Implementation of a Continuous-Inextensible-Surface Piezocomposite Airfoil

Onur Bilgen* and Michael I. Friswell†
Swansea University, Swansea, Wales SA2 8PP, United Kingdom

DOI: 10.2514/1.C031908

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 with asymmetric profile and zero excitation with symmetric profile. 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 conducted on a prototype airfoil. The experimental results are compared to the theoretical predictions, highlighting agreements and discrepancies.

I. Introduction

SMOOTHE and continuous aerodynamic control surface designs have been a research interest since the beginning of modern aviation, with 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. Significant attention in research has been given to using conformal piezoelectric actuators to achieve shape change in variable-camber airfoils. Barbarino et al. [1] have shown that morphing of camber using piezoelectric materials has resulted in the largest number of wind-tunnel and flight tests for small aircraft when compared with other morphing categories, such as planform and out-of-plane morphing categories, and also when compared with 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 vehicles. In 2002, Eggleston et al. [2] experimented with the use of piezoceramic materials, shape-memory alloys, and conventional servomotors in a small 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 a concept called post-buckled precompression for aerodynamic applications. Roll control authority was increased on a 1.4 m span unmanned air vehicle. Kim et al. [6,7] designed and fabricated a flapping wing by using a graphite/epoxy composite material and a macro-fiber composite (MFC) actuator. A 20% 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 authority. The in-plane poling and subsequent voltage actuation allows the MFC to use the 31 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 piezocomposite actuators on a 0.76 m 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. [12] 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 first flight of the completely MFC-controlled aircraft on 29 April 2010. This vehicle became the first fully solid-state piezoelectric-material controlled, nontethered, flight-tested fixed-wing aircraft.

The preceding examples 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.
This paper first presents 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 the results.

II. Motivation for the Proposed Airfoil

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, in which 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 is 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, lightweight, and easy-to-fabricate structure.

In the preceding context presented, a piezocomposite semi-solid-state variable-camber airfoil, previously evaluated by Bilgen et al. [14], is employed as a baseline. This baseline airfoil was proposed as a replacement for the exit-guide vanes of a vertical takeoff-and-landing ducted-fan vehicle. 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 MFC actuated bimorphs. A compliant parallellogram (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/deg was measured, which exceeds the NACA 0009 lift slope (0.083/deg) by 72%. The results showed the clear advantage of the lift generation by the coupled camber and angle-of-attack (AOA, α) change induced by excitation voltage. The variable-camber airfoil produced a maximum lift-to-drag ratio (L/D) of 13.4 at 1500 V (α = 5.78 deg) and an L/D ratio of −11.2 at −1500 V (α = −5.20 deg). The NACA 0009 airfoil produces a maximum L/D ratio of 16.3 at α = 4.21 deg and an L/D ratio of −12.3 at α = −4.97 deg. 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 with 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 LE 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 backward 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 extensible airfoil surface and a set of “simpler” boundary conditions to remedy the two preceding problems outlined. 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). The proposed concept and the optimization are discussed next.

III. Optimization Using Genetic Algorithm and Static-Aeroelastic Model

This section first presents a brief background on aerostructural optimization and the genetic algorithm (GA) that is adopted in this research. Next, the proposed airfoil is introduced and the optimization problem is defined. Finally, the theoretical results from the optimization analyses are presented.

A. Brief Background on Aerostructural Optimization

Optimization for aerospace structures is almost always covered under the field that is typically referred to as multidisciplinary design optimization (MDO). The reader is referred to a recent review by Martins and Lambe [20] in which existing MDO architectures are classified based on their problem formulations and decomposition strategies, and the benefits and drawbacks of the architectures from both a theoretical and experimental perspective are discussed. Aerospace structures are desired to be highly efficient and in some cases highly compliant; therefore multidisciplinary optimization and the analysis of fluid–structure interaction (FSI) has become a standard approach for developing an aircraft. A significant amount of research has been conducted in the context of aerostructural optimization. Maute and Allen [21] focused on topology optimization of aeroelastic structures. Farhat [22] addressed computational fluid dynamics-based optimization. Gauger et al. [23] and Ozkaya and Gauger [24] considered nonparametric aerodynamic shape optimization.

