Implementation of a Continuous-Inextensible-Surface Piezocomposite Airfoil

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The theoretical and experimental evaluation of a variable-camber airfoil which employs a continuous inextensible surface and surface bonded piezoelectric actuators is presented. The partially-active surface is designed to have sufficient bending stiffness in the chordwise direction to sustain chordwise shape under aerodynamic loading. In contrast, the in-plane stiffness is relatively high; however the necessary deformations that are required to change the aerodynamic response can still be attained while maintaining the surface perimeter constant. Coupled with two carefully selected boundary conditions, the proposed piezocomposite airfoil can achieve significant change in aerodynamic response. The surface geometry properties are determined using a Genetic Algorithm optimization method. The optimization is conducted to achieve maximum change of lift output per square root of drag which is the difference in the aerodynamic response for the airfoil at maximum excitation (asymmetric) and zero excitation (symmetric). A coupled analysis of the fluid-structure interaction is employed assuming static-aeroelastic behavior which allows the realization of a design that can sustain aerodynamic loads. The theoretical response is supplemented with extensive bench-top and wind tunnel experiments on a representative prototype. The experimental results are compared to the theoretical predictions, highlighting agreements and discrepancies.

1. Introduction

SMOOTH and continuous aerodynamic control surface designs have been a research interest since the beginning of modern aviation, the first controlled, powered and heavier-than-air flight by the Wright Brothers in 1903. Establishing a wing configuration that is stiff enough to prevent flutter and divergence, but compliant enough to allow the range of available motion, has been the central challenge in developing a smooth and continuous wing. A significant attention in research has been given to using conformal piezoelectric actuators to achieve shape change in variable-camber airfoils. Barbarino et al. [1] has shown that morphing of camber using piezoelectric materials has resulted in the largest number of wind tunnel and flight tests in aircraft when compared to other morphing categories, such as planform and out-of-plane morphing categories, and when compared to other actuation sources, such as conventional actuators, shape-memory alloys, rubber-muscle actuators and others.

In the case of piezoelectric material devices, the rapid development and the reduced cost of small electronics in the last decade has led to several examples of operational small unmanned (and/or remotely piloted) fixed-wing, rotary-wing and ducted-fan aircraft that use smart materials. The following discussion presents only a few examples of such aircraft. In 2002, Eggleston et al. [2] experimented with the use of piezoceramic materials, shape-memory alloys, and conventional servomotors in a morphing wing aircraft. A series of wind tunnel tests showed the feasibility of the smart material systems. Barrett et al. [3] employed piezoelectric elements along with elastic elements to magnify the control deflections and forces in aerodynamic surfaces. Vos et al. [4,5] conducted research to improve the Post-Buckled-Precompression concept for aerodynamic applications. Roll control authority was increased on a 1.4 meter span unmanned air vehicle. Kim and Han [6,7] designed and fabricated a flapping wing by using a graphite/epoxy composite material and a Macro Fiber Composite (MFC) actuator. A twenty percent increase in lift was achieved by changing the camber of the wing at different stages of flapping motion. The MFC actuator was originally developed at NASA Langley Research Center [8,9] and offers structural flexibility and high actuation.

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authority. 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 piezoceramic actuators with through-the-thickness poling [10]. Bilgen et al. [11,12] presented an application for piezo-composite actuators on a 0.76 meter wingspan morphing wing air vehicle. Adequate roll control authority was demonstrated in the wind tunnel as well as in flight. Bilgen et al. presented static flow vectoring via an MFC actuated thin bimorph variable-camber airfoil [13], and an MFC actuated cascading bimorph variable-camber airfoil [14]. 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 and Ciresa [15] 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. [16] presented the design and verification of a smart wing for an unmanned aerial vehicle. The proposed smart wing structure consists of a composite spar and ailerons that have bimorph active ribs consisting of MFC actuators. In 2010, Butt et al. [17,18] and Bilgen et al. [19] developed a completely servo-less, wind-tunnel and flight tested remotely piloted aircraft as a part of a senior design project. The team developed 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. This vehicle became the first fully solid-state piezoelectric material controlled, non-tethered, flight tested fixed-wing aircraft.

