Conceptual Modeling of an Adaptive Torsion Wing Structure

R.M. Ajaj1, M.I. Friswell2, W.G. Dettmer3
College of Engineering
Swansea University, Swansea, United Kingdom, SA2 8PP

G. Allegri4
Department of Aerospace Engineering
University of Bristol, Bristol, UK, BS8 1TR
and

A.T. Isikveren5
Bauhaus Luftfahrt e.V. Lyonel-Feininger-Str. 28
80807 Munich Germany

This paper presents the conceptual analysis of a novel Active Aeroelastic Structure (AAS) device, which allows tailored twist deformations of wing structures to be achieved. The Adaptive Torsion Wing (ATW) concept is a thin-walled closed section two-spar wing-box whose torsional stiffness can be adjusted by changing the area enclosed between the front and rear spar webs. This is done by translating the spar webs in the chord-wise direction inward and towards each other using internal actuators. As the webs move closer to each other, the torsional stiffness of the structure reduces, while its bending stiffness in the span-wise direction is unaffected. The reduction in torsional stiffness allows external aerodynamic loads to induce twist on the structure and to maintain its deformed shape. These twist deformations can be controlled by changing the relative position of the webs as a function of the flight conditions to obtain an optimal or targeted level of performance. A Quasi-static Aeroelastic Suite has been developed in MATLAB\textsuperscript{TM} to model the ATW concept and to study its behavior with respect to different web shifting strategies. Finally, the variation of structural figures of merit such as torsion constant, tip twist, shear centre position, and minimum actuation energy are evaluated and discussed.

1 Research assistant, College of Engineering, Swansea University, Wales, UK, SA2 8PP, AIAA member.
2 Professor of Aerospace Structures, College of Engineering, Swansea University, Wales, UK, SA2 8PP.
3 Senior lecturer, College of Engineering, Swansea University, Wales, UK, SA2 8PP.
4 Lecturer in Aerospace Structures, Department of Aerospace Engineering, University of Bristol, Bristol, UK, BS8 1TR.
5 Head, Visionary Aircraft Concepts and Deputy Chief Technical Officer, Bauhaus Luftfahrt e.V. Lyonel-Feininger-Str. 28, 80807 Munich, Germany, AIAA member.
**Nomenclature**

- \( a \) = lift-curve slope
- \( A \) = enclosed area (\( m^2 \))
- \( ds \) = infinitesimal segment along the perimeter of the closed section (\( m \))
- \( ec \) = distance between aerodynamic centre and shear centre (\( m \))
- \( \{ F \} \) = nodal forces and moments vector (N or Nm)
- \( G \) = shear modulus (N/m²)
- \( GJ \) = torsional stiffness (Nm²)
- \( J \) = torsion constant (\( m^4 \))
- \( [K] \) = stiffness matrix (N/m or Nm)
- \( l \) = wing semi-span (\( m \))
- \( m \) = number of nodes per wing semi-span
- \( n \) = number of partitions per wing semi-span
- \( t \) = thickness (\( m \))
- \( U \) = speed (m/s)
- \( W \) = work done (J)
- \( y \) = nodal position along wing semi-span
- \( \{ \delta \} \) = nodal deflections vector (m or rad)
- \( \Delta U_{\text{strain}} \) = change in strain energy (J)
- \( \Delta y \) = span of an element (\( m \)) along the wing semi-span
- \( \theta \) = twist angle (rad)
- \( \rho \) = air density (kg/m³)

**Subscripts**

- \( \text{act} \) = actuation
- \( \text{cs} \) = closed section
- \( \text{ext} \) = external
- \( \text{div} \) = divergence
- \( f \) = flutter
- \( \text{os} \) = open section

**I. Introduction**

Adaptive structures allow achieving morphing capabilities that have the potential to enhance aircraft performance and broaden their flight envelopes. Active Aeroelastic Structures (AAS) are a subset of adaptive structures which allow significant performance improvements by manipulating the aerodynamic shape/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 penalized 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 reduces 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 undertaken thorough investigation in a number of research programs and projects across the world. In the United States of America (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 maximize 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 behavior of a representative wing. His design concept also
aimed to enhance the roll rate of high performance aircraft at large 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 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 90 degrees. 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 wing-box 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 the rib holes. Nam et al. demonstrated that the torsion-free wing can provide significant aeroelastic amplification, leading to an increase in roll-rate between 8.44 to 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 span. The spar is used to change the wing bending and torsional stiffness as it is rotated between its vertical and horizontal positions.