In the current research, the approach to determine and optimize the structure of the variable-camber morphing airfoil is based on a GA optimization technique. GAs 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 [25]. GAs 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 [26]. 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 GA 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 and structurally feasible variable-camber morphing airfoil.

B. Optimization Problem and Process

This paper follows the formal steps of a simple GA which is described by Mitchell [25] and is widely used in the literature. The
GA is started 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. Once the parameters of interest, described later, are initialized, a finite-element (FE) model is constructed. The model is first checked for geometric abnormalities before conducting the static-aeroelastic analysis. If the geometry appears regular, two FSI analyses are performed. The static-aerodynamic model, described later, is used to solve the FSI problem, and is executed for each individual of a generation. The analysis is conducted twice for each individual, once for the case in which the electrical excitation is zero, and a second time in which the excitation is at a desired value, which has a nonzero value.

The performance of each individual is estimated by a fitness function, quantified in terms of the change in lift-coefficient-per-square-root-of-drag-coefficient, \( F = \Delta(\sqrt{C_l}/\sqrt{C_d}) \). The objective of the GA is set to maximize this fitness function. The fitness function is chosen to favor the increase in lift and penalize the increase in square-root-of-drag. The choice of penalizing \( \sqrt{C_d} \) is made so that the optimizer does not move too far from the \( C_{l_{\text{max}}} \) 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 a GA are applied. Selection, crossover, 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, which enables the analysis to have 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 optimization processes.

It is noted that the optimal solution is not only capable of maximum performance, according to the selected fitness function, but also satisfies the FSI problem. The individuals, or a set of input parameters, which are not capable of carrying aerodynamic loads and therefore result in the failure of static-aerelastic convergence are discarded during the optimization. Such individuals were rarely observed during the initial generations and virtually disappeared in the later generations as the GA converged to an “optimum” solution. It should be noted that such individuals are highly compliant structures and they are not feasible for the concepts proposed in this research. Before the execution of the GA runs, 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 bounds of each parameter, which are treated at once in every optimization run, are determined using this parametric analysis.

C. Proposed Airfoil and Optimization Parameters

Figure 1 shows an illustration of the proposed airfoil and the proposed geometric parameters to be optimized. Note that most of the features on this figure are exaggerated to aid visibility. In reality, the thicknesses of the substrate and the piezoelectric material layer (PZT) are very small compared with the maximum thickness of the airfoil.

To establish a continuous-inextensible-surface variable-camber airfoil, the upper and lower surfaces must have different curvatures. This paper suggests an airfoil with upper surface employing a single monotonic curvature and a lower surface employing two alternating curvatures. The top, leading-bottom, and trailing-bottom PZT actuators, labeled as \( pzt1, pzt2, \) and \( pzt3 \) respectively, are subjected to three independent effective voltage levels, \( V_{pzt1}, V_{pzt2}, \) and \( V_{pzt3} \) respectively. In the case in which all actuators are in the unimorph configuration and are bonded on the outer surface of the airfoil substrate, it is assumed that the voltages are applied so that 1) the top- and bottom-leading active layers are in extension, resulting in a negative and a positive curvature respectively, and 2) the bottom-trailing active layer is in compression, resulting in a negative curvature. As noted before, the MFC actuator, which operates in the \( 33 \) mode of piezoelectricity, is proposed as the active layer; however, the FE model is constructed assuming 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, which is 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.

Figure 1 shows the whole airfoil and zoomed images of important areas with arbitrarily selected parameters for illustrative purposes. The main parameters of interest are 1) boundary conditions and their distribution, 2) substrate thicknesses \( t_{\text{sub}, \text{t}}, t_{\text{sub}, \text{b}}, t_{\text{sub}, \text{pzt}} \), 3) end location of the leading edge substrate \( x_{\text{sub}, \text{le}} \), and 4) start and end locations of three PZT actuators \( x_{\text{pzt}, \text{begin}}, x_{\text{pzt}, \text{end}} \). The substrate material Young’s modulus is initially fixed to that of aluminum (70 GPa). The excitation voltage of the PZT actuators can have a value in the range of \(-1500\) to \(+1500\) V. 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 \(+1500\) V resulting in equivalent output in compression and extension; however, the excitation range is \(-500\) to \(+1500\) V for an MFC actuator in reality, as suggested by the manufacturer. Each of these parameters will be discussed in the following paragraphs. In Fig. 2, a pair of possible configurations of the boundary conditions is shown. In Fig. 2a, the uniform cross-section wing, referred to as the two-dimensional (2-D) configuration, is shown. This wing would be attached to the vehicle at both ends (e.g., as an exit-guide vane) through the use of two semicompliant joints that act as the pinned boundary conditions, labeled as \( \text{Pin1} \) and \( \text{Pin2} \). Bending moments on the internal structure that supports these joints are less severe when compared to a fixed-wing vehicle, assuming that the aspect ratio is relatively lower for the former. In Fig. 2b, 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 desired boundaries are also constrained. In both configurations, however, both of the boundary...
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 fixed for ease of implementation; however, for the 2-D case, 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 curved beam supported by a pair of fixed boundary conditions theoretically creates a nonlinear response (e.g., bistability), however, such behavior is not dominant in a physical implementation of the concept considering the locations and the compliance of the boundary conditions (i.e., pins).

