On the effectiveness of active aeroelastic structures for morphing aircraft

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ABSTRACT

This note assesses the benefits of active aeroelastic structures (AAS) in enhancing flight performance and control authority. A representative AAS concept, whose torsional stiffness and shear centre position can be altered depending on the instantaneous flight condition, is employed in the wing of a medium altitude long endurance (MALE) UAV. A multidisciplinary design optimisation (MDO) suite is used in this study. It turns out that AAS can be very effective when used for enhancing control authority of the vehicle but have limited benefits in terms of flight performance (lift to drag).

NOMENCLATURE

A enclosed area (m^2)
D drag (N)
ds infinitesimal segment along the perimeter of the closed section (m)
G shear modulus (N/m^2)
J torsion constant (m^4)
L lift (N)
Lr rolling moment (Nm)

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sc shear centre position (% chord)
t_{eq} wall thickness (m)
U airspeed (ms^{-1})
W UAV weight (N)
N yawing moment (Nm)
θ twist angle (radian)

Subscripts

dd design dive
div divergence
fr flutter

1.0 INTRODUCTION

Active aeroelastic structures (AAS) are a subset of adaptive structures that allow significant performance improvements by manipulating the aerodynamic profile of a lifting surface, without the need for large planform modifications that typically require complex and heavy mechanisms. Traditional design strategies avoided flexible wing designs to prevent aeroelastic problems and maintain structural integrity over a wide range of flight conditions. This resulted in significant weight penalties, typically ranging from 2% to 5% of the structural wing weight(1) which penalised the aircraft performance and increased fuel burn. On the contrary, AAS exploit the aeroelastic deformations due to structural flexibility in a beneficial manner in order to enhance flight performance. The authority of conventional control surfaces can also be augmented via AAS, thus leading to flexible and lighter wing designs. Since AAS use the external aerodynamic loads to deform and maintain their displaced shape, this may reduce the actuation energy requirements associated with these structures.

AAS seems to be a very attractive and promising alternative to achieve morphing capabilities. Recently, the use of AAS to enhance flight performance and enhance control authority and stealth characteristics for air-vehicles has been under thorough investigation in a number of research programs and projects across the world. In the USA, both the Active Flexible Wing (AFW) program(2) and the Active Aeroelastic Wing (AAW) program(3,4) investigated the use of flexible wing structures coupled with leading and trailing edge control surfaces. The structural deformations of an advanced fighter wing were manipulated in order to eliminate aileron reversal problems at large dynamic pressures and to maximise the rolling performance according to design intent without using the horizontal tail to augment roll performance. Furthermore, Griffin *et al*(5) investigated the use of a smart spar concept to vary the torsional stiffness and to control the aeroelastic behaviour of a representative wing; this design concept also aimed to enhance the roll rate of high performance aircraft at high dynamic pressures. The solution proposed was based on the simultaneous actuation of control surfaces and the modification of the wing torsional stiffness using the aforementioned smart spar concept. The latter has a web that can either transfer shear between the upper and lower spar caps or disable such load transmission mechanism. This is achieved by allowing the smart spar to move from a reference position along the leading edge to a diagonal arrangement where the front caps at the wing root are connected to the aft most ones at the wing tips. Similarly, Chen *et al*(6) developed the variable stiffness spar (VSS) concept to vary the torsional stiffness of the wing and again enhance the roll performance. Their VSS concept consisted of a segmented spar having articulated joints at the connections with the wing ribs and an electrical actuator capable of rotating the spar through 90º. In the horizontal position, the segments of the spar are uncoupled and the spar offers no bending stiffness. In the vertical position, the segments join completely and the spar provides the maximum torsional and bending stiffness. The concept allows the stiffness and aeroelastic deformations of the wing to be controlled depending on the flight conditions.

Nam *et al* (7) took the VSS solution a step forward and developed the torsion-free wing concept. This aimed to attain a post-reversal aeroelastic amplification of wing twist. The primary structure of the torsion free wing consists of two main parts. The first is a narrow wingbox tightly attached to the upper and lower wing skin in order to provide the basic wing torsional stiffness. The second part consists of two variable stiffness spars placed near the leading and trailing edges, passing through all of the ribs. Nam *et al*. demonstrated that the torsion-free wing can provide significant aeroelastic amplification, leading to an increase in roll-rate between 8% and 48% over the baseline performance in the worst possible flight conditions. Florance *et al*(8) investigated the use of the VSS concept to exploit the wing flexibility and to improve the aerodynamic performance of the vehicle. Their wing incorporated a spar with a rectangular cross-section that runs from the wing root up to 58% of the overall wing semi-span. The spar is used to change the wing bending and torsional stiffness as it rotates between vertical and horizontal positions.