In Europe, the Active Aeroelastic Aircraft Structures (3AS) research project [9-13] which involved a consortium of 15 European partners in the aerospace industry and was partially funded by the European Community, focused on developing AAS concepts through exploiting structural flexibility in a beneficial manner. The final aim was to improve the aircraft aerodynamic efficiency and flight control. One of the novel concepts proposed in the 3AS was the All-Moving Vertical Tail (AMVT) with a variable torsional stiffness attachment. The AMVT concept was employed to design a smaller and lighter fin while maintaining stability and rudder effectiveness for a wide range of airspeeds. The AMVT employs a single attachment whose position can be adjusted in the chord-wise direction relative to the position of the centre of pressure to achieve aeroelastic effectiveness above unity [14]. 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 [15]. As part of the 3AS project, Cooper et al. [16,17] 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 wing-box 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 position. Prototypes of such concepts were built and tested in the wind tunnel to examine their behavior under aerodynamic loadings.

This paper presents a novel AAS concept, which facilitates targeted aeroelastic twist deformations of the structure in a beneficial manner. The Adaptive Torsion Wing (ATW) concept is a thin-walled closed section two-spar wing-box whose torsional stiffness can be adjusted by changing the area enclosed between the front and rear spar webs. The enclosed area is modified by translating the spar webs in the chord-wise direction towards each other using mechanical actuators as shown Fig. 1.

American Institute of Aeronautics and Astronautics
As the webs move closer towards each other, the torsional stiffness of the structure reduces while its bending stiffness in the span-wise direction remains unaffected. The reduction in torsional stiffness allows the external aerodynamic loads to induce twist on the structure and maintain its deformed shape. These twist deformations can be controlled by changing the relative position of the webs as a function of the flight conditions to obtain an optimal level of performance.

II. The Adaptive Torsion Wing (ATW) Concept

The ATW concept is a promising AAS, because the amount of actuation energy required is low when compared to other adaptive structures where the actuators are required to directly deform the structure and maintain its deformed shape. In terms of practical applications, the ATW has a significant potential to achieve morphing capabilities. Such applications can be summarized as follows:

- Increase lift coefficient during takeoff and landing (replace flap and slats);
- Replace or augment the performance of conventional ailerons;
- Control the static aeroelastic profile of the wing to minimize drag for different flight conditions;
- Enhance the stealth characteristics of the aircraft; and,
- Provide active load alleviation due to gust and maneuver loads.

As mentioned above, the ATW concept is a thin-walled closed wing-box (Fig. 1c) whose torsional stiffness can be adjusted by changing the relative position of the front and rear spar webs. The torsional stiffness ($GJ$) for a thin-walled rectangular section can be estimated from the second Bredt-Batho equation as:

$$GJ = \frac{4GA^2}{\oint ds/t} \tag{1}$$

where $G$ is the shear modulus (Nm$^{-2}$), $J$ is the torsion constant (m$^4$), $A$ is the enclosed area (m$^2$), $t$ is the equivalent wall thickness (m), and $ds$ is an infinitesimal segment (m) along the perimeter. If a single material is used in the wing-box, the resulting torsional stiffness depends solely on the square of the enclosed area;
therefore the torsional stiffness of the section can be altered by varying the position of either: the front spar web, the rear spar web, or both, to change the enclosed area, as shown in Fig. 1. The change in web positions (Fig.1b), results in two components of torsional stiffness: the first component is from the closed section while the second component is from the open section(s). The total torsional stiffness of the wing-box becomes:

\[ G_I = G_{I_{cs}} + G_{I_{os}} \]  

(2)

where \( G_{I_{cs}} \) is the torsion stiffness (Nm\(^2\)) of the closed section and \( G_{I_{os}} \) is the torsion stiffness (Nm\(^2\)) of the open section(s). The analysis in this paper accounts for both components, however the component from the open section is of lower order of magnitude in comparison to the closed section component.