In addition to the location and the distribution of the boundary conditions, the substrate thickness is an important parameter assuming that the PZT layer thickness ($t_{\text{pzt}}$) and the chord are fixed. 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, and the actuator thickness is kept constant. The leading section of the airfoil has a constant thickness of $t_{\text{subs}}$. The leading section substrate, starting at the LE and ending at $x_{\text{subbeg}}$, 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 $t_{\text{subm}}$. The main substrate region is determined by the beginning and the end of the active PZT region, labeled as $x_{\text{optbeg}}$ and $x_{\text{optend}}$ respectively. The intention with the main passive substrate region is to have a lightweight 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 and avoid delamination at the substrate–PZT interface. The substrate thickness under the PZT actuator is labeled as $t_{\text{subpzt}}$. The intention with this is 1) to 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 preceding parameters, each chordwise location parameter ($x_1, \ldots$) 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 nonuniform 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 the active region. These are expected results, however, because these structural parameters are coupled with the aerodynamic state; the multiparameter optimization must be conducted to understand the coupled behavior.

D. Theoretical Analysis with Static-Aeroelastic Model

A shell-like variable-camber 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 structural parameter and the boundary conditions for the variable-camber device are 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 [27] based program is developed and used to solve the static FSI problem by iterating between a panel method software XFOIL [28,29], and a finite-element code ANSYS [30]. Before the FSI iteration is started, the non-aero-loaded airfoil shape is analyzed in XFOIL to initialize the process. The panel method is used to calculate the 2-D 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 the lift and drag due to the change in pressure induced deformation. These two steps are iterated until convergence 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. The FSI convergence is assumed when the maximum displacement, lift, and drag coefficients have less than 0.5% change between two consecutive iterations and when they all show monotonic decrease. As previously noted, dynamic effects are known to be negligible because of the proposed boundary conditions and previous experimental observations. The theoretical 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 [29]. 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 [28,29], 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 coefficient and lift-to-drag ratio performance.

The passive material, also referred to as the substrate, of the airfoil is modeled as a homogeneous 2-D area mesh using the PLANE82 high-order quadrilateral (Q8) type element in ANSYS. The MFC actuator is modeled as a monolithic piezoelectric layer using a homogeneous 2-D 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 model. Approximately 10,000 elements are used to ensure convergence of the FE model for all airfoil models evaluated in the study. The number of elements chosen
is relatively high to accommodate the highly nonuniform pressure distribution data from the panel method.

E. Optimization Results for the Two-Dimensional Configuration

In this paper, only the optimization results of the 2-D configuration, as illustrated in Fig. 2a, is presented. Figure 3 shows the maximum and average fitness for the selected 2-D 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 (−500 to +1500 V). When the optimization is terminated at 200 generations, the chromosomes of the best-fit individuals are examined.

Figure 4a shows an illustration of the geometric properties of the optimized structure. Note that all parameters, as described in Sec. III.C, are simultaneously considered for all optimization runs. The selected GA run showed that placing Pin1 close to the LE (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 during this run. The analysis showed that using a leading-edge substrate thickness \( t_{\text{subsle}} \) of 50.8 \( \mu \)m 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 \( t_{\text{sub}} \) is 127 \( \mu \)m and the substrate under the PZT \( t_{\text{subpzt}} \) is 390 \( \mu \)m 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 4b shows the two operational states used to determine the fitness value of the optimum configuration. In Fig. 4b, the NACA 0012 airfoil profile is shown as reference to the variable-camber airfoil.

