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FURTHER DEVELOPMENT OF A VARIABLE CAMBER MORPHING MECHANISM USING THE DIRECT CONTROL AIRFOIL GEOMETRY CONCEPT

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SUMMARY

This paper reports on the design, manufacture and testing of an improved variable camber morphing wing mechanism following the study by Evans et al. (2016), who employed the so-called Direct Control Airfoil Geometry (DCAG) concept to actuate the trailing edge flap of a NACA 0012 wing. The skin attachment, the skin material and lack of automation were identified as the major inadequacies withholding proper functionality of the original prototype model. This paper thus discusses how these issues have been addressed and how further advancement was made in demonstrating the feasibility of the DCAG concept on a small-scale wing demonstrator. Specifically, the updated design incorporates a new skin, a flexible corrugated under skin structure, and a controller. It is shown that the new design has an improved aerodynamic efficiency compared with both a single slotted flap, and the original prototype model.

Keywords: DCAG Concept, Variable Camber Morphing, Morphing Skin Material, Corrugation, Controller.

INTRODUCTION

Conventional fixed aircraft wings are constrained by the conflicting requirements of multiple objectives at various flight conditions across a mission cycle (Barbarino et al., 2014). This often results in sub-optimal designs at each condition. A potential solution is the use of morphing High Lift Devices (HLD) and control surfaces to improve the *L/D* performance over a wider flight envelope.

One promising method for realising variable wing camber has been achieved through the use of re-designed Trailing Edge (TE) flaps for which the aerofoil structure is separated and then reattached with a rotary degree of freedom (Monner, 2001). An actuation system is used to generate torque and adjust the relative camber of the flaps. A wing with morphing variable camber TE was shown to optimise the lift-to-drag (*L/D*) ratio between 3 -10 % (Monner, 2001).

Beyond the drag improvements gained aerodynamically, further economic savings may be obtained by reducing the morphing mechanism's weight compared with a conventional TE flap system. This may be achieved via the use of light and smart materials, and by designing innovative variable camber systems which can be used for various roles such as an air brake, aileron, or a lift augmenting flap (Wildschek et al., 2009).

Some progress has been made recently into using morphing technologies to increase the maximum lift coefficient beyond what could be achieved using a conventional TE flap. A key technological challenge in the design of a variable camber morphing wing is that the skin must be able to flex around the altered camber whilst being able to withstand aerodynamic loads and maintain the desired profile, both chordwise and spanwise. Additionally, the actuator mechanism must be able to apply torque evenly over a distributed area.

Much can be learnt from the Fish Bone Active Camber (FishBAC) morphing concept by Woods and Friswell (2012) which employs a skeleton-like structure to impose smooth continuous change in aerofoil camber. For instance, a pre-tensioned elastomer skin was employed to eliminate buckling once deflected. A further design by Takahashi et al. (2016) utilised the highly anisotropic nature of a corrugated structure to give chordwise flexibility and spanwise stiffness. Both designs employed wires to actuate the aerofoil and thus relied on the respective skin attachment structures to provide the main load bearing properties of the device. The Direct Control Aerofoil Geometry (DCAG) mechanism originally conceived by Müller and Müller, (n.d.) and realised by Evans et al., (2016), directly imposes continuous change in both aerofoil camber and surface profile. The device is based on the 'rotational principle' in that by allowing the wing rib to rotate 90°, a profile change is imposed.

The overall aim of this work is to design, manufacture, and test an improved variable camber TE morphing wing mechanism following the study by Evans et al. (2016) to address identified inadequacies withholding proper functionality of the current prototype. The objectives are:

1. Design of an enhanced internal mechanism and skin attachment method.
2. Selection of a suitable skin from tensile testing and fatigue testing.
3. Automation of the manual mechanism.
4. Numerical/experimental testing of design to assess aerodynamic performance.

PRELIMINARY DESIGN

Generally, a TE camber altering morphing wing consists of a load bearing component, a load transferring component, an actuation method, and a flexible skin. Initially, the previous design was evaluated to assess which areas required improvement. Figure.1 depicts the previous model demonstrating how such design was largely unsuccessful in imposing the aerodynamic profile both chordwise and spanwise through the angles of deflection, especially on the lower surface.