The examples above clearly show the feasibility of piezoelectric materials in small unmanned aircraft; however optimization and static-aeroelastic tailoring is neglected in most cases. The motivation for the research presented here is to model, optimize and validate the static-aeroelastic effectiveness of a variable-camber morphing wing. The proposed concept employs surface bonded piezoceramic materials that provide the necessary deformations to generate desired aerodynamic output. In addition, an optimized internal passive structure establishes the desired boundary conditions and spanwise load carrying characteristics. First, the paper focuses on the motivation for the proposed variable-camber airfoil. Second, the theoretical optimization of the static-aeroelastic response by identifying substrate structural parameters and the distribution of boundary conditions is presented. Next, bench top experimental results are presented highlighting the deformation of the airfoil induced by piezoelectric excitation. Finally the wind tunnel experiments are presented. Theoretical predictions are compared to the experimental results, highlighting agreements and discrepancies. The paper concludes with a brief summary of results.

II. Motivation for the Proposed Morphing Airfoil Concept

In general, morphing wing structures achieve shape change in a unique fashion; however some concepts, more specifically the ones employing smart material systems, may not produce enough aerodynamic effects when compared to conventional wing structures. Typically, morphing wings that employ piezoelectric materials fall into this category where the main purpose is to increase aerodynamic efficiency by achieving surface continuity and by reducing the number of parts and mass concentrations. Since most piezoelectric materials are limited in their strain output, these materials are typically not proposed for achieving dramatic shape change that allows an aircraft to operate in a wide range of fluid conditions.

In the current research, the purpose for employing piezoelectric materials is to achieve similar aerodynamic function as conventional control surfaces while reducing the number of discrete surfaces, discontinuities and parts. In return, such a concept is likely to reduce maintenance and fabrication costs, and reduce the weight of the overall aerodynamic surface; however the analysis of these desired features are beyond the scope of the current research. Here, the attention is directed to the actuation output of such structures, quantified roughly in terms of ability to induce lift while causing minimum increase in drag. The design of such an airfoil requires attention to optimizing 1) the piezoelectric and substrate features, 2) the semi-solid-state (compliant) internal mechanisms if necessary and 3) the distributed boundary conditions. A central challenge in determining such structures is to decide on the level of complexity of the design so that the final aerodynamic objective is met with a relatively simple, light-weight and easy-to-fabricate structure.

In the context presented above, a piezocomposite semi-solid-state variable-camber airfoil, previously evaluated by Bilgen et al. [14], is employed as a baseline. The baseline variable-camber airfoil employs two cascading bimorph actuators in the top and bottom surfaces of the airfoil which are pinned at the trailing edge. These active surfaces were chosen to be Macro-Fiber Composite actuated bimorphs. A compliant parallelogram (box structure) was used to create the desired boundary conditions to the leading section of the curved bimorph surfaces. Wind tunnel experiments were conducted previously to compare the prototype variable-camber airfoil to other similar (in shape) fixed-camber airfoils. The lift and drag measurements were conducted at 15 m/s and at a chord Reynolds number of 127,000. A lift curve slope of 0.144 per-degree was measured, which exceeds the NACA 0009 lift slope (0.083 per-degree) by 72%. The results showed the clear advantage of the lift generation by the coupled camber and

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angle-of-attack (AOA, $\alpha$) change induced by excitation voltage. The variable-camber airfoil produced a maximum lift-to-drag ratio (L/D) of 13.4 at 1500 Volts ($\alpha = 5.78^\circ$) and an L/D ratio of -11.2 at -1500 Volts ($\alpha = -5.20^\circ$). The NACA 0009 airfoil produces a maximum L/D ratio of 16.3 at $\alpha = 4.21^\circ$ and an L/D ratio of -12.3 at $\alpha = -4.97^\circ$. The variable-camber airfoil has comparable L/D performance when compared to the fixed-camber airfoils with similar thickness. A relatively high experimental drag was observed for the morphing airfoil due to its blunt (elliptical) leading-edge (LE) when compared to the LE of the NACA 0009 airfoil.

The aerodynamic performance of the baseline airfoil, quantified in terms of change in lift coefficient, was as desired; however the design failed to take full advantage of solid-state piezoelectric material actuation. First, the baseline airfoil had a small discontinuity in the lower surface. In the prototype of the baseline design, this gap with variable-length, between the solid leading-edge and the variable-camber trailing-section, was covered using a flexible strip of plastic. This method allowed the active bimorph surface to slide forward and backwards with respect to the fixed LE geometry. Another issue was that the solid-state compliant box mechanism, formed by four compliant hinges, introduced extra weight and complexity, although structural complexity was necessary to implement the necessary kinematics. In the concept proposed here, the authors suggest a continuous and inextensible airfoil surface and a set of “simpler” boundary conditions to remedy the two problems outlined above. 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 piezoelectric actuators. This airfoil is attached, or pinned, to a “three-dimensional” spar structure (e.g. a rectangular spar box with spanwise taper).

