Design, manufacture and test of a camber morphing wing using MFC actuated smart rib

Jesee Kimaru, Abdessalem Bouferrouk*
Department of Engineering Design and Mathematics, UWE, Bristol, UK, BS16 1QY.
*Corresponding author: abdessalem.bouferrouk@uwe.ac.uk

***Abstract*— This paper discusses the design, manufacture and testing of a light weight, camber morphing wing concept for UAV application. The concept is based on using an MFC actuator attached to a composite plate which extends along the main wing and connects leading and trailing edge sections. The flexible composite plate acts as a smart wing rib to create a dynamic change in wing upper surface camber by pushing, simultaneously, on the front and back wing sections. By controlling the applied voltage to the MFC, the composite plate maybe deflected to give the required amount in the wing's upper surface displacement. The morphing part of the wing is constructed as a hollow section while the top skin is made of an ultra-thin elastometric sheet which allows morphing change without sagging. Fast production of the front and back wing parts was achieved using fused deposition manufacturing resulting in rigid, light-weight sections. Wind tunnel tests show that for a range of angles of attack, an increase in aerodynamic performance of the morphed wing is achieved, demonstrating the viability of the proposed concept.**

Keyword:* *wing morphing, MFC, camber change, composite plate, smart rib

I. INTRODUCTION

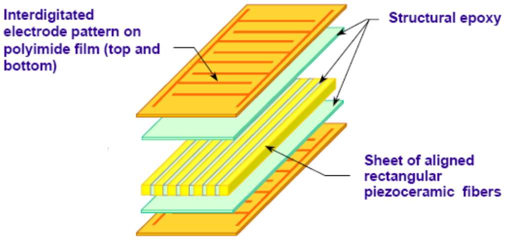
Early aviation pioneers attempted to achieve bird like flight through warping and other techniques. Limited by technology, they opted for what is currently known as conventional hinged control surfaces. These devices create gaps in aircraft surfaces, causing structural surface discontinuities that may adversely affect the smooth evolution of the flow over a wing, resulting in increased drag and airframe noise [1]. However, recent technological advancement is clearing a path for innovation in the use of smart materials and devices that allow shape changing characteristics in wing structures with aerodynamic and structural performance benefits. This is particularly true for applications involving UAVs. A number of design methods and manufacturing technologies have also been developed in recent years to address a wide range of aerodynamic and structural issues related to UAVs [2]. In particular, passive and active morphing concepts (e.g., via camber change, surface twist, spanwise and chordwise extensions) have been demonstrated in full scale and wind tunnel tests [2]. Continuing along this line of research, this study presents the design, manufacture and testing of a bespoke morphing wing concept incorporating a piezoelectric smart material. It will be shown that an elastic deformation of the primary wing section will provide an improved aerodynamic configuration using smart material. Smartness in a material can be described as "the self-adaptability, self-sensing memory and multiple functionalities of the materials or structures" which highlights a new generation of materials with extensive capabilities to adapt according to external stimuli [3]. A number of active and passive smart materials have been developed for morphing applications including compliant surfaces, servomechanisms, Shape Memory Alloys (SMAs), Shape Memory Polymers (SMPs), Piezoelectrics, and Electro Active Polymers (EAPs). For active morphing, materials can be used either as mechanism or be surface bonded to a structure in the form of actuators [2]. A response of the material can be stimulated by various incentives as a result of changes in temperature, pressure, or electric fields [3].

