Surface Actuated Variable-Camber and Variable-Twist Morphing Wings Using Piezocomposites

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A surface actuated variable-camber morphing airfoil employing a type of piezoceramic composite actuator known as Macro-Fiber Composite is presented. The proposed airfoil employs two cascading active surfaces and a pair of optimized pinned boundary conditions. The optimized locations of pinned boundary conditions and the geometric features allow for a variable and smooth deformation in both directions from a flat camber line. The continuity of the airfoil surface is achieved by using a single substrate that wraps around the airfoil shape. This substrate forms the surface of the airfoil and it serves as the host material for the two cascading bimorph actuators. The cascading bimorphs are pinned together at the trailing edge with a compliant hinge, which is also formed by the substrate material. The paper focuses on the theoretical static-aeroelastic response characterization. A parametric study of the fluid-structure interaction problem is employed to optimize the geometric parameters and the boundary conditions of the variable-camber airfoil. The coupled treatment of the fluid-structure interaction allows the realization of a design that is not only feasible in a bench top experiment, but that can also sustain large aerodynamic loads. The paper identifies the effects of four important structural parameters to achieve the highest possible lift coefficient and lift-to-drag ratio. Practical recommendations are presented to achieve a working prototype.

**Keywords:** Variable-camber airfoil, morphing, bimorph, Macro-Fiber Composite, piezoceramic, low RE number

I. Introduction

The desire for smaller and lighter aircraft has driven a need to investigate the use of smart materials for flight and flow control. For example, field-deployable aircraft have flexible wings that can be folded during transportation, and they can be unfolded for operation. These compliant wings can be realized with the integration of smart materials. Piezoelectrics remain the most widely used smart material because they offer actuation and sensing over a wide range of frequencies. Specifically, piezoelectrics have been employed in aerospace structures to perform shape and flow control. A Macro-Fiber Composite (MFC) is a type of piezoelectric device that offers structural flexibility and high actuation authority (up to 0.2% in-plane strain). A challenge with piezoelectric actuators is that they require high voltage input. In contrast, the current drain is low which creates small power consumption and...
requires relatively lightweight electronic components. For smart material actuated devices, another challenge is found in operating a relatively compliant, thin structure (desirable for piezoelectric actuators) in situations where there are relatively high external (aerodynamic) forces. Establishing a wing configuration that is stiff enough to prevent flutter and divergence, but compliant enough to allow the range of available motion is the central challenge in developing a piezocomposite airfoil. Novel methods of supporting the airfoil can take advantage of aerodynamic loads to reduce control input moments and increase control effectiveness. The next section presents a selection of research that deals with camber morphing in aircraft using piezoelectric materials.

A. Aerodynamic Camber Morphing with Piezoelectric Materials

Piezoelectric materials offer relatively high force output over a wide frequency range. Although the strain output is very small for low excitation levels, the response is relatively linear. In the linear regime, the fast response of Lead-Zirconate-Titanate (PZT) actuators caused initial interest in the field of aerodynamic vibration control. Many researchers focused on the application of piezoelectrics to the blades of rotary wing aircraft to improve their performance and effectiveness. Steadman et al. [1] showed an application of a piezoceramic actuator for camber control in helicopter blades. Giurgiutiu et al. [2] has researched performance improvement on rotor blades using strain-induced actuation methods (using PZTs). Wind tunnel experiments proved the control authority of the PZT actuators. Giurgiutiu [3] presented a comprehensive review on the application of smart material actuation to counteract aeroelastic and vibration effects in helicopters and fixed wing aircraft. Other “smart rotor” concepts have also been presented: leading- and trailing-edge flaps actuated with smart material actuators, controllable camber/twist blades with embedded piezoelectric elements/fibers, and active blade tips actuated with tailored smart actuators. For flap actuation, devices range from piezobimorphs (Koratk and Chopra [4.5]), piezostacks (Lee [6], Lee and Chopra [7.8], Straub et al. [9.10], Janker et al. [11]), and piezoelectric/magnetostrictive-induced composite coupled systems (Bernhard and Chopra [12], Rogers and Hagood [13], Derham and Hagood [14], Cesnik and Shin [15], Cesnik et al. [16], Shin [17], Shin et al. [18], Kovalovs [19]).

