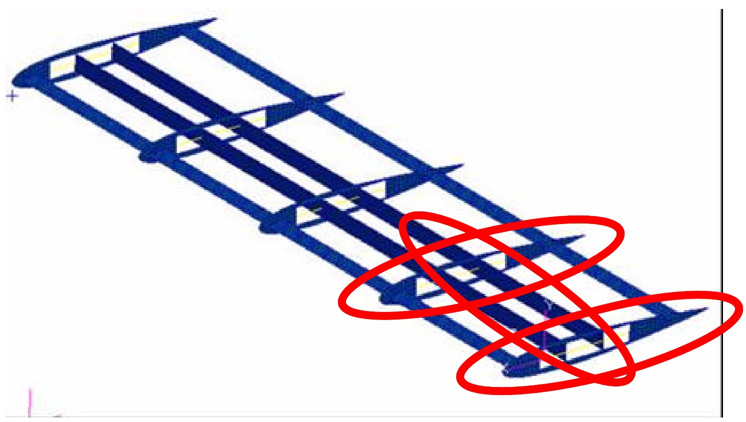

Figure 15. Spars That Have Most Effect on the Drag.

7.0 CONCLUSIONS

Two adaptive stiffness approaches have been introduced, based upon either moving spars chordwise or rotating them. It has been shown that it possible to influence the static aeroelastic behaviour of simple wings via changes in the internal structure and to achieve minimum drag whilst maintaining the same lift. The approach needs to be considered on full-scale aircraft models in order to determine whether the benefits are substantial enough to apply in practice.

8.0 ACKNOWLEDGMENTS

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9.0 REFERENCES

[1]Kusmina, S et al. ”Review and Outlook for Active and Passive Aeroelastic Design Concepts for Future Aircraft“ ICAS 2002.

[2]Pendleton, E., ‘Back to the Future - How Active Aeroelastic Wings are a Return to Aviation’s Beginnings and a Small Step to Future Bird-like Wings’, RTO-SMP Panel Meeting. 2001.

[3]Perry R, Cole S.R. and Miller G.D., “ Summary of an Active Flexible Wing Program” J.Aircraft v32 n1 Feb 1995 pp 10-15

[4]Flick, P. & Love, M.‘The Impact of Active Aeroelastic Wing Technology on Conceptual Aircraft Design’. AVT Panel. Ottawa. 1999.

[5]Pendleton, E., Bessette, D., Field, P., Miller, G. & Griffen, K., ‘ Active Aeroelastic Wing Flight Research Program and Model Analytical Development’ AIAA J.Aircraft v37 n4 July 2000 pp 554-561.

[6]Heeg, J., Spain, C.V., Florance, J.R., Wisemann C.D., Ivanco, T.G., DeMoss, J.A. & Silva, W.A., “Experimental Results from the Active Aeroelastic Wing Wind Tunnel Test Program. 46th AIAA Structures, Structural Dynamics and Materials Conference 2005. AIAA 2005-2234.

[7]Wlezien-R-W; Horner-G-C; McGowan-A-R; Padula-S-L; Scott-M-A; Silcox-R-J; Simpson-J-O. “The Aircraft Morphing Program” SPIE Smart structures and Materials Meet 1998. pp 176-187

[8]Schweiger, J. & Suleman, A., “The European Research Project – Active Aeroelastic Structures” CEAS Int Forum on Aeroelasticity and Structural Dynamics 2003

[9]Florance J.R., Heeg, J. Spain C.V., Ivanco, T.G., Wieseman C.D, & Lively P.S., “Variable Stiffness Spar Wind-Tunnel Model Development and Testing”. 45th AIAA Structures, Structural Dynamics and Materials Conference 2004 AIAA 2004-1588.

[10]Chen, P.C., Sarhaddi, D., Jha, R., Lui, D.D., Griffin, K. & Yurkovich, R., “Variable Stiffness Spar Approach for Aircraft Manoeuver Enhancement Using ASTROS” AIAA J.Aircraft v37 n5 Sept 2000 pp

865-871.

[11]Bae, Jae-Sung; Seigler, T Michael; Inman, D.J., Aerodynamic and Static Aeroelastic Characteristics of a Variable-Span Morphing Wing" J.Aircraft v42 n2 pp 528-534 2005.

[12]Cesnik, C.E.S. & Brown, E.L., "Active Warping Control of a Joined-Wing Airplane Configuration" 44th AIAA Structures, Structural Dynamics and Materials Conference 2003 AIAA 2003-1715.