It has been common practice in morphing studies to use secondary control surfaces (e.g. leading and trailing edge sections of the wing) as targets for morphing applications. This is not, however, the method followed in this paper which proposes an alternative mechanism based on using the main wing as the morphing surface with the help of a flexible internal rib. This morphing concept can be said to mimic some natural fliers which articulate their wings in flight, e.g. hummingbirds and bats, or some types of flapping insects. Such concepts would find great use in military applications of UAVs. In this study, the morphing characteristics are investigated using macro fiber composites (MFC) which will be embedded onto a flexible rib structure. MFCs (developed by NASA) have the potential to help realise the morphing technology and it is therefore reasonable to expect such technology to allow performance gains for different mission requirements and flight profiles, e.g. in terms of a good response time [4], and improved lift-to-drag ratios. One reason for selecting MFCs for this study is because of their higher flexibility compared with other piezoelectric actuators. The MFC technology has already been proven in aerospace applications, e.g. in rotorcraft design optimization [5] and active buffet suppression on wings [6]. If one considers the aerodynamic view point, then modifying the wing profile is an effective means for changes in shape [7], though this may be difficult for small scale aircraft such as UAVs, e.g. due to limited space available or when the required change in shape is insignificant. As highlighted by Gern et al. [8], UAVs in particular require actuators that are very light weight, compact and possess low power consumption to allow the required change in shape to occur. Existing mechanisms for changing wing shape are typically complex in design, bulky, heavy, and exhibit a slow response rate which may negate any aerodynamic benefits these systems may offer [7]. For example, a servo based system typically consists of moving parts including bearings, gears, shafts and motor coils [9]. In such traditional setup, servo systems take up a large percentage of the volume, power and weight of the aircraft [9]. MFCs have the potential to replace traditional servo-motor actuators, thus offering simpler and cost effective implementations of wing morphing concepts. It is worth noting that for a wing to provide better flight optimisations, it must do so in a reversible way; that is without loss of baseline shape following a morphing deflection. This requires the use of materials that do not suffer from appreciable sagging deformations. Furthermore, the wing of an aircraft is an important element for stability and lateral (roll) control. As part of this investigation, a controller is designed that will, in the long term, enable the wing to morph and change its flight characteristics not only for better aerodynamic performance but also for stability.

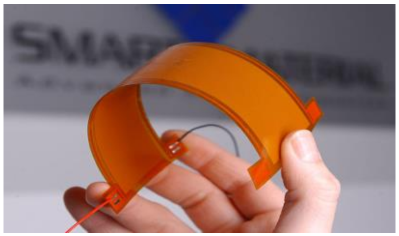
In this study the aim is to undertake the following tasks to demonstrate proof of the proposed concept: (i) design for manufacture and assembly of morphing wing, (ii) developing a robust system to control the morphing motion of the MFC actuated rib, (iii), manufacture and assembly of final design for use in wind tunnel testing, (iv) wind tunnel testing of assembled wing to determine viability of mechanism, and (v) analysis and comparison of baseline and morphed wing results to assess aerodynamic performance gains.

II. MFC ACTUATORS

MFC is the most common material made of piezoceramics [10]. The MFC used here (made by Smart Material Corp.) consists of rectangular piezoceramic rods that are sandwiched between layers of adhesive and electroded polyimide film which contains interdigitated electrodes (Fig 1a). The electrodes allow the transfer of strong applied voltages to the rods. When the MFC is bonded to a flexible surface/structure, it provides a mechanism for distributed deflection [7]. The MFC used for this study was an M 8514 P1 type producing a d_{33} elongation effect. It is the standard model, and can receive a voltage supply in the range -500V and 1500 V. The MFC patch has an active length of 85 mm, an overall length of 100 mm, an active width of 14 mm, and a thickness of 0.3 mm.



(a)



(b)

Figure 1. MFC actuator: (a) MFC structure, (b) MFC type used in the study (images curteousy of Smart Materials Corporation).

Because of the orientation of the fibres in the piezoelectric matrix, the MFC can produce directional actuation [2], i.e. either expansion or contraction. The actuator is flexible (Fig. 1b), durable and reliable with properties that enable it to conform to surfaces. The MFC is sealed in a damage tolerant skin and therefore makes it fit for purpose as an actuator. The MFC can work in different modes as shown in Fig. 2. As a thin surface, the MFC actuator can be bonded to various types of structures or embedded in a composite structure. Applied voltage will bend and distort the host material according to the work mode applied. In this study, changing the wing camber is achieved by applying the bending work mode (Fig. 2) onto a host material to enable chord flexure. The MFC's thin and flat profile allows it to be used in tight areas where other actuators (e.g. hydraulic, pneumatic) with larger volumetric requirements cannot be installed.

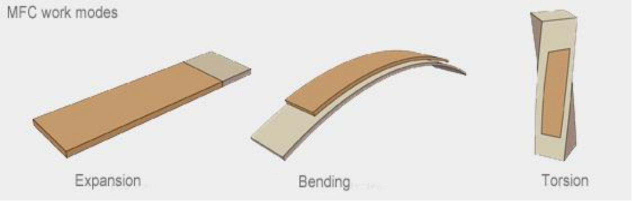


Figure 2. MFC working modes.

III. METHODS

The following processes and methods were followed in the development of the proposed smart rib concept.