Figure 5 shows the theoretical 2-D lift coefficient and lift-to-drag ratio operational response of the airfoil at 10 and 20 m/s freestream velocities. 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. In Fig. 5, both the effect of change in the Reynolds number and the effect of deformation due to aerodynamic loading are observed. Although the lift output is lower at 20 m/s due to the reduced AOA, the lift-to-drag ratio is still higher across the operational range due to the increase in the Reynolds number. 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 may be invalid.

IV. 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 in which certain parameters were fixed instead of being part of the optimization process. For example, a commercially available MFC model is the M8528-P1, and it has an active region of 85 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 moduli of brass (100 GPa) and stainless-steel (200 GPa) can be considered instead of the modulus 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 (48% chord), and the pzt2 length is set to 42 mm (24% chord) in the chordwise direction. All other parameters (excluding the fixed parameters mentioned in the preceding text) are previously described in Sec. III.C, and they are considered for the optimization study presented in this section. The FE model, previously presented in Fig. 1, is updated accordingly and the GA optimization is repeated.

Fig. 4 The optimized airfoil in unimorph configuration at 10 m/s freestream velocity \( (Re_{\text{chord}} = 118,000) \), showing a) geometric parameters and b) operational states.

Fig. 5 Theoretical (2-D) a) lift coefficient and b) lift-to-drag ratio induced by excitation voltage at 10 and 20 m/s. Static-aeroelastic results for the optimized variable-camber airfoil in the unimorph configuration. \( Re_{\text{chord}} = 118,000-236,000 \).

Fig. 6 Geometric parameters of the optimized airfoil in bimorph configuration with predetermined active area lengths.
Fig. 7 Theoretical operational states of the optimized airfoil at 10 m/s freestream velocity with all of the active areas in the bimorph configuration and substrate modulus of 200 GPa. \( Re_{\text{chord}} = 118,000 \).

Figure 6 illustrates the important parameters of the optimized airfoil in bimorph configuration with predetermined active area lengths as previously described. The figure corresponds to the optimized shape for a substrate material with 200 GPa modulus.

As presented for the previous cases, a parametric analysis of the operation is performed using excitation voltage as the independent variable. Figure 7 presents the operation of the airfoil at discrete voltage levels. In Fig. 7, one can notice that the case in which active area lengths are fixed and in bimorph configuration is similar to the case in which active area lengths are part of the optimization process and in unimorph configuration. Figure 8 shows the theoretical 2-D lift coefficient and lift-to-drag ratio of the airfoil at 10, 20, and 30 m/s freestream velocities.

The response presented in Fig. 8 is similar to one observed in Fig. 5. It appears that the reduction in active area coverage is partially compensated by the introduction of the second PZT layer, which forms a bimorph structure.

A. Prototype and Bench-Top Tests

A prototype is fabricated using the parameters determined by the optimization study previously presented. The “optimal” parameters are used as general guidance and could not be applied exactly due to in-house fabrication limitations. First, an aluminum mold of the original NACA 0012 profile, with 178 mm chord, was fabricated using a CNC milling machine. Next, several layers of 25.4 \( \mu \)m thick stainless-steel sheets were laid on the aluminum mold in the desired locations and in the desired quantity. The bimorphs were placed near the root and the tip of the airfoil, which resulted in 37% coverage of active material in the spanwise direction. In total, three sets of MFC bimorphs 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 were bonded using 3M DP460 type two-part epoxy in successive order. A standard vacuum-bagging technique was used to ensure that the epoxy layer was as uniform and as thin as possible. 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 9 shows the fabricated prototype during its nonactuated and actuated states. The airfoil has a 178 mm chord and 149.5 mm span.

The internal structure that joins the inside surface of the airfoil to the wind-tunnel load balance was manufactured using a rapid prototyping technique. The semiconformant joints are realized by the use of two square-cross-section rubber strips in the spanwise direction as illustrated in Fig. 2a. These strips form the compliant joint between the airfoil shell and the rapid prototyped internal structure and they are adhered with two-part epoxy. Initial bench-top tests showed that the prototype achieved approximately 20 mm chord, 149.5 mm span.

