A Method for the Actuation of Continuous Control Surfaces

SPONSOR
University of Arizona AIAA Student Branch

FACULTY ADVISOR
Dr. Jesse Little

TEAM LEADER
Austin Smith

TEAM MEMBERS
Ruben Adkins
Josef Merki
Zachary Miller
David Springer
Wen Quan Tan

DATE
May 5, 2015
Figure 14. Experimental drag coefficient at variable AoA and MFC voltages .............................................. 16
Figure 15. Change of lift coefficient at various applied MFC voltages ................................................................. 17
Figure 16. Aerodynamic response of the MACCS system ......................................................................................... 18
Figure 17. Time response of NF/SF force .............................................................................................................. 20

Nomenclature

AME Aerospace and Mechanical Engineering
AoA, α Angle of Attack
C_L Lift Coefficient
C_M Moment Coefficient
GUI Graphical User Interface
L/D Lift to drag ratio
LE Leading Edge
MACCS Method for the Morphing Actuation of Continuous Control Surfaces
MFC Macro Fiber Composite
PID Proportional-integral-derivative (control)
PWM Pulse-width modulation
PZT Lead zirconium titanate (piezoceramic)
Re Reynolds Number
SMC Smart Materials Corporation
TE Trailing Edge
TYP Typical
UAV Unmanned aerial vehicle
XFLR5 X-foil analytical airfoil software

1.0 Team Member Responsibilities

Austin Smith: Concept, voltage controller design and implementation, feedback control implementation. Software design.

Ruben Adkins: Concept, feedback control design, characterization, and implementation. Testing analysis. Software design.

Josef Merki: Wind tunnel mounting interface and construction, wind tunnel testing methods.

Zachary Miller: Wind tunnel testing methods and composite surface construction and design.

David Springer: Preliminary airfoil analysis and characterization, and post-test analysis using XFLR5. Test plan development, testing, testing analysis, data generation.

Wen Quan Tan: Preliminary airfoil analysis and characterization using XFLR5.
2.0 Motivation and Summary

The stringent requirements of small-scale unmanned aerial vehicle (UAV) flight make it difficult to include mechanical wing actuators or any enhancements beyond the static geometry. Conventional actuators are unfeasible because UAVs of this size almost always employ thin airfoils. It was the intention of this project to develop and test a method to actuate control surfaces without intruding on any of a UAV’s core design constraints. This was performed through intelligent application of the Macro Fiber Composite (MFC), which acts as a control surface membrane capable of dynamic manipulation. Voltage input into an MFC causes it to elongate and alter the curvature of a surface it is bonded to—consequently altering the aerodynamic characteristics of that surface. By using MFCs, wing thickness is no longer an obstruction to aerodynamic manipulation, while system power consumption is still comparable to that of a traditional actuator. The overall design is simple with several base components: the MFC, the composite shell, the electronic driving controls, and the main spar. Electronics are operated with the assistance of a force-feedback controller to mitigate aerodynamic disturbances and hysteresis of the structure. This simplicity of design makes it powerful, lightweight and compact, while still competing with the performance of readily available technology.

In order to validate the general concept, a simple thin beam analysis is proposed. Assuming a thin, linear-elastic fiberglass beam with a thin MFC adhesive layer, the MACCS method competes tightly with a digital servo of comparable working scale—that is, the MFC’s generated bending moment is similar to the servo’s maximum torque production. Albeit the location of the moment application would differ. However, on a dual-actuator application the MACCS system theoretically outperforms a servo system in power consumption, response time, and total weight. The study assumes in the full wingspan configuration that the actuators are on separate wing assemblies. Previous work has been done in the development of similar actuation systems. However, these systems employ heavy shell materials such as sheet metal and large, lab-bound amplifiers. Although these setups may prove the capability of the MFC as a surface actuator, the system as a whole is not feasible for direct integration into a flight-capable UAV. The proposed MACCS method is also the first to demonstrate use of a realistic thin airfoil as opposed to a larger-Re profile.
3.0 System Components