In Europe, the Active Aeroelastic Aircraft Structures (3AS) research project(9-11) which involved a consortium of 15 European partners in the aerospace industry and was partially funded by the European Community, focused on developing active aeroelastic design concepts through exploiting structural flexibility in a beneficial manner. The final aim was to improve the aircraft aerodynamic efficiency. One of the novel concepts proposed was the all-moving vertical tail (AMVT) with a variable torsional stiffness attachment(12,13). The AMVT concept achieved a smaller and lighter fin while maintaining stability and rudder effectiveness for a wide range of airspeeds. The AMVT employs a single attachment and the position of the attachment can be adjusted in the chord-wise direction relative to the position of the centre of pressure to achieve aeroelastic effectiveness above unity(12). Furthermore, the 3AS project investigated a variety of variable stiffness attachments and mechanisms for the AMVT concept including a pneumatic device developed at the University of Manchester(13). As part of the 3AS project, Cooper *et al*(14-16) investigated two active aeroelastic structure concepts that modify the static aeroelastic twist of the wing by modifying its internal structure. The first concept exploited the chord-wise translation of an intermediate spar in a three spars wingbox in order to vary its torsional stiffness and the position of the shear centre. The second concept was similar to the VSS concept where rotating spars are employed to vary the torsional and bending stiffness as well as the shear centre positions. Prototypes of such concepts were built and tested in the wind tunnel to examine their behaviour under aerodynamic loadings.

The majority of the studies listed above focused on AAS for flight control purposes but rarely considered the use of these structures to enhance operational performance through manipulating the lift distribution. The design of future aircraft urges the need to maximise the functionality of single systems to maximise synergy, reduce complexity, and reduce operating cost. Therefore, this note assesses the multi-functionality capability of AAS in improving operational performance and control authority to maximise synergy on-board a medium altitude long endurance (MALE) UAV. A representative AAS concept similar to the Adaptive Torsion Wing (17-20) is considered for this study. Then concept consists of a wingbox whose torsional stiffness and shear centre position be altered depending on the instantaneous flight condition. Then it is integrated with the rectangular wing of the MALE UAV to allow aeroelastic deformations. The wingbox is modelled as an Euler-Bernoulli beam with a rectangular thin-walled closed cross-section whose torsional stiffness (*GJ*) can be estimated from the second Bredt-Batho equation as

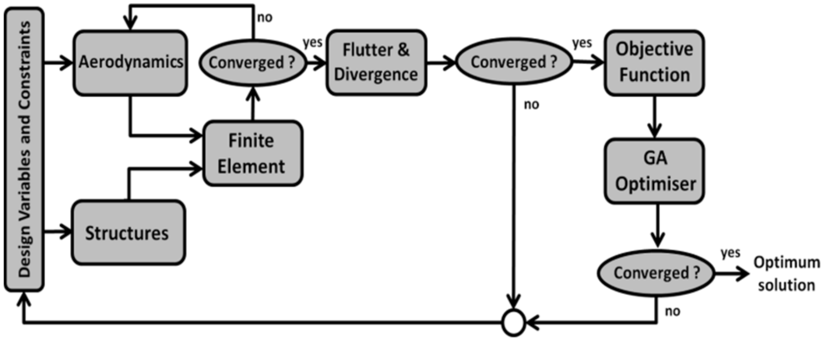

Figure 1. Flowchart and relational diagram of the MDO Suite.

Table 1
The UAV's specifications

UAV specifications	**Values**
Wing area	$22{\cdot}44m^2$
MTOW	800kg
Aerofoil	NACA 4415
Cruise speed	$60ms^{-1}$
Design dive speed	$\approx 82ms^{-1}$
Span	12m
Chord	1·87m
Wing loading	$35{\cdot}70kg/m^2$
Shear centre position	42% chord

$$GJ = \frac{4GA^2}{\oint \frac{ds}{t_{eq}}} \quad \ldots (1)$$

where G is the shear modulus, J is the torsion constant, A is the enclosed area, t_{eq} is the equivalent wall thickness, and ds is an infinitesimal segment along the perimeter.