In order to measure the exact geometry of the airfoil in response to excitation voltage, an accurate method had to be employed. First, a calibration experiment is conducted at discrete voltage levels using a digital camera. All geometric parameters are calculated from the image of the airfoil end-section. High spatial resolution can be obtained with the camera at the penalty of increase in test time. The measurement is taken without air flow in order to limit aerodynamic effects. As noted earlier, 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 side are actuated with an opposite field and with 3:1 fixed ratio. The higher of the two excitation voltages is used for labeling in the plots. A negative sign simply indicates actuation in the reverse direction. Figure 10 shows the displacement of the airfoil end section digitized from a series of photos for a unidirectional peak-to-peak voltage sweep. The measured deformation fields, shown in Fig. 10, are close to the predicted shapes presented in Fig. 7 for the positive

Fig. 8 Theoretical (2-D) 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 the bimorph configuration.
excitation range. The experimental operational states for negative excitation demonstrate undesirable behavior and such behavior is attributed to at least two sources: 1) The variation of glue thickness under the MFC actuators and 2) the variation of output of each MFC actuator. Although the recommended maximum excitation voltage is +1500 V, the excitation of +1785 V was safely and repeatedly achieved. As desired, the airfoil surface is a continuous profile without any discontinuities.

B. Wind-Tunnel Setup

Aerodynamic experiments were conducted in a low speed, open circuit, and closed test section wind-tunnel facility which is capable of reaching 28 m/s freestream velocity. At the inlet, an aluminum honeycomb flow-straightener and a fiberglass mesh is used to condition the flow. After the converging nozzle, the test section has a 610 by 610 mm (24 × 24 in.) octagonal cross section. The test section can be converted to a 610 by 152 mm (24 × 6 in.) rectangular cross-section by the use of two removable splitter plates. An average 0.12% turbulence intensity is measured using a constant temperature anemometry technique with a 0.1–10 kHz band-pass filtered signal for the current test velocity range of 5–20 m/s. The wind-tunnel fan is driven by a motor and the speed is electronically controlled. The test specimen can be rotated in the test section about its pitch axis by the use of a motor-driven rotary stage. A six-component load-cell and a strain-gage amplifier, models MC3A-100 and MSA-6 manufactured by AMTI Inc., are used to acquire forces and moments in three axes simultaneously. The flow velocity and temperature are electronically monitored. Flow velocity during the tests is observed using four static ports at the inlet of the test section, 1.21 m upstream of the quarter-chord of the airfoil, and an Omega PX653 type pressure transducer. The temperature of the flow is measured using a thermocouple and an Omega CCT series amplifier and conditioner, and recorded for each run. The test section is configured for a 2-D experiment using two splitter plates, as shown in Fig. 11.

The quarter-chord of the airfoil is located at 356 mm from the beginning of the splitter plates along the streamwise direction. The span axis is oriented normal to floor of the test section (and ground). The balance assembly through the load cell and the sting supports the test airfoil without contacting the tunnel walls. The test section between the splitter plates 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. Mueller and Burns [31] show that gap sizes around 0.5% of the span are usually acceptable and do not affect the results. For the airfoils tested here, the gap is approximately 0.98%. Although the gap dimension is small, the percentage is still higher than recommended because of the small span of the airfoils.

The displacement measurements are conducted at the quarter-chord location and at 100 mm from the quarter-chord along the mid-span section for each operational point. The two displacement measurements are correlated to the full displacement field data which was previously recorded using the digital camera (described in the previous section). The displacement is measured using an MTI LTC-300-200-SA laser displacement sensor with ±20 μm resolution, mounted on the side-wall of the test-section on a stepper-motor controlled linear stage.

In addition, three control channels are designated for controlling various parameters on the specimen. One of the channels is used to supply the control voltage to the airfoil which is amplified using a TREK 2220 high-voltage amplifier with 200 V/V gain. The single output of the amplifier is divided using a unique voltage divider circuit that allows asymmetric and bipolar excitation necessary to drive the MFC bimorph actuators without depolarizing them [32]. All parameters are controlled and measured automatically with a National Instruments (NI) cDAQ data acquisition system and a personal computer. A total of 16 channels are monitored using four NI 9239 four channel, isolated, 24-bit voltage input cards. The output signals are generated using two NI 9263 16-bit, four channel voltage output cards. For each test, a 20 s data is sampled at 100 Hz and then averaged to get the mean value for each measurement of interest.