A. *Design and manufacture of the wing*

The study began with a design concept for the morphing wing which is produced using CAD tools, and then following an iterative design process, it was possible to ensure that a bespoke design approach which supports all functionalities of a light-weight structure was adhered to. In an initial step, various aerofoil geometries were analysed for their aerodynamic performance by constructing CAD models for CFD assessment. CFD was used as its cost effective and validated results are sufficiently accurate. The cross-section of the main wing was chosen to be a NACA 4610 profile with a camber that morphs up to 20° angle of attack (AoA) at a maximum air speed of 20 m/s. CFD results (not shown) confirmed that the aerofoil and morphing transformation selected was suitable for further development and full manufacture. A CAD model of the morphing wing concept is shown in Fig. 3. It consists of a main wing morphing section, placed between the rigid leading and trailing edge segments. For the purposes of demonstrating the ability of a wing rib to change wing camber, the main wing section was made hollow. Embedded in the main wing is a 3-layer rectangular, flexible composite fiber (CF) plate of size 120 mm x 20 mm, acting as a smart morphing rib. The dimensions of the plate are: length (120mm), width (20mm) and thickness (0.5mm). The idea for the morphing mechanism is to use the flexible fiber composite rib to force the main wing part to deflect when actuated by the MFC. In a more realistic configuration, the plate and the MFC actuator would be buried inside the wing structure below the top skin. The concept is different to the usual morphing trailing edge airfoils seen in literature, e.g. [11], [12, [13].

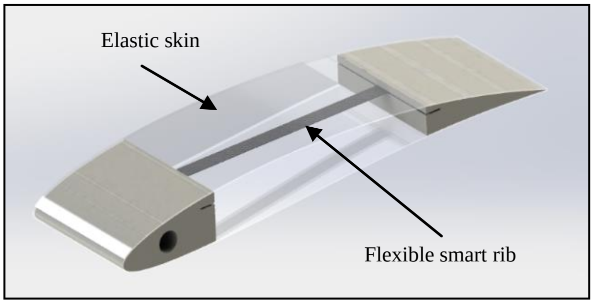


Figure 3. CAD model of the morphing wing concept.

The wing's outer skin can be made of any elastic material (e.g. rubber, silicon sheets) to provide it with the ability to stretch and detract without sagging. The elastic material should also ensure the wing surface has a smooth profile suitable for wind tunnel testing. The skin of the wing was selected to be an ultra thin, highly elastic silicone sheet that is applied onto the aerofoil wing surface area. The skin is bonded onto the surface area using adhesive and lightly ironed at low temperature to eradicate any trapped air or skin creases. To maintain a boundary layer alond the wing section, it was important to ensure that no bumps were left on the wing surface that would consequently generate flow separation during wind tunnel tests. The morphing wing section is located between 25% and 75% of the wing chord. A scale model of a total chord length of 300 mm was manufactured, suitable for in-house wind tunnel testing. The MFC actuator is bonded onto the CF rib using a thin layer of a strong 2-part adhesive, on four contact points. To enable morphing, the rib sustains considerable bending displacement and returns to its equilibrium form without permanent deformation. In order to assemble the parts together, the manufactured carbon fiber rib slides into slits (Fig. 3) on the walls of the back faces of the leading and trailing edge sections. This way, the CF rib forms a fish bone type structure. A demonstration of the wing assembly with the smart rib is shown in Fig. 4. In this paper, we only consider the case when the plate is deflected by the MFC such that a downward camber change is achieved, similar to the effects of a conventional trailing edge flap when it is deflected downwards to increase the camber of the wing.

Figure 4. Manufactured and partially assembled wing with MFC actuator bonded on top of the smart composite rib.

Fig. 5 shows how the MFC was bonded onto a carbon fiber plate using an adhesive material. The macro fiber composite actuator is attached onto the upper surface of the carbon fiber spar and left to bond for a minimum of 9 hours.

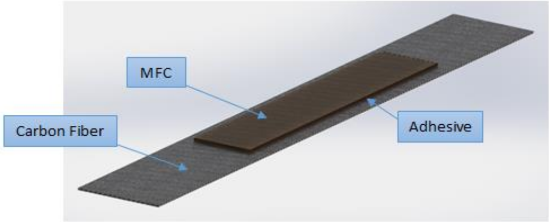


Figure 5. MFC bonded to the composite plate using adhesive.

Fused Deposition Modelling (FDM) was used to produce the leading and trailing edge sections of the wing, and 3D printing was used as the manufacture process to achieve a light-weight and rigid structures in a short period of time. The wing's hollow curvature shape made it difficult to machine in a traditional manner such as milling or laser cutting, and of the available FDM process was the most appropriate approach.