The ATW wing-box concept allows the static aeroelastic shape of the wing to be controlled to maximize the performance benefits or to enhance flight control depending on the instantaneous flight conditions and mission objectives. The spar webs are connected to the hollowed spar flanges through connecting shafts. In this paper, it is assumed that the structural combination behaves as an ideal structure. The choice between moving the front web, the rear web, or both must take into account other structural design considerations such as the change in shear centre position due to the web shift, as this can have a significant impact on the behavior of the structure. Furthermore, the choice between the three options must account for the increase in system and structural weight and complexity, as well as the actuation requirements of the system. In this section, a qualitative assessment is performed to compare the three different options.

A. Shifting the front web

Shifting the front spar web produces significant increases in the tip twist and lift force, because the shear centre is moved aft away from the aerodynamic centre. However, this reduces the divergence speed of the wing significantly and limits the use of the ATW concept to low speed flight segments such as take-off and landing.

B. Shifting the rear web

On the other hand, shifting the rear spar web forward leads to a limited increase in the tip twist and lift force, associated with a slight drop in the divergence speed; this implies that the ATW concept can be applied for high speed flight segments such as cruise, but the benefits achieved are limited. However, moving the rear spar remains effective until the shear centre shift relative to the aerodynamic centre outweighs the reduction in torsional stiffness, and the lift force and tip twist start to drop.

C. Shifting both webs

The options of shifting the front web or shifting the rear web offer some advantages and disadvantages; therefore, it is desirable to find a combined shift strategy for the spar webs in order to achieve performance benefits across the entire flight envelope. This can be achieved by allowing both the front and rear web to translate inwards in certain fashions depending on the objective of the concept and the instantaneous flight conditions. In this way, the torsional stiffness can be reduced while limiting the shear centre shift to a predefined range. However, this option increases the systems’ weight and complexity. This paper focuses on the more general option whereby the two webs can translate in the chord-wise direction towards each other.

III. Conceptual Modeling

Detailed high-end low-fidelity modeling has been performed to verify the feasibility of the ATW concept and define its possible areas of applications. The ATW concept is here described within the framework of a quasi-static aeroelastic problem, where the changes in web positions alter the torsional stiffness of the wing and this leads to additional twist deformation induced by the instantaneous aerodynamic loads. The coupling between the aerodynamic loads and wing deflections continues until a state of equilibrium is achieved. To verify the feasibility of the ATW concept and account for the pronounced aero-structural interaction between the aerodynamics and the structure, a Quasi-static...
Aeroelastic Suite was developed in MATLAB™. The suite is composed of Tornado Vortex Lattice Method [18, 19] coupled with a Wing Section model [20], and a one-dimensional Finite Element (FE) beam model.

To simplify the analysis and the modeling process, a representative untapered, unswept rectangular wing of a conceptual Light Sport Aircraft (LSA) is considered as shown in Fig. 2. The conventional two spar wing-box, made entirely from Aluminum 2024-T3 alloy, is replaced with an Aluminum 2024-T3 alloy ATW wing-box concept where the front spar web located originally at 20% of the local wing chord and the rear spar web located originally at 70% of the local wing chord are allowed to translate towards each other up to maximum displacement equal to 27.5% of the wing-box chord (Fig. 2). The design parameters of the aircraft used in the analysis are listed in Table 1.

![Figure 2. Representative rectangular wing of the LSA.](image)

Table 1: Design parameters of the representative LSA aircraft.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span</td>
<td>10     [m]</td>
</tr>
<tr>
<td>Wing area</td>
<td>12.5   [m²]</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>8</td>
</tr>
<tr>
<td>Root chord</td>
<td>1.25   [m]</td>
</tr>
<tr>
<td>Length</td>
<td>7.0    [m]</td>
</tr>
<tr>
<td>MTOW</td>
<td>550    [kg]</td>
</tr>
<tr>
<td>Wing airfoil</td>
<td>NACA 63215</td>
</tr>
<tr>
<td>Wing loading</td>
<td>44     [kg/m²]</td>
</tr>
<tr>
<td>Configuration</td>
<td>low wing</td>
</tr>
<tr>
<td>Skin thickness</td>
<td>0.001  [m]</td>
</tr>
<tr>
<td>Spar web thickness</td>
<td>0.0005 [m]</td>
</tr>
</tbody>
</table>

A. The Quasi-static Aeroelastic Suite

The Quasi-static Aeroelastic Suite employs the Tornado Vortex Lattice Method [18,19] for the aerodynamic calculations coupled with a Wing Section model [20], and a one-dimensional Finite Element (FE) beam model (with torsion). Figure 3 presents a relational diagram and flowchart indicating how the single expert modules interact.

