

Experimental Measurement of a Blade Section With a Continuous Trailing-Edge Flap

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ABSTRACT

This paper presents the experimental bench-test and wind-tunnel-test results for a prototype rotor-blade section with an integrated Continuous Trailing-Edge Flap (CTEF). The CTEF is a monolithic active blade design that uses piezoelectric-fiber actuators to deform the trailing edge of an airfoil, and thereby induce changes in lift and pitching moment. Based on prior analytical modeling, a CTEF test article was manufactured and subjected to bench testing and low-speed wind-tunnel testing. Bench testing was conducted over a range of actuation frequencies and voltages, and the deformation of the airfoil section was measured. In the wind tunnel, deflection under aerodynamic load and the aerodynamic performance were measured. Measured performance was slightly less than predicted, but the results demonstrate that the CTEF concept does perform as expected.

INTRODUCTION

On-blade active control of helicopter rotor systems appears to provide a means for achieving many of the goals for future helicopter designs, but has largely failed to move beyond the research stage of development. A significant number of model-scale and full-scale rotor concepts have been developed and tested (an overview of which is presented in ref. 1). The primary impediment to the adoption of these technologies has been the combination of cost and complexity associated with the rotor designs. Active-flap designs have been heavily studied, but the discrete flaps used in these designs have an inherent mechanical complexity due to their use of hinges and actuation mechanisms. The large centrifugal loads and bending deformations experienced by a rotor blade make designing a reliable flapping mechanism very challenging. The result of this is that even though a significant number of active-flap designs have been tested, the technology has not reached production aircraft.

To address the limitation of discrete active flaps, researchers have also investigated a number of other concepts to achieve a similar effect without the use of a discrete hinge. Grohmann et al. (refs. 1 and 2) have developed what they refer to as an Active Trailing Edge. This concept uses a piezoelectric bimorph embedded in the trailing edge of the rotor blade that deforms up and down to create the effect of an active flap. The developed design has modular replaceable components, but the overall blade design is still relatively complex. Another concept that has been investigated for

helicopter rotors is the controllable-camber airfoil (refs. 3 and 4). This concept is similar to fixed-wing morphing technology (ref. 5) and seeks to create lift and moment by deforming the airfoil cross-section via active internal structural elements. This concept permits deformation over a larger chordwise section of the airfoil, and optimization of the design enables exceptional theoretical performance; however, manufacturability of the developed designs has largely not been addressed.

The Continuous Trailing-Edge Flap, CTEF, concept presented in this paper was developed to determine if a monolithic active blade design could be developed that was functional, manufacturable, and cost-effective (refs. 6-8). The CTEF combines the simplicity of the piezoelectric bimorph with the “whole blade” approach used in controllable camber airfoils. The resulting design was analytically shown to provide sufficient authority for primary flight control of a swashplateless utility class helicopter (ref. 8).

As a result of the success demonstrated by the prior analysis work, a prototype CTEF blade section has been designed and built to validate the CTEF concept. The objective of this paper is to present the experimental bench-test and wind-tunnel-test results for a prototype rotor-blade section with an integrated CTEF. First, the deformation of the prototype airfoil during bench testing is presented, including the response at various actuation voltages and frequencies. Next, the deformation and aerodynamic performance of the CTEF prototype at velocities up to 270 ft/s have been measured, and will be compared to analytical results.

TEST ARTICLE DESIGN

The CTEF test article, as shown in Figure 1, uses Macro-Fiber Composite (MFC) piezoelectric-fiber actuators (ref. 9)

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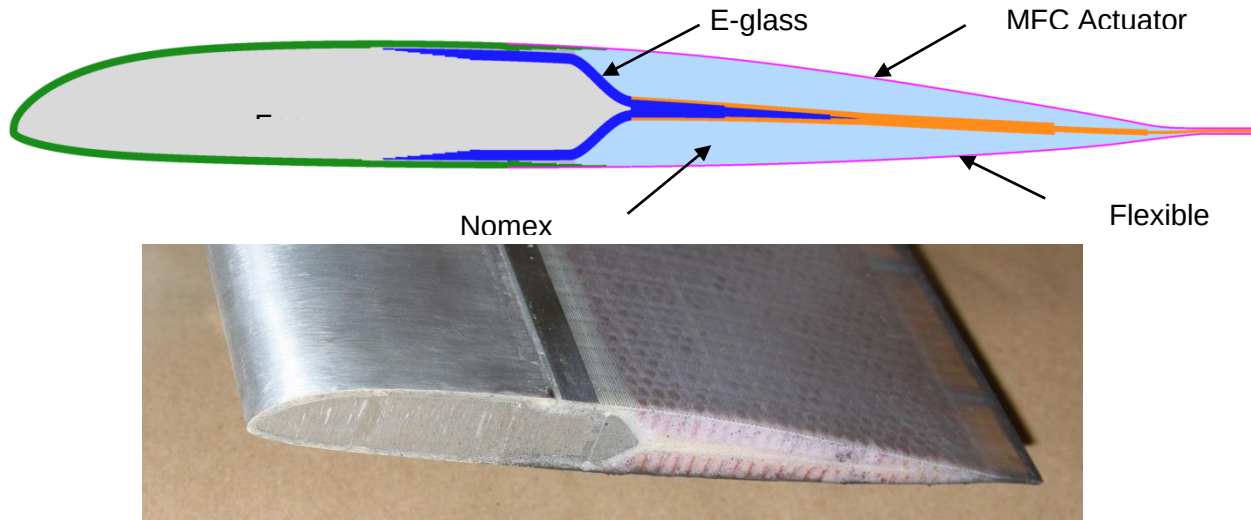


Figure 1. Cross-sectional views of the designed and as-built CTEF test article.

bonded to an E-glass spine to form an integral bimorph actuator within the blade section. Application of positive voltage to the upper-surface MFCs and opposite-polarity voltage to the lower-surface MFCs induces a downward deflection of the trailing edge, an increase in lift coefficient, and a nose-down pitching moment. The CTEF cross-sectional design for the blade-section prototype was based on the design presented in reference 8. The only differences between the two designs are that the test-article bimorph is attached to a traditional aluminum spar rather than integrated into a composite spar design, and that the flexible skin used on the trailing edge is a flexible metal mesh within a silicone film rather than a nylon film.