3.1 Macro Fiber Composite (MFC)

3.1.1 Research/Theory

The Macro Fiber Composite (MFC) is “piezoelectric fiber composite which has an interdigitated electrode, rectangular cross-section and unidirectional polycrystalline piezoceramic (PZT) fibers embedded in the polymer matrix.” (Park & Kim, 2005) Simply, it is thin rectangular membrane capable of deforming in a number of directional modes when appropriate voltage is passed to it. Invented by NASA Langley in 1996, the MFC is a novel technology offering high flexibility while maintaining structural robustness (Keats, et al., 2000). Through intelligent manipulation, these composites enable for a wing cross section to be populated with control surfaces enabling enhanced aerodynamic performance with the ultimate intention to create an autonomous environmentally driven vehicle. Debiasi et al successfully demonstrated the use of MFCs to deform the upper and lower surfaces of an airfoil changing it from a symmetric NACA 0014 to various non-determinate airfoils. They commented the usefulness of this smart material that it will be useful to tailor the aerodynamic performances of an airfoil (Debiasi, Bouremel, Lu, & Ravichandran, 2013). It is important to note that the MFC differs from other similar smart materials such as the Flexible Matrix Composite (FMC) which has been demonstrated for similar use in bio-technology.

![Macro Fiber Composite sheet](Smart Materials Corporation)
The MFC is an array of electrodes and polyimide film which has variant work modes depending on lay-up and voltage application. The MFC is actuated through a high voltage low current set-up with an operating range of -500V to 1500V. (Smart Materials Corporation, 2014) The voltage input determines the work mode (available in expansion or contraction) of the MFC while current input determines the response rate of the MFC. Input is controlled by the user or by an environmentally stimulated software package.

3.1.2 Design and Sizing
A number of different MFC sizes are available, but a design compromise was found which appropriately balanced cost, surface area, and MFC force requirements. The M8514-P1 (3.40” x 0.55”) was ultimately chosen for the initial testing as it neatly balanced the requirements for size (area) and cost. Because the MFC requires such a large voltage to actuate, an amplifier is required. The initial source used was a Sorenson SGA DC power supply, which is capable of a 600 V output. Wire inputs to the supply were manually switched in order to obtain a reverse-polar output voltage. The Sorenson supply was used to obtain the initial deflection data.

Four M8557-P1 (3.4” x 2.24”) MFCs were implemented in parallel on the final airfoil section model. These MFCs covered the entire upper surface of the model and therefore maximum strain production and surface deflection. Deflection on the order of millimeters was achieved.

3.1.3 Construction/Deployment
The MFC was bonded to the exterior upper fiber composite surface of the section. Exterior upper surface bonding allowed for the production of an augmented convex curvature due to layer curvature compliance. Since the maximum strain produced by the MFCs is in an elongating mode, this position is optimal for airfoil deflection. Bonding is implemented via Fibreglast System 2000 epoxy, which is the same system used in the fiber composite surface layup. Vacuum bagging was used to aid in adherence during cure and to remove excess epoxy.
4.0 Test Wing

The MACCS wing is a composite structure manufactured with cost, simplicity, and material elasticity in consideration. The wing was to be rigid enough to withstand aerodynamic loading, but elastic enough to deform with the MFC.

4.1 Development and Manufacture

4.1.1 Research/Theory

A number of base materials were compared, but options weighed against the use of materials such as sheet metal or polycarbonate as they were either too heavy or weak. A composite lay-up is preferable for most modern aeronautics applications. However, carbon fiber is very stiff and also conductive, making it a poor choice for this application. Key design points such as stiffness and density are tabulated in Table 1. Ultimately, a fiberglass composite was selected for its high specific stiffness, and moderate absolute stiffness with respect to carbon fiber.

<table>
<thead>
<tr>
<th>Material Cost $/lb</th>
<th>Fiberglass</th>
<th>Polycarbonate</th>
<th>Sheet Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength, yield (psi)</td>
<td>30,000</td>
<td>9,500</td>
<td>60,000</td>
</tr>
<tr>
<td>Stiffness (psi)</td>
<td>1,200,000</td>
<td>375,000</td>
<td>3,000,000</td>
</tr>
</tbody>
</table>

Table 1. Design points for the MACCS wing structure.