In addition to the research in vibration control applications, “static” control of aerodynamic surfaces using piezoelectric materials started in early 90’s for large aircraft. In static-aeroelastic control, researchers employed both the low amplitude (mostly linear) and high amplitude (non-linear) excitation ranges of piezoelectric material. Lazarus et al. [20] examined the feasibility of using representative box wing adaptive structures for static-aeroelastic control. Pinkerton and Moses [21] discussed the feasibility of controlling the wing geometry employing a piezoelectric actuator known as the thin layer composite-unimorph ferroelectric driver and sensor (THUNDER). Hysteresis nonlinearity was observed in the voltage-to-displacement relationship. Barrett and Stutts [22] proposed an actuator that uses a pair of piezoceramic sheets arranged in a push-pull assembly to turn a spindle of an aerodynamic control surface. Wind tunnel testing showed the feasibility of the concept. Geissler et al. [23] adopted piezoelectric materials as the actuation element for a morphing leading edge: however, in this case the leading edge is an independent element able to rotate around an internal hinge. Munday and Jacob [24] developed a wing with conformal curvature, driven by a THUNDER actuator internally mounted in a position so to alter the upper surface shape of the airfoil, resulting in a variation of the effective curvature. Wang et al. [25] presented results from the DARPA/AFRL/NASA Smart Wing Phase 2 Program which aimed to demonstrate high-rate actuation of hingeless control surfaces using several smart material-based actuators including piezoelectric materials. Grohmann et al. [26,27] presented the active trailing edge and active twist concepts applied to helicopter rotor blades. The paper presented the optimization of sizing and placement of piezo-composite patches so that desired wing weight and pitching moment output is obtained.

The rapid development and the reduced cost of small electronics in the last decade led to the interest of using piezoelectric materials in small unmanned (and/or remotely piloted) fixed wing, rotary and ducted fan aircraft. The 2002 Virginia Tech Morphing Wing Design Team (Eggleston et al. [28], of the Department of Aerospace and Ocean Engineering) experimented with the use of piezoceramic materials (THUNDER), shape-memory alloys (SMAs), and conventional servomotors. Wind tunnel testing showed the feasibility of the smart material systems. Barrett et al. [29] employed piezoelectric elements along with elastic elements to magnify control deflections and forces. The so-called Post-Buckled-Precompression (PBP) concept was employed as guide vanes in a small rotary aircraft. The PBP concept, in its earliest incarnation, was primarily intended to increase the coupling coefficient exhibited by piezoelectric transducer elements (Lesieute and Davis [30]). Vos et al. [31,32] conducted research to improve the PBP concept for aerodynamic applications. Roll control authority was increased on a 1.4 meter span unmanned air vehicle. Kim and Han [33,34] designed and fabricated a smart flapping wing by using a graphite/epoxy composite material and an MFC actuator. A twenty percent increase in lift was achieved by changing the camber of the wing at different stages of flapping motion. Bilgen et al. [35,36] presented a unique application for piezo-composite actuators on a 0.76 meter wingspan morphing wing air vehicle. In this application, two MFC patches are bonded to
the wings of a small demonstration vehicle, and the camber of the wing is changed with voltage. Adequate roll control authority is demonstrated in the wind tunnel as well as in flight. All electronics, including MFC power electronics, are powered by an 11.1 V Lithium-Polymer battery, a common choice for remotely controlled aircraft. Bilgen et al. presented static flow vectoring via an MFC actuated thin bimorph variable-camber airfoil [37], and an MFC actuated cascading bimorph variable-camber airfoil [38]. Wind tunnel results and analytical evaluation of the airfoils showed comparable effectiveness to conventional actuation systems and no adverse deformation due to aerodynamic loading. Paradies et al. [39] implemented MFCs as actuators into an active composite wing. A scaled prototype wing was manufactured and models were validated with static and preliminary dynamic tests of the prototype wing. Wickramasinghe et al. [40] presented the design and verification of a smart wing for an unmanned aerial vehicle (UAV). The proposed smart wing structure consists of a composite spar and ailerons that have bimorph active ribs consisting of MFC actuators.