The test article has a 9.84-in-chord VR-18 airfoil with 0° tab and a 12.1-inch span. The design uses four layers of MFC actuators on each side of the trailing edge bimorph, which starts at 0.50c. The airfoil regions above and below the bimorph are filled with a Nomex honeycomb and covered with a flexible skin made by embedding a flexible stainless-steel mesh within a layer of silicone. The bimorph has an E-glass fabric spine separating the upper and lower layers of MFCs, which tapers from a thickness of 0.0945 in at 0.50c to zero at 0.76c. This spine and the bimorph can be observed in the cross-sectional layout presented in Figure 1. To minimize fabrication costs, stock MFC actuator sizes were used to construct the test article. Four full-width M-8557-P1 MFCs and one half-width M-8528-P1 actuators were used for each layer along the span of the test article. The widths of the stock actuators did not exactly sum to 12.1 inches, so small gaps were present between the MFCs. The layers of MFC actuators were staggered along the span, thereby minimizing the effect of gaps between the individual actuators. This staggered pattern can be seen in Figure 2, which shows the CTEF prior to installation of the skins and honeycomb cores onto the trailing edge. As a result of these gaps and the MFC packaging, the active piezoelectric fraction is 83.3 percent of the theoretical value that would represent the MFC

piezoelectric fibers in each layer being present over the entire span of the test article.

The MFC actuators are rated for a voltage range of -500V to +1500V. Thus, for applications that only require $\pm 500V$, a single amplifier can be used to power the CTEF bimorph. This is accomplished by reversing the polarity on the lower-surface actuators such that positive amplifier voltage results in positive voltage on the upper surface and negative voltage on the lower surface, thereby inducing downward bimorph bending. In order to utilize voltages beyond +500V, a bias voltage is required. In this work a +250V bias voltage was used to achieve an effective CTEF voltage range of $\pm 750V$, and separate amplifiers were used to power the upper and lower surfaces. Prior experience has shown that voltages in excess of this range lead to high rates of actuator failure for this type of application, so the decision was made limit the voltages used in this study. Results presented in this work are referenced to a single “CTEF voltage”, so a 750V cyclic

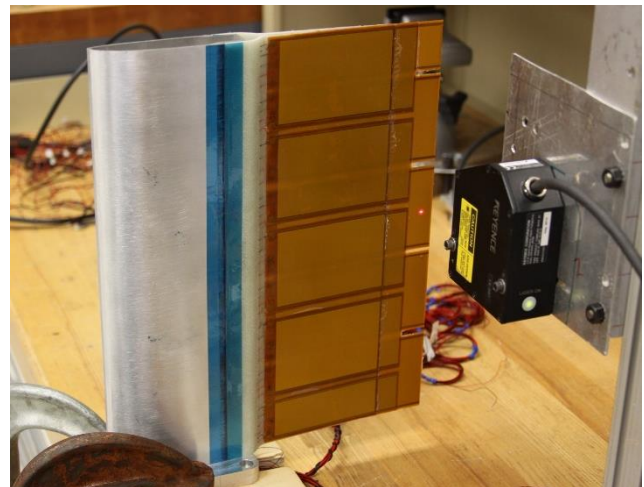


Figure 2. Bench measurement of the CTEF test article prior to skin installation.

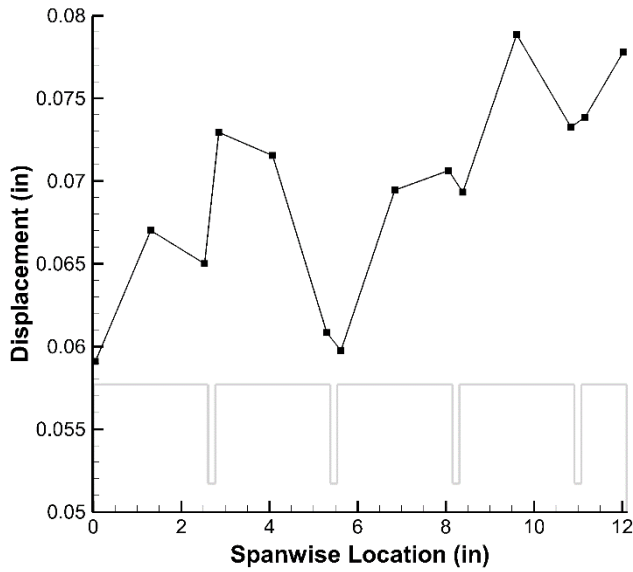


Figure 3. Measured deflection along the CTEF trailing edge at 0.2Hz 500V prior to installation of the skin.

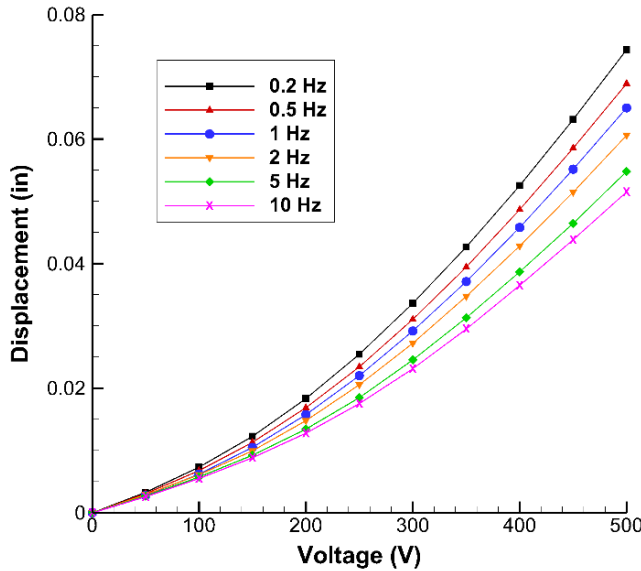


Figure 4. Measured trailing-edge deflection without skin at various voltages and frequencies.

