Low Reynolds Number Behavior of a Solid-State Piezocomposite Variable-Camber Wing

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The low speed, low Reynolds number wind-tunnel analysis of a previously proposed solid-state piezocomposite variable-camber wing is presented. The wing employs a continuous inextensible surface, continuous boundary conditions and surface bonded independent piezoelectric actuators. The partially-active surface is designed to have sufficient bending stiffness in the chordwise and spanwise directions to sustain its shape under aerodynamic loading. The paper focuses on characterization through statistically defensible wind tunnel experiments based on Design of Experiments methodology. Significant aerodynamic response is quantified in terms of change in lift coefficient. The empirical results from a regression model demonstrate significant aerodynamic authority of the solid state variable-camber wing when operated in Reynolds numbers above 200,000 and in low turbulence conditions.

I. Introduction

RECENT attention in research has been given to using conformal piezoelectric actuators to achieve shape change in aerodynamic surfaces. A review article in 2011 by Barbarino et al. [1] showed that “morphing” of camber and twist of the wing 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 also when compared to other excitation methods, such as conventional actuators, shape-memory alloys (SMAs), rubber-muscle actuators and others. The following sections present the background and the motivation of the research.

A. Background

The significantly 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. In 2002, Eggleston et al. [2] experimented with the use of piezoceramic materials, shape-memory alloys, and conventional servomotors in a morphing wing test aircraft. A series of wind tunnel tests showed the feasibility of the smart material systems on this vehicle. 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. Bilgen et al. [8,9] presented an application for piezocomposite 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. In 2010, Butt et al. [10] and Bilgen et al. [11] developed a completely servo-less, wind-tunnel and flight tested, remotely piloted aircraft. This vehicle became the first fully solid-state piezoelectric material controlled, non-tethered, flight tested fixed-wing aircraft. Ohanian et al. [12] presented an extensive aerodynamic comparison of a MFC actuated compliant control surface to a servo-actuated conventional control surface for an MAV application.

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The examples above show the feasibility of piezoelectric materials in small unmanned aircraft. The following are a few examples of piezocomposite aerodynamic control surfaces which are validated in the wind tunnel environment. 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 [14,15]. The wind tunnel results and the analytical evaluation of the airfoils showed comparable effectiveness to conventional actuation systems and no adverse deformation due to aerodynamic loading. Paradies and Ciresa [16] 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. [17] presented the design and verification of a smart wing for an unmanned aerial vehicle. The proposed smart wing structure consisted of a composite spar and ailerons that have bimorph active ribs consisting of MFC actuators.

B. Motivation
The coupled optimization and aeroelastic tailoring are neglected in the cases mentioned above. In this context, Bilgen et al. proposed, optimized and demonstrated two unique solid-state piezocomposite structures: 1) A variable-camber airfoil [18,19,20] and 2) a variable-camber / variable-twist wing [21] for ducted-fan and fixed-wing aircraft, respectively, that operate in the low speed and low Reynolds number regime. A theoretical modeling, optimization and experimental validation are presented for both concepts. The prototypes employ a continuous inextensible surface, continuous boundary conditions and surface bonded piezoelectric actuators. The partially-active aerodynamic surfaces are designed to have sufficient bending stiffness in the chordwise and spanwise directions to sustain 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 a constant surface area. Coupled with the continuous boundary conditions and the spar structure, the proposed piezocomposite airfoil and wing can achieve significant change in aerodynamic response quantified in terms of lift coefficient and lift-to-drag ratio. These previous papers focused on theoretical optimization and experimental examination of the fundamental aerodynamic response. A small subset of the domain was investigated experimentally (in the wind tunnel) due to the large number of combinations of all electromechanical variables.

Unlike in a conventional (non-morphing) aerodynamic structure, there are a large number of parameters that can be controlled to change the circulation in a piezocomposite wing. The prototype proposed and examined in Ref. [21] has a minimum of 10 independent piezoelectric devices on it distributed along the spanwise direction and on the upper and lower wing surfaces. The evaluation of the complete parameter domain is not a practical option due to the non-linearity and the highly-coupled behavior of the parameters. The main goal for the current research is to examine the static-aeroelastic effectiveness of the variable-camber morphing wing, within the complete range, using an efficient and statistically defensible test procedure. Such experimental characterization is best carried out within a design and analysis framework which can provide statistically defensible empirical mathematical models and uncertainty estimates. Design of Experiments (DOE) has been known to provide both of these deliverables in a wide variety of disciplines [22,23]. Historically aerospace ground testing has embraced One-Factor-at-A-Time (OFAT) test schedules, most likely due to the relatively low noise environment of modern test facilities [24, 25]. The wind tunnel test described herein was performed using DOE principles that have been proven in practice [26,27,28,29,30,31]. The resulting regression models provide a basis for understanding and optimization, bounded by robust uncertainty estimates.