The 2010 Virginia Tech Wing Morphing Design Team (Butt et al. [41,42], of the Department of Aerospace and Ocean Engineering; Bilgen et al. [43], of the Department of Mechanical Engineering) have developed a completely servo-less, wind-tunnel and flight tested remotely piloted aircraft. The MFC actuators were used to form variable-camber, continuous, piezo-composite wings instead of the traditional servomotor controlled (and discrete) control surfaces. The team was able to develop lightweight control surfaces and the necessary driving high-voltage DC-DC converters, culminating in a landmark first flight of the completely MFC controlled aircraft on April 29, 2010. An electric motor driven propulsion system was used to generate thrust and all systems were powered with a single Lithium-Polymer battery. This vehicle became the first fully MFC controlled, flight tested aircraft. It is also known to be the first fully piezoelectric controlled, non-tethered, flight tested fixed-wing aircraft.

B. Current Research Motivation

There are several benefits of employing continuous shape (or more specifically camber) control via active materials over the discrete trailing edge control using conventional control surfaces in small aircraft. The term camber control simply refers to the change of the curvature of the airfoil by means of actuators. First, the low Reynolds number flow regime can result in flow separation that reduces the effectiveness of a trailing edge control surface. Second, small aircraft cannot afford to lose energy through control surface drag because of their severe power limitations. Finally, the opportunity for flow control is inherent in the active material due to its direct effect on circulation and its high operating bandwidth. Smart actuators are effective in dynamic laminar separation bubble control (also referred to as flow control).

The motivation for the current research is to determine the aerodynamic effectiveness of a variable-camber airfoil concept. The proposed concept employs piezoceramic materials that provide the actuation forces and moments, and they also form the surface of the airfoil. The research focuses on fundamental (and isolated) airfoil characteristics, quantified in terms of conventional two-dimensional aerodynamic coefficients. First, a previously presented variable-camber airfoil design is introduced as a baseline to the current concept. Next, the present concept for variable-camber airfoil is introduced. The static-aeroelastic response of the airfoil is theoretically evaluated for lift and lift-to-drag performance for range of structural configurations. The paper concludes with a brief discussion of the results.

II. Baseline Variable-camber Airfoil

A variable-camber airfoil was previously presented by Bilgen et al. [38] and it serves as a baseline to the design proposed in this paper. The baseline design employs two cascading active bimorph actuators (which form the top and bottom trailing surfaces of the airfoil) that are pinned at the trailing edge. These active surfaces are chosen to be MFC actuated bimorph laminates. The Macro-Fiber Composite actuator was developed at NASA Langley Research Center [44,45]. An MFC is a layered, planar actuation device that employs rectangular cross-section, unidirectional piezoceramic fibers embedded in a thermosetting polymer matrix. The in-plane poling and subsequent voltage actuation allows the MFC to utilize the 33 piezoelectric effect, which is higher than the 31 effect used by traditional PZT actuators with through-the-thickness poling [46]. There has been extensive analytical and experimental research focused on utilizing MFC as an actuator (or sensor) for structural control. Williams [47] and Bilgen [48] provide a detailed linear and nonlinear characterization of the mechanical and piezoelectric behavior of the MFC actuator.

A compliant parallelogram (box structure) is used to create the desired boundary conditions to the leading end of the active bimorph surfaces. Figure 1 shows the kinematic model and the parameters of the airfoil. In the figure, \( \beta \) is the leading edge (LE) incidence angle and MCL is the mean-camber-line. The compliant box can simply be
described as a four-bar mechanism. The two parallel bars that connect the top and bottom surfaces have constant length \((L)\).