CTEF voltage implies that a sinusoidal signal with a half-peak-to-peak amplitude of 750V is applied on top of a +250V offset. Similarly, an applied static voltage of +750V should be taken to mean that the voltage of the upper-surface actuators is +1000V, and the voltage of the lower-surface actuators is -500V.

BENCH TESTING

Bench testing was performed on the test article prior to installation in the wind tunnel to quantify the performance without the presence of aerodynamic loads. Also, because of the window configuration in the wind tunnel, only a limited portion of the test article span was available for deformation

measurements once it was installed in the wind tunnel. Thus, detailed measurements of the deformation over the entire surface of the test article were performed on the bench to evaluate the deflection uniformity during actuation.

Prior to installation of the flexible skin and honeycomb cores onto the trailing edge, a set of measurements was made along the trailing edge to quantify the deflection of each actuator within the bimorph (Figure 2). The objective of this measurement was to evaluate the impact that the addition of the skin and honeycomb have on the actuation authority of the bimorph. In addition, this test provided the opportunity to assess the individual operation of each actuator to verify that the installation of the trailing-edge skin did not result in actuator failure. Non-contact laser displacement sensors were used to measure both static and sinusoidal displacements at discrete locations along the CTEF chord and span.

Figure 3 presents the measured deflection magnitude at various locations along the trailing edge during 500V actuation at 0.2Hz. The shaded line depicts the MFC geometry along the span to provide a reference for the measurement locations. These results show a 25-percent variation in the bimorph deflection along the span of the test article. This variation is a result of variations in MFC performance and bond-line thickness between the actuators.

The trailing edge deflection was measured at various frequencies and voltages in order to quantify the nonlinearity of the bimorph prior to installation of the flexible skin. The measured results, which are presented in Figure 4, show a nonlinear response that has also been observed in prior work with the MFC actuators (ref. 10). The deflection is observed to be nonlinearly proportional to voltage, while at the same time decreasing as actuation frequency increases. The 30-percent decrease in deflection between 0.2Hz and 10Hz is of particular concern for CTEF application control authority, but is not specifically addressed in this work. It should be

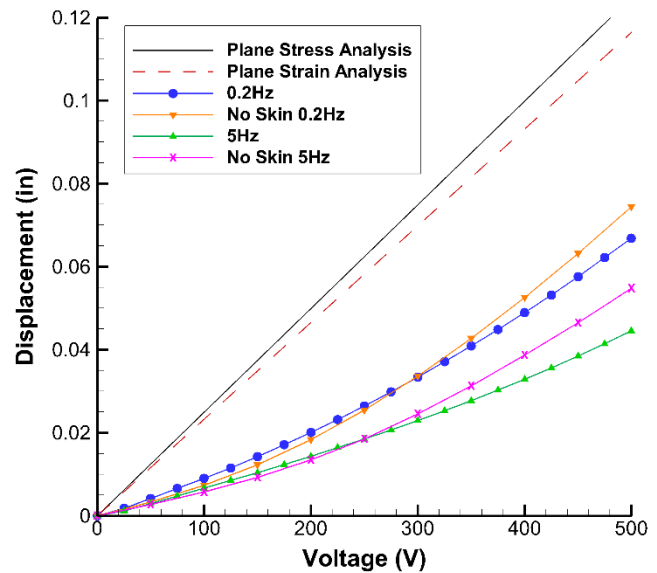


Figure 5. Comparison of trailing-edge deflection between analysis, with-skin measurements, and without-skin measurements.

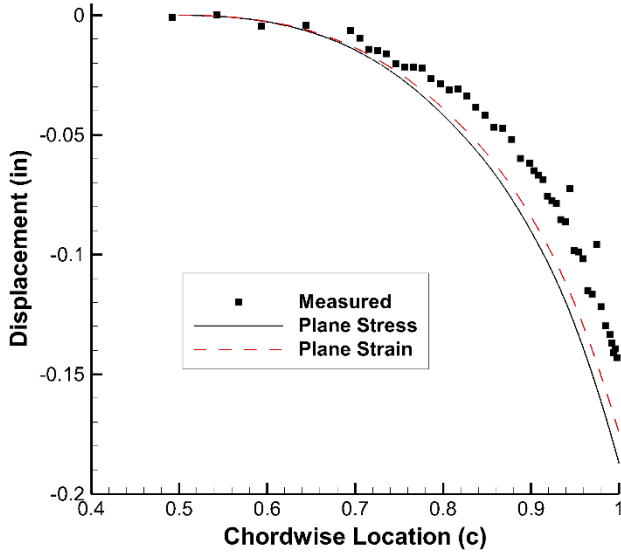


Figure 6. CTEF deflection along the airfoil chord for +750V actuation without aerodynamic loading.

noted that the MFC manufacturer's material properties were derived based on static actuation at maximum voltage. The assumed linearity results in large errors in analytical predictions at low voltage, and implies that the difference between analysis and experiment should be significantly less at maximum voltage. Further, the analysis assumes 100 percent coverage of the piezoelectric bimorph, as opposed to the 83.3 percent actual coverage, so a number of opportunities exist to develop more accurate analytical models of the CTEF in future efforts.

Following the installation of the honeycomb cores and flexible skin above and below the bimorph, bench test measurements were repeated at various actuation voltages and frequencies. Comparisons were then made between the measured deflections with and without the skin, and between analysis and the experimentally measured values. The trailing-edge deflection as a function of voltage, for 0.2Hz and 5Hz actuation, is presented in Figure 5. As one would expect,

the deflection at 500V is slightly less following the installation of the skin. Interestingly, the deflection at low voltages is actually greater at this particular location with the skin installed, and the deflection as a function of voltage is more linear.