2.0 MDO SUITE

To perform this evaluation study, a low-fidelity multidisciplinary design optimisation (MDO) suite was developed and employed. The suite consists of a genetic algorithm (GA) optimiser coupled with the tornado vortex lattice method (VLM)[20], a structural and shear centre model, a finite element (FE) model, and flutter and divergence checks, as shown in Fig. 1. Ajaj *et al*[21,22] provided further details about the suite.

The specifications of the UAV are listed in Table 1.

The geometry of the UAV in Tornado VLM is shown in Fig. 2.

To maximise the benefits of the concept and to accurately control the spanwise aeroelastic twist, each semi-span of the flexible wing is discretised into five equal partitions as shown in Fig. 3. The torsional stiffness and shear centre position of each partition are allowed to vary. The contribution of the connecting ribs to the torsional stiffness is neglected in this work. The design of the structure is beyond the scope of this note and will be discussed in future work.

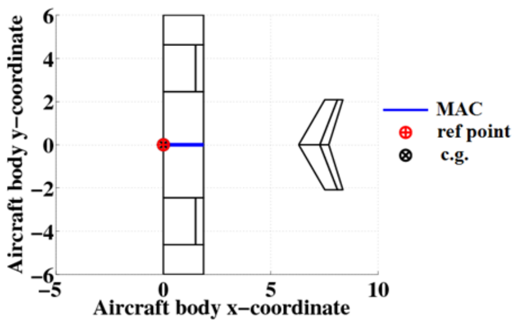

Figure 2. The geometry of the UAV in Tornado.

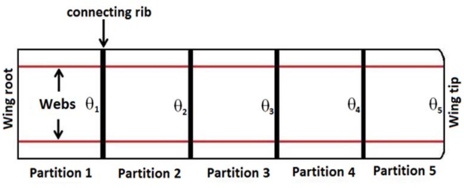

Figure 3. The multi-partition flexible wing.

3.0 FLIGHT PERFORMANCE

The baseline UAV has an aerodynamic efficiency factor of 20. The objective of the performance study is to maximise the aerodynamic efficiency factor (lift-to-drag ratio) at the start of cruise using the flexible wing concept where the vehicle is flying with an airspeed of 60ms^{-1} at 3,050m. The MDO suite generates the different wing configurations having different spanwise torsional stiffness and shear centre positions. GA runs are performed between flight speeds of 20ms^{-1} to 60ms^{-1} to find the minimum drag speed. Once the minimum drag speed is achieved, the optimiser assesses the aerodynamic efficiency and generates a new individual. The same process is repeated until the optimum configuration is found. The UAV is trimmed at each flight speed by adjusting the angle of attack. Two scenarios are examined here. In the first one, the wing initial configuration has no geometric pre-twist while in the second the initial configuration of the wing has built-in geometric pre-twist.

Scenario I: without geometric twist

The initial configuration of the wing has no geometric pre-twist, and the improvement in the aerodynamic efficiency has to be achieved from the aeroelastic twist induced by the airflow on the wing by altering its torsional stiffness and shear centre position are altered. Table 2 summarises the optimisation problem.

Scenario II: with geometric twist

To enhance the benefits of the concept a new set of design variables are added. These new design variables are the geometric (built-in) twists of each of the wing partitions. This allows the spanwise lift distribution to be controlled using both the geometric and aeroelastic twists. Table 3 summarises the new optimisation problem.

In Tables 2 and 3, GJ_i is the torsional stiffness of the ith partition, sc_i is the shear centre position of the ith partition, and θ_i twist at the outboard end of the ith partition. Since the wing and web positions are symmetric (with respect to the aircraft centreline) the total number of design variables is 10 for Scenario I and 15 for Scenario II as the geometric twist at the root of the wing is set to zero. A GA population of 50 generations, with 50 individuals was selected for Scenario I, while a population of 100 generations, with 75 individuals, was selected for Scenario II because the number of design variables has increased.

