DEVELOPMENT AND TESTING OF A VARIABLE CAMBER MORPHING WING MECHANISM

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SUMMARY

The aim of this study was to develop, build and test a morphing wing design in a low-speed wind tunnel to demonstrate its viability as a practical morphing mechanism. The original concept this study is based upon is the so-called Direct Control Airfoil Geometry (DCAG) which has not previously been manufactured or physically tested. The concept was studied for a NACA 0012 wing trailing edge flap configuration, scaled to 1m chord and 0.33m span due to design constraints for manufacture, assembly and wind tunnel testing. A silicone rubber wing skin was used which provided certain morphing capability, although it did not fully adhere to the proposed flap geometry. The study demonstrated that the DCGA concept physically works as a feasible trailing edge morphing mechanism and can resist aerodynamic and structural loadings. The findings so far are promising for future integration of the DCAG concept on full-scale aircraft.

Keywords: Direct Control Airfoil Geometry, Morphing Wing Mechanism, Trailing Edge Flap

INTRODUCTION

This study details the design, manufacture and testing of a novel morphing wing concept. A number of existing morphing wing mechanisms were reviewed. One example is the shape memory alloy (SMA) morphing mechanism (Elzey, 2005). This design features two SMA plates bonded to a stainless steel truss core. Heating of one face causes it to expansion, hence a controllable deflection can be achieved. The main problem found with the SMA mechanism was that the material had a long cool-down time and therefore 'fast-rate' or 'real-time' control of the deflection was difficult.

Another mechanism found from literature was the Direct Control Airfoil Geometry (DCAG). This mechanism did not suffer from the slow cool-down problem as it is purely based on mechanical movement. The DCAG also offers further benefit of aerofoil profile change in addition to curvature.

Therefore, it was decided that the DCAG mechanism, initially proposed by Müller et al. (n.d.), could be developed for aerofoil trailing edge design, manufacture and testing. This is because the DCAG concept is able to perform a continuous change in both the aerofoil camber and surface profiles. Such an ability to change both the curvature and profile was found to be relatively rare and beneficial than that of other existing mechanisms.

Although the DCAG design was proposed, the concept has not yet been developed to manufacturing and wind tunnel testing stage thus its viability was yet to be proven and realised. The main components of the DCAG include a cylindrically tapered and curved wing rib, a curved shaft running through the rib, a guide for the curved shaft with end ball bearing, and a rotation arm attached to a rod. The device is based on the "rotational principle" by allowing the wing rib to rotate (up to maximum 90°) and by doing so it provides a continuous change in terms of the curvature and profile geometry of a baseline main wing, as shown in Fig. 1). When the rib is viewed from one plane, the device is un-deflected, after the rib is rotated 90° and viewed from the same plane, the rib is deflected (see Fig.1).

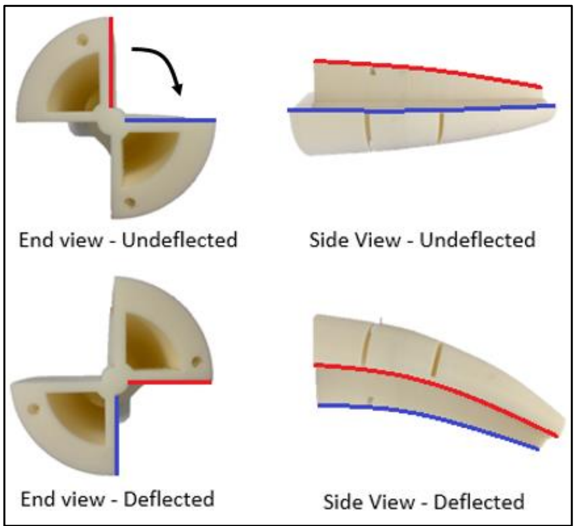

Fig. 1. DCAG Rib Showing Effect of Rotation on Deflection.

In this study, the DCAG concept is considered for the trailing edge and optimised for manufacture and assembly. After this, the morphing wing was tested in a low-speed wind tunnel facility to validate and assess its mechanism.