Figure 5 also presents the analytical predictions for the trailing-edge deflection. These predictions were made using a simple one-dimensional algorithm originally presented in reference 7. The 1-D solution algorithm was developed by taking 2-D curvilinear shell equations based on the Sanders-Koiter shell theory, including transverse shear and piezoelectric effects, then collapsing them down to 1-D by assuming either plane-stress or plane-strain along the spanwise direction of the blade. It is important to note that this model assumes linear piezoelectric behavior based on the manufacturer-specified static material property values, therefore it is unable to capture the nonlinearity associated with voltage and frequency described above. Thus, the analysis greatly over predicts the deformation at lower voltages and higher frequencies. Figure 6 presents the predicted and measured deflection along the chord of the test article for +750V static actuation. The comparison between test and analysis are significantly better for deformation produced at the higher voltage. The measured deflection at the trailing edge is 0.139 in., while the predicted displacements are 0.187 in. for the plane-stress analysis and 0.174 in. for the plane-strain analysis. Thus, the plane-stress model over predicts the displacement at the trailing edge by approximately 23 percent, while the plane-strain model over predicts the displacement at the trailing edge by approximately 17 percent. However, the analysis does not take into account that the active piezoelectric fraction is 83.3 percent, as discussed above. Therefore, the simple 1-D algorithm appears to give reasonably accurate predictions at the higher actuation voltages. Because of the uncertainty induced by these known sources of discrepancy, it is not readily apparent whether the plane-stress or plane-strain assumption is more appropriate, and so the plane-strain model is used for the predictions presented in the remainder of this paper.

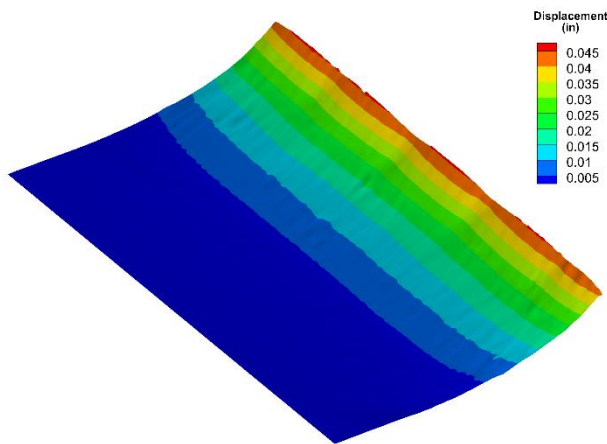


Figure 7. Measured deflection profile of the CTEF test article at 5Hz 500V.

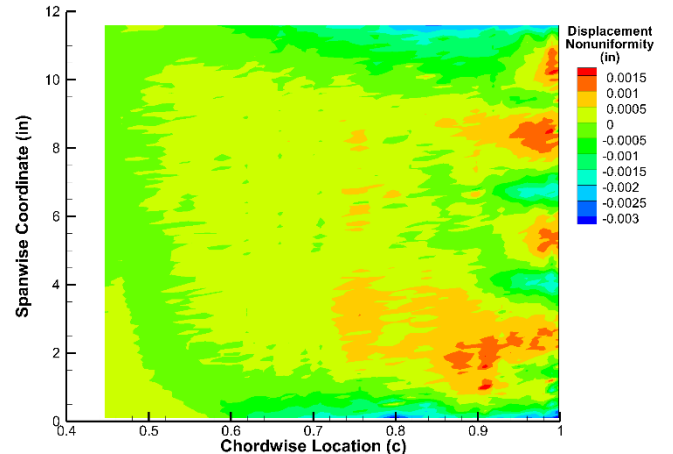


Figure 8. Non-uniformity of the measured CTEF deflection at 5Hz 500V relative to a smooth profile.

Looking at the measured deflection over the entire surface of the CTEF test article, presented in Figure 7, one sees that the displacement is much more uniform than was observed prior to installation of the skin. There is slightly less displacement at the free sides of the test article, but this is likely because the MFC packaging results in there being no active material in the first and last 0.14 inches along the span. A least-squares computation was performed to compute a best-fit profile assumed to be constant along the span. The actuation non-uniformity was computed by subtracting this best-fit profile from the measured profile, which is presented in Figure 8. The effect of the individual MFC actuators on the displacement now becomes visible, but the overall displacement variation across the test article is considerably less than ± 0.002 inches. Therefore, the CTEF design is shown to be effective at inducing a smooth, uniform trailing-edge deformation, even with the use of discrete MFC actuators. The uniformity could be further improved through the use of custom MFC actuators that spanned the entire width of the CTEF.

WIND-TUNNEL TESTING

Following bench testing of the CTEF test article, testing was performed in a small low-speed wind-tunnel to quantify the performance of the CTEF in the presence of aerodynamic loads. The tunnel had a 12.1-in by 17.3-in cross section, and was capable of speeds up to approximately 270 ft/s. Glass windows on the sides of the tunnel permitted the laser displacement sensors to be used for measuring the deflection over a portion of the test article. A balance was used to measure the lift, drag and moment produced by the test article; however, balance limits prevented load measurements from being made at combinations of large angles-of-attack and high speeds. CTEF displacements were measured for these points during separate runs in which the balance was not installed. Air density during testing was measured to be

0.002313 slug/ft³, and a speed-of-sound of 1130 ft/s and viscosity of 3.82E-7 lbf·s/ft² were used in the analytical predictions. Measurements were taken at 25 ft/s speed increments and at angles-of-attack from -4° to $+10^\circ$ on 2° increments. Two complete sets of measurements were made: one at a 500V maximum voltage and one at a 750V maximum voltage. At each speed and angle-of-attack combination for the 500V set, the CTEF was actuated statically at -500V, -300V, -100V, 0V, +100V, +300V, and +500V, and dynamically at 500V frequencies of 0.2, 0.5, 1, 2 and 5 Hz. For the 750V set, the CTEF was actuated statically at -750V, -500V, 0V, +500V, and +750V, and dynamically at 750V frequencies of 0.2, 0.5, 1, 2 and 5 Hz. At most speed and angle-of-attack combinations the displacement was only measured at two points on the trailing edge. For each angle-of-attack, however, a number of profile scans were also made along the chord of the airfoil, and detailed frequency and voltage sweeps were also measured for some cases. The results presented below are a representative subset of the measured experimental data compared to the 1-D analytical predictions.