4.1.2 Wing Manufacture

The fiberglass composite model was constructed from in-house developed female molds for the S7012. The final product is displayed in Figure 3. Constructed airfoil test assembly

The bottom surface lay-up consists of three six ounce fiberglass sheets in a 0°-90° configuration, and the top surface consists of two six ounce fiberglass sheets in the same 0°-90° orientation. The top surface consists of only two layers because the MFCs add a layer of thickness. Because the MFC causes elongation in the chord direction, the 0°-90° orientation allows the greatest fiber stretch (opposed to 45°-45° orientation). Additionally, the orientation results in the most predictable deformation, per the intended operation of the system. In order to prevent delamination caused by the MFC stress, the epoxy was cured all at once in a homogenous process. FibreGlast 2000 epoxy resin** and 60 minute hardener was vacuum bagged with the fiberglass at 20 in. of Hg for 24 hours to cure.
The MFCs were bonded to the top surface of the test wing using the same FibreGlast 2000 epoxy resin and hardener and cured in a vacuum bag at 20 in. of Hg for 24 hours. The electronic circuit was soldered to the MFC leads and the spar was bonded to the location of maximum thickness using a mix of FibreGlast 2000 epoxy, 60 minute hardener, and glass microspheres.

4.1.3 MFC Attachment
Per the design of the prototype system, the MFC array is bonded to the exterior fiber composite surface of the section and produces an augmented convex curvature relative to the airfoil shape. Bonding is implemented via Fibreglast System 2000 epoxy, which is the same system used in the fiber composite surface layup. Vacuum bagging was used to aid in adherence during cure and to remove excess epoxy.

4.2 Wind Tunnel Interface

The analysis of the airfoil assembly is to be completed using the University of Arizona Aerolab Educational Wind Tunnel (EWT). Due to the sizing of the airfoil, implementing pressure taps to analyze the characteristics of the flow would have been difficult and potentially inaccurate as the spacing between taps would have been large; because of this, an internal force balance (sting) was chosen as the measurement device. Since MFCs entirely cover the top surface of the airfoil, traditional insertion of the sting into the trailing edge was not desirable. With rear insertion, deflection of the airfoil would have been hindered significantly. Designing for a rear-insertion would have required discontinuity at the center of the airfoil, and consequently the implementation of pressure taps. As discussed, pressure taps are not an optimal choice of instrumentation for this test assembly. Thus, a simple spar was introduced to the airfoil to give a solution to this problem. Additionally, a conventional spar

Figure 4. Steel Spar under Theoretical Maximum Load

Fig. 5. Wind tunnel mounting assembly with MACCS test wing.
demonstrates system interaction with a typical UAV structure.

The spar setup, as seen in Figure 4, allows for the airfoil to be connected to the sting balance most efficiently. The spar connects directly to the sting via a sheath and set screw. The sheath then connects to the spar through a notched face, which helps maintain assembly rigidity throughout testing; rigidity most specifically in the sense of undesired rotation. Finally, the sting is aligned with the wind tunnel yaw plate via an offset block. A large benefit to this design is that the sting is mounted outside of the test section, greatly reducing instrumentation drag. The spar is constructed out of steel, while the sheath and offset block are constructed out of aluminum. Since the intent of the airfoil structure is to promote bending, the width of the spar is only 0.2", and is located at the quarter-chord of the airfoil. Through the use of XFLR5, a maximum theoretical normal force of 15.5 N and axial force of 1.52 N were found for an un-deflected airfoil. Seeing as the spar is by nature thin and long, steel was chosen over aluminum for rigidity. More specifically, the yield strength of steel is over five times higher than that of aluminum. In a flight-viable structure this could be substituted with a square carbon tube. As seen in Figure 9 and Figure 10 below, the Von Mises stress distribution over the spar shows a concentration in the corner, as expected. An ANSYS analysis for an aluminum spar predicts a maximum stress of about 35 MPA—this is only about 64% of the yield strength value. However the spar is permanently adhered to the airfoil, and in the event of failure the spar cannot easily be removed in this design. Additional views of the wind tunnel interface design can be seen in Figure 6, Figure 7, and Figure 8.