### III. Theoretical Analysis with Static-Aeroelastic Model

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 static-aeroelastic model. The static behavior of similar structures is previously observed experimentally (and also shown here in the following sections) and hence dynamic behavior is assumed to be negligible. A MATLAB [20] based program is used to solve the static fluid-structure interaction (FSI) problem by iterating between a panel method software XFOIL [21,22], and a finite-element code ANSYS [23]. Before the iteration starts, the non-aero-loaded airfoil shape is analyzed in XFOIL to initialize the FSI process. The panel method is initially used to calculate the two-dimensional lift and drag coefficients and the pressure distribution. After the first approximation, the program enters an 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 lift and drag due to the change in pressure induced deformation. These two steps are iterated until no change is observed in the parameters of interest (i.e. deformation and aerodynamic coefficients). Due to the static-aeroelastic nature of the problem, the solution converges typically after five iterations. As noted above, dynamic effects are known to be negligible because of the boundary conditions and previous experimental observations. The analysis in this paper considers only chordwise distribution of aerodynamic loads and structural deformations.

For the XFOIL simulations, a 0.07% (in terms of the mean velocity) turbulence level is assumed, which is consistent with the turbulence level in a typical wind tunnel. It must be noted that XFOIL predictions for AOA above the maximum lift angle are not accurate [22]. Due to the limitation of the deflection of the piezoelectric actuators considered, the XFOIL analysis presented here (for a 12.0% thick airfoil) never passes beyond this AOA. A total of 400 panels are used in XFOIL to achieve numerical convergence for the panel method analysis. As reported in the literature [21,22], XFOIL predicts slightly higher lift coefficients and lower drag coefficients when compared to experimental results; therefore the predictions must be viewed as an upper limit to the actual lift and lift-to-drag performance.

The passive material, also referred to as the substrate, of 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. An experimental evaluation of the peak-to-peak deflection-voltage relationship, deduced from previous data, is used to determine the material properties of the MFC actuator in the finite-element (FE) model. Approximately 10,000 elements are used to ensure convergence of the finite-element model for all airfoil models evaluated in the study. The number of elements chosen is relatively high to accommodate the highly non-uniform pressure distribution data from the panel method.
IV. Optimization using Genetic Algorithm

The approach to determine and optimize the internal passive structure of the variable-camber morphing wing is based on a Genetic Algorithm (GA) optimization technique. Genetic algorithms were invented by John Holland in the 1960s and were developed by Holland and his students and colleagues at the University of Michigan in the 1960s and the 1970s [24]. Genetic Algorithms belong to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover [25]. Mitchell [24] and others describe the formal steps of a simple genetic algorithm which is employed in this paper. GAs assume that high-quality “parent” candidate solutions from different regions in the parameter space can be combined via crossover to, on occasion, produce high-quality “offspring” candidate solutions. Each individual is characterized by its own genetic code or chromosome, which are represented by real values, generated as a set of values selected within suitable intervals for each optimization parameter. Some intelligence is integrated by the authors within the Genetic Algorithm in terms of parameters available to the optimization process, together with their degrees of freedom and constraints, to fulfill the proposed design criteria and achieve an aerodynamically feasible variable-camber morphing wing. The optimization process, illustrated in Figure 1, starts with the creation of a trial set of substrate parameters for each individual according to the genetic methodology, based on the random selection of a value, within the established range, for each parameter being part of the optimization. Before the optimization study, a parametric analysis is conducted to understand 1) the sensitivity of aerodynamic output to the structural parameters and 2) the domain of structural parameters that result in feasible solutions.