Analytical predictions of the CTEF deformation and the aerodynamic lift, drag and moment were made by coupling the 1-D structural algorithm discussed above to the XFOIL analysis code, as was done in prior CTEF work (ref. 7). XFOIL is a 2-D aerodynamics analysis tool that uses either an inviscid or viscous linear-vorticity panel method with Karmen-Tsien compressibility corrections (ref. 11). XFOIL was loosely coupled to the structural algorithm, and the fluid-structure interaction was iteratively solved. The airfoil deformation was computed by the structural analysis, and the deformed airfoil shape was supplied to XFOIL for computation of the pressure distribution and aerodynamic coefficients. The pressure distribution was then applied to the CTEF in the structural analysis, and iteration continued until the deformation and aerodynamic coefficients converged.

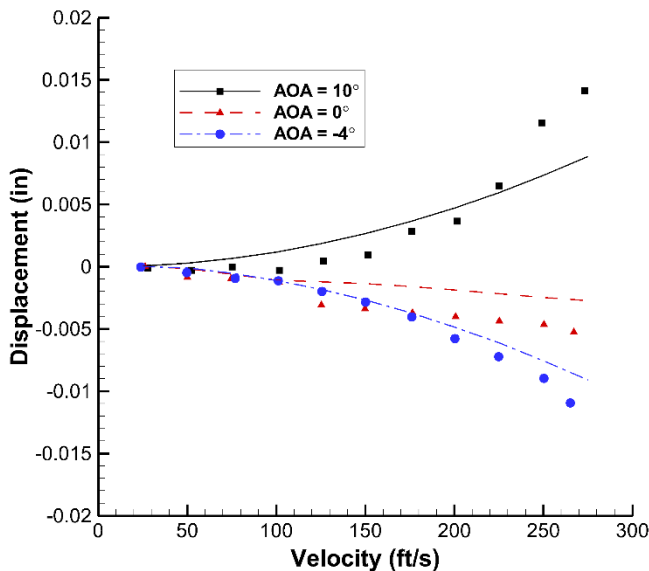


Figure 9. Trailing-edge deflection in the wind tunnel at 0V actuation.

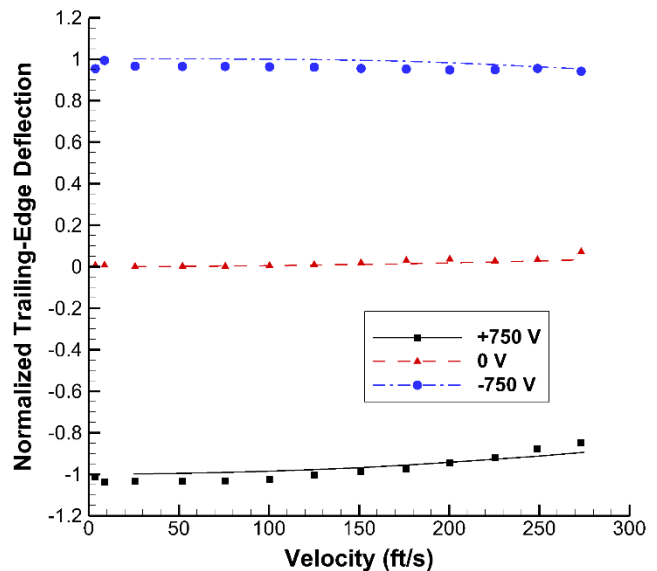


Figure 10. Trailing edge deflection normalized to zero-velocity deflection for 8-degree angle-of-attack.

Predictions were made using both plane-stress and plane-strain structural assumptions and both inviscid and viscous XFOIL options. The predicted results presented below are all from the plane-strain viscous solution method, and represent what the authors consider to be the best combination of fidelity and analysis speed for initial design of a CTEF rotor.

The first question to be examined is how well the CTEF is able to resist bending in the presence of aerodynamic load. Figure 9 presents the deflection at the trailing edge with zero actuation voltage as a function of tunnel velocity. The results are presented for angles-of-attack of -4° , 0° , and $+10^\circ$. The values predicted by the 1-D analysis are represented by lines, and the measured values are represented by symbols, a formatting style that is used for all figures in this section. As one would expect, the trailing edge deflects measurably at increasing airspeeds, with a deflection of 0.014 in. at 270 ft/s and an angle-of-attack of $+10^\circ$. The predicted deflections are reasonably close, but they do under-predict the deflection induced at higher airspeeds. This implies that stiffness of the trailing edge is less than predicted, but it is not clear whether the source for this is error in the analysis or differences between the designed and as-built geometries of the bimorph.

Next, the deflection produced by actuation is presented in Figure 10. These results compare the measured and predicted trailing-edge deflection at an angle-of-attack of $+8^\circ$ during +750V, 0V and -750V static actuation. In this case, both analytical and experimental displacements have been normalized to the trailing-edge deflection produced by 750V static actuation without aerodynamic loads applied. For the predicted results this deflection is 0.174 in, and for the measured results this value is 0.139 in. The sources for this difference in actuation authority were discussed above with the bench testing results, and normalizing the results in this manner permits better comparison of the relative deformation of the CTEF at a variety of angles-of-attack and tunnel velocities. Since the CTEF prototype was designed for nominal operation at Mach 0.65, it is expected that the deflection would be only slightly reduced at the maximum speeds this tunnel is capable of. At 270 ft/s the measured +750V displacement was reduced by approximately 15 percent, while the -750V displacement was reduced by less than 3 percent. The predicted displacement reductions were 11 percent and 5 percent, respectively. The fact that the analysis under-predicts the reduction for +750V and over-predicts the reduction for -750V indicates that the analysis is under-predicting the stiffness of the trailing edge rather than incorrectly predicting the actuation-induced deformation. This observation agrees with that made based on the 0V results shown in Figure 9.