![Diagram](image)

**Figure 1: Baseline airfoil design and geometric parameters. Morphed state is illustrated.**

The airfoil can be mounted to the vehicle either at the center or at the ends of the vertical bars. The change in camber of the active surface of the airfoil causes the box to comply and generate a shear-like motion while keeping the end-slope of the bimorphs equal to each other. When the airfoil is in the non-actuated state, the link length \((L)\) is equivalent to the LE thickness \((T)\) of the airfoil. The initial percent thickness \((Th=L/chord*100)\) is calculated at the zero volt state. The LE geometry is chosen to be elliptic in the actual prototype of this concept (discussed later). The airfoil thickness is determined depending on the application, where an optimum configuration can be achieved for a desired function of various aerodynamic coefficients.

A. **Theoretical Aerodynamic Response**

The method for theoretical analysis is presented in detail in Ref. [38]. Figure 2 shows the theoretical change in lift coefficient and lift-to-drag ratio for the airfoil with 127 mm chord. The airfoil is subjected to 15 m/s free-stream velocity.

![Graph](image)

**Figure 2: Theoretical (2D) a) lift coefficient and b) lift-to-drag ratio for novel airfoil subjected to free-stream velocity of 15 m/s.** \(Re_{chord} = 1.27\times10^6\).

The 2% thick airfoil reaches a \(CL_{max}\) value of 1.12 at 1400 V due to early flow separation. In contrast, the 6% thick airfoil shows the highest lift trend. The 12% thick airfoil shows the lowest drag coefficient trend (not shown here). Considering the stiffness of the airfoil, the flow induced deformation is assumed negligible at 15 m/s. A smooth surface is assumed for the analysis which is the main reason for the deviation of the lift curve from the actual performance around \(CL_{max}\). As reported in the literature, XFOIL predicts slightly high lift coefficients and low drag coefficients when compared to experimental results and therefore the predictions must be viewed as an upper boundary to actual performance. The maximum theoretical L/D is 42.6 for the 10% thick airfoil at 1300 V. This operation point corresponds to a camber of 4.12% and an AOA of 7.21°. The 2% thin airfoil shows the lowest L/D trend due to early stall and LE separation. Overall, the aerodynamic analysis clearly shows that a single bimorph airfoil (which is approximately 1% thick) is not as effective as generating lift force when compared to a thick airfoil at the same surface curvature (and excitation voltage).

B. **Measured Structural Response**

Using the theoretical predictions above, two prototypes are manufactured with two active surfaces (cascading bimorphs made with four MFC M8557-P1 [49] actuators each) and a single four-bar (box) mechanism as the internal structure. The airfoil has 127 mm chord, 133 mm span and 15 mm thickness. The two bimorphs used in the
airfoil are fabricated by sandwiching a 27 µm thick stainless-steel material with the MFC actuators. The MFC actuators have a voltage range of approximately -500 V to 1500 V. Since the airfoil has two surfaces, both in a bimorph configuration, the MFCs on the opposite sides are actuated with an opposite field and with 3:1 fixed ratio. First, bench top experiments were conducted to reveal the displacement-to-excitation relationship. During this test, the actuation voltage is swept from -1400 V to 1400 V and swept back to -1400 V. The effect of piezoelectric hysteresis is relatively large; however, it should also be noted that the deflection is repeatable. A non-linear analysis was not conducted; instead the shape of the airfoil at each test condition is measured directly. This measurement is also necessary to observe the additional deformation (if any) due to aerodynamic loading (for wind tunnel tests discussed next). It is also observed that the actual airfoil outline does deviate from the theoretical (and desired) airfoil. Most of this deviation occurs due to the interface between the active section and the rapid-prototyped elliptic LE. In summary, the airfoil achieved a peak -4.14% camber and -6.3° AOA at -1400 V excitation. The airfoil achieved a peak +5.24% camber and 7.01° AOA at +1400 V excitation.