To achieve this, the following tasks were undertaken:
1. Design for manufacture and assembly when developing the morphing concept;
2. Carry out CFD in conjunction with initial wind tunnel testing for validation purposes;
3. Manufacture and assembly of final design for use in wind tunnel testing;

4. Build and wind tunnel test the morphing wing to determine the viability of the mechanism;
5. Analysis and comparison of CFD and wind tunnel test results.

INITIAL DESIGN CONSIDERATIONS

This study starts with a CAD model production as shown in Fig. 2. The cross section of main wing is a NACA 0012 aerofoil profile, with the trailing edge flap accounting for the aft 30% of the chord and deflecting from 0° to 30°. The wing was to be tested in a low-speed wind tunnel at a typical operation speed of 10m/s to validate the effectiveness of the mechanism in producing increased lift force due to the deflected flap. Wind tunnel testing was considered when designing the model, leading to a 1m chord and a 0.33m span.

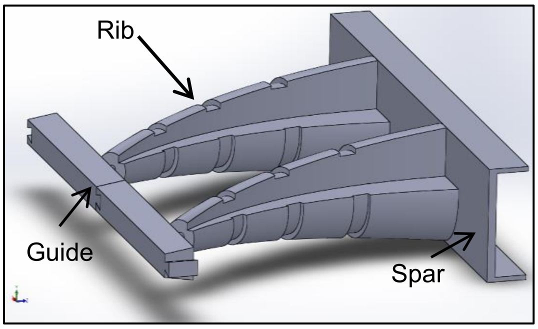

Fig. 2. 3D CAD Model of the DCAG Flap Assembly.

At this stage, automation of the rib rotation movement was not considered and will be an area to improve on in a follow-up study.

In order to ensure the validity of the CAD design, two reduced-scale non-morphing wing models were manufactured by foam cutting, representing a fully deflected (30°) profile and a non-deflected (0°) profile, respectively. Following wind tunnel testing results (not shown), it was confirmed that the design was suitable for further development to a full-scale test model.

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) was used to investigate a model of the morphing trailing edge geometry in order to predict the stresses in the spar due to aerodynamic loading. In addition, the deflection of the skin displacement was also analysed, aiding in the materials selection stages of the study. It can be seen from Table 1 that the two preferred skin materials are Neoprene and natural rubber Latex due to the low deflection compared to that of the silicone. In this study, silicone rubber was taken forward as the chosen skin material as it represents worst scenarios of all three materials considered. The other two materials will be considered in future testing.

Table 1. FEA Skin Deflection Results.

Material	Non-Deflected Displacement (mm)	Deflected Displacement (mm)
Neoprene	0.381	0.044
Latex	0.390	0.044
Silicone	2.883	0.328

FEA results also revealed (not shown) that an appropriate thickness for the C-spar was 2mm, which required 8 layers of Glass Fibre Reinforced Epoxy (CFRE) each at 0.250mm.

MANUFACTURE

A full-scale model suitable for an in-house wind tunnel test section (2.14m×1.53m) was manufactured. Fused Deposition Modelling (FDM) was used to produce the ribs and guides, and 3D printing was chosen as the manufacture process, due to the rib complexity. The double curvature shapes made it difficult to machine in a traditional manner and of the available processes FDM was the most appropriate approach.

The manufacturing trials highlighted some processes not being optimised for repeatability which would lead to further difficulties when attempting to reproduce the model. Fig. 3 shows a partially assembled wing before the flap's flexible skin was attached.

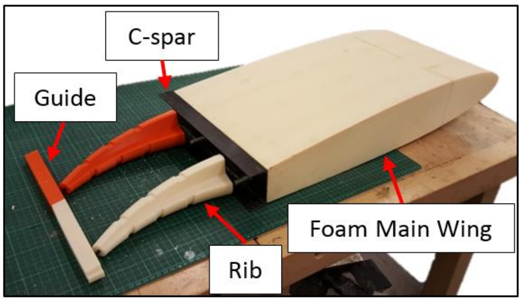

Fig.3. Partially Assembled Wing.

In order to make the rib design sympathetic to assembly, the slots included in the initial prototype which were originally designed to contain a bearing assembly which would secure the skin to the ribs whilst still allowing the rotation of the ribs. If these were kept in the design there would have been inevitable complications when assembling this part due to a large number of small parts.