For Scenario I, the optimum configuration has an aerodynamic efficiency factor of 20, which is equal to the baseline efficiency factor. This indicates that when the torsional stiffness and shear

Table 2
Without geometric twist

Objective	**Maximise (*L/D*)**
Variables	GJ_i sc_i $i = 1, 2, \ldots, 5$
Constraints	$195\text{kNm}^2 \leq GJ_i \leq 700\text{kNm}^2$ $38\% \leq sc_i \leq 48\%$ altitude = 3,050m $L = W$ $U_{div} \leq 1{\cdot}25\, U_{dd}$ $U_{fr} \leq 1{\cdot}25\, U_{dd}$

Table 3
With geometric twist

Objective	**Maximise (*L*/*D*)**
Variables	GJ_i sc_i θ_i $i = 1, 2, \ldots, 5$
Constraints	$195\text{kNm}^2 \leq GJ_i \leq 700\text{kNm}^2$ $38\% \leq sc_i \leq 48\%$ $-0{\cdot}05\text{rad} \leq \theta i \leq 0{\cdot}05\text{rad}$ altitude = 3,050m $L = W$ $U_{div} \leq 1{\cdot}25\, U_{dd}$ $U_{fr} \leq 1{\cdot}25\, U_{dd}$

Table 4
Optimum spanwise parameters

Scenarios	Parameters	Partitions P1	P2	P3	P4	P5
Scenario I	*GJ* (kNm^2)	670	670	680	660	455
	sc (%)	43	43	42·5	42·5	39
Scenario II	*GJ* (kNm^2)	625	652	526	535	561
	sc (%)	43	42	42	41·6	41·7

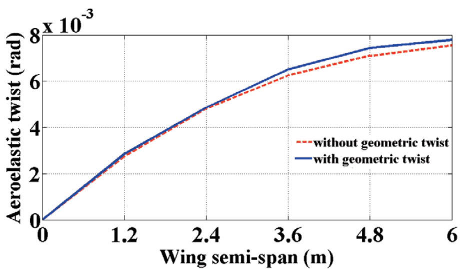

Figure 4. The spanwise aeroelastic twist of the flexible wing.

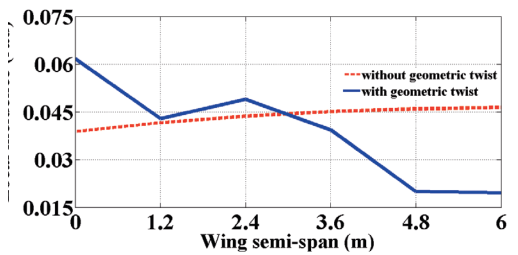

Figure 5. The spanwise incidence of the flexible wing.

centre position were varied without geometric pre-twist, no performance improvements were achieved. The optimum torsional stiffness distribution and shear centre positions are listed in Table 4 (Optimum no twist) shows that for partitions 1, 2, 3 and 4 the optimiser tends to keep the torsional stiffness high and the shear centre close to the aerodynamic centre to minimise the aeroelastic twist and hence prevent the lift distribution shifting outboard which will jeopardise the aerodynamic efficiency. On the other hand, for partition 5 the optimiser shifts the shear centre forward, close to the allowable limit (39%). This reduces the moment arm (distance between the aerodynamic centre and shear centre) and hence the tip aeroelastic twist will be very small.

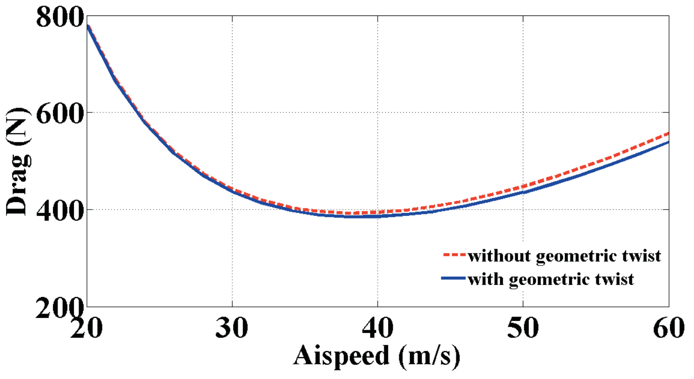

Figure 6. The drag polar of the flexible wing.