C. Outline
This paper, first briefly presents the previously proposed solid-state variable-camber wing and the theoretical method used for optimization of the static-aeroelastic response by identifying substrate structural parameters and the distribution of boundary conditions. Next, the DOE methodology is presented. Finally the prototype and the current wind tunnel experiments are presented. Theoretical predictions of aerodynamic coefficients from the regression model are compared to the experimental results, highlighting agreements and discrepancies. The paper concludes with a brief summary of results.

II. Solid-State Wing Concept and Optimization
A. Proposed Solid-State Wing Concept
As mentioned above, the concept employs a continuous inextensible surface, continuous boundary conditions and surface bonded piezoelectric actuators. The partially-active aerodynamic top and bottom surfaces are designed to have sufficient bending stiffness in the chordwise and spanwise directions to sustain shape under aerodynamic loading.
loading. The wing is proposed to have spanwise taper; therefore the cross-sectional geometry has to be optimized considering three-dimensional aerodynamic and structural effects. A NACA 0012 profile is selected for the non-actuated state of the wing. In order to establish a continuous-inextensible-surface variable-camber wing, it is first noted that the upper and lower surfaces must have different curvatures. To achieve variable-camber, a cross-section with upper surface employing a single monotonic curvature and a lower surface employing two alternating curvatures is proposed (see Ref. 21). The top and bottom surfaces are partially covered by surface-bended actuators where each actuator can be subjected to an independent voltage level from the others. The trailing-edge is formed by joining the top and bottom surfaces creating a compliant “hinge” at the trailing edge. The boundary conditions of the prototype are shown in Figure 1.

![Figure 1: Illustration of the proposed boundary conditions for a three-dimensional configuration.](image)

The cross-section of the wing is non-uniform in the spanwise direction. The structural parameters are determined through the use of the optimization technique which is briefly discussed next.

**B. Static-Aeroelastic Optimization**

A shell-like variable-camber wing, with reasonable chordwise and spanwise stiffness and displacement output, is possible with an MFC actuator given that the boundary conditions and structural features are favorable. Therefore, the static-aeroelastic response of the morphing wing to structural parameters and the boundary conditions were determined using a static-aeroelastic model. 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 [32]. 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 [33]. Mitchell [32] and others describe the formal steps of a simple genetic algorithm which was employed in this research. The static-aeroelastic model is used to solve the fluid-structure-interaction (FSI) problem, and is executed for each individual of a generation within the GA optimization. The performance is estimated by the fitness function, quantified in terms of the change in lift-coefficient-per-square-root-of-drag-coefficient, $F = \Delta(\text{Cl}/\sqrt{\text{Cd}})$.

The main parameters of interest are 1) boundary conditions and their distribution, 2) substrate thickness distribution, 3) actuator distribution. 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 FSI model are assumed to be fixed for ease of implementation. The details of the model and the complete optimization results are presented in Bilgen et al. [20].

**III. Design of Experiments for Wind Tunnel Testing**

The formal design of experiments in its broadest sense is a process for planning an experiment so that appropriate data can be collected and analyzed by statistical methods, resulting in valid and objective conclusions. In recent years the use of formally designed experiments in wind tunnel testing has grown in popularity. Design of Experiments (DOE) is a complete experimental design and analysis process that differs from traditional One-Factor-at-A-Time (OFAT) type testing. It begins with pretest planning with known levels of confidence and statistical power, progresses to developing test matrices for response models of given order, offers protection against unwanted
sources of variability and finally provides statistically defensible mathematical models and estimates of uncertainty. This section will provide a brief overview of the topic and present the approach developed for the current wind tunnel analysis.

A. Guiding Principles

A test matrix benefits from three basic tenets of DOE: replication, randomization, and blocking [22,23]. Randomization is the cornerstone of statistical methods in experimental design and requires that the order of the runs are randomly determined. It provides protection against lurking variables and allows for identification of systematic errors through examination of the residuals. Replication is the repetition of runs within the experiment. Replication of design points allows the researcher to determine an internal estimate of system noise and uncertainty. Blocking is a technique used to improve the precision with which comparisons among the factors of interests are made. Blocking is used for reducing the variability transmitted through nuisance factors, that is, factors that may influence the experimental response, but that are of no interest to the researcher. For example, variations in wind-tunnel measurements are often encountered when comparing overnight runs or shifts. Assigning groups of runs to blocks helps separate the shift-to-shift variability due to atmospheric conditions or personnel changes, or from changes in the force balance precision due to the variation of temperature and other ambient conditions.