Also, due to the very thin trailing edge thickness, which limited the applicability of general attachment methods, magnetic tape was deemed to be the most suitable method. Therefore a simple recess was designed into the rib to encompass a magnetic strip. This method would ensure the close contact between the skin and rib but is much simpler to assemble.

The original proposed method of attaching the skin to the ribs, via a stiff rail, was deemed not feasible when reviewing possible manufacturing techniques as no effective bonding technique was available. Several methods were investigated where the simplest method, use of a magnetic tape, was trailed. The magnetic tape, however, was found not strong enough to keep the lower skin in close contact with the deflected rib, but not the upper surface. Therefore a stronger tape or a different mechanism should be investigated.

The skin was pre-tensioned before being glued onto the top of the C-spar, the guide, and then the bottom of the C-spar. The decision to use a C-spar instead of an I-section, originally proposed by Muller et al (n.d.), was mainly due to the nature of the connection of the spar to the rotating rib as the I-section spar could not be used as the flanges on the rib side of the spar would impede the rib during rotation. The C-spar was further modified so that the remaining flanges on the spar were angled thus the foam wing could be accommodated by the change.

Initially it was suggested that the guide shaft should be integrated into the rib structure through 3D printing. However, due to the small geometry of the part and the fragility of the 3D printed material, the breakage of the guide shaft was considered a substantial risk.

A decision was made to manufacture the guide shaft from a steel rod and threaded ball bearing. The steel was much more suitable to this application due to its greater strength. As the guide shaft is a curved piece, it is not possible to assemble it into the rib as a separate component. Two shorter shafts were manufactured and bonded to the ends of the ribs.

It was found during assembly that the skin sagged between the ribs for the upper surface. This was solved by inserting a thin glass fibre reinforced epoxy (GFRE) plate under the skin that conformed to the curvature of the rib geometry. It is recommended that an anisotropic skin, such as a flexible polymer with integrated spanwise carbon rods, should be used to limit this deformation whilst still allowing chordwise extension.

WIND TUNNEL TESTING

The aim of wind tunnel testing was to determine whether or not the morphing wing model could achieve the lift performance enhancement compared with that of of a non-morphing model, at the same angles of attack and flap deflection angle. The wind tunnel tests were run at 10m/s, the flap deflections vary between 0° and 30°, and the angles of attack from 0° to 20° in an increment of 2°. Because of the small aspect ratio of the model, two end-plates were added to minimise the 3D effect of wing tip vortices. The plates were first run on their own in the wind tunnel, followed by the main tests to determine correction factors (e.g. drag caused by the end plates and struts) needed to be subtracted from the main test results. The assembled morphing wing model with end plates in a wind tunnel is shown in Fig. 4.

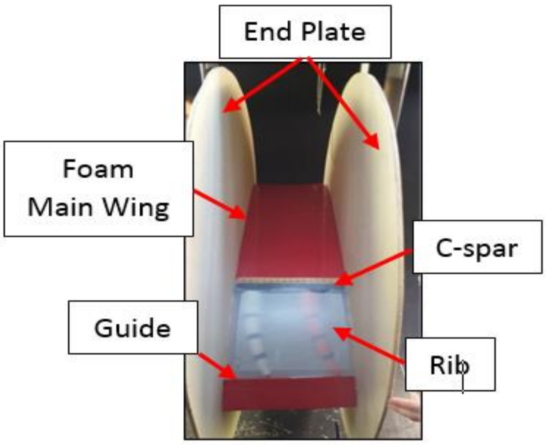

Fig. 4. Assembled Wind Tunnel Model.

NUMERICAL MODELING

CFD analyses and potential flow panel method (Javafoil) were conducted to provide a quantitative comparison with wind tunnel test results in terms of lift performance.

The steady RANS CFD analyses using SST turbulence model with uniform inflow of a medium turbulence intensity (similar to that of wind tunnel test environment) considered two 2D simulations: an un-deflected NACA 0012 and a deflected NACA 0012 with a smooth flap tuning at 30% chord and at 30° i.e. idealised clean versions of the physical model in both configurations.

The converged CFD results were then post-processed and used to compare with the wind tunnel measurements.