B. Control system design

Before bonding the MFC onto the composite rib, it was necessary to test the apparatus and design a suitable Proportional Intergral (PI) controller for it in order to establish some knowedge about the obtained displacements as a function of applied voltages. An AMD2012-CE3 driver is used to supply voltage of up to 2000 volts via Pulse Width Modulation (PWM) from a signal generator. The signal generator was produing 0.1ms to 5ms waves with an amplitude of 5 volts at 50 Hz. A PWM control output from the CPU is connected to the amplifier for controlling voltage to the MFC actuator. A closed loop model was designed in Matlab Simulink, mimicking the behaviour of the actuator using a controller. Incorpating a feedback loop into the system using sensors (e.g. laser scanner or strain gauge) is an opportunity for further study to deliver actuator displacement values to compensate any errors fed between the desired and actual position. The lab test involved supplying 12V DC from a wall power regulator at a nominal current of 114mA and a PWM wave from a TG220 function generator. A voltage of 12VDC is supplied into the amplifier and attenuated at a ratio of 1/200. When a 5V PWM wave is propagated into the control pin, 1000V pulse flows into the attenuator where a cathode-ray oscilloscope (CRO) plots the waveform in resolution (Fig. 6). By rapidly switching the current on and off, a PWM is formed and can be used to view the charge and discharge response of the amplifier.

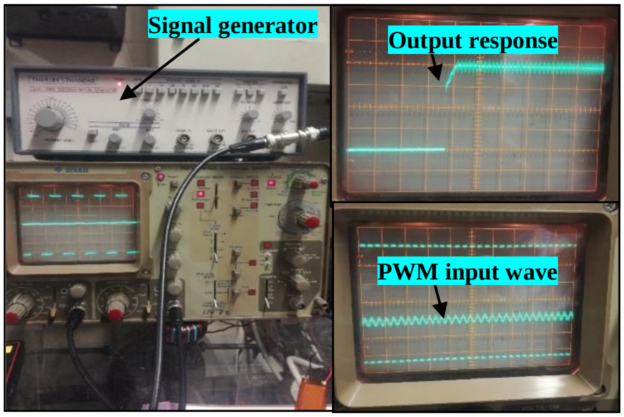


Figure 6. Signal generation and supply setup for the MFC controller.

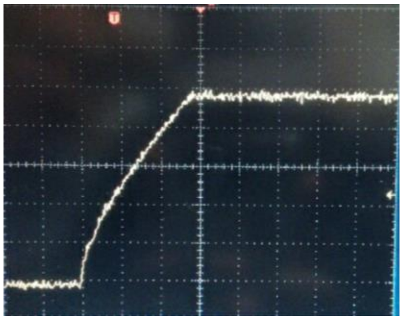
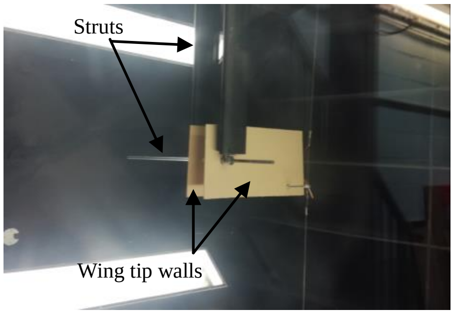


Figure 7. Open loop response of MFC.

A study of the open loop control system response time was observed as shown in figure 5. A PWM input from 0.1ms to 5ms produced an output change from 0V to 2000V with a rise time of 3ms. It is important to note that the open loop model shows a fast and critically damped response as a result of the propagating PWM input. Compared with Simulink modelled plots (not shown), the plot in Fig. 7 validates modelled simulations and hence further work was carried out to model a closed loop system to determine the overall system response of the MFC actuator. The time response is in the 3ms to 10ms range as implemented with a strain gauge and behaves as a critically damped oscillation to a desired displacement. The system has a good response and can be applied onto UAV wings with the potential to be deployed onto rotor craft as morphing blades [4].

