Aerodynamic Evaluation of Miniature Trailing-Edge Effectors for Active Rotor Control

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ABSTRACT
This work presents progress on a detailed aerodynamic evaluation of Miniature Trailing-Edge Effectors (MiTEs) for active rotor control. We begin with a 2D computational fluid dynamics (CFD) study focused on establishing the dependency of MiTE effectiveness and performance upon basic geometric parameters on a VR-12 airfoil. The CFD study demonstrated that a MiTE placed at 10% chord upstream of the trailing-edge and sized at approximately 1% chord is capable of delivering moment coefficient increments of approximately ±0.03, or the same moment authority as a conventional flap moving ±2.3 degrees. Wind tunnel experiments were performed on a model blade section equipped with an operational MiTE in order to validate the CFD results, and strong agreement was shown. Finally, a small set of 3D unsteady CFD simulations with prescribed blade motion of a rotor equipped with MiTEs were performed. Under high-thrust, moderate speed conditions, MiTEs deployed sinusoidally at 4/rev frequency were capable of reducing 4/rev integrated aerodynamic loads in the vertical direction by approximately 80%.

NOTATION1

| Symbol | Description |
|--------|-------------|
| $C_l$  | Lift coefficient |
| $C_d$  | Drag coefficient |
| $C_m$  | Moment coefficient |
| $C_{Fz}$ | Hub normal force coefficient |
| $F_z$  | Hub normal force per unit span |
| $M$    | Mach number |
| $R$    | Rotor radius, ft |
| $Re_c$ | Reynolds number based on chord |
| $U$    | Freestream Velocity |
| $V$    | Helicopter Flight Speed |
| $c$    | Blade chord |
| $h_f$  | MiTE height |
| $f$    | Actuation frequency, Hz |
| $x$    | Coordinate in chordwise direction |
| $x_f$  | Chordwise MiTE location |
| $y$    | Coordinate in lateral direction |
| $z$    | Coordinate in vertical direction |
| $\Omega$ | Rotor speed, rad/sec |
| $\alpha$ | Angle of attack, degrees |
| $\kappa$ | Reduced frequency, $oc/2U$ |
| $\omega$ | Oscillation frequency, rad/s |
| $\phi$  | Actuation phase shift, degrees |

INTRODUCTION
A Miniature Trailing-Edge Effector (MiTE) is a small tab placed near the trailing-edge of an airfoil on the lower or upper surface oriented perpendicular to the freestream direction. MiTEs can be rapidly actuated and/or segmented in the spanwise direction in order to quickly change the local section lift, drag, and moment coefficients of a wing or blade. Similar to Gurney flaps, they change the effective camber of an airfoil when deployed, and if a good portion of the MiTE remains within the airfoil boundary layer, the impact on drag is small (Refs. 1-4).

MiTEs have already shown strong potential for solving a variety of fixed-wing aerodynamic problems including flutter suppression and wake vortex alleviation (Refs. 5-7). Recently, they have also shown potential for solving several problems associated with dynamic stall of rotorcraft blades (Ref. 8-13). An array of MiTEs deployed successfully on rotorcraft blades could potentially be used for performance enhancement, vibration and noise reduction, increased maneuverability, and automated blade tracking. The main advantage provided by MiTEs is that they are fairly small and require little actuation authority to deploy.

Over the last 20 years, a variety of techniques have been investigated with the goal of achieving active rotor control. These include individual blade control, rapidly actuated conventional trailing-edge flaps, and blade integral twist control (Refs. 14-17). In terms of aerodynamic performance, and with no regard to actuation and mechanical constraints, MiTEs tend to generate more drag per unit lift than a conventional flap or an actively twisting blade. With their small size, however, they can be more easily integrated into a rotor blade envelope and require less power to actuate. The smaller actuators reduce the overall and on-blade weight increase usually encountered with active rotor control techniques. Thus, the overall system performance with MiTEs may be better despite the slight drag increase.

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With the ultimate goal of accurately determining the system-level benefits, this work presents an ongoing aerodynamic evaluation of MiTEs for active rotor control. Results from a 2D CFD parametric study, a set of wind tunnel tests, and a 3D unsteady rotor CFD study will be discussed.

2D CFD PARAMETRIC STUDY
A parametric study was conducted to determine the dependence of aerodynamic authority and performance upon the location and size of the MiTE. Similar studies have been conducted in the past on different airfoil shapes (Ref. 4). This effort was focused not only on evaluating the potential aerodynamic benefits of MiTEs, but also upon finding a configuration which can be accomplished with a relatively simple mechanical design. Thus, the two main parameters varied were the chordwise location of the MiTE, \( x_f \), and the height of the MiTE from the airfoil surface, \( h_f \). Three MiTE locations \((x_f/c = 0.90, 0.95, \text{and } 1.0)\) and 10 different MiTE heights were considered \((h_f/c = \pm 0.0025, \pm 0.005, \pm 0.01, \pm 0.015, \text{and } \pm 0.02)\). We define positive \( h_f \) to be on the lower surface. Each case was run at angles of attack between 0° and 14° in 2° increments.

Figure 1. Schematic diagram of MiTE near trailing-edge of airfoil illustrating the two primary parameters that were varied in the 2D CFD study.

Several snapshots of the 2D CFD mesh are shown in Figure 2. The solver chosen for this study was CFL3D with the Spalart-Allmaras turbulence model. Free stream Mach number, \( M_{\infty} \), was set to 0.2 for most cases in order to allow comparison with experiments that were planned for a low-speed wind tunnel. Several cases were run at Mach number of 0.6, which confirmed the trends shown at the lower Mach number.

Figure 2. CFD mesh used for case with MiTE height 0.01c placed at 0.95c.

Drag results are shown in Figure 4. It is clear that increasing MiTE height at a given angle of attack tends to increase the drag coefficient. The increase is much more pronounced when the MiTE is placed on the lower surface, owing once again to