RESULTS AND DISCUSSION

The wind tunnel tests, CFX predictions, and Javafoil results are compared to assess the level of agreement between the three methods.

Fig. 5 depicts a comparison of the relative percent increase of lift force (expressed as ($\Delta C_l/C_l$) x 100). The data show that the CFX simulation overestimated the change in lift produced by the wing compared with that of the experiments. Data from Javafoil, however, show slightly better correlation with the wind tunnel results in terms of trend. It is interesting to note that the amount of lift relative percentage increase actually reduces with angle of attack up to 15° and after this point, it increases again.

Compared with those predictions by both CFX and Javafoil, results of DCAG design did not achieve all potential that was expected, e.g. a clean deflected case should exhibit a significant increase in lift force than that of an un-deflected case. However present in-house wind tunnel results do not fully support this to some extent. In addition, benefit of having a flap is widely accepted but this is not clearly seen from CFX and Javafoil results.

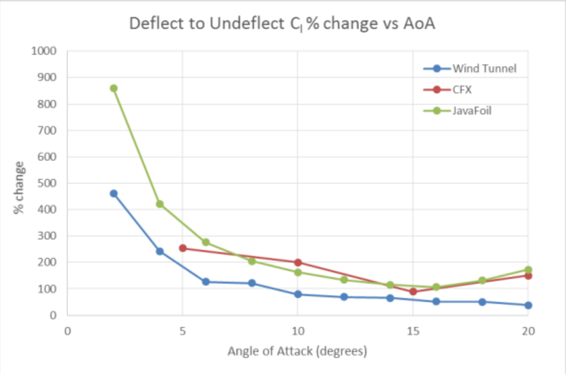

Fig. 5. Wind Tunnel & CFD Results ΔC_l Comparison.

Based on un-deflected C_l results it could be concluded that as the wind tunnel data show similar trend of lift force variations as that of Javafoil, proposed DCAG design at un-deflected conditions shows no adverse impact on lift force, and thus it can be considered a reasonably successful model in this regard.

However, from the deflected results, it can be concluded that proposed DCAG is less promising, since the lift performance predicted by CFX only achieved approximately two-thirds that of Javafoil. While the reason for this is not clear, it is possible that the lower surface of the morphing flap may not have been fully attached to the profile of the rotating rib thus causing some degree of distortion of the deflected shape, further impacting on the lift predictions.

These observed differences between experiment, Javafoil, and CFX results suggest that further work is required to improve simulation and experiment accuracy as well as to fully understand the morphing mechanism.

CONCLUSIONS AND FUTURE WORK

The main finding of this study is that the DCAG concept by Muller et al. can be adapted for an effective trailing edge morphing mechanism. It is further demonstrated that both the functionality and the manufacturability of the selected morphing wing concept are achievable if certain design and manufacturing considerations are taken into account. As a result, the DCAG concept can be adapted for full-scale aircraft applications to show its potential for scalability.

The project has also highlighted some areas which require further investigation. The main issue was the method of skin attachment to the ribs. A magnetic tape was used to keep the skin and ribs in contact, but the tape used was not strong enough to maintain a consistent connection. Other feasible attachment methods need further investigation in conjunction with the skin material selection. The choice of skin material has affected the model performance. It was found during the assembly that the skin sagged between the ribs. It is recommended that an anisotropic skin, such as a flexible polymer skin with integrated spanwise carbon rods could be used to limit such deformation whilst still allowing chordwise extensions. Another area of further research would be to automate the rotation of the ribs, as opposed to manually rotating them. This could be achieved by integrating a control system with an appropriate mechanism.

The work required to develop this further for integration into a real life application would certainly be feasible, realistic and beneficial to an increasingly sustainable aerospace industry.

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NOMENCALTURE

AoA	Angle of Attack
C_l	Lift Coefficient
ΔC_l	Change in Lift Coefficient
CFD	Computational Fluid Dynamics
CFRE	Carbon Fibre Reinforced Epoxy
DCAG	Direct Control Airfoil Geometry
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
GFRE	Glass Fibre Reinforced Epoxy
RANS	Reynolds Averaged Navier-Stokes
SMA	Shape Memory Alloy
SST	Shear Stress Transport
UWE	University of the West of England

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