C. Measured Aerodynamic Response

Wind tunnel experiments are conducted to compare the prototype variable-camber airfoil to other similar (in shape) fixed-camber airfoils. Four airfoils are presented: 1) Novel, variable-camber airfoil; 2) NACA 0009 airfoil; 3) NACA 0013 airfoil; 4) A rapid prototyped (RP) airfoil generated from the profile of the variable-camber prototype (at zero camber state.) The fourth airfoil is tested to determine the effects of the surface roughness. The NACA 0009 has a maximum thickness of 11.3 mm, and the NACA 0013 airfoil has a maximum thickness of 16.5 mm. The variable-camber and the RP airfoils have an equivalent thickness of 15 mm. The rapid-prototyped airfoils have 133 mm span, 127 mm chord and a finite trailing edge (TE) thickness of 1.0 mm. The lift and drag measurements are conducted at 15 m/s and at a chord Reynolds number of 127,000. For the variable-camber airfoil, the true AOA (the voltage-induced AOA) is given as the independent variable. The mounting angle (β) is zero. In other words, there is no rotation of the airfoil supports for the morphing airfoil data presented. This allows a “fair” comparison between the fixed and variable-camber airfoils. The lift coefficient and lift-to-drag ratio (L/D) comparison is presented in Figure 3. Note that the arrows in the legend specify the direction of sweep of voltage (Volt) and AOA (α).

![Lift Coefficient vs Angle of Attack](image1.png)

**Figure 3: Measured a) lift coefficient and b) lift-to-drag ratio (2D) comparison at 15 m/s. \(Re_{chord}=1.27\times10^5\).**

There is a significant increase in lift due to camber induced by voltage input. A lift curve slope of 0.144 per-degree is measured which exceeds the NACA 0009 lift slope (0.083 per-degree) by 72%. The plot shows the clear advantage of the lift generation by coupled camber-AOA change induced by voltage. The NACA 0013 and the RP airfoils develop similar lift-curve-slope; however the NACA 0013 achieves a slightly higher \(C_{l_{max}}\). The overall performance comparison of the airfoils is done by looking at the lift-to-drag ratio presented in Figure 3b. The variable-camber airfoil produces a maximum L/D ratio of 13.4 at 1500 Volts (α=5.78°) and an L/D ratio of -11.2 at -1500 Volts (α=-5.20°). The NACA 0009 airfoil produces a maximum L/D ratio of 16.3 at α=4.21° and an L/D ratio of -12.3 at α=-4.97°. The variable-camber airfoil has higher L/D performance when compared to the fixed-camber airfoils with similar thickness (NACA 0013 and RP). In comparison to the conventional airfoils, the morphing airfoil generates a comparable change in lift-to-drag ratio. A relatively high experimental drag was observed for the morphing airfoil due to its blunt (elliptical) LE when compared to the LE of NACA 0009 airfoil. The variable-camber prototype does not have a continuous surface as desired due to in-house fabrication limitations and this is one of the issues addressed by the current paper. This is evident when the drag performance of the morphing airfoil...
at zero AOA is compared to its rapid-prototyped replica airfoil (RP) with a continuous and relatively smooth surface. Since the variable-camber airfoil is aimed at generating lift forces for vehicle control, performance in lift is considered more important than the performance in drag.

III. Proposed Airfoil Concept

The high structural deflection requirement (of aerodynamic applications) creates the need for semi-solid-state mechanisms and distributed boundary conditions to be employed along with piezoelectric actuation. The baseline concept presented in the previous section generates a significant amount of deformation and lift change induced by excitation voltage. On the other hand, the design still has a discontinuity between the leading section geometry and the variable-camber trailing section. In the prototype of the baseline design, this gap (with variable-length) is covered using a flexible strip of plastic which allows the active bimorph surface to slide forward and backwards with respect to the fixed LE geometry. Another issue is that the solid-state compliant box mechanism (formed by four “live” hinges) introduced extra weight and complexity due to limited in-house fabrication capabilities.

In the current concept, illustrated in in Figure 4, the authors propose a continuous airfoil surface and a set of “simpler” boundary conditions to remedy these problems. The continuity in the airfoil surface is achieved by using a single substrate that wraps around the airfoil shape. This substrate forms the surface of the airfoil and it serves as the host material for the two cascading bimorph actuators. This airfoil is attached to the three-dimensional spar structure (e.g. a rectangular spar box with spanwise taper) at two locations. In Figure 4, the locations of these two boundary conditions (Pin1 and Pin2) are exaggerated to aid visibility.