---

American Institute of Aeronautics and Astronautics
1) Aerodynamics
The Quasi-static Aeroelastic Suite utilizes the Tornado Vortex Lattice Method (TVLM) \([18, 19]\) for the aerodynamic predictions. Tornado is a linear aerodynamics code, and thus has limitations in application such as neglecting wing thickness and viscous effects, leading to a lack of conformity for angles above 8-10° for slender wings. These limitations mean that Tornado cannot be used within certain parts of the flight envelope. Nevertheless, linear aerodynamic theory is still very useful, as most aircrafts typically operate within the linear region (operating lift coefficients at reference speeds) in cruise, as well as both the takeoff and landing phases. These are the flight stages in which most of the research and analysis in this paper has been undertaken. The use of more advanced nonlinear aerodynamic prediction tools is not possible due to the substantial increase in solution time and complexity that would result.

2) Wing Section Model
The Wing Section Model \([20]\) is based on the thin-walled theory. The wing is discretized into elements, and generic sizing of the equivalent upper and lower skin panels (including stringers), and spar webs, is performed locally along the wing span. This allows the mechanical/structural properties of the wing to be estimated at different span-wise locations. An expert module dedicated to identifying the location of the shear centre according to different web positions is also embedded within the model. The wing is sized assuming that the webs are at their original positions (maximum torsional stiffness) as shown in Fig 1a. Within the structural model, two modules to estimate the flutter and divergence speed of the wing for different web positions were embedded.

i) Flutter speed
The flutter speed \(U_f\) of the wing is estimated using Galerkin’s Method \([21,22]\) for unswept rectangular cantilever wings. This method is limited to the fundamental torsion-bending binary flutter mode. The uncoupled flexural and torsional modes of the cantilever wing with uniform cross-section are respectively represented by the functions \(f(y)\) and \(\varphi(y)\) defined as:

\[
f(y) = \cosh(ky) - \cos(ky) - 0.734 (\sinh(ky) - \sin (ky))
\]

where
where $y$ is the nodal position along the wing semi-span and $l$ is the wing semi-span. These flutter modes are approximated as the fundamental modes of purely flexural and purely torsional oscillations in still air of a cantilever beam of uniform cross-section [23]. After assuming the mode shapes, they are substituted in the two equations of motion given in [21] and the equations are solved to obtain the flutter speed. In fact, the flutter speed could be estimated using higher fidelity approaches, however at the conceptual design level; the use of high fidelity approaches will increase the computation time significantly. The emphasis here is to gain a fundamental understanding of the performance gain and power requirements associated with the ATW concept, and so detailed high fidelity modeling is beyond the scope of this study.

ii) Static Divergence speed

The static divergence speed is estimated using the analytical solution for a finite rectangular wing. The divergence condition is satisfied when the tip twist tends toward infinity. From the 2nd order differential equation that describes the static equilibrium of the wing, the dynamic pressure and hence the divergence speed at which the tip twist becomes infinite can be estimated. The divergence speed ($U_{\text{div}}$) is therefore estimated as [21]:

$$U_{\text{div}} = \sqrt{\frac{\pi^2 \frac{G J}{2 \rho a e c^2 l^2}}{}}$$

where $\rho$ is the air density (kg/m$^3$), $a$ is the lift-curve slope, and $ec$ is the distance (m) between the aerodynamic centre and the shear centre.

iii) Shear centre position

The shear centre module models the actual wing-box as an equivalent rectangular wing-box as shown in Fig. 5. The shear centre is defined as the point in the cross-section through which shear loads produce no twisting [23]. Therefore its position is estimated by equating the moment produced by the overall shear force acting on the cross-section and the total moment produced by the shear forces in the individual members of the wing-box (equivalent skins and webs). The individual shear forces in each member are obtained by integrating the shear flow in those members as shown in Fig. 4.