For Scenario II, an improvement in the aerodynamic efficiency factor of 2·5% was achieved, yielding an aerodynamic efficiency factor of 20·5. Figure 4 shows that the spanwise aeroelastic twist of the two scenarios are very similar over the first three partitions. However the aeroelastic twist for Scenario II is slightly larger than that of Scenario I over the partitions 4 and 5. Figure 5 shows spanwise variation of the local incidence (angle of attack plus geometric twist plus aeroelastic twist). For Scenario I, the local incidence varies almost linearly across the span. This means that the lift distribution is concentrated in the outboard region of the wing resulting in low Oswald efficiency factor. In contrast, for Scenario II, the incidence has its highest values (0·062 radians) at the root and starts to drop over the first partition until it reaches 0·040 radians. Then it starts to increase over partition 2 until it reaches 0·050 radians. Again, it starts dropping gradually over partitions 3 and 4. The local incidence remains almost constant over partition 5. This results in a slight drop of the drag polar curve, as shown in Fig. 6, providing a 2·5% increase in the aerodynamic efficiency.

4.0 ROLL CONTROL

This section investigates whether the flexible wing can provide roll authority similar to that of conventional ailerons. The roll control is achieved by changing the torsional stiffness and shear centre position on one side of the wing only. The aeroelastic twist induced by the airflow increases the lift on one side of the aircraft leading to a large rolling moment. At the start of cruise, a symmetric aileron deflection of 5º generates a rolling moment (RM) of L_r = 8kNm and an adverse yawing moment (YM) of N = 745Nm, resulting in an RM to YM ratio of 10·74. The objective in this study is to maximise the ratio of RM to YM (rolling efficiency factor) while meeting other design constraints. The optimisation problem is summarised in Table 5

A GA population of 250 generations with 500 individuals has been selected. The optimum configuration is capable of providing a rolling moment of L_r = 8kNm with an adverse yawing moment of N = 478Nm. This resulted in an RM to YM ratio of 16·73. A symmetric aileron deflection to achieve the same rolling moment resulted in a RM to YW ratio of 10·74. This indicates that varying the spanwise torsional stiffness and shear centre position is a superior rolling device when compared to conventional ailerons as it can minimise the associated adverse yawing moment by

Table 5
Roll control using the flexible wing

Objective	**Maximise (L_r/N)**
Variables	GJ_i sc_i $i = 1, 2, \ldots, 5$
Constraints	$125k\text{Nm}^2 \leq GJ_i \leq 700\text{kNm}^2$ $35\% \leq sc_i \leq 50\%$ $8\text{kNm} \leq L_r \leq 10\text{kNm}$ $N \leq 745\text{Nm}$ altitude = 3,050m $U_{div} \leq 1{\cdot}25\ U_{dd}$ $U_{fr} \leq 1{\cdot}25\ U_{dd}$

Table 6
Problem definition

Objective	**Maximise (L_r/N)**
Variables	GJ_i sc_i $i = 1, 2, \ldots, 5$
Constraints	$125\ \text{kNm}^2 \leq GJ_i \leq 700\text{kNm}^2$ $35\% \leq sc_i \leq 50\%$ $355\ \text{kNm}^2 \leq GJ_1 \leq 700\text{kNm}^2$ $40\% \leq sc_1 \leq 44\%$ $8\text{kNm} \leq L_r \leq 10\text{kNm}$ $N \leq 745\text{Nm}$ altitude = 3,050m $U_{div} \leq 1{\cdot}25\ U_{dd}$ $U_{div} \leq 1{\cdot}25\ U_{dd}$

Table 7
Optimum webs positions to maximise rolling efficiency with root constraints

Case	Parameters	P1	P2	P3	P4	P5
Without	GJ (kNm^2)	125	670	700	700	700
root constraints	sc (%)	45	43	42	42	42
With	GJ (kNm^2)	361	125	447	421	698
root constraints	sc (%)	42	43	46	47	43

up to 35%, which would result in much lower overall drag especially at low speed flight phases where induced drag is dominant. The optimum wing configuration (without root constraints) from the GA is listed in Table 7. A tip twist of 2·1º was achieved. It should be noted that the optimiser reduces the stiffness close to its lower bound in partition 1 at the wing root. Furthermore, the optimiser tends to maximise the torsional stiffness in partitions 2, 3, 4, and 5. Figure 7 shows the spanwise aeroelastic twist. The change in aeroelastic twist is the largest over partition 1 and then it settles down and starts to drop gradually until it becomes negligible over partition 5. Therefore to maximise the RM to YM ratio, the optimiser shifts the lift distribution (maximum aeroelastic twist) inboard although this results in a smaller rolling arm (smaller yawing moment). By examining the optimum torsional stiffness and shear centre position, the optimiser tries to minimise the torsional stiffness and shift the shear centre rearward around the root section. In practice, this is difficult to achieve due to the various functions of the wing root and the conflicting design requirements, in addition to large reductions in flutter and divergence speeds. Therefore to avoid the low torsional stiffness in the wing root partition, a new constraint is added yielding a new optimisation problem, which is summarised in Table 6.