Analysis of the experimental data is performed using statistical hypothesis testing and regression model building so that the response values can be accurately estimated or predicted using empirical models [22,23]. These models are usually polynomial functions of the input variables (factors) and factor interactions. The model is tested for adequacy by computing a residual sum of squares based variance which can be directly compared to random error from replicates. One of the chief benefits in using DOE methods versus the traditional OFAT methods is the ability to include interaction terms in the analysis. The OFAT method allows only for one variable to be changed at a time, therefore it typically evaluates only main effects. The DOE method allows, and partially requires, the change of more than one factor simultaneously, thus allowing for the discovery of interaction between variables.

B. Experiment Design

The foundation for DOE classical designs is the factorial experiment [22]. A factorial design is one which varies all factors simultaneously for all possible combinations. Using two levels for each factor represents a run-efficient method for developing a first order plus interaction model. A full-factorial design in two factor space is shown below in Figure 2 with the addition of a point at the origin know as a center.

![Figure 2: A full-factorial design in two factor space.](image)

Replicated centers afford a test for possible augmentation to support quadratic model terms. The supported regression model is shown with up to two-factor interactions by:

$$y = \beta_0 + \sum B_i x_i + \sum \sum_{i \neq j} B_{ij} x_i x_j + \ldots + \epsilon \quad i = 1, 2, \ldots, k$$

The B’s are the fitted regression coefficients and the x’s are the factors (independent variables).

A refinement (augmentation) to the factorial design is the central composite design (CCD) which adds design points along the axes through the origin of the design space as shown by the square symbols of Figure 3 [23,26].
This approach supports a full second order model:

\[ y = B_0 + \sum_i B_i x_i + \sum_i B_{ii} x_i^2 + \sum_{i \neq j} B_{ij} x_i x_j + \epsilon \quad i = 1, 2, \ldots, k. \]

The location of the axial points defines this CCD as a face-centered design (FCD).

The nested face-centered design is a recent development which allows the nesting of two FCD designs to support the addition of pure cubic terms to the empirical model. The two FCD’s may be tuned by fractionating the factorial designs as presented by Landman et al. [24]. The design in two-factor space is shown below in Figure 4.

C. Analysis of Results

Data collected from the wind tunnel tests are analyzed using least squares estimation with the aid of Design Expert TM, a commercially available program. First, a tentative regression model with all factors is developed for each of the aerodynamic coefficients (responses) which can include main effects, factor interactions, pure quadratics, and pure cubic terms (see Ref. 27 for details). The purpose of this analysis is to determine which terms affect each response in order to develop an empirical model that accurately predicts response values for any factor settings within the design space. Using the mean squares for each model term versus the mean square for error, an F-test is performed to determine statistical significance. The model is subsequently refined by dropping insignificant terms and a table of significance, called the analysis of variance (ANOVA) table, is computed [22,23]. The model is considered tentative until assumptions of normality, independently distributed errors with constant variance, are tested. The model residuals, the difference between model response values and the regression model predicted response values, are estimates of the true model errors. Finally the regression model is used to predict responses for points not in the design, a process known as confirmation.

IV. Experimental Analysis

A. Prototype and Bench Top Tests

A prototype was developed using the parameters determined by the optimization study presented in Bilgen et al. [21]. The wing consists of a rigid (rapid-prototyped) internal spar structure and a partially-active shell. This shell is actuated by bimorphs which were placed in a non-uniform arrangement between the “root” and the “tip” of the wing.
along the spanwise direction. In total, 10 sets of MFC bimorphs were placed on the top and bottom surfaces of the wing. Each set consists of a bimorph pair. 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 5 shows the fabricated prototype.

![Figure 5: The top surface (a) of the solid-state wing prototype. Tip (b) and root (c) sections.](image)

Initial bench top tests showed that the prototype achieved approximately 20 mm trailing edge deflection between the -100% and +100% actuation states. Figure 6 presents the response of the wing to peak-to-peak excitation.

![Figure 6: Solid-State variable-camber wing static bench-top test results at a) -1500 V and b) +1500 V excitation.](image)

Note that 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 a 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.