![Figure 4. The shear flow in the equivalent wing-box.](image)

3) Finite Element (FE) Model

The FE models the wing-box as an Euler-Bernoulli beam. It rearranges the span-wise aerodynamic loads into equivalent loads at the nodes of each element (defined by the Wing Section Model). The stiffness matrices of the elements are transformed from their local coordinates to the wing coordinates (global) and then the wing stiffness matrix $[K]$ is assembled from the stiffness matrices of those elements. Then, the
nodal deflections of the wing-box in six degrees of freedom (3 in translation and 3 in rotation) are computed from:

\[ \mathbf{F} = [K]\mathbf{\delta} \]  

(7)

where \( \mathbf{F} \) is the nodal forces and moments vector (N or Nm) acting on the wing, \([K]\) is the global stiffness matrix (N/m or Nm) for the wing, \((\mathbf{\delta})\) is the nodal deflection vector (m or rad) of the wing. These nodal deflections are fed into Tornado to modify the wing vortex lattice geometry and generate new aerodynamic loads. This process iterates until equilibrium between aerodynamic loads and wing deflection is established, hence the final wing deflection is reached.

4) Operation of the Quasi-static Aeroelastic Suite

Based on the reference flight condition which is assumed as initial cruise in this case, the VLM generates the appropriate span-wise aerodynamic forces and moments on the wing. The Wing Section model converts these forces and moments to stresses and starts sizing the upper and lower equivalent skins and the webs of the front and rear spar, so that they are able to withstand the aerodynamic loads multiplied by an appropriate load factor and a factor of safety of 1.5. Then a finite element mesh is introduced on the wing and the stiffness matrix for each element is computed. The resulting aerodynamic forces and moments acting on each element are resolved into nodal forces and moments. The loads and structural stiffness matrices are arranged into the FE model, and the nodal deflections for each element are estimated. The wing deflections are fed back into the VLM, and new aerodynamic loads are generated and passed again to the FE model. The process iterates until the change in wing lift is below a prescribed tolerance.

B. Effect of Web Positions on Wing Structural Parameters

The change in web positions has a direct impact on different wing-box structural parameters. These include the torsional constant (torsional stiffness), shear centre position, tip twist angle, wing lift, divergence speed, and flutter speed. The variations of these parameters as functions of the web positions are computed using the aeroelastic suite and presented in Figs. 5 to 10. The analysis in this section was conducted at the initial cruise flight point, whose flight/operating conditions are listed in Tab.2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>3050 [m]</td>
</tr>
<tr>
<td>Air density</td>
<td>0.9041[kg/m³]</td>
</tr>
<tr>
<td>Speed</td>
<td>50 [m/s]</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>2.78 [deg]</td>
</tr>
</tbody>
</table>

All of the results presented in Fig.5-10 are normalized by their corresponding values when the two webs are in their original positions (Fig. 1a). Note that the view angle in the figures is varied to provide the reader with the best view of the corresponding surfaces.
Figure 5. Variation of normalized torsion constant with different web positions.

Figure 6. Variation of normalized shear centre positions with different web positions.

Figure 7. Variation of normalized lift with different web positions.

Figure 8. Variation of normalized tip twist with different web positions.
As shown in Fig. 5, the variation of the torsional constant \( (J) \) is almost linear with different web positions. Both the front and rear webs produce an equal change in the torsion constant, because they have the same influence on the enclosed area. Figure 5 also shows that shifting the front web alone or the rear web alone by 27.5% of the chord reduces the torsion constant by 35%. Similarly, Fig. 6 presents the variation in the shear centre position with different web positions. The front and rear webs produce an equal change in the shear centre position but in different directions. If the front spar web is shifted back by 27.5% of the chord, then the shear centre is pushed aft by 15% of the chord; similarly if the rear spar web is moved forward by 27.5%, then the shear centre is shifted forward again by 15% of the chord.

Unlike the torsion constant and the shear centre position, the changes in the front or rear web positions produce different effects on the tip twist and lift force. Figure 7 presents the variation in tip twist with different web positions. The tip twist achieved by moving the front web while keeping the rear fixed, is much higher than that achieved by moving the rear web while keeping the front fixed. The main reason is that moving the front web also pushes the shear centre back, so the lift moment arm increases. For instance, shifting the front web by 27.5% of the chord while keeping the rear fixed in its original position doubles the tip twist. On the other hand, shifting the rear web by 27.5% while keeping the front web fixed in its original position increases the tip twist by 40%. Figure 8 presents similar results in terms of lift produced by the wing; the total lift is more sensitive to the front spar web shift due to the larger twisting angles attained.