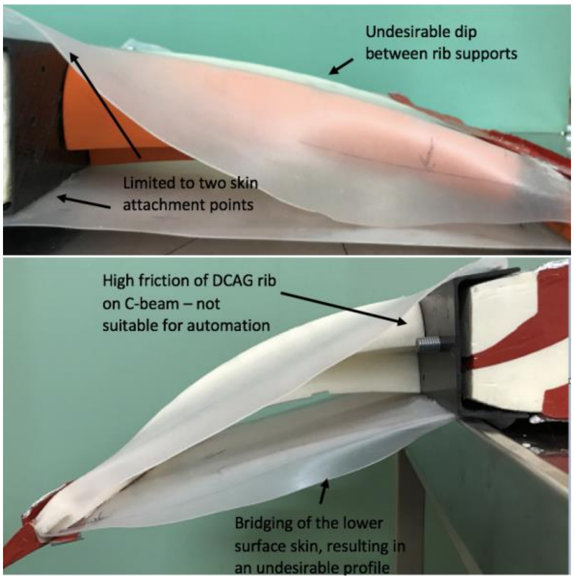


Fig. 1. Demonstration of inadequate skin attachment and internal mechanism from the original manufactured design (Evans et al., 2016) at 0° (upper) and 30° (lower) deflection.

This study has improved the aerodynamic profile of the device by implementing a corrugated structure, taking inspiration from Takahashi et al. (2016). The DCAG ribs were made thinner, to allow them to be encased in the corrugated structure. The anisotropic properties of the corrugated structure gave the device spanwise stiffness, chordwise flexibility and the ability to transfer the aerodynamic loads to the rotating ribs - the main load bearing components of the mechanism. Actuation of the device was applied via the ribs, as in the previous iteration, where the curvature of the rib provides a continuous change in profile geometry.

The four types of shapes for the corrugated structure most commonly employed are sinusoidal, re-entrant, rectangular and trapezoidal. The type of corrugation needs to be carefully selected, as each geometry has different associated structural and flexural properties. Mechanical behaviour analysis by Dayyani et al. (2013) demonstrated how a corrugated structure coated with an elastomer material exhibits changes in its structural properties. Their analysis showed that elastomer coated trapezoidal shapes were superior in terms of bending and tensile stiffness compared with other corrugated shapes. Therefore, for this investigation trapezoidal shaped corrugation was selected as the geometry for the corrugated structure, see Fig. 2 for the CAD model.

To replace a conventional flap, it was known high deflection angles of 25°+ were required. This is larger than TE morphing structures generally seen in literature for an equivalent corrugated structure, e.g. Takahashi et al. (2016) used – 20°, and Thill et al. (2010) used - 12°. To permit the high angle of deflection, a flexible skin such as an elastomer would be required rather than a solid skin such as Carbon Fibre Reinforced Polymer (CFRP) e.g. as used by Takahashi et al. (2016). Fibreglass was chosen as the material for manufacture of the fcorrugated structure due to the low-cost of the material and relative ease of the lay-up into complex geometries compared with alternatives such as CFRP.

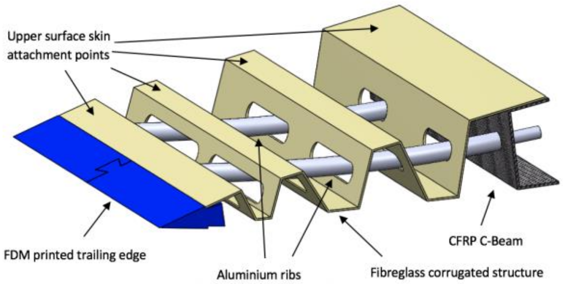


Fig. 2. CAD model of the design of the internal structure at 0° deflection. Note the trapezoidal corrugated shapes for skin attachment, both on the upper and lower surface of the mechanism.

The TE in the design by Evans et al. (2016) was comprised of a Fused Deposition Modeling (FDM) printed piece that the end of the ribs would slot into via a ball bearing. The TE flap mechanism had a chord length of 0.3 m and a span of 0.33 m and once attached to the small scale NACA 0012 demonstrator, resulted in the total aerofoil chord length of 1 m.

