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APPLICATION OF OUT-OF-PLANE WARPING TO CONTROL ROTOR BLADE TWIST

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Introduction

Extensive research efforts have been devoted in recent years to the application of active material actuation for rotorcraft blades. Piezoelectric materials have been studied as the preferred candidates for high-frequency on-blade actuation due to the ease of control provided by their rapid response to the applied electric field. For these rotor blade applications, piezoelectric actuators would be typically expected to induce a significant change in the shape of the blade, with the aim of inducing large changes in airloads. To this end, the use of piezoelectric actuators to deflect the trailing edge surface or tip section of rotor blades has been widely investigated.

However, current piezoelectric materials are inherently constrained by limited authority because of their very small linear actuation strain/displacement capability. Therefore, an amplification of the actuator output is required to achieve a larger strain, and hence, the desired dynamic airfoil twist/camber deformation. Mechanical amplification devices have been used to amplify the available piezoelectric actuation. While this approach has met with some success, the performance of such actuation methods in a demanding, long-term, fielded, full-scale rotor blade environment is currently unproven. Their performance may be degraded by the following factors: friction, free play, and aerodynamic and inertial loads. The additional complexity of the required amplification mechanisms goes against the reason for using active material actuation, i.e., the development of a simple reliable actuation scheme with no moving components. Finally, all full-scale configurations tested thus far are limited to actuating a discrete trailing edge flap with limited authority and, and thus, subject to the aerodynamic inefficiencies of a limited span application. In an alternative approach, the strain induced by embedded actuators was used to cause overall twisting of the complete rotor blade. Here again, success was limited in terms of the resulting blade deformation magnitude. While more efficient than the first approach described above, the embedded actuator approach has an inherent limitation, the relatively weak actuators are used in an attempt to deform a nominally stiff structure. Additionally, this approach requires that the actuators be structurally integrated into the blade spar thus making the during-service repair of any failed actuators very difficult.

A brief description of the present new concept, *Out-of-plane Warping for Twist Control*, follows. The rest of the Abstract contains an outline of the rigorous substantiating analyses that have been (and are) being performed. The full paper will include more details.

Out-of-plane Warping for Twist Control

In the present three-dimensional concept, the blade section is cut open to create a torsionally compliant mechanism that acts as its own amplification device, and in which the out-of-plane warping controls the blade deformation. To illustrate this concept, Fig. 1 below shows a rotor blade with a trailing edge flap (for simplicity, the support structure of the flap is not shown). The trailing edge flap is a torsionally compliant structure with an open section controlled by the out-of-plane cross-sectional warping. *Actuation of the out-of-plane warping then induces significant twisting of this component. This is exactly the reciprocal effect of the well known out-of-plane warping induced by twisting.* The symbol "F" in Fig. 1 shows the point where actuation is applied. Because of the very low torsional stiffness of open sections, little actuation effort is required here to warp the section, resulting in significant twisting Φ. This concept can be applied to a 15% of chord trailing edge flap by actuating only a small portion of the airfoil, as shown in Fig. 1. It is also possible to actuate a 75% of chord flap extending over the entire length of the blade to create a large camber change for the whole rotor blade as shown in Fig. 2. The resulting camber change over the entire blade could be used to provide cyclic control, thereby eliminating the need for swash plates. Additionally, the larger span extent reduces the aerodynamic losses related to end effects compared to a limited span flap.

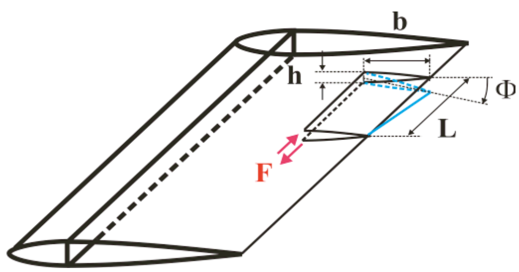

Fig. 1. Warping actuation concept applied to a rotorcraft elevon. For clarity, the support structures for the elevon are not shown on the figure.