Figure 9 illustrates the variation of divergence speed with different web positions. This is significantly reduced by shifting the front web while keeping the rear web fixed; for instance, shifting the front web by 27.5% while keeping the rear web at its original position reduces the divergence speed by about 30%. However, shifting the rear web while keeping the front web fixed produces a slight reduction in divergence speed up to a certain position where the divergence speed starts to increase again. The main reason for this trend is due to the \( \frac{1}{ec^2} \) term which appears on the right side of Eq. 6. At a critical position of the rear web the reduction in the distance separating the aerodynamic centre and shear centre \((ec)\) starts to dominate the reduction in torsion constant \((J)\); hence the divergence speed starts to increase again.

Figure 10 presents the variation of flutter speed with different web positions. The variation of flutter speed is essentially governed by that of the torsion constant \((J)\). The variation of the shear centre position relative to the aerodynamic centre does not affect the flutter speed variation, because each of the webs produces almost the same impact on the flutter speed variation.

Figures 5 to 10 validate the qualitative assessment performed above, indicating that translating the front web while fixing the rear web provides significant increase in lift as well as tip twist. However it reduces
the divergence and flutter speeds significantly and limits the use of the ATW concept to low speed flight 
phases such as take-off and landing. On the other hand, shifting the rear web while keeping the front web in 
its original position provides a small increase in lift and tip twist up to a certain limit where they start to 
drop because the effect of the shear centre position starts to dominate the reduction in torsional stiffness. 
The choice between translating the front web, rear web, or both depends solely on the application and the 
loading scenario. Furthermore, it can be concluded from the above figures that a targeted wing deformation 
(lift of tip twist) can be achieved by different combinations of web positions. Therefore, a Multi-
disciplinary Design Optimizer (MDO) is required to determine the best combination of web positions to 
maximize the tip twist or lift for a given instantaneous flight condition while minimizing the actuation 
ergy required.

IV. Actuation Requirements

The major benefit of the ATW concept is that the energy required to twist the structure and to maintain 
its deformed shape can be extracted from the external aerodynamic loads once the change in torsional 
stiffness is induced by the internal actuators. This reduces the required actuation energy in comparison with 
other adaptive structure concepts where actuators are required to directly twist the structure and 
continuously maintain its shape. The benefits of this analysis is to provide the aircraft designer with an 
estimate of the minimum level of actuation energy and driving forces required and it defines the range of 
mechanisms and actuators (potentially off the shelf) that can satisfy such operational constraints. In the 
following analysis it is assumed that once the spar webs reach their final positions they are locked using 
some sort of a locking mechanism. This paper does not focus on designing and analyzing the internal 
mechanism and internal actuators, as this will be dealt with in future work.

A. Actuation energy

The amount of energy required to initiate the energy extraction from the flow depends on various 
factors:

- the distance travelled by the webs;
- the relative position of the webs;
- the flight conditions (altitude and speed);
- the load path (transfer of loads between wing box components); and,
- the details of the mechanism employed.

However, at the level of conceptual modeling, detailed knowledge of the actuation mechanism 
employed is unavailable. Therefore, it is necessary to provide the designer with an estimate of the actuation 
ergy required without going into detailed design considerations. This implies that the fraction of the 
actuation energy dissipated in the form of friction, aerodynamic damping and other conversion losses are 
neglected. Furthermore, in this analysis the spar webs are assumed to be locked in their final positions and 
the changes between their original positions and final positions occur in an instantaneous fashion. Under 
such assumptions, the minimum actuation energy required is equal to the change in the elastic potential 
ergy of the wing after its torsional stiffness is varied, which is also equal to the work done by the external 
aerodynamic loads. Therefore the minimum actuation energy \( W_{\text{act}} \) required when neglecting losses can 
be obtained as follows:

\[
W_{\text{act}} = \Delta U_{\text{strain}} = W_{\text{ext}}
\] (8)