Next, the lift, moment and drag produced by the CTEF airfoil in the wind tunnel are examined and compared with the values predicted by the XFOIL analysis. The aerodynamic coefficients are presented in Figure 11 for +750V, 0V and -750V static actuation as a function of airfoil angle-of-attack, except for the drag coefficient, which is plotted in its traditional manner as a function of the lift coefficient. The tunnel speed for the results presented is 100ft/s, but the results

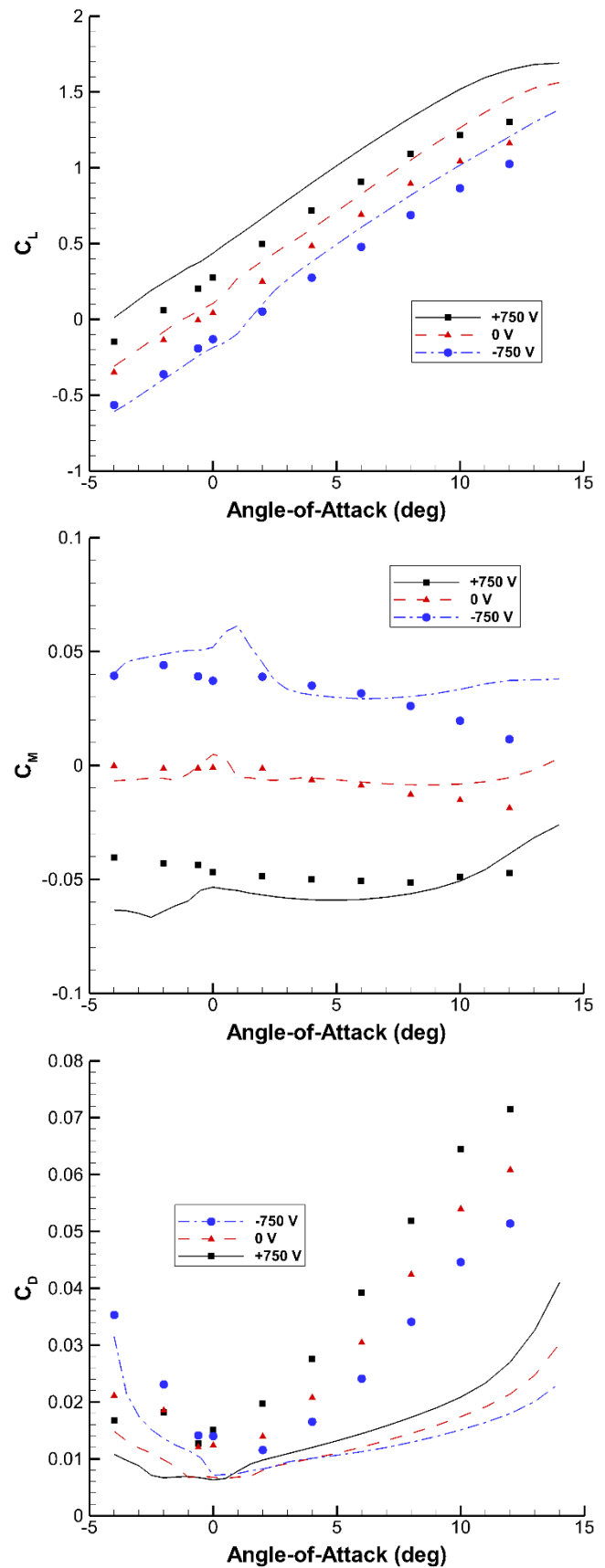


Figure 11. Airfoil lift, moment and drag coefficients at 100 ft/s tunnel speed.