SKIN SELECTION

Rigorous skin selection processes were undertaken, via tensile and fatigue tests, to determine a suitable skin to place on top of the internal corrugated structure. Since the morphing flap must undertake deflection angles of 25°+, it was identified that to permit the deflection, an elastomer material would be most suitable. A range of silicone of 0.5 and 1 mm thickness between 30 and 80 Shore were analysed via fatigue and tensile testing.

To allow for automation, the requirement was to minimise the force required to reach full deflection (41.5 mm) with suitable motors. Therefore, it was found that silicone of 40 Shore and 0.5 mm thickness to be most suitable, due to the lowest force of 6.4 N required to reach the required extension. To attach the silicone skin to the corrugated structure, a specialised silicon glue, Elastosil E41, was used. The skin was pre-tensioned using clamps between each skin attachment point. To pre-tension the skin, the wing was set to slightly over maximum deflection and was then attached to the upper and lower surfaces. As a result, undesired skin sagging was largely prevented.

AUTOMATION OF MANUAL MECHANISM

An analogue torque wrench was used to determine the torque required to actuate the mechanism without the skin attached. The torque required was 0.88 Nm and thus allowed a suitable motor to automate the manual mechanism to be chosen. Two 1.9 Nm torque stepper motors were then utilised to actuate the DCAG ribs, controlled via an Arduino Uno microcontroller, see Fig.3 for hardware setup. Subsequently, implementation of the proposed hardware and software proved successful. Automation without skin attachment was achieved up to 23° downwards and upwards deflection. With the skin attached, the controller permitted 15° and 10.27° downwards and upwards deflections, respectively.

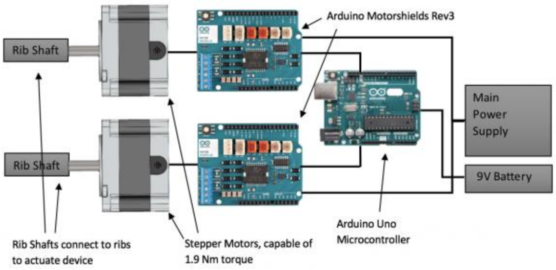
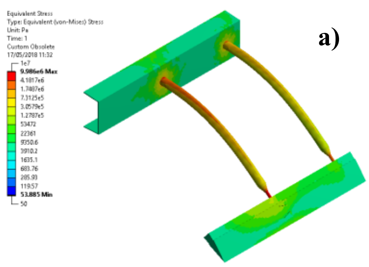


Fig.3. Visualisation of hardware setup for automating the morphing mechanism, showing the Arduino Uno (right) and two Arduino Motorshields Rev3, one for each motor (middle), connected to the wing ribs (left).

A notable improvement the new automation system gave was the ability for 94 points of deflection across the range of morphing motion, permitting an angle setting every 0.31°. By contrast, for the previous prototype only two angles were obtainable: 0° and 30°.

FEA ANALYSIS

Finite Element Analysis (FEA) was utilised to evaluate the design and to better understand the load distribution across the flap. The main use of the FEA was to demonstrate that the location and orientation of the ribs is crucial. Specifically, when the two ribs are placed further apart and rotate in opposite directions it is possible to achieve a more even stress distribution across the load bearing ribs as shown in Fig. 4b. The optimum orientation of the ribs also resulted in 18.7% (von-Mises) stress reduction across the assembly compared with the case when the two ribs were closer to each other and rotate in the same direction (Fig. 4a).



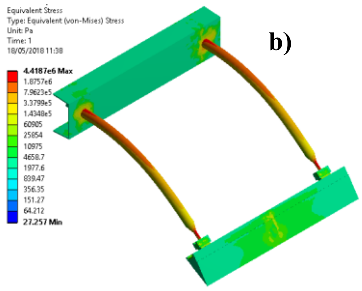


Fig.4. FEA analysis of the (von-Mises) stress on the two different rib orientations.

CFD ANALYSIS AND WIND TUNNEL TESTING

The final improved mechanism (Fig. 5) underwent 2D wind tunnel testing alongside CFD simulations using Ansys Fluent with the RANS k-ε realizable turbulence model. For the wind tunnel tests, a conventional single slotted flap was also tested for comparison purposes. Tests were run at a tunnel velocity of 20 m/s and at 0° angle of attack to match the experimental tests.