Hence, the change in total elastic strain energy stored in the wing is:

\[
\Delta U_{\text{strain}} = \sum_{i=1}^{n} \frac{GJ(i)}{2} \left( \frac{\Delta \theta_y(i)}{\Delta y(i)} \right)^2 \Delta y(i)
\] (9)

where \( GJ(i) \) is the torsional stiffness at the \( i^{th} \) wing element, \( \Delta \theta_y(i) \) is the change in twist angle across the 
span of the \( i^{th} \) element, \( \Delta y(i) \) is the span of the \( i^{th} \) element, and \( n \) is the number of elements. On the other 
hand, the total external work done \( W_{\text{ext}} \) by the external loads on the wing assuming an instantaneous 
change in torsion stiffness \( GJ \) is:
\[ W_{ext} = \sum_{i=1}^{m} \frac{T(i) \Delta \theta(i)}{2} \]  \hspace{1cm} (10)

where \( T(i) \) is the nodal torque at the \( i^{th} \) node, \( \Delta \theta(i) \) is the change in twist angle at the \( i^{th} \) node, and \( m \) is the total number of nodes across the wing semi-span and it’s equal to \( n+1 \).

It can be concluded that Fig. 11 and Fig. 12 are almost the same. Figure 11 and 12 show that the amount of actuation energy required to translate the front web is higher than that required to translate the rear web. The physical reason behind this is the change in the position of the shear center relative to the aerodynamic center. The aft shift of the shear center associated with the movement of the front web increases the moment arm; hence it increases the external work done by the aerodynamic forces on the wing. On the contrary, the forward shift of the shear center associated with the shift of the rear web reduces the moment arm, resulting in lower external work (i.e. less strain energy stored in the wing).

**B. Driving forces**

The variation of the minimum driving forces required to translate the webs can be obtained from the variation of the actuation energy by using numerical differentiation. Therefore, the actuation force required to translate the front web \((F_{x_f})\) a distance \(\Delta x_f\) on one side of the wing can be estimated by:

\[
F_{x_f} = \frac{1}{2} \frac{\partial W_{act}(x_f, x_r)}{\partial x_f} \approx \frac{W_{act}(x_f + \Delta x_f, x_r) - W_{act}(x_f, x_r)}{2 \Delta x_f}
\]  \hspace{1cm} (11)

While the actuation force required to translate the rear web \((F_{x_r})\) a distance \(\Delta x_r\) on one side of the wing can be estimated by:

\[
F_{x_r} = \frac{1}{2} \frac{\partial W_{act}(x_f, x_r)}{\partial x_r} \approx \frac{W_{act}(x_f, x_r + \Delta x_r) - W_{act}(x_f, x_r)}{2 \Delta x_r}
\]  \hspace{1cm} (12)
Similar to the actuation energy, Fig. 13 and 14 indicate that the actuation forces required to drive the front web are much larger than those required to drive the rear web and this is mainly due to the change in the shear centre position relative to the aerodynamic centre. For instance, the actuation force to move the front web by 27.5% on one side of the wing while the rear web is at its original position is 300 N. On the other hand, the actuation force to move the rear web by 27.5% on one side of the wing while the front web is at its original position is 150 N.

V. Conclusions

An Active Aeroelastic Structure (AAS) concept has been introduced. The Adaptive Torsion Structure (ATW) concept allows the instantaneous twist deformation of a lifting surface to be controlled by changing the chord-wise position of the front and rear spar webs. A detailed conceptual modeling of the ATW concept has been performed using a high-end, low-fidelity Quasi-static Aeroelastic Suite. Preliminary results indicate that significant increases in tip twists and lift force can be achieved by moving the front spar web. However, this is also associated with large reductions in divergence speed and large increases in actuation energy and forces. The benefits of the concept can be maximized by a combined movement of the front and rear webs. The conceptual analysis presented here suggests the feasibility of the ATW concept. However, further higher fidelity analysis combined with testing of a scaled prototype are required to demonstrate the actual benefits of the concept and to assess the associated increases in the system’s complexity and structural weight.

Acknowledgments

The authors acknowledge funding from the European Research Council through Grant Number 247045 entitled "Optimisation of Multiscale Structures with Applications to Morphing Aircraft".

References


American Institute of Aeronautics and Astronautics