![Elbow Design top view](image1.png) ![Elbow Design top/side view](image2.png)

*Figure 6. Additional views of the tunnel mount interface.*
Figure 7. Wind Tunnel Setup Explode front/side view

Figure 8. Wind Tunnel Setup base/side view
4.3 Software Interface/Feedback Control

4.3.1 Electronic Hardware

4.3.1.1 Research

As stated in section 4.1, the MFC requires a large voltage in order to operate as designed. Since the Sorenson supply does not support the full 1500 V output required for full range operation of the MFC, two AMD2012-CE3 amplifiers were used instead. The AMD2012-CE3 amplifier has been designed specifically for use with MFCs and can output between -500V and 1500V using a 500V bias signal. An Arduino microcontroller is used to control the amplifier output via a LabVIEW graphical user interface (GUI). The Arduino has over 10 digital output channels, and 5 analog input channels, which grants the designer freedom to incorporate control signals and sensor signal gathering simultaneously. A USB cable allows for control of the Arduino directly from a computer. However, operating programs can be easily uploaded to the microcontroller memory in a flight-deployable system. Direct computer control is merely convenient for wind tunnel data acquisition and system identification.

4.3.1.2 Design

The electronic system is further comprised of the following: a voltage amplifier, Arduino-type microcontroller, low pass filter, power source, and computer. Since the MFC requires such a large voltage input in order to operate, voltage amplification was the key motivation for all electronic design. The AMD2012-CE3 amplifier sold by Smart Materials produces the required voltage amplification, with a mass of only 14 g. Power output from the amplifier is sufficient to drive two M8557-P1 MFCs without compromising response time. Per the amplifier design, voltage output is piecewise-linear-proportional to signal input voltage. Calibration of the amplifier depicts this piecewise linear trend and is featured in Figure 9.

![AMD2012-CE3 Calibration](image)

*Figure 9. AMD2012-CE3 voltage output versus Arduino signal voltage output calibration curve.*

An Arduino Uno equivalent controller is used to operate the amplifier using a PWM signal. The amplifier accepts either PWM signals or analog signals,
however the Arduino clock timing is significantly offset from that of the amplifier (about 180 Hz). In order to produce a pseudo-analog signal, the Arduino output is smoothed with a simple low pass filter. The time constant of the filter has been optimized to about 4.4 ms as a balance between system response and signal oscillation. 4.4 ms is about double the Arduino PWM delay of 2 ms. Additionally, the choice of a larger resistor to accomplish this reduces current draw from the Arduino. Large current draw inherently causes the Arduino voltage output to drop below its intended value to compensate for power limitations. Voltage drop was as low as 0.05 V prior to optimization, which translates to a loss of approximately 30 V from maximum amplifier output.

Electrical power is drawn directly from a wall socket 12 V AC/DC adapter, although a conventional lithium polymer UAV battery could be substituted easily. A key benefit of the AMD2012-CE3 is its enabling line. By inputting voltage from the Arduino into the “EN” line, all amplifier rails are disabled, drastically reducing idle power consumption. Arduino power is obtained directly through the computer USB connection, but can be obtained through a 12 V battery as well. In a professional design the microcontroller, computer, and radio receiver would be combined into one unit for simplicity and weight reduction.

![Figure 10. MACCS electronic subsystem circuit diagram](image)
4.3.2 Feedback Control

4.3.2.1 Theory

After successful development of the MACCS wing prototype, a feedback controller was implemented allowing for simple deployment and a more autonomous, predictable response. Fiberglass structures show a fair amount of hysteresis during deformation. It is also a well-known problem that the MFC shows significant hysteresis and creep during use. (Schrock, Meurer, & Kugi, 2011) This error is present in the initial test data and is characteristically a major blocker to successful use of the MFC. The hysteresis is caused by a memory effect between the input and output of the voltage signal; various methods to control this memory effect have been proposed, and some control methods have been well researched by Schrock et al. The problem is very complicated as the MFC represents a nonlinear system, where the requirement for higher voltages (among the necessary -500V to 1500V) manifests a more unstable response. Additional to hysteresis, the MFC exhibits a creep behavior where the deflection does not consistently hold a position as time increases. The creep effects are small, but as the analytic solution of the camber bending shows, even a camber delta as small as 0.5% can cause a large change in aerodynamic performance. In short, the major issue to solve is an unchanging control of the MFC, where creep and hysteresis effects are subdued.