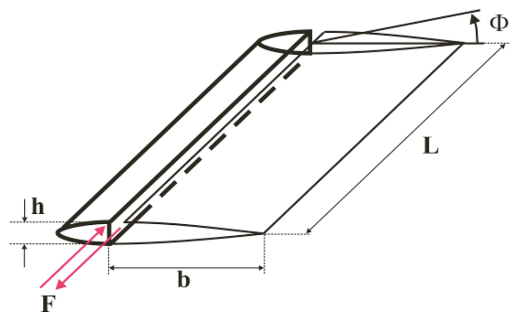

Fig. 2. Warping actuation concept applied to a rotorcraft blade.

However, the above implementations need to react the very large external, aerodynamic moments. Fig. 3 below shows a typical lift distribution over an airfoil. It can be seen that the way the above concepts are constructed, the moment generated by the lift over the aft section of the rotor blade has to be reacted. However, when the airfoil is considered as a whole, the total moment about the quarter chord is minimal, due to force equilibrium.

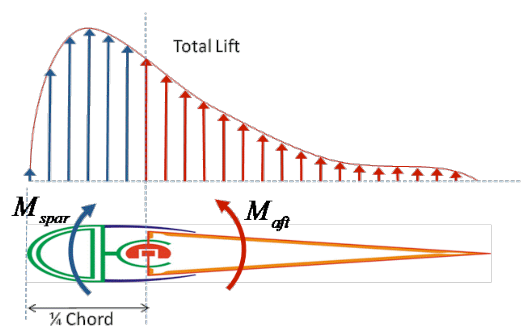

Fig. 3. Lift distribution over a typical airfoil.

The above observation has led to the current concept, *Full-Blade Warping*, in which the blade structure is cut open along the entire length of both the leading and the trailing edges, thus forming, as before, a torsionally compliant structure. When actuated along the leading edge, the entire airfoil section rotates as a rigid body around the pitch axis, resulting in a large relative tip twist Φ, Fig. 4 below. This unique structure takes the shape of an I-beam with curved flanges, and with the airfoil vertical shear web forming the I-beam's vertical web.

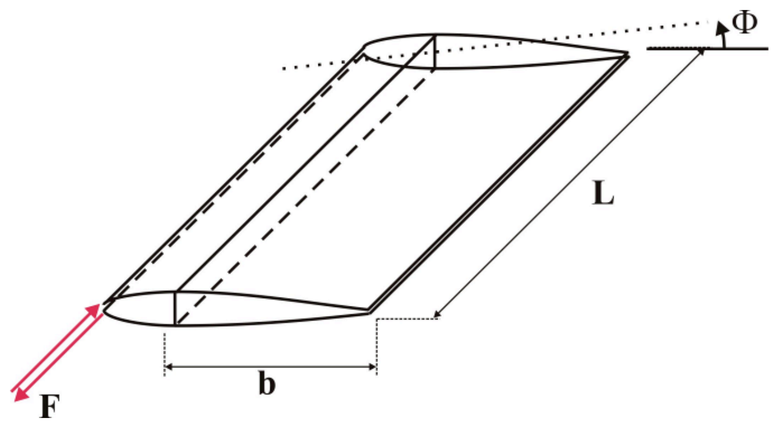

Fig. 4. Full-blade warping concept.

Results

Overall, the key observations to date, based on substantiating analyses and limited bench-top testing, are summarized as follows:

i) Vlasov beam theory has been shown to properly model the kinematics of the warping concept. Results have been validated through the use of the 3D shell models from the commercially available analysis ABAQUS.

ii) The general design guidelines regarding a viable flap concept have been determined, as follows:
  a) A 1 to 2 mm relative displacement is required
  b) The blade sections should rotate rigidly about a point

iii) The response of the original 75% flap configuration to external aerodynamic pitching moments has been computed, and it has been determined that such a flap configuration would be excessively compliant to external loads, and that the actuator load requirements would be excessively high.

iv) Subsequent to Item iii) above, the current *Full-Blade Warping* concept has been proposed, and analyzed. This concept takes advantage of the low aerodynamic moments about the quarter chord.

v) In general, the warping actuation is not inherent to a particular shape of the airfoil, such as a trailing edge flap or a 75% flap.

vi) The warping actuation is effective for open sections of any shape, providing a unique and great design flexibility.

vii) To successfully apply the full-blade warping concept, the structural configuration under consideration needs to optimized.