Fig. 9 Prototype of the variable camber airfoil concept in its a) nonactuated and b) fully actuated states. The top surface of the airfoil is also shown.

Fig. 10 Experimental operational states of the optimized airfoil without aerodynamic loading. The excitation voltage is swept from −1785 V to +1785 V. Note that the orthogonal dimensions are in equal scale.
The experimental measurements are prone to the relative errors induced by the uncertainty in setting the pitch angle, the flexibility in the balance system and the nonlinearity in the load-cell. The absolute values have uncertainties due to several parameters such as air density, flow velocity measurements, and the theoretical wall and BL corrections. The uncertainty analysis of each measurement is conducted by following the AIAA Standard [33].

C. Wind-Tunnel Buoyancy and Wall-Effect Corrections

The wind-tunnel wall effects and buoyancy corrections were applied as necessary using the standard techniques found in Barlow et al. [34]. The reported lift and drag coefficients are calculated by

\[ C_l = C_{lu}(1 - \sigma - 2\epsilon_{sb} - 2\epsilon_{wb}) \]  
\[ C_d = C_{du}(1 - 3\epsilon_{sb} - 2\epsilon_{wb}) \]

Barlow suggests several corrections due to the existence of the walls around the airfoil. The solid blockage term \( \epsilon_{wb} \) and the wake blockage terms \( \epsilon_{wb} \) respectively. The \( C_{lu} \) and \( C_{du} \), uncorrected lift and drag coefficients, are calculated by

\[ C_{lu} = F_{\text{lift}}/(0.5\rho c^2 v_{Q}^2) \]  
\[ C_{du} = (F_{\text{drag}} - F_{\text{bd}})/(0.5\rho c^2 v_{Q}^2) \]

where \( F_{\text{lift}} \) and \( F_{\text{drag}} \) are the measured lift and drag forces, \( F_{\text{bd}} \) is the drag on the airfoil caused by the longitudinal pressure gradient, \( \rho \) is the density of air, \( c \) is the chord, \( h \) is the reduced span (due to boundary layer displacement thickness), \( v_{Q} \) is the flow speed calculated at the quarter-chord location. Note that density is calculated using the relatively fixed absolute pressure measured in the lab and the temperature of the flow which is recorded during each test. In addition, streamline curvature correction is applied in which the angle-of-attack (\( \alpha \)) is calculated by [35]:

\[ \alpha = \alpha_u + \frac{57.3}{2\pi} \left( \frac{\pi c^2}{48h^2} \right) (C_{lu} + 4C_{m\alpha}) \]

where \( \alpha_u \) is the measured AOA, \( h = 610 \text{ mm} \) is the section width, and the \( C_{m\alpha} \) is the (negligible) uncorrected pitch-moment coefficient.

Actual velocity and reduction in span is calculated as follows: First, a calibration test is conducted in the empty test section between the static ports (sufficiently upstream of the airfoil location) and the Pitot-static tube located at different locations along the flow-axis. The velocity is measured with the Pitot-static tube at each location, and the development of boundary layer (BL) is calculated by applying Bernoulli’s equation and conservation of mass. From Fox et al. [37], the BL displacement thickness (from the calibration experiment) is calculated approximately as 1.2 mm. Since there is a 1.50 mm gap between the tunnel wall and the airfoil, no reduction in span is applied due to the boundary layer. The flow velocity during aerodynamic tests is calculated by applying the calibration described in the preceding text, between the static-port and the Pitot-static tube at the quarter-chord location, to the static-port measurement which is recorded at each test point.