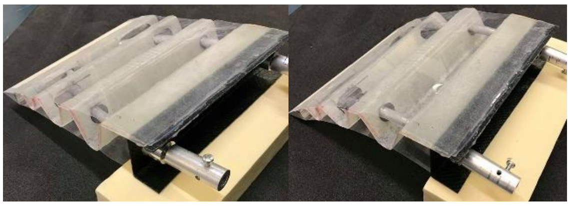


Fig. 5. Final camber morphing flap assembly.

CFD results (not shown) indicates that the lift morphing device gave a 24% improvement in lift-to-drag (L/D) ratio. Wind tunnel testing undertaken in the UWE sub-sonic wind tunnel contradicted this value, demonstrating an increase of *L/D* of only 14.6% compared with the conventional flap. The disparity may be attributed to bridging in the skin, effectively leading to straight sections between the skin attachment points and thus an aerodynamic profile which induced more drag than the geometry simulated in CFD. It is clear from the experimental data in Fig. 6 that the morphing TE flap consistently offers greater *L/D* performance compared with the single slotted flap across the whole range of deflection angles tested.

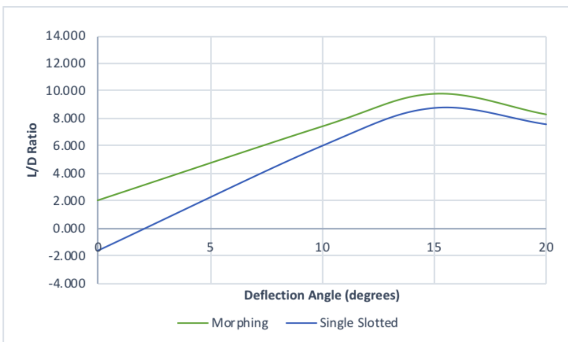


Fig. 6. Wind tunnel results comparing the morphing flap against the single slotted conventional flap at 20 m/s and 0° angle of attack.

Comparing the wind tunnel results (Fig. 6) of the previous iteration against this model, at a deflection angle of 15°, the *L/D* was shown to be 3.8 for the previous design and 9.6 for this design.

FINAL DESIGN

Fig. 5 shows the final improved morphing design with the skin attached. Here, the ribs rotate opposite to one another. As guided by the FEA analysis, this was implemented to spread the aerodynamic loads more evenly across both ribs at full deflection. Additionally, while deflecting the wing, the re-orientation also had the added benefit of stopping the warping out of shape while being deflected, as had previously been the case with the ribs rotating in the same direction. A further addition to the design was a linear guide rail on the FDM printed TE. It had been identified that a lot of friction was being induced by the pin and ball system over the TE. The solution utilised a rail attached to the TE with a carriage of a low coefficient of friction to one another. The study has advanced the DCAG concept by the implementation of a corrugated structure to offer the required skin support to deliver aerodynamic superiority compared to the previous design as evidenced by wind tunnel testing.

CONCLUSIONS

The present paper describes an approach to achieve chordwise camber variation based on a morphing TE flap. The variable camber morphing wing flap designed in this work has been shown to improve the baseline *L/D* ratio by 14.6% compared to a conventional single slotted flap, aerodynamic profile, structural integrity, and control system of the mechanism compared to the previous iteration. The following are the main achievements:

- The DCAG ribs were made thinner to allow for a corrugated structure for the purposes of skin attachment resulting in the aerodynamic profile being more effectively maintained. This was evidenced by an increase in *L/D* from 3.8 to 9.8 for 15° deflection compared to the original model.
- The tensile testing of the silicone skins demonstrated the 30 Shore silicone to be most suitable for the improved design as it required the least amount of force (6 N) to reach the 41.5 mm elongation necessary for the full 27° deflection.
- CFD analysis compared the performance of the morphing TE flap against a single slotted flap of the same size. On average, a 24.1% improvement in *L/D* was observed over the downwards deflection range at 20 m/s upstream flow velocity, thus justifying the final profile.
- Wind tunnel testing demonstrated average *L/D* improvements for the morphing flap compared with the single slotted flap of 14.6%, though testing was limited to 0° angle of attack.
- Automation without the skin attached successfully demonstrated both downwards and upwards deflections to 23°. Automation with the skin attached permitted 15.26° downward and 10.27° upward deflections.

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NOMENCALTURE

x distance along chord length, m
c aerofoil chord length, m

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