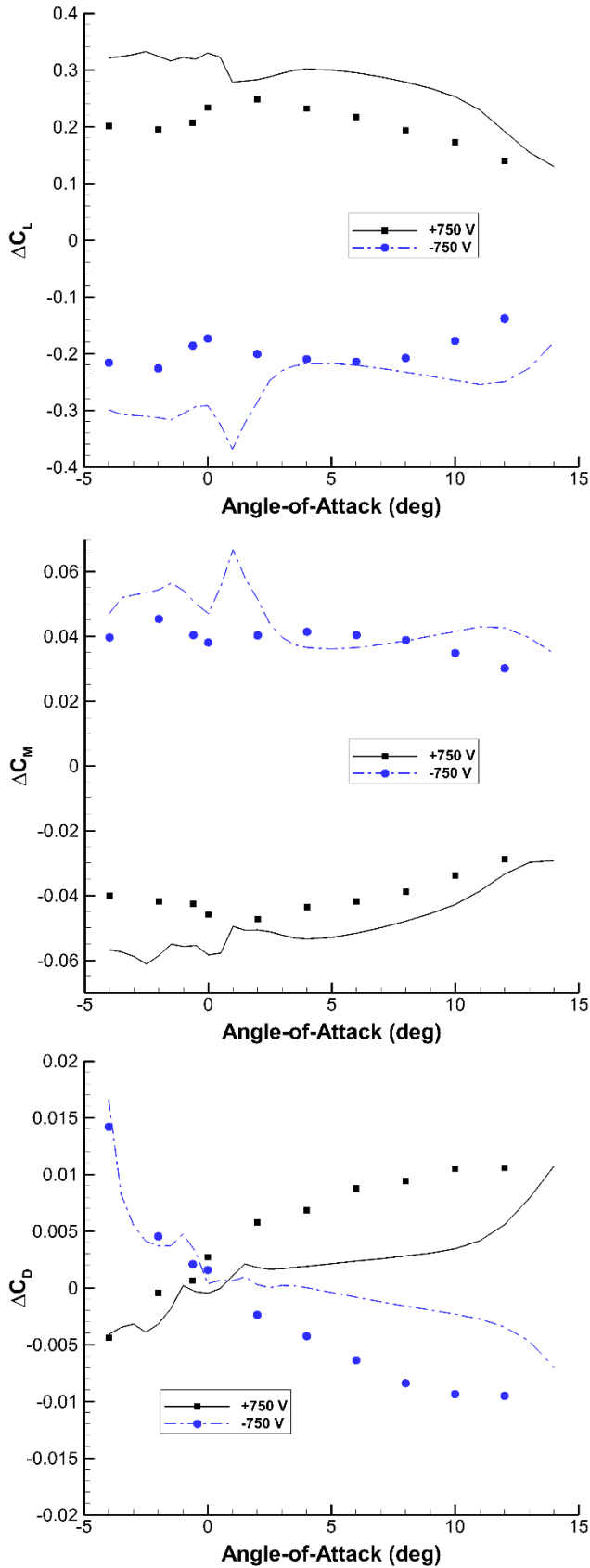


Figure 12. Change in airfoil lift, moment and drag coefficients induced by CTEF actuation at 100 ft/s tunnel speed.

at other airspeeds demonstrate similar trends. The corresponding change in the aerodynamic coefficients (ΔC_L , ΔC_M and ΔC_D) relative to the 0V values that were produced by +750V and -750V static actuation is presented in Figure 12 and is discussed in parallel with the results in Figure 11.

The first trend that is observed is that the measured lift-slope (Figure 11) is noticeably less than that predicted by the analysis at all CTEF voltages. This, combined with the trailing-edge displacement results, indicate that the CTEF trailing edge is more flexible than predicted and is consequently losing lift as it deforms at high angles-of-attack. The change in lift coefficient produced by CTEF actuation (Figure 12) is only slightly under-predicted by the analysis if one takes into account the active piezoelectric fraction of 83.3 percent, as discussed above. Also at high angles-of-attack, above approximately 8° , the CTEF begins to produce less change in lift during actuation. This trend is predicted to some extent by the analysis, but the exact profile of the change in lift coefficient differs across the angle-of-attack range.

Most interesting are the sudden changes in the ΔC_L (Figure 12) around 0° to 2° angle-of-attack that appear in both measured and predicted values. These sudden changes can also be observed in the moment coefficient and ΔC_M as well. This response only occurs at low air speeds, disappearing above 175 ft/s. Since it occurs in both experiment and analysis, this appears to be a physical phenomenon associated with the VR-18 airfoil; however, the analysis does a relative poor job of predicting the exact nature of this phenomenon. Some CFD analysis has been performed to verify its presence, but a detailed investigation of this behavior is beyond the scope of this paper.

The airfoil pitching moment, as presented in Figure 11, is relatively constant, although it too begins to diminish at high angles-of-attack. The predicted moment coefficient exhibits greater variation with changes in angle-of-attack than the measured moment, at least at the 100 ft/s airspeed presented in Figures 10 and 11. Similar to ΔC_L , predicted and measured ΔC_M (Figure 12) becomes more constant at higher airspeeds. The magnitude of the predicted change in moment coefficient agrees well with the measured values, and in some instances the difference is less than the 83.3-percent active piezoelectric fraction would suggest.

The measured airfoil drag was significantly greater than predicted by the XFOIL analysis. It is important to consider that the measured drag is derived from balance measurements rather than through the use of the momentum method and measurements of the airfoil wake. Thus, the measured drag contains the effects of the small gaps between the test article and the tunnel walls, which can significantly increase the aerodynamic drag on the test article and should not be included in the drag coefficient. Further, the predicted drag is known to be low due to the limitation of the XFOIL analysis, and CFD analysis has been performed that demonstrated greater drag for the unactuated airfoil. There is concern about the drag for the current CTEF design due to the silicone material used for the trailing-edge skin. Since it is

silicone, it has a feel that can be described as “sticky,” and it is unknown how this surface material contributes to airfoil drag. Since the drag coefficient is an important parameter in determining the rotor efficiency, one conclusion from this testing is that better drag measurements should be a priority during any future CTEF wind-tunnel testing to determine if the skin and manufacturing techniques contribute to an increase in drag for the CTEF.

Looking beyond the amplitude differences in the drag coefficient, the analysis and experiment show very similar trends. One advantage of the C_L - C_D plot format is that it demonstrates that the CTEF is very efficient at generating lift during actuation. For positive angles-of-attack, +750V actuation can be observed in Figure 11 to exhibit a lower drag coefficient at a given lift coefficient than the unactuated blade in both the experimental and analytical results; however, for those same angles-of-attack, -750V actuation produces more drag at a given lift coefficient than the unactuated blade. For cyclic actuation of the CTEF during flight, these two responses would mostly cancel each other, but there is potential for optimization of a CTEF rotor blade design to minimize the rotor power during use.

The aerodynamic coefficients presented thus far were at an airspeed of 100ft/s, and consequently demonstrated some unexpected low-speed responses. The effect of tunnel speed on the changes in lift, moment and drag coefficients induced by ± 750 V CTEF actuation is presented in Figure 13. The angle-of-attack for this case was $+4^\circ$. As a result of the low-speed phenomenon discussed above, the lift and moment induced by CTEF actuation increases with increasing tunnel speed up to approximately 200 ft/s. The analytical predictions exaggerate this trend, but it can be observed in both measured and predicted results. Above 200 ft/s, the results stabilize and exhibit the expected characteristics in which the coefficients decrease slightly with increasing airspeed. Above 200 ft/s, the predicted ΔC_L and ΔC_M for +750V are 29 percent and 23 percent greater than measured, respectively. The predicted ΔC_L and ΔC_M for -750V are 35 percent and 31 percent greater than measured, respectively.