C. *Wind tunnel tests*

The performance of the morphing wing concept was quantified in the University of the West of England’s 2.14m x 1.53m high speed wind tunnel section. In preparation for the wind tunnel, the wing model was sandwiched between precision cut smooth walls (Fig. 8) with a bore hole at about 25% chord length from the leading edge for fitting onto the wind tunnel mounting mechanism. The wind tunnel runs were conducted whilst maintaining the wind tunnel speed at 20 m/s. The Reynolds number was about 400,000. During each run, the angle of attack of the wing was varied from - 8° to 20° to provide a wide range of data and investigate the airfoil’s characteristics to their full extent, including stalling where flow separation occurs and the wing experiences some lift loss and drag increase. The force data was recorded at an incremental AoA of 4°. At this wind tunnel velocity and range of AoA, the elastic outer skin did not display any vibration or unusual deformation, but rather sustained a good response to MFC actuation. The small size of the MFC actuator restricted the size of the tested wing and therefore, due to the small aspect ratio of the wing, two walls were added to minimise the 3D effects of wing tip vortices. Prior to the main experiment, a tear test was also conducted to determine corrective factors (e.g. drag from the wing tip walls and supporting struts) needed to be deducted from the main results.



(a)

(b)

Figure 8. Test setup: (a) Strusts & walls, (b) wing model between plates.

D. *Numerical CFD*

CFD analysis using Ansys CFX were conducted to provide a quantitative comparison with wind tunnel tests in terms of lift and drag performance. The Reynolds Averaged Navier Stokes (RANS) solver with *k-ω* SST turbulence model was used as it provides reasonably good results including cases with flow separation. The inflow condition was uniform velocity, with a turbulence intensity of about 3-4%. Such turbulence intensity is higher than usual due to the design of the wind tunnel: the contraction ratio is not large enough and the flow turning section is small thus not allowing the flow to settle down to sufficiently low intensity levels. This means that drag predictions are higher due to higher friction drag. CFD simulations were considered for 2D cases: an un-deflected NACA 4610 and a deflected NACA 4610 with a morphing between 25% and 75% chord location. A typical airfoil mesh is shown in Fig. 9.

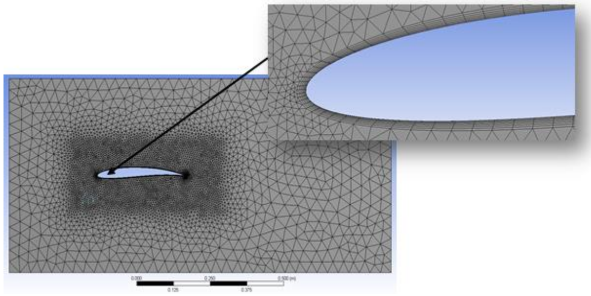


Figure 9. Mesh details for the NACA 4610.

For the undeflected case, the CFD results were post-processed for comparison purposes. Fig. 10 shows comparisons of lift coefficient versus AoA between CFX predictions and experiments. There is fairly good agreement (average error of 4%) between both methods, including prediction of the stall angle. However, differences grow beyond stall. Drag predictions (not shown) showed less favourable agreements than lift (average error of 10%) which would require further investigations on mesh quality, turbulence model, etc. Nonetheless, the fairly reasonable agreements mean that the experimental results can be extended to the morphing case with good confidence.

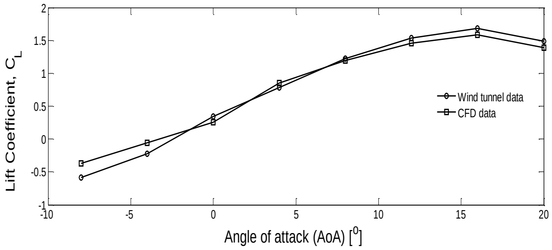


Figure 10. C_L comparison of experimental and CFD baseline data.

IV. RESULTS AND DISCUSSION

The aerodynamic performance is quantified in terms of of lift and drag force coefficients, C_L and C_D. Presented in Fig. 11, wind tunnel results show increased aerodynamic lift performance throughout the whole range of AoAs for the morphed wing. The morphed wing generates more lift with a peak C_L of 2.057 at an AoA of 14° whilst the non-morphed aerofoil achieves a lower peak C_L value of 0.89 at the same angle. The stalling AoA for baseline and morphed cases are similar at around 13°, though the morphed aerofoil section seems to have a smoother transition to stall than the non-morphed aerofoil configuration. This may indicate that for the morphed wing, flow separation is gradual and of a more stable nature unlike the non-morphed configuration. The improvements in lift for the morphing wing come, however, at the expense of a drag penalty (Fig. 12). The increase in drag is particularly significant beyond AoA of 6°. The increased drag is a direct consequence of increased lift generation as expected from wing theory. Plotting the overall aerodynamic efficiency (i.e. lift-to-drag ratio, or C_L/C_D, see Fig. 13) it is clear that the efficiency increases for the morphed case, reaching a maximum at -4°, and then reducing thereafter. From AoA = 8°, there is no improvement in aerodynamic efficiency which can be explained by the rapid rise in drag beyond this angle. While the displacements obtained due to morphing (not shown) at 1500 V were small, this is acceptable for UAVs where tiny modifications in shape are often sufficient. However, this also means that if larger displacements are desired, the morphing should be performed with a number of MFCs bonded onto few composite ribs.