### B. Wind Tunnel Setup

Aerodynamic experiments were conducted in two different facilities in order to fully understand the low Reynolds number behavior of the prototype. First, a set of parametric evaluations took place in facility (1). Next, a second and smaller set of parametric evaluations took place in facility (2). The DOE design runs were conducted in the facility (2) using the nested FCD in 3 factors: reference rotation angle, flow velocity, and actuator excitation voltage. The differences between the two facilities are described below as these details are necessary to derive conclusions from the experimental data.

**Facility (1)** is a low speed, open circuit and closed test section wind tunnel facility which is capable of reaching 28 m/s free-stream 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 mm by 610 mm (24” by 24”) octagonal cross section. The test section is converted to a 610 mm by 381 mm (24” by 15”) semi-octagonal cross section by the use of a removable splitter plate. The streamwise turbulence of the flow in the empty test section is measured by a standard Hot Wire Anemometry technique. The lowest turbulence level is observed at around 5 m/s and the highest level around the lower range of the wind tunnel. In summary, an average 0.1 % turbulence intensity is derived from 0.1 Hz - 10 kHz band-pass filtered signal for the test speed range of 5 - 20 m/s.

**Facility (2)** is a low speed, closed circuit and closed test section wind tunnel facility which is capable of reaching 55 m/s free-stream velocity. After the converging nozzle, the test section has a 914 mm by 1219 mm (36” by 48”) rectangular cross section. The streamwise turbulence of the flow in the empty test section is previously
measured by a standard Hot Wire Anemometry technique. In summary, an average 0.2% turbulence intensity is measured over the velocity range tested.

In both facilities, 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 multi-component strain gage load-cell (AMTI MC3A) is used to acquire forces and moments in three axes simultaneously in facility (1). Facility (2) employed a NASA Langley five component semi-span strain gage balance of model designation GACC-1. The flow velocity during the tests is observed using a set of static ports, in a ring arrangement, sufficiently upstream of the inlet of the test section through a differential pressure transducer. The temperature of the flow is measured using a thermocouple and recorded for each run. The barometric pressure is also monitored and recorded. The test section is configured for a semi-span experiment and the span axis is oriented normal to floor of the test section (and to the ground). The control signal to the wing is amplified and buffered using a TREK 2220 high-voltage amplifier with 200 V/V gain. All parameters are controlled and measured automatically with a National Instruments (NI) cDAQ data acquisition system and a personal computer. For each test point, a 10 second data block is sampled at 100 Hz and then averaged to get the mean value for each measurement of interest.

Barlow [34] suggests several wind tunnel corrections due to the existence of the walls around the wing, the buoyancy caused by the longitudinal pressure gradient and the development of the boundary layer along the walls. The solid blockage term, $\epsilon_{sb}$, and the wake blockage term, $\epsilon_{wb}$, which are described in Barlow [34], can be calculated relatively accurately for conventional wings. Since the specimen in discussion has a non-conventional geometry, the wind tunnel wall effects and buoyancy corrections are neglected to maintain the validity of absolute values of the reported coefficients. The reported lift and drag coefficients, $C_l$ and $C_d$, are assumed to be equal to the uncorrected lift and drag coefficients, $C_{lu}$ and $C_{du}$, which are calculated by: $C_l = C_{lu} = F_{lift} / (0.5 \rho c b_e v_q^2)$ and $C_d = C_{du} = F_{drag} / (0.5 \rho c b_e v_q^2)$ where $F_{lift}$ and $F_{drag}$ are the measured lift and drag forces, $\rho$ is the density of air, $c$ is the mean-aerodynamic-chord, $b_e$ is the reduced semi-span (due to boundary layer displacement thickness) and $v_q$ is the flow speed calculated at the quarter-chord location.

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 uncertainty in the load-cell or the balance. The absolute values have uncertainties due to several parameters such as air density and flow velocity measurements. The uncertainty analysis of each measurement is conducted by following the AIAA Standard [35].

C. Comparison of Baseline Wing Aerodynamic Response

A baseline symmetric tapered wing was tested for its fundamental aerodynamic characteristics to serve as a baseline reference for the solid-state piezocomposite wing in both facilities. This wing is virtually equivalent to the variable-camber wing in terms of planform. The span is 248 mm and the mean aerodynamic chord is 166 mm. The complete wing structure is theoretically symmetric although a small amount of asymmetry may exist due to tolerance limitations caused by the manufacturing and assembly processes. Figure 7a and Figure 7b present the experimental three-dimensional (3D) lift and drag coefficients at different flow velocities and from different facilities labeled as (1) and (2). Figure 7a also presents the theoretical two-dimensional (2D) infinite-span and the 3D finite span lift curves for reference. An aspect ratio (AR) of 1.5 is assumed for the planform of both the baseline and the morphing wings.