In this Abstract, due to length limitations, only two key results are presented, the bench-top test results and the full-blade warping concept results to date, as follows. The full paper will include more details.

Bench-top test of basic warping actuation concept

A limited bench-top test has been conducted using a 2.5 ft length section of an actual UH-60A rotor blade, provided by Sikorsky Aircraft, one of the team members in this study. This test piece was cut-open along the blade span in the aft section and secured on a bench top where spanwise forces were applied along the cut-open section as shown in Fig. 5 below. The section was stiffened along the edge where the cut was made and support guides were used to simulate a typical slider joint that would be used to connect the aft section to the D-spar of the blade. The applied forces, the resulting twist and the out-of-plane warping displacement along the cut edge were measured. Of the three sets of tests conducted, results from one of the tests are shown in Fig. 6 below.

This bench top test provided a preliminary assessment of the original concepts, validated the ABAQUS analysis and the theoretical observations in the sense that for a successful application of the original concept, sections should be allowed to rotate as a rigid body (see Item ii) above). Any other means of rotation is accompanied by a deformation involving the shell modes.

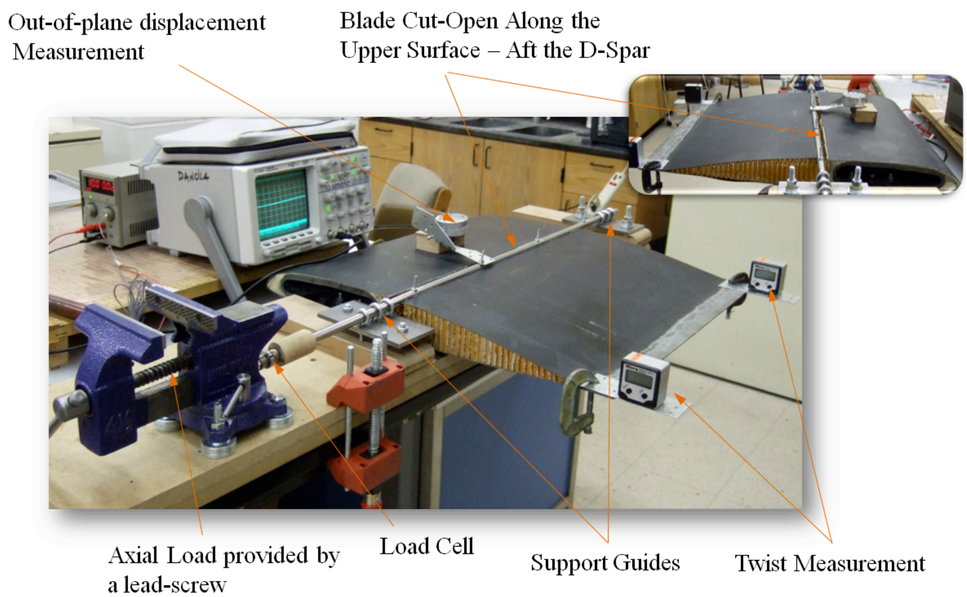

Fig. 5. Experimental set-up

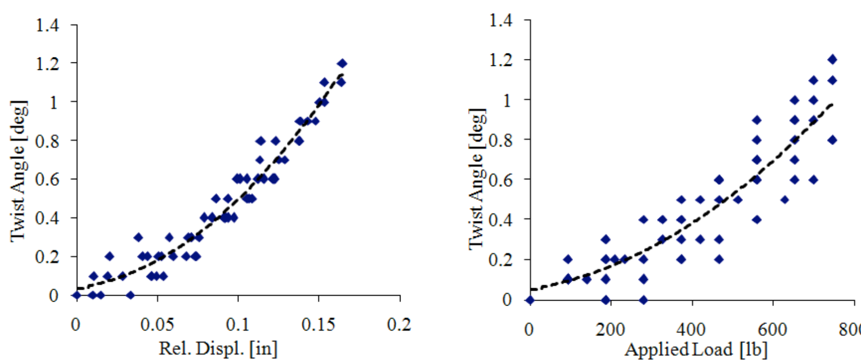

Fig. 6. Test results for the blade section with the support guides, section twist versus applied load and relative displacement.