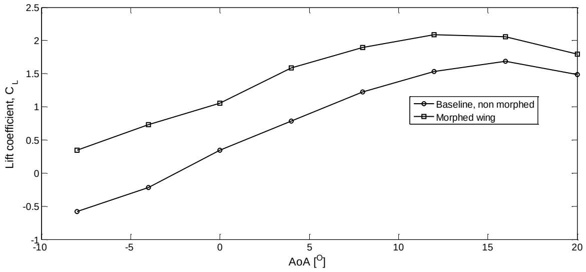


Figure 11. C_L comparisons between morphed and baseline cases.

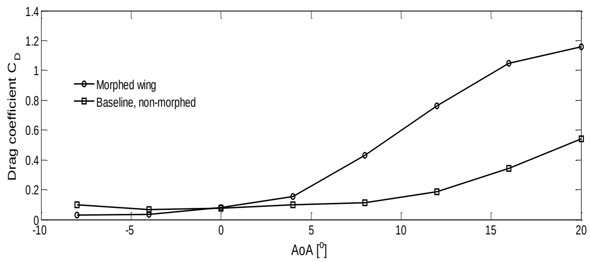


Figure 12. C_D comparisons between morphed and baseline cases.

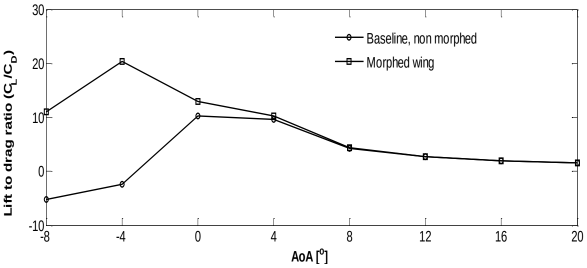


Figure 13. C_L/C_D comparison between moprhed and baseline cases.

V. CONCLUSIONS

This study has presented the design, manufacture and testing of a bespoke morphing wing concept incorporating piezoelectric material to actuate a smart rib for wing camber change. The main finding of this study is that the morphing concept proposed demonstrates that the functionality and manufacturability of the selected morphing transformation using an MFC actuator are achievable if certain design and manufacturing considerations are taken into account. Designing a controller for the system was successfully implemented in MatLab Simulink. A linear model of the MFC actuator was derived from experimental results via electrical laboratory tests carried out through the entirety of the study and used to model the displacement behaviour of the MFC actuator when there is an input voltage into its terminals. A closed loop model was modelled in designing the controller which simulated the response of the controller to an input from the wing's CPU for a desired actuator position. The aerodynamic efficiency C_L/C_D is shown to improve as a result of morphing using a smart rib, but only for a range of low angles of attack. The system's response times were found to be sufficient for applications where response time matters (e.g. rotor blade). The concept can be adapted for practical UAV morphing wing applications to show its potential for scalability. The design for manufacture approach followed allows the work required to develop this further for integration into real life applications in an increasingly sustainable aerospace industry.

As avenues for further research, stresses on the composite rib have not been considered so it is important to carry out finite element analysis (FEA) on the rib and validate with laboratory tests (where MFC can be used as a sensor to measure structural strain). In addition, one should investigate the viability of different skin materials through bending tests in order to identify the most suitable material to support the wing's aerodynamic loading. Testing with distributed MFCs and composite plates would demonstrate the full range of displacements that may be achieved. Last but not least, one has to account for energy expenditure from the MFC morphing system, consider complexity and cost of integrating it a flying model, asses changes in flight dynamics, and the potential of developing feedback control laws with MFC that enable UAVs to demonstrate different flying maneuvers efficiently.

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AUTHORS' BACKGROUND

Your Name	Title*	Research Field	Personal website
Abdessalem Bouferrouk	Dr (Senior lecturer)	Flow control, wing morphing, renewable energy	http://people.uwe.ac.uk/Pages/person.aspx?accountname=campus%5Ca-bouferrouk
Jesee Kimaru	Masters student	Wing morphing, manufacturing, aerospace systems	

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