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The experimental lift and drag measurements are close to the theoretical predictions for a finite-span wing from facility (2). In contrast, a velocity dependency is observed in the data from facility (1). There are several aerodynamic reasons for the differences observed in the baseline experiments. The primary reason for a lower than expected lift curve slope is the Reynolds number regime in which the tests are conducted. It is well known that “at Reynolds numbers above 70,000 and below 200,000, an extensive level of laminar flow can be obtained and therefore airfoil performance improves although the laminar separation bubble (LSB) may still present a problem for a particular airfoil.” The reader is referred to Mueller [36] for details. The turbulence observed in the wind tunnel is artificially helpful in reducing the effect of the LSB and aerodynamic hysteresis although the dominant effects of the LSB are clearly visible in the test data from facility (1). The observation of LSB in similar piezocomposite wings and its active reduction and delay in low Reynolds number flow regime have been demonstrated by Bilgen et al. [37,38]. As expected, a significant increase in lift curve slope is observed as the Reynolds number is increased in the 70,000 – 200,000 regime. In contrast, the tests in facility (2) are conducted above the Reynolds number of 200,000; therefore aerodynamic response is closer to that of the theoretical finite span wing.

Another important detail is the gap between the root of the wing and the tunnel surface. There is roughly a one and two millimeter gap between the root of the wing and the adjacent tunnel surface for the tests conducted in facilities (2) and (1) respectively. This gap ensures that the root of the wing does not come in contact with the adjacent surface due to transverse vibration of the “sting” or the rotation of the wing about the pitch axis. Mueller and Burns [39] show that gap sizes around 0.5% of the span are usually acceptable and do not affect the test results. For the semi-span specimens tested here, the maximum gap height is estimated as 0.8% for the tests conducted in facility (1). Although the gap dimension is small, the gap percentage is still higher than the recommended value, specifically for the tests conducted in facility (1). This gap leads to unaccounted flow as the pressure gradient across the two surfaces of the wing increase as a function of camber and angle-of-attack.

Similar conclusions can be derived from the experimental drag response which is presented in Figure 7b. In summary, both the lift and drag coefficient measurements are as expected and the discrepancies from theoretical predictions are identified. These observations on the baseline wing response are important because they establish a certain level of confidence in the conclusions derived from the measurements.

D. Morphing Wing Aerodynamic Response

The variable-camber wing was also previously evaluated for its fundamental aerodynamic characteristics (see Ref. 21). These parametric OFAT type tests were performed by setting the excitation voltage at a fixed value, then sweeping the support angle (β) of the wing up and down. The complete list of excitation voltages is: -1500 V and +1500 V. The support angle was swept from -25 to 25 and back to -25 degrees in 0.5 degree increments. The procedure outlined here was necessary for correct identification and separation of two possible sources of non-linear phenomena: aerodynamic hysteresis, and piezoceramic material hysteresis. The angle β is swept up and down for several voltage levels, however, aerodynamic hysteresis was not observed due to the turbulence in the wind tunnel. As the support angle is swept up and down, no measurable deformation is observed due to the change of aerodynamic load distribution on the wing. The wing sustained aerodynamic loading at the maximum tested free-
stream velocity of 23 m/s. The large voltage-induced peak-to-peak change in lift in the post-stall region was noted, however, it was lower than expected.

In the current study, the DOE methodology is employed to create a randomized test schedule. The velocity, support angle and excitation voltage are varied within the test matrix with extensive replication, resulting in a total of 102 tests. A total of five velocity levels (20, 25, 30, 35, 40 m/s); five support angle levels (-3, 0, 3, 6, 9 degrees); and five voltage excitation levels (-1500, -750, 0, 750, 1500 V) were considered. The lift and drag coefficient measurements as a function of test index are presented in Figure 8. The pitch moment results are not presented.

![Figure 8: Experimental (3D) lift (a) and drag (b) coefficient results from the Design of Experiments runs for the variable-camber wing in the 20 - 40 m/s range. \(R_{MAC} = 215,000 - 430,000\).](image)

The wing is symmetrically excited where both top and bottom surfaces deflect in the same direction as a function of voltage. The positive peak excitation (Figure 6a) and the negative peak excitation (Figure 6a) values are considered. The regression model is constructed using the experimental data from the DOE runs presented above. Table 1 provides a summary of the significant model terms identified in the ANOVA analysis, expressed as a percent of the maximum response.