Full-blade warping

An ABAQUS model of the full-blade warping concept has been constructed based on 3D shell elements, similar to that of the earlier analyses. A static prescribed displacement analysis was performed to demonstrate the twisting of the new blade configuration. The concept allows the blade to achieve a 30 deg tip twist for as little as 2 mm relative displacement applied along the leading edge open lips. *This analysis verifies that the warping actuation is not inherent to any particular shape of the airfoil, such as a trailing edge flap or a 75% flap and is effective for open sections of any shape, thus providing a unique and great design flexibility.* Calculations have shown that, compared to the original 75% flap concept, the current full-blade warping concept would require about 20 times less actuation load.

This proposed full-blade warping concept is very different from the current state-of-the-art rotor blade sectional designs. Its aeroelastic implications are being determined in this ongoing study using the multibody dynamics analysis DYMORE, Ref. 1. In addition to the lower aerodynamic moments, the full-blade warping concept provides mechanical and aerodynamic advantages, as follows: the placement of actuators in an inertially preferred chordwise location (forward of the quarter chord location) and maintaining the overall airfoil shape. A schematic of one such configuration is shown in Fig. 5 below. Although the full-blade warping concept creates an open section in the rotor blade, in its actual implementation, the open leading and trailing edges would be hermetically sealed using relatively soft elastomeric seals, while allowing the required relatively small, 1 to 2 mm, out-of-plane warping displacement to take place along the open section edges.

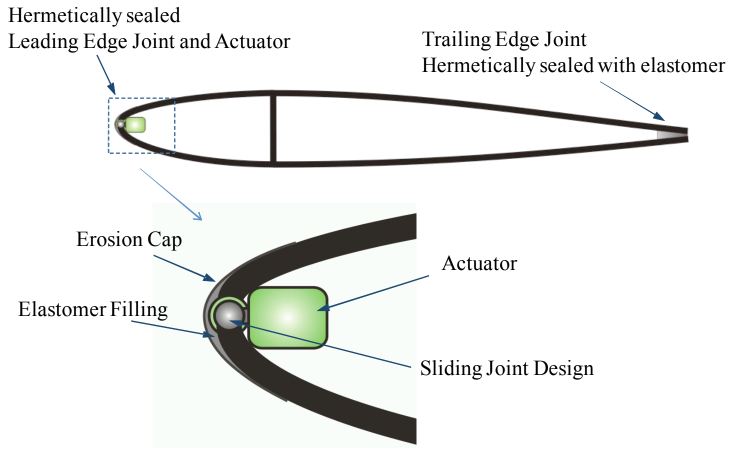

Fig. 5. Full-foil warping concept.

Concluding Remarks

The goal of this ongoing study is to develop and demonstrate the feasibility of a blade actuation system to dynamically change the twist, and/or the camber, of an airfoil section and, consequently, alter the in-flight aerodynamic loading on the blade for efficient flight control. The required analytical and finite element tools are under development to enable an accurate and comprehensive aeroelastic assessment of the current *Full-Blade Warping* and *3D Warping Actuated Trailing Edge Flap* concepts. The feasibility of the current concepts for swashplateless rotors and higher harmonic blade control is also being investigated.

In particular, the aim is to complete the following objectives, some of which have been completed (as noted below) and others that are currently ongoing:

i) Develop a Vlasov finite element model and validate against the ABAQUS shell models (completed).

ii) Implement the 3D warping actuation concept within the comprehensive analysis code DYMORE.

iii) Perform preliminary aeroelastic simulations of blades using DYMORE with 3D warping actuation:
   a) Investigate the blade behavior under 1 per/rev actuation. Determine whether sufficient twist can be generated and sustained to achieve primary blade control.
   b) Investigate the behavior of a trailing edge flap configuration under higher harmonic excitations. Determine how much twist can be obtained at the harmonics 2-5 per/rev.

iv) Determine actuator specifications such as the power required, load and displacements, and identify the stress and strain distributions in the actuated blades.

In general, the completion of Item ii) above will give an additional research capability in rotorcraft dynamics analyses, i.e., the capability to calculate the rotor blade twist due to warping, something that is not currently available in any of the existing comprehensive rotorcraft analyses.

Acknowledgements

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References

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