Based on the results measured during wind-tunnel testing, the analysis appears to be less accurate at the higher airspeeds in which a CTEF rotor blade would like be operated. The source of this error is not entirely clear. It may be partially a result of the nonlinear material behavior demonstrated in the bench testing results, in which case if the CTEF were operated at ± 1000 V this error would be reduced. Alternatively, it may be indicative of other issues with the linear material properties and the behavior of the MFCs in embedded structures. The predictions are dependent upon the manufacturer-supplied homogenized material properties that are used to describe the effective behavior of the manufactured MFC. There could, potentially, be a difference between the manner in which the MFC performs when embedded in a structure, as opposed to when it is tested on the bench. The prediction error at higher airspeeds may also be a result of the limitation of the 1-D structural model and the XFOIL aerodynamic analysis, in which case more detailed

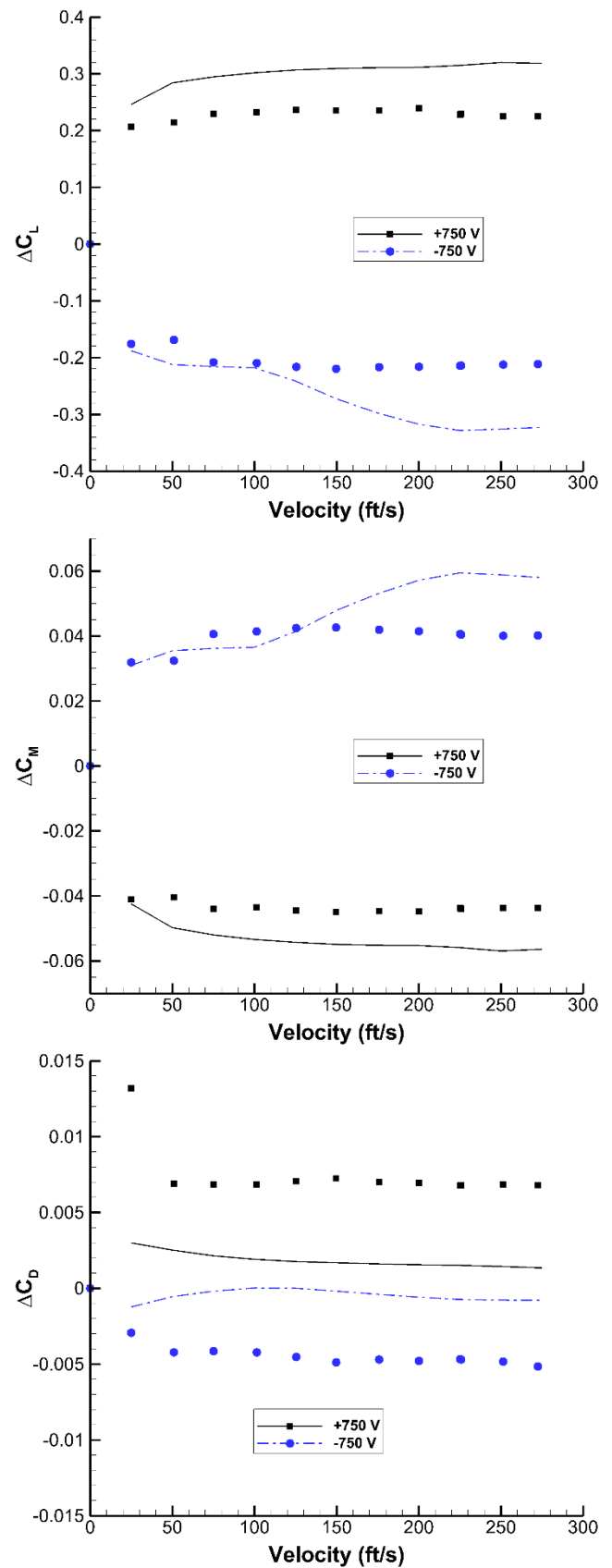


Figure 13. Change in airfoil lift, moment and drag coefficients induced by CTEF actuation at 4-degree angle-of-attack.

modeling of the CTEF needs to be performed to investigate this possibility. Finally, it may be a result of the manufacturing process resulting in a structure that does not perform as well as expected. The bimorph design is very sensitive to changes in ply thickness and the material stiffness of the surrounding inactive layers, and therefore excessive bond-line thickness or improper adhesive application may result in a degradation of CTEF performance.

CONCLUSIONS

This paper presented the results from bench testing and wind-tunnel testing of a prototype CTEF blade section. The results showed that the CTEF performed generally as expected during both bench testing and wind-tunnel testing, however, the analytical models are not yet sufficiently mature to accurately predict CTEF displacement on a bench or under aerodynamic load. During operation in the wind tunnel, $\pm 750\text{V}$ static actuation induced changes in the lift coefficient of approximately ± 0.2 and changes in moment coefficient of approximately ± 0.04 . Based on prior work, these quantities of aerodynamic control authority affirm the potential viability of a CTEF for individual blade control in rotorcraft applications. In addition, the following specific conclusions have been drawn

1. The CTEF was shown to be effective at inducing a smooth, uniform trailing-edge deformation, even with the use of discrete MFC actuators.
2. The CTEF displacement was shown to be nonlinearly dependent upon both voltage and actuation frequency.
3. The unactuated CTEF deflected slightly more than predicted when aerodynamic loads were applied, but the aerodynamic lift and moment induced by CTEF actuation were close to the values predicted.
4. The 1-D structural analysis code and the XFOIL aerodynamic code produced reasonably accurate predictions for the deformation, lift and moment of the CTEF. Drag measurements require more study on both the analytical and experimental sides.
5. Better drag measurements should be a priority during any future CTEF wind-tunnel testing to determine if the skin and manufacturing techniques contribute to an increase in drag for the CTEF.
6. Analytical modeling of the CTEF needs to be examined to determine the cause of differences in deformation that were observed at higher airspeeds.

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