<table>
<thead>
<tr>
<th>Term</th>
<th>(C_L) (% Max)</th>
<th>(C_D) (% Max)</th>
<th>(C_M) (% Max)</th>
</tr>
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<tbody>
<tr>
<td>A-Beta</td>
<td>40.7</td>
<td>12.7</td>
<td>8.8</td>
</tr>
<tr>
<td>B-Velocity</td>
<td>0.8</td>
<td>4.1</td>
<td>0.7</td>
</tr>
<tr>
<td>C-Excitation Voltage</td>
<td>34.6</td>
<td>13.1</td>
<td>54.6</td>
</tr>
<tr>
<td>AB</td>
<td>0.0</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>AC</td>
<td>0.0</td>
<td>27.3</td>
<td>0.0</td>
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<td>BC</td>
<td>2.9</td>
<td>2.1</td>
<td>1.6</td>
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<tr>
<td>(C^2)</td>
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<tr>
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<td>6.7</td>
</tr>
<tr>
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<tr>
<td>(C^3)</td>
<td>6.5</td>
<td>0.0</td>
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</table>

As expected, the linear terms are the most dominant in the lift response. The drag coefficient shows significant dependency on the voltage main effect and the angle-voltage interaction. There is a pure quadratic effect of the support angle on drag. The pitch moment shows significant dependency on the linear effect of the excitation voltage. It is important to note that the aerodynamic coefficients show small dependency on velocity, hence the Reynolds number, from the data collected in facility (2). As these tests were conducted well above the Reynolds number of 200,000, the observation made here is as expected. The support angle causes direct change in the angle-of-attack,
and the excitation voltage causes a coupled change in angle-of-attack and camber simultaneously so first principles support the quadratic dependencies. The summary statistics are presented in Table 2 and show the model fit as well as the ANOVA derived estimate for uncertainty expressed as a standard deviation of the response coefficient [23].

<table>
<thead>
<tr>
<th>Summary Statistics</th>
<th>$C_L$</th>
<th>$C_D$</th>
<th>$C_M$</th>
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<td>R-Squared</td>
<td>0.994</td>
<td>0.975</td>
<td>0.979</td>
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<tr>
<td>Adjusted R-Squared</td>
<td>0.993</td>
<td>0.972</td>
<td>0.978</td>
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<td>Prediction R-Squared</td>
<td>0.992</td>
<td>0.965</td>
<td>0.975</td>
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<tr>
<td>Standard Deviation</td>
<td>0.0193</td>
<td>0.0021</td>
<td>0.0065</td>
</tr>
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</table>

Figure 9 presents the comparison of the regression model that is developed using the test data from facility (2) to the parametric evaluation obtained at facility (1). Note that the rotation angle of the support structure ($\beta$) is given as the independent variable for the figures in this section which is necessary for clear presentation of the data.

Figure 9: Experimental 3D comparison of (a) lift and (b) drag coefficients for the variable-camber wing in response to the excitation voltage, the rotation angle and the freestream velocity. $Re_{MAC,1} = 251,000$; $Re_{MAC,2} = 270,000$.

As noted above for the response of the baseline wing, the variable-camber wing also shows difference in aerodynamic performance between the two wind tunnel facilities where these differences are attributed to difference in chord Reynolds number and the flow quality. Figure 9a demonstrates that the change in lift coefficient induced by excitation voltage is significant in a low turbulence condition, although both facilities show that flow induced adverse deformations are small within the dynamic pressure range considered in this paper. Figure 9b shows that both facilities captured the same trend in drag coefficient response. Generally speaking, the negative peak excitation case results in higher minimum drag coefficient when compared to the positive peak excitation case.

V. Conclusions

This paper presented the low Reynolds number aerodynamic evaluation of a variable-camber tapered wing which utilizes surface-induced deformations with MFC actuators. The experimental results, based on the Design of Experiments runs, are presented for the free-stream velocity range of 20 - 40 m/s and a chord Reynolds number range of 215,000 - 430,000. The empirical results from the regression model demonstrate the significant aerodynamic authority of the solid state variable-camber wing when operated in Reynolds numbers above 200,000 and in relatively low turbulence conditions and the relative insensitivity to Reynolds numbers above 200,000.

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