The model solves the static fluid-structure interaction problem, and is executed for each individual of a generation. The performance is estimated by the fitness function, quantified in terms of the change in lift-coefficient-per-square-root-of-drag-coefficient, \( F = \Delta (CL/ \sqrt{CD}) \). The fitness function is chosen to favor the increase in lift and penalize the increase in square-root of drag. The choice of penalizing \( \sqrt{CD} \) is made so that the optimizer does not move too far from the \( CL_{max} \) condition (caused by large voltage induced AOA). This fitness function places similar (a more linear) emphasis on the increase of lift and decrease of drag as a function of AOA. To maximize the objective function, the typical steps of the GA are applied. Selection, cross-over and mutation operators are all executed to create a new generation starting from the best fit individuals of the previous one. Fitness-proportionate selection is employed, although it is well known that this selection criterion may cause “premature convergence.” A fitness dependent convergence criterion is not employed. Instead a fixed number of generations, between 100 and 300, are evaluated in a given complete set of generations, which are referred to as runs. Multiple runs of the same optimization allows the GA to start with different, randomly selected, initial conditions; enabling the analysis a better chance to converge to a “global” optimum. Since randomness plays a large role in each run, two runs with different random-number seeds, or initial conditions, will generally produce different behaviors. As practiced often by researchers using GAs, approximately 35 to 50 runs are evaluated for different optimization cases that are presented next. Here, it must be noted that the GA is not proposed as “the best” optimization method nor are the
results accepted as “the global optimum” solution. The GA is used to obtain a structure that performs reasonably well in theory, and also in practice given the in-house fabrication limitations. The results from the different runs of the GA are evaluated by sound engineering judgment. In contrast to these limitations, the GA method can easily be adopted for systems with variable complexity; therefore it is preferred over other optimizations processes. One must observe that the optimal solution is not only capable of maximum performance, according to the selected fitness function, but also satisfies the FSI problem. The structural solutions which are not capable of carrying aerodynamic loads are discarded during the optimization.

A. Optimization Parameters

Figure 2 shows an illustration of the finite-element model used in the optimization study. Note that most of the features on this figure are exaggerated to aid visibility. In reality, the thickness of the substrate and the piezoelectric material layer, referred to as pzt, is very small compared to the maximum thickness of the airfoil. As noted before, the MFC actuator, which operates in the 33 mode of piezoelectricity, is proposed for the concept; however the model is constructed using a monolithic layer of PZT material which operates in the 31 mode. In addition, for the sake of simplicity of the model, the unimorph configuration is initially proposed; however a bimorph configuration is also evaluated later in this paper. The airfoils examined here, without electrical excitation and aerodynamic loading, have a NACA 0012 airfoil profile, and chosen because of its popularity in the literature. The trailing-edge is formed by pinning the two active surfaces and it is assumed to have a minimum thickness of 0.25% chord. The airfoil is assumed to have a 178 mm chord length due to wind tunnel limitations.

The figure shows the whole airfoil and zoomed images of important areas. The main parameters of interest are 1) boundary conditions and their distribution, 3) substrate thicknesses \(( t_{\text{subs le}}, t_{\text{subs}}, t_{\text{subs_pzt}})\), 4) end location of the leading edge substrate \(( x_{\text{subs_le}})\), 5) start and end locations of three PZT actuators \(( x_{\text{pzt_begin}}, x_{\text{pzt_end}})\). The substrate material Young’s modulus is fixed to that of aluminum (70 GPa). The excitation voltage of the PZT actuators can have a value in the range of -1500 to +1500 Volts. Each of these parameters will be discussed in the following paragraphs.

In Figure 3, a pair of possible configurations of the boundary conditions is shown. In Figure 3a, the uniform cross-section wing, referred to as the two-dimensional configuration, is shown. This wing would be attached to the vehicle at both ends (e.g. as an exit guide vane). Bending moments on the internal structure are less severe when compared to a fixed-wing vehicle assuming that the aspect ratio is relatively lower for the former. In Figure 3b, the proposed configuration for a fixed-wing vehicle is shown. The cross-section will no longer be uniform in the spanwise direction. In this configuration, all points on the airfoil surface that lie between the two selected pin locations, Pin1 (which is the leading boundary condition) and Pin2, are also constrained. In both configurations, however, both of the pin locations are allowed to be attached to the upper or lower (interior) surface of the airfoil during the optimization process. The boundary conditions in the FE model are assumed to be pinned-pinned for ease of implementation; however, for the two-dimensional case, one can choose the second boundary condition \((\text{Pin2})\) 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.
The MFC actuator has a fixed ceramic thickness of 180 µm and a total device thickness of 300 µm. The substrate is divided into three sections to allow three different thicknesses to be optimized while the actuator thickness is kept constant. The leading section of the airfoil has a constant thickness of \( t_{\text{subs,le}} \). The leading section substrate, starting at the LE and ending at \( x_{\text{subs,le}} \), is expected to be small and more compliant when compared to the rest of the substrate. The main substrate thickness, adjacent to the leading section substrate, has a thickness of \( t_{\text{subs}} \). The main substrate region is determined by the beginning and the end of the active PZT region, labeled as \( x_{\text{pzt,begin}} \) and \( x_{\text{pzt,end}} \) respectively. The intention with the main (passive) substrate region is to have a light-weight substrate (without the weight penalty of the PZT material) that can carry bending moments and possibly be the region where boundary conditions are attached to the airfoil. The main substrate overlaps with a fraction of the active PZT region in order to reduce stress concentrations at the substrate-PZT interface. The substrate thickness under the PZT actuator is labeled as \( t_{\text{subs,pzt}} \).