D. Aerodynamic Response

Two types of experiments are conducted to evaluate the aerodynamic performance of the variable-camber airfoil. The first test scheme is designed to identify the hysteresis behavior of the morphing airfoil due to its piezoceramic bimorph nature and its response to different dynamic pressure levels. In these tests, only a fixed support angle of zero degrees is considered while the applied voltage is changed. Figure 12 shows the experimental AOA of the airfoil in response to actuation voltage and freestream velocity. The voltage is swept from \(-1500 \text{ V} \) to \(+1500 \text{ V} \) and back down to \(-1500 \text{ V} \). The AOA that is presented in the figure is the geometric angle between the chord line and the freestream velocity direction. The angle is calculated at each voltage level using measurements from the laser displacement sensor and the calibration data from the digital camera measurements. The tests are conducted at the freestream velocities of 5, 10, 15, and 20 m/s. All plots represent the aerodynamically loaded airfoil. A maximum of 5.4 deg AOA change is observed for the peak-to-peak actuation range at 5 m/s. The effect

![Fig. 11](image1.png)  
![Fig. 12](image2.png)
of dynamic pressure is clearly visible as the voltage-induced change of geometry is adversely affected by the increase in flow velocity. 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 nonlinear voltage–geometry relationship is due to piezoceramic hysteresis, which can be linearized by the use of a classical Preisach model if desired [38]. The measured curves indicate that an increase in voltage magnitude above +1500 V or below −1500 V will result in a slightly higher deflection. This is desired because the MFCs can safely be actuated up to 1785 V, as shown previously. Figure 13 presents the experimental 2-D aerodynamic response in terms of lift coefficient and lift-to-drag ratio. The airfoil response is to excitation voltage and freestream velocity. The lift coefficient is measured as −0.319 V at −1500 V and 0.238 at +1500 V for the freestream velocity of 5 m/s. The end slopes of the two curves indicate that higher lift can be achieved if voltage amplitude is increased. A maximum change of 0.553 in lift coefficient is calculated for the peak-to-peak voltage input at 5 m/s. A relatively low lift-to-drag ratio is observed for the airfoil due to a relatively blunt LE, mainly caused by wiring and the “bumps” on the surface (which are both due to the fabrication limitations). When drag and lift are evaluated together, a significant change in lift can be achieved for a small drag penalty. Such results confirm an important motivation of using a variable-camber airfoil without articulated surfaces.

As observed in the structural response, the aerodynamic coefficients show the dependence of the airfoil response to the freestream velocity. It is noted that the predicted change in the aerodynamic coefficients, shown in Fig. 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. During the fabrication of the prototype, 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 an airfoil that has 37% active material coverage in the spanwise direction. In light of these differences, if one observes the −600 V to +600 V range in Fig. 8 which corresponds to the 37% of the +/−1500 V excitation, a good correlation between the predictions and the observations (Fig. 13) can be seen.

Finally, a second test is conducted, in which the aerodynamic response of the variable-camber airfoil is compared to other similar fixed-camber airfoils. The aim of this test is to show the similarities of continuously coupled camber-AOA actuation when compared to the mechanical AOA actuation. The variable-camber airfoil is compared to conventional NACA 0012 and NACA 4412 airfoils. Both NACA airfoils have a maximum thickness of 21.4 mm. All of the tested airfoils have 149.5 mm span, 178 mm chord and a finite trailing edge thickness of 1.0 mm. Figure 14 presents the experimental comparison of the 2-D aerodynamic response of the three airfoils quantified in terms of lift coefficient and lift-to-drag ratio at 10 m/s freestream velocity. In this comparison, the NACA airfoils are tested in the AOA range of −10 to 20 deg. 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
between a NACA 0012 airfoil and a NACA 4412 airfoil. A variable-camber airfoil is capable of achieving the lift increment $0.0135$ to a NACA 4412 profile. The prototype airfoil produced a change in aerodynamic response of 59,000 V, representing 83% of the recommended actuation range for a NACA 4412 profile.

Applications to Morphing Aircraft.

Experimental wind-tunnel analysis is presented for the freestream flow over a NACA 4412 airfoil with a change in camber from -0.10 to +0.10, representing 83% of the recommended actuation range for a NACA 4412 profile. The active material electromechanical properties are chosen equivalent to the Macro-Fiber Composites. A prototype is fabricated and an experimental wind-tunnel analysis is presented for the freestream velocity range of 5–20 m/s, chord Reynolds number range of 59,000–236,000, and the turbulence intensity of 0.12%. The experiments demonstrated the feasibility of the proposed concept. The prototype airfoil produced a change in aerodynamic response that is similar to the one observed between a NACA 0012 profile and a NACA 4412 profile.

Acknowledgment

This work is supported by the European Research Council grant number 247045, titled “Optimization of Multi-scale Structures with Applications to Morphing Aircraft.”

References