4.3.2.2 Transient Characterization

A LabVIEW virtual instrument (VI) has been implemented both to control the MFC voltage and to provide a means for integrating a force-feedback controller. Since all testing of the MACCS system is conducted in a lab setting, it is convenient to simplify software efforts using LabVIEW. Via a USB serial port, the Arduino is able to communicate directly with a wind tunnel computer. It is also convenient, then, to prove the implementation of a feedback controller using a
wind tunnel force balance. However in a flight-viable system, a leading edge pressure transducer or in situ strain gauge bridge would be used instead. The aim of the feedback controller is to mitigate aerodynamic disturbances and hysteresis of the aerodynamic structure. As discussed, hysteresis is inherently characteristic of both the MFC and of fiber composites in general. Currently lift production by a continuous surface actuator is not extraordinary. However applications regarding turbulence mitigation are practical at this stage, especially with regards to the remarkable response rate of an MFC-driving system. Due to the complexity of mathematically modeling a surface actuator and fiber composite wing, an empirical approach was chosen for model development. Using the LabVIEW System Identification Toolkit, models were developed for a range of \( \alpha \), \(-4^\circ\) to \(12^\circ\). A sample response from wind tunnel testing and corresponding model are shown in Fig. 11. The corresponding transfer function is Eqn. 1 below. The response can be roughly approximated as first-order, though the scale for this response is very small. Provided with a range of plant models, controllers can be easily created and tuned using the Control Design and

\[
y(s) = \frac{0.000027381}{1 + 0.299937s} u(s) \tag{1}
\]

It is evident in the plot that there is a fair amount of noise within the force balance signal output. However, the system modeler is able to simply extract a mean signal and move forward with a response identification. For this particular response, the airfoil was set to a \(2^\circ\) angle of attack. Separate plants were developed for each angle of attack as the response shape does change slightly.

4.3.2.3 MFC Feedback Controller

A more practical feedback controller is necessary for a completely flight-deployable solution. A force balance sensor detects changes in the wing
structure almost 500 ms after deformation has occurred, according to Figure 16. Aerodynamic response of the MACCS system. Thus, the MACCS team has designed a controller which makes use of axial strain gauges along the elongating direction of the MFC. These gauges serve to measure the attained MFC deflection and compensate for the hysteresis effect by changing the voltage applied. As seen in Figure , four separate axial strain gauges form a full bridge and serve as the feedback sensor for the MFCs. Utilization of the structural strain rate circumvents the slower response and sensing of the low-Re airflow.

Figure 12. Feedback controller circuit diagram.

The same Arduino Uno microcontroller runs a Texas Instruments INA125 SP amp to amplify the sensor signal. Gain of the system can be tuned manually by the 60 kOhm potentiometer, such that the amplified bridge output is within the 5V range of the Arduino input pins. It is important to note that the same microcontroller is used in this application, so it does not require a large overhaul in the electronics subsystem. In the future, the axial gauges can be substituted for a full rosette allowing different work modes to also be integrated, such as twist and dihedral.

5.0 Wind Tunnel Testing Results

5.1 Lift and Drag Coefficient
Voltages were applied to the MFC array on the upper surface of the test wing. The MFC array forced the deformation of the upper surface, effectively changing the camber and therefore the aerodynamic characteristics. Aerodynamic coefficients were collected through extensive testing in the EWT. The airfoil was tested using the methods described above and data was collected in order to characterize the final wing structure and aerodynamic properties. The shape of the test wing not a perfect match to the S7012 airfoil shape because of the limited fabrication resources available. The wingtips of the structure have also not yet been covered, therefore additional drag was expected to be observed.