An RM to YM ratio of 14·95 was achieved. A rolling moment L_r = 8 kNm and a yawing moment of N = 535Nm were achieved. The adverse yawing moment has reduced by 28% in comparison to ailerons. A tip twist of 2·4º was achieved. The optimum web configuration from the GA is listed in Table 7.

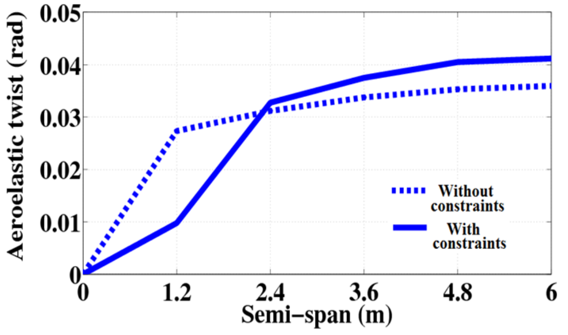

Figure 7. Spanwise aeroelastic twist over the flexible wing to maximise rolling efficiency.

The optimiser reduces the torsional stiffness in partitions 1 and 2 close to their lower boundaries. For partitions 3 and 4 the optimiser reduces the torsional stiffness and moves the shear centre rearward close to its allowable limit, while it increases the torsional stiffness of the fifth partition and keeps the shear centre in its original position. Figure 7 shows the spanwise aeroelastic twist to maximise the RM to YM ratio where the movements of the root's webs are constrained. The largest change in the twist occurs over partition 2. Then the rate of twist starts to settle down and becomes almost zero over partition 5. The tip twist achieved with the root constraint is higher than the case without constraint. Furthermore the lift distribution is constrained on the outboard of the wing when compared to the case where there is no root constraint.

5.0 CONCLUSIONS

The limitations of active aeroelastic structures (AAS) in providing performance benefits come from the fact that they depend on the airflow to deform them, and hence they can only deform in one direction. However, when geometric twist was added, a 2·5% improvement in the aerodynamic efficiency was achieved. The main reason for this is that AAS are only capable of having positively increasing aeroelastic twist (pitch up) along the wing span, and hence the spanwise lift distribution shifts outboard resulting in a lower Oswald efficiency factor and hence higher induced drag. The geometric pre-twist concentrated the lift distribution inboard providing a drop in the induced drag. From a roll control point of view, AAS wing showed superior behaviour when compared to conventional ailerons as they are capable of providing the required rolling moment with a lower adverse yawing moment. The effectiveness of AAS as roll devices is because the maximum aeroelastic twist occurs at the wingtip due to the boundary condition (clamping) at the root. For roll control, both the aeroelastic twist and the moment increase along the wing semi-span (from root to tip). AAS can only provide performance benefits if the shear centre of the wing can move ahead of the aerodynamic centre. This is not easily achieved with a closed-section wingbox.