The intention with this is to 1) achieve a high PZT induced transverse displacement by achieving the optimum substrate-to-PZT thickness ratio and 2) to use the combined bending stiffness of the substrate-PZT composite to carry aerodynamic loads. In addition to the parameters described above, each chordwise location parameter (\( x \)...) can have an independent value for the three conformal actuators on the airfoil surface.

This stepped, three-level substrate arrangement has several advantages in terms of performance and practicality. First, the non-uniform aerodynamic pressure distribution has a much higher magnitude close to the LE. A thick (and therefore stiff) substrate may be required around the leading region. At the same time, a portion of the LE has to be compliant to allow the range of motion for the active regions. At the regions where PZTs are located, 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 unimorph actuator. These are expected results, however since these structural parameters are coupled with the aerodynamic state, the optimization study is conducted to understand the coupled behavior.

The top, leading-bottom and trailing-bottom PZT actuators, referred to as \( pzt1, pzt2 \) and \( pzt3 \) respectively, are subjected to three independent effective voltage levels, \( V_{\text{pzt1}}, V_{\text{pzt2}} \) and \( V_{\text{pzt3}} \) respectively. Note that the electric field is corrected for the fact that the 33 mode interdigitated MFC actuator is modeled as a 31 monolithic PZT ceramic in the FE model. Here, it is also assumed that the PZT actuator has a symmetric excitation range of -1500 to +1500 Volts; however this voltage range is -500 to +1500 Volts in reality.

### B. Optimization Results – Two Dimensional Configuration

In this paper, only the optimization results of the two-dimensional configuration, as illustrated in Figure 3a, is presented. Figure 4 shows the maximum and average fitness for the selected two-dimensional configuration optimization study. This case is chosen out of 35 GA runs because of its relatively high fitness value of 10.4 and its operational behavior in the complete actuation range (-1500 to +1500 V). When the optimization is terminated at 200 generations, the chromosomes of the best fit individuals are examined.
Figure 4: Maximum and average fitness during optimization.

Figure 5a shows an illustration of the geometric properties of the optimized structure. The selected GA run showed that placing $Pin1$ close to the leading edge (at 5% chord) and placing the $Pin2$ at 25% chord results in the highest fitness value. The effect of the three regions of substrate thicknesses on the fitness is also investigated. The analysis showed that using a leading-edge substrate thickness, $t_{subs,le}$, of 50.8 µm results in the highest fitness. The leading-edge substrate starts at 1% chord on the top surface and ends at 5% chord on the bottom surface. The main substrate thickness, $t_{subs}$, is 127 µm and the substrate under the PZT, $t_{subs,pzt}$, is 390 µm thick. The top surface PZT layer starts at 5% chord and ends at 95% chord. The leading-bottom PZT starts at 5% chord and ends at 25% chord. The trailing-bottom PZT starts at 30% chord and ends at 100% chord. Figure 5b shows the two operational states, used to determine the fitness value of the optimum configuration. In Figure 5b, the NACA 0012 airfoil shape is shown as reference to the variable-camber airfoil.

Figure 5: a) Geometric parameters and b) operational states of the optimized airfoil at 10 m/s free-stream velocity.

Figure 6 shows the theoretical two-dimensional (2D) lift coefficient and lift-to-drag ratio operational response of the airfoil at 10 and 20 m/s free-stream velocities.