The lift curve of the nominal (un-morphed) wing shown in Figure 13 displays consistently lower values of lift coefficients than that of the theoretical S7012 airfoil shown in Figure 13. However, the fabricated wing structure does not display the same stalling characteristics as the S7012, allowing for higher AoA flight. Increasing voltage via the MACCS system showed a consistent rise in lift coefficients for progressively higher angles of attack. The highest change in lift coefficient was observed to be approximately 0.08. As mentioned in previous sections, having this system installed on the AeroVironment Raven can potentially provide an increase in lift of up to 2.5 pounds-force. This is the result that was originally sought by the group, and validates that the MACCS system achieves its design goals in providing a variable camber wing that can dynamically increase lift forces.
The drag was expected to increase from the theoretical nominal values as well due to the unsealed wingtips and testing interface. This is observed, as can be seen in Figure 14. This plot also shows the increased drag caused by the application of increased voltage via the MACCS system. This result was also expected, as having more exposed surface area due to the morphing of the structure should increase the induced drag forces experienced. Sealing the wingtips will reduce the total drag and should result is smaller drag changes. Because the modeled test wing is not exactly modeled as a S7012, measuring the changes in aerodynamic coefficients as a result of MFC deflection is vital. Figure 15 displays the change in $C_L$ and $C_D$ in the MACCS test wing as a result of the MFC deflection. This plot is useful to quantify the delta changes seen from implementation of the system.

![Graph](image)

*Figure 15. Change of lift coefficient at various applied MFC voltages.*

### 5.1.1 Dynamic Response

The system identification in LabVIEW permitted a quantitative and qualitative analysis of the response time of the MACCS system. As each transfer function was developed for the different angles of attack, the first order rise time was computed and compiled to Figure 16.
This plot describes how quickly the change in deflection is realized by the airflow around the wing—effectively how quickly a change in voltage can manifest itself as a change in aerodynamic performance. The average response time is 615.5 ms, many orders higher than the electronic hardware response time of approximately 50 ms. Therefore, the system works at a much higher rate than is realizable by nature, so there is no problem with lagging electronics. However at higher Re, the aerodynamic response rate will also increase. Further work to characterize the response at Re = 200k is in the future of scope the system.

6.0 Conclusions
An array of Macro Fiber Composite (MFC) piezoceramic actuators are demonstrated to produce quantifiable change the lift and drag coefficients of a particular test wing when used as continuous control surface actuators. Because the MFC is a thin membrane compact actuator this research develops many applications for unmanned aerial vehicles (UAVs). The MFC’s compact size, low weight, and low power consumption are more desirable than current electromechanical servo options. Testing at range of angle of attacks (−4° to 12°) in the University of Arizona Aerolab Educational Wind Tunnel present solid evidence of the MFCs ability to actuate control surfaces on the small-UAV scale. More MFCs will serve to magnify this response and increase the changes seen in lift coefficient, and a strain gauge driven feedback controller will tune the system and mitigate any hysteresis effects present.
7.0 Related Documents

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIAA Conference Judging Presentation</td>
<td>Presentation</td>
</tr>
<tr>
<td></td>
<td>Design Day</td>
<td>Poster</td>
</tr>
<tr>
<td>AME 420a Proposal</td>
<td>Project Proposal AME420a Fall 2014</td>
<td>Proposal</td>
</tr>
<tr>
<td>MACCS Progress Report</td>
<td>Fall 2014 Progress Report</td>
<td>Report</td>
</tr>
</tbody>
</table>

***All related documents can be viewed at reader’s request.***

8.0 Acknowledgments

This work was carried out under the support of the University of Arizona AIAA Student Branch and the University of Arizona Aerospace and Mechanical Engineering Department. The project team thanks Hi-Tech Machining, and Aerolab USA for their support. The team also thanks the project mentor Dr. Jesse Little.

9.0 References


10.0 Appendix

Although the changes are small, they are indicative changes. Passing through the minimum 500V to the maximum 1500V causes measurable changes as indicated in Figure 17. Each step voltage was passed to the system for roughly ten seconds, and the changes in aerodynamic normal force were measured by the sting balance. The pyramid structure demonstrates quantifiable changes, while being able to maintain the response for a period of time. However, noticeable drift is present in the system. This is an inherent problem to the MFC—a feedback controller is developed to mitigate this error.

\[
\text{Aerodynamic NF Response to MFC Deflection}
\]

![Graph showing the time response of NF/SF force from Aerolab at Re = 100,000 and \( \alpha = 3^\circ \). Initial value is un-deflected MFC with voltage 0V followed by step increments in the following sequence: -471V, 0V, 500V, 1000V, 1483V, 1000V, 500V, 0V, -471V, and final value 0V. Considerable drift is present in the system, causing a large hysteresis error. The raw data was smoothed using a moving average.}