![Figure 4: A simplified illustration of the variable-camber airfoil design. Actuated and non-actuated states are shown.](image)

In Figure 4, the label “AOA” represents the angle-of-attack. The boundary conditions in the design are pinned-pinned (similar to a simply-supported beam) for ease of implementation; however one can choose the second boundary condition (Pin2) as a slider (allowing motion in the chordwise axis and restricting motion in the lift axis). A pair of pinned-pinned boundary conditions theoretically creates a nonlinear displacement response but this is not dominant in an actual implementation of the airfoil geometry and the pin locations. Starting with the baseline design, multiple configurations can be generated by changing the location of the pins. The two extreme configurations occur when: 1) the first pin is moved to the LE and the second pin is moved to the TE which is similar to a sail or a simply-supported beam; 2) both the first and second pins are moved to the leading edge, hence the airfoil becomes equivalent to a cantilevered beam.

The airfoil examined here (without electrical excitation and aerodynamic loading) has an elliptical leading edge (with 2:1 ratio) and a circular-arc trailing section. The TE is formed by pinning the two bimorph surfaces and it is assumed to have a finite thickness of 0.05% chord. A constant curvature is assumed for the bimorph trailing section due to the uniform chordwise coverage of the active material (MFC actuator). The nonlinear voltage-displacement relationship of a single cantilevered MFC bimorph actuator is experimentally quantified (previously) with laser displacement measurements (see Ref. 37). Figure 5 presents the measured chordwise deformation of a thin bimorph airfoil in response to electrical excitation. Since the airfoil is in a bimorph configuration, the MFCs are actuated asymmetrically with an opposite field and with a 3:1 fixed ratio. The higher of the two supply voltages (V) is used for labeling in the figure. A negative sign simply indicates actuation in the reverse direction as indicated in Figure 5. The AOA and the effective camber are calculated by fitting a 127 mm circular-arc to the measured data points. The percent-camber (C) is the percentage of the height over the chord of the circular-arc.
In Figure 5, the actuation voltage is swept from -1400 V to 1400 V and swept back to -1400 V. The effect of piezoelectric hysteresis can be observed in the difference between the deflection at zero voltage during the positive and negative voltage sweeps. However, the deflection is very repeatable, as seen at the maximum positive and negative voltage levels. Figure 5 also shows that a circular-arc is a good approximation; however the actual shape does deviate from a circular arc. The peak-to-peak camber-voltage relationship (deduced from the data of Figure 5) of a single bimorph is used to determine the material properties in the finite-element (FE) model.

A. Static-Aerelastic Analysis Method

A thin shell-like morphing airfoil (with reasonable chordwise stiffness and displacement output) is possible with an MFC actuator given that the boundary conditions and structural features are favorable. Therefore, the support system for the variable-camber device is determined here using a parametric analysis. A MATLAB [50] based program is used to solve the static fluid-structure interaction (FSI) problem by iterating between a panel method software XFOIL [51,52], and a finite element code ANSYS [53]. Before the iteration starts, the non-aero-loaded airfoil shape is analyzed in XFOIL to initialize the FSI. XFOIL calculates lift and drag coefficients and the pressure distribution and the program enters the iteration loop. First, the pressure distribution is applied to the airfoil geometry in ANSYS which calculates the aero-loaded (deformed) airfoil shape. Second, the deformed airfoil shape is analyzed in XFOIL to calculate change in the lift and drag due to the change in pressure induced deformation. These two steps are continued until no change is observed in the parameters of interest (i.e. deformation and aerodynamic coefficients). Due to the static nature of the problem, the solution converges with a few iterations. Note that the dynamic effects are known to be negligible (and ignored in the analysis) because of previous experimental observations. The analysis in this paper considers only chordwise distribution of aerodynamic loads and structural deformations.

For XFOIL simulations, a 0.85% (of the mean velocity) turbulence level is assumed, which is consistent with the measured turbulence level in the previous wind tunnel data. It must be noted that XFOIL predictions for AOA above maximum lift angle are not accurate [52]. Due to the limitation of the deflection of the piezo-composite bimorph, the XFOIL analysis presented here (for a 9.0% thick airfoil) never passes beyond this AOA limit (see Figure 2). Approximately 400 panels are used in XFOIL to achieve numerical convergence for the airfoils considered in this section. As reported in literature [51,52], XFOIL predicts slightly higher lift coefficients and lower drag coefficients when compared to experimental results; therefore the predictions must be viewed as an upper boundary to actual lift and lift-to-drage performance.