Figure 6: Theoretical (2D) a) lift coefficient and b) lift-to-drag ratio induced by excitation voltage at different velocities. Static-aerodynamic results for the optimized variable-camber airfoil in unimorph configuration.
In Figure 6, both the effect of change in the Reynolds number and the effect of deformation due to aerodynamic loading are observed. At 10 m/s, the dynamic pressure is relatively low; therefore the flow induced deformations are small. At higher dynamic pressures (i.e. 20 m/s) the flow induced deformations are more noticeable. It is important to note that the identified optimum structural parameters apply to a specific range of dynamic pressures and when this range is exceeded, the structure is no longer “optimized” and the assumption of static-aeroelastic behavior will be invalid. In the cases presented here, the optimization is conducted at the 30 m/s flow velocity condition; however the operational limit is “artificially” selected as 20 m/s resulting in an effective “factor-of-safety” value of 2.25.

V. Case Study and Experimental Validation

This section presents the experimental validation of the morphing airfoil concept. Before the airfoil was manufactured a separate optimization had to be conducted where certain parameters were fixed instead of being part of the optimization process. For example, a common commercially available MFC is the M8528-P1 and it has an active region of 85 mm by 28 mm. It is preferred to use this actuator as is, although one can cut it in half and create two actuators with equal lengths. In order to reduce the thickness of the substrate, the Young’s modulus of brass (100 GPa) and stainless-steel (200 GPa) are considered instead of that of aluminum. Finally, a bimorph configuration, instead of a unimorph configuration can be employed to increase the energy density of the active areas. In the case of the bimorph configuration, the MFC in extension is subjected to +1500 V and the MFC in compression is subjected to -500 V. This excitation scenario maximizes the usage of both MFC actuators according to the suggested ratings. Only the voltage that corresponds to the MFC in extension is used for labeling purposes in the figures and axes presented in the rest of this paper. Given these considerations and in-house fabrication limitations, the unimorph is replaced by a bimorph, the pzt1 and pzt3 lengths are fixed to 85 mm, and the pzt2 length is set to 42 mm. The FE model is updated accordingly, the GA optimization is conducted and the parametric analysis of the operation is performed. Figure 7 presents the operation of the airfoil at discrete voltage levels.

![Figure 7: Theoretical operational states of the optimized airfoil at 10 m/s free-stream velocity with all of the active areas in the bimorph configuration.](image)

In Figure 7, one can notice that the achieved displacements are lower compared to the case where lengths of the PZT actuators were part of the optimizations process. Figure 8 shows the theoretical 2D lift coefficient and lift-to-drag ratio of the airfoil at 10 and 20 m/s free-stream velocities.
Figure 8: Theoretical (2D) a) lift coefficient and b) lift-to-drag ratio induced by excitation voltage at different velocities and different substrate moduli. Static-aeroelastic results for the optimized variable camber airfoil in bimorph configuration.

A prototype is fabricated using the parameters determined by the optimization study presented in this section. The optimal parameters are used as general guidance and were not applied exactly due to additional fabrication limitations. First, an aluminum mold of the original NACA 0012 profile was fabricated using a CNC milling machine. Next, several layers of 25.4 µm thick stainless-steel sheets were laid on the aluminum mold in the desired locations and in the desired quantity. In the spanwise direction, the bimorphs were placed near the “root” and the “tip” of the wing which resulted in 37% coverage of active material. The fact that the structure has 37% coverage in the spanwise direction is partially compensated by the introduction a second PZT layer to form a bimorph structure for each active region.

In addition, three sets of MFC actuators were placed on the top and bottom surfaces of the airfoil according to the optimization study. Each set consists of two bimorph pairs, placed near the ends of the airfoil in the spanwise direction. The top surface consists of a bimorph set that is made up of four MFC M8528-P1 type actuators. The bottom surface consists of a bimorph set that is also made up of four MFC M8528-P1 type actuators. The third bimorph set was made of four MFC M8528-P1 actuators that were cut in half in the length direction; hence their active area became approximately 42 mm long. Each active and passive layer was bonded using 3M DP460 type two-part epoxy in successive order. Standard vacuum-bagging technique was used to ensure that the epoxy layer was as uniform and as thin as possible. Figure 9 shows the fabricated prototype during its non-actuated and actuated states. The airfoil has a 178 mm chord and 149.5 mm span.