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REFERENCES

1. TORENBEEK, E. Development and application of a comprehensive, design-sensitive weight prediction method for wing structures of transport category aircraft, 1992, Report LR-693, Delft University of Technology.
2. MILLER, G.D. Active flexible wing (AFW) technology, 1988, Report: AFWAL-TR-87-3096, Rockwell International North American Aircraft Operations, Los Angeles, CA, USA.
3. CLARKE, R., ALLEN, M.J., DIBLEY, R.P., GERA, J. and HODGKINSON, J. Flight test of the F/A-18 active aeroelastic wing airplane, 2005, AIAA 2005-6316, AIAA Atmospheric Flight Mechanics Conference and Exhibition, San Francisco, CA, USA.
4. PENDLETON, E.W., BESSETTE, D., FIELD, P.B., MILLER, G.D. and GRIFFIN, K.E. Active Aeroelastic Wing Flight Research Program: Technical program and model analytical development, *J Aircr*, 2000, **37**, (4), pp 554-561, doi: 10.2514/2.2654.
5. GRIFFIN, K.E. and HOPKINS, M.A. Smart stiffness for improved roll control, *J Aircr*, 1997, Engineering Notes, **34**, (3), pp 445-447.
6. CHEN, P.C., SARHADDI, D., JHA, R., LIU, D.D., GRIFFIN, K. and YURKOVICH, R. Variable stiffness spar approach for aircraft manoeuvre enhancement using ASTROS, *J Aircr*, September-October 2000, **37**, (5).
7. NAM, C., CHEN, P.C., SARHADDI, D., LIU, D., GRIFFIN, K. and YURKOVICH, R. Torsion-free wing concept for aircraft maneuver enhancement, 2000, AIAA 2000-1620, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Atlanta, GA, USA.
8. FLORANCE, J.R., HEEG, J., SPAIN, C.V. and LIVELY, P.S. Variable stiffness spar wind-tunnel modal development and testing, 2004, AIAA 2004-1588, 45th AIAA/ASME/ASCE/AHS/ASC/Structures, Structural Dynamics and Materials Conference, Palm Springs, California, USA.
9. KUZMINA, S., AMIRYANTS, G., SCHWEIGER, J., COOPER, J., AMPRIKIDIS, M. and SENSBERG, O. Review and outlook on active and passive aeroelastic design concept for future aircraft, 2002, ICAS, **432**, 2002, pp 1–10, ICAS 2002 Congress, 8-13 September 2002, Toronto, Canada.
10. SCHWEIGER, J. and SULEMAN, A. The European research project – Active Aeroelastic Structures, 2003, CEAS Internatiomnal Forum on Aeroelasticity and Structural Dynamics.
11. SIMPSON J., ANGUITA-DELGADO L., KAWIESKI G., NILSSON B., VACCARO V. and KAWIECKI, G. Review of European research project Active Aeroelastic Aircraft Structures (3AS), 2005, European Conference for Aerospace Sciences (EUCASS), Moscow, Russia.
12. AMPRIKIDIS, M., COOPER, J.E. and SENSBURG, O. Development of an adaptive stiffness all-moving vertical tail, 2004, , AIAA 2004-1883, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Palm Spring, CA, USA.
13. COOPER, J.E., AMPRIKIDIS, M., AMEDURI, S., CONCILIO, A., SAN MILLAN, J. and CASTANON, M. Adaptive stiffness systems for an active all-moving vertical tail, 2005, European Conference for Aerospace Sciences (EUCASS) 4-7 July 2005, Moscow, Russia.
14. COOPER, J.E. Adaptive stiffness structures for air vehicle drag reduction, Multifunctional Structures/ Integration of Sensors and Antennas Meeting Proceedings RTO-MP-AVT-141, 2006, (pp 15-1-15-12). Paper 15, Nueuilly-sur-Seine, France.
15. COOPER, J.E. Towards the optimisation of adaptive aeroelastic structures, 2006, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK.
16. HODIGERE-SIDDARAMAIAH, V. and COOPER, J.E. On the use of adaptive internal structures to optimise wing aerodynamics distribution, 2006, AIAA 2006-2131, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, RI, USA.
17. AJAJ, R.M, FRISWELL, M.I., DETTMER, W.G., ISIKVEREN A.T. and ALLEGRI, G. Roll control of a MALE UAV using the adaptive torsion wing, *Aeronaut J*, March 2013, **117**, (1189), pp 299-314.
18. AJAJ, R.M, FRISWELL, M.I., DETTMER, W.G., ALLEGRI, G. and ISIKVEREN A.T. Dynamic modelling and actuation of the adaptive torsion wing, *J Int Material Systems and Structures*, November 2013, **24**, (16), pp 2045-2057.
19. AJAJ, R.M. FRISWELL, M.I., DETTMER, W.G., ALLEGRI, G. and ISIKVEREN, A.T. Performance and control optimisations using the adaptive torsion wing, *Aeronaut J*, October 2012, **116**, (1184), pp 1061-1077.
20. MELIN, T. A vortex lattice MATLAB implementation for linear aerodynamic wing applications, December 2000, Royal Institute of Technology (KTH).
21. AJAJ, R.M., SMITH, D., ISIKVEREN, A.T. and FRISWELL, M.I. A conceptual wing-box weight estimation model for transport aircraft, *Aeronaut J*, May 2013, **17**, (1191), pp 533-551.
22. SMITH, D.D., AJAJ, R.M., ISIKVEREN, A.T. and FRISWELL, M.I. Multi-objective optimization for the multiphase design of active polymorphing wings, *J Aircr*, July-August 2012, **49**, (4), pp 1153-1160.