The passive material in the airfoil is modeled as a homogeneous 2D area mesh using PLANE82 high-order quadrilateral (Q8) type element in ANSYS. The MFC actuator is modeled as a monolithic piezoelectric layer using a homogeneous 2D area mesh consisting of PLANE223 high-order quadrilateral (Q8) coupled-field elements. The plane element type is chosen (instead of the beam element type) because of the dense, non-uniform and distributed loading at the leading edge with significant components in the in-plane direction as well as the out-of-plane direction. The material properties used in the finite element model are checked using previous experimental data. Approximately 20,000 elements are used to ensure convergence of the finite element model for all airfoil models.
evaluated in the parametric study. The number of elements chosen is relatively high to accommodate the highly non-uniform pressure distribution data from XFOIL. Figure 6 shows an example of the finite element model used in the parametric study. There is a high concentration of aerodynamic loading (shown with arrows normal to the surface) at the leading edge. Note that the most of the features on this figure are exaggerated to aid the visibility. In reality, the thickness of the substrate and the PZT layer is very small compared to the maximum thickness of the airfoil.

![Finite Element Model](image)

**Figure 6:** Example of the finite element model used in the parametric study. a) Complete model. b) Zoomed image of the leading edge and pressure distribution. c) Transition from passive leading section to the active trailing section. d) Zoomed image of the live hinge that connect the cascading active surfaces at the TE.

The figure shows the whole airfoil and zoomed images of important areas. In addition to the effect of the location of boundary conditions, the substrate thickness is an important parameter assuming that the PZT layer thickness \( t_{\text{pzt}} \) is fixed. The MFC actuator has a fixed thickness of 300 µm. The leading section of the airfoil has a constant thickness of \( t_{\text{subs}} \). This “stiff” substrate overlaps with a fraction of the active trailing section. This substrate is then reduced to a thickness of \( t_{\text{pzts}} \). This arrangement is due to several reasons. First, the non-uniform aerodynamic pressure distribution has a much higher magnitude close to the LE. A thick (and therefore stiff) substrate is required around the LE. At the trailing section, the laminate formed by the active material and a thinner substrate has enough bending stiffness to carry aerodynamic loads. Another important reason for the stepped thickness is that the “optimum” leading section substrate thickness is more likely to be different than the “optimum” substrate thickness for a bimorph (or unimorph) actuator. These are expected results, however since these structural parameters are coupled with the aerodynamic state, a parametric analysis is presented next to understand the coupled behavior.

### B. Parametric Analysis Results

The main parameters of interest are 1) \( \text{Pin1} \) location, 2) \( \text{Pin2} \) location, 3) leading section substrate thickness, and 4) thickness of the substrate under the active material. The substrate material is assumed to be stainless-steel. The first pin is fixed in both axes; in contrast the second pin is restrained only in the lift axis. The top MFC actuator is subjected to an effective +1500 V and the bottom MFC actuator is subjected to an effective -500 V. Note that the actual applied electric field is adjusted so that the unimorph FE model has a matching transverse displacement response to the actual bimorph device. In addition, the electric field is also corrected for the fact that the 33 mode interdigitated MFC actuator is modeled as a 31 monolithic piezoceramic.

First, the effects of pin locations on the lift coefficient and lift-to-drag ratio are investigated. A fixed leading section substrate thickness \( (t_{\text{subs}} = 203 \, \mu m) \) and a fixed trailing section substrate thickness \( (t_{\text{pzts}} = 25.4 \, \mu m) \) is assumed. Figure 7 presents the lift coefficient and lift-to-drag ratio for the proposed airfoil subjected to free-stream velocity of 15 m/s. The plots represent the aerodynamically loaded (and converged) response.
The analysis shows that placing Pin1 close to the leading edge results in the highest lift output. The highest lift coefficient and the lift-to-drag ratio is achieved for the configuration with Pin1=10%c and Pin2=20%c. The actual displacement of this configuration is presented in Figure 8. Note that the x and y axes are equally scaled.