Figure 9: Prototype of the variable camber airfoil concept in its a) non-actuated and b) fully actuated states. The top surface of the airfoil is also shown.
The internal structure that joins the inside surface of the airfoil to the wind tunnel load balance was manufactured using a rapid prototyping technique. Initial bench top tests showed that the prototype achieved approximately 20 mm trailing edge deflection between the -100% and +100% actuation states. The measured deformation field, presented in Figure 10, is close to the predicted shape presented in Figure 7. Although the recommended maximum excitation voltage is +1500 V, the excitation of +1785 V was safely and repeatedly achieved. It is noted that the airfoil shell is relatively light and compliant. As desired, the airfoil surface is a continuous shape without any discontinuities. The hinge connection at the trailing edge is established by a strip of externally adhered Kapton tape that joins the top and bottom trailing surfaces.

Figure 10: Experimental operational states of the optimized airfoil without aerodynamic loading.

Aerodynamic experiments were conducted in an open-loop, closed test section wind tunnel. The test section was configured for a two-dimensional experiment using two splitter plates as shown in Figure 11. The test section is 152.5 mm tall; hence there is a 1.5 mm gap between the two ends of the airfoil and the wind tunnel splitter plates.

Figure 11: The wind tunnel experimental setup showing a) an illustration of main components and b) picture of the airfoil in the 2D test section. Note that upper and lower walls of the test section are omitted in both images.

The tests were conducted at the free-stream velocities of 5, 10, 15 and 20 m/s. Figure 12 shows the experimental AOA of the airfoil in response to actuation voltage and free stream velocity. The voltage is swept from -1500 V to +1500 V and back down to -1500 V. The AOA that is presented in the figure is the geometric angle between the chord line and the free-stream velocity direction. The angle is calculated at each voltage level using measurements from a laser displacement sensor.
The effect of dynamic pressure is clearly visible as the voltage induced change of geometry is adversely effected by the increase in flow velocity. The piezoelectric hysteresis is also clearly visible. The tests are conducted between the peak-to-peak actuation range in both directions. This actuation method reveals the major hysteresis loop for the airfoil. The hysteresis is mainly due to the piezocomposite nature of the MFC actuator. Figure 13 presents the experimental two-dimensional aerodynamic response in terms of lift coefficient and lift-to-drag ratio. The airfoil response is to excitation voltage and free-stream velocity.

As observed in the structural response, the aerodynamic coefficients show the dependence of the airfoil response to the free-stream velocity. It is noted that the predicted change in the aerodynamic coefficients, shown in Figure 8, appears higher than the experimental values. This difference is caused by two major reasons. First, the thickness properties of the fabricated airfoil are different from the optimized airfoil. The homogeneous substrate of the optimum structure is replaced by a laminate that has a stainless-steel outer layer and a plastic inner layer. This modification resulted in the reduction of the bending stiffness from the desired substrate. Second, the theoretical prediction corresponds to the structure with uniform spanwise distribution of actuation; in contrast, the experiments are conducted for a wing that has 37% active material coverage. In light of these differences, if one observes the -600 V to +600 V range in Figure 8, a good correlation between the predictions and the observations (Figure 13) can be seen.

Finally, the variable-camber airfoil is compared to conventional NACA 0012 and NACA 4412 airfoils. Figure 14 presents the experimental comparison of the two-dimensional aerodynamic response of the three airfoils quantified in terms of lift coefficient and lift-to-drag ratio at 10 m/s free-stream velocity. In this comparison, the NACA airfoils are tested in the AOA range of -10 to 20 degrees. The up and down AOA sweeps for the NACA airfoils showed no
aerodynamic hysteresis; therefore average values are presented. The variable-camber airfoil is rotated to discrete “mechanical” AOA and then actuated in the range of -1000 V to +1500 V, representing 83% of the recommended actuation range for an MFC bimorph.

As expected, the effective range of the variable-camber airfoil is reduced as the average aerodynamic loading is increased by the rotation of the whole airfoil. In relative terms, the variable-camber airfoil is capable of achieving the lift increment between a NACA 0012 airfoil and a NACA 4412 airfoil.

VI. Conclusions

This paper presented the static-aeroelastic modeling, optimization and validation of a variable-camber airfoil that employs surface-induced deformations. 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 aerodynamic loads. The effects of several structural parameters are studied to achieve the highest value for the fitness function. The active material electromechanical properties are equivalent to the Macro-Fiber Composite actuator. The theoretical results are presented for the free-stream velocity range of 10 - 20 m/s, chord Reynolds number range of 118,000 – 236,000 and an assumed turbulence level of 0.07%. The experimental results show the feasibility of the design.

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References