The remainder of the parametric analysis considers the cases with Pin1 located at 10% chord. Now, the effects of the leading section substrate thickness and Pin2 location on the lift coefficient and lift-to-drag ratio are investigated. A fixed trailing section substrate thickness ($t_{trailing} = 25.4 \mu m$) and a fixed Pin1 location ($Pin1 = 10%c$) is assumed. Figure 9 presents the lift coefficient and lift-to-drag ratio for the proposed airfoil subjected to free-stream velocity of 15 m/s.

The analysis shows that placing Pin2 at 55%c and using a leading section thickness of 50.8 µm results in the highest lift output and placing Pin2 at 35%c and using a leading section thickness of 178 µm results in the highest lift-to-drag ratio. The highest lift coefficient achieved is 1.77 and the highest lift-to-drag ratio achieved is 40.3. The actual displacements of these configurations are presented in Figure 10.
Figure 10: Morphed airfoil that corresponds to highest a) lift coefficient and b) lift-to-drag ratio subjected to free-stream velocity of 15 m/s. \( Re_{chord} = 1.27 \times 10^5 \).

Finally, the effects of the trailing section substrate thickness and Pin2 location on the lift coefficient and lift-to-drag ratio are investigated. A fixed leading section substrate thickness \( t_{subs} = 25.4 \mu m \) and a fixed Pin1 location \( (Pin1 = 10\%c) \) is assumed. Figure 11 presents the lift coefficient and lift-to-drag ratio for the proposed airfoil subjected to free-stream velocity of 15 m/s.

The analysis shows that placing Pin2 at 55\%c and using a trailing section thickness of 50.8 \( \mu m \) results in the highest lift output and placing Pin2 at 45\%c and using a trailing section thickness of 10.2 \( \mu m \) results in the highest lift-to-drag ratio. The highest lift coefficient achieved is 1.79 and the highest lift-to-drag ratio achieved is 40.2. The actual displacements of these configurations are presented in Figure 12. As noted earlier, the \( x \) and \( y \) axes are equally scaled.

Figure 11: Theoretical (2D) a) lift coefficient and b) lift-to-drag ratio for proposed airfoil subjected to free-stream velocity of 15 m/s. \( Re_{chord} = 1.27 \times 10^5 \).

Figure 12: Morphed airfoil that corresponds to highest a) lift coefficient and b) lift-to-drag ratio subjected to free-stream velocity of 15 m/s. \( Re_{chord} = 1.27 \times 10^5 \).
IV. Conclusions

This paper proposed a variable-camber airfoil that employs surface-induced deformations instead of the more typical internal actuation. The coupled treatment of the fluid-structure interaction allows the realization of a design that is not only feasible in a bench top experiment, but that can also sustain large aerodynamic loads. The effects of four important structural parameters are studied to achieve the highest possible lift coefficient and lift-to-drag ratio. The highest lift coefficient of 1.79 is achieved by a configuration with 1) Pin1 at 10%c, 2) Pin2 at 55%c, 3) leading section substrate thickness of 25.4 µm and 4) trailing section thickness of 50.8 µm. The highest lift-to-drag ratio of 40.3 is achieved by a configuration with 1) Pin1 at 10%c, 2) Pin2 at 35%c, 3) leading section substrate thickness of 178 µm and 4) trailing section thickness of 25.4 µm. The substrate material is assumed to be a stainless-steel, and the active material electromechanical properties are equivalent to the Macro-Fiber Composite actuator. The results are presented for a free-stream velocity of 15 m/s, chord Reynolds number of 127,000 and an assumed turbulence level of 0.85%. In comparison to the baseline variable-camber airfoil (with solid-state internal hinges and 9.0% chord thickness), the proposed airfoil (with a pair of pinned-sliding boundary conditions) produce higher lift coefficient and slightly lower lift-to-drag ratio. The advantages of the new concept are: 1) it has a continuous surface and 2) it requires more practical internal boundary conditions when compared to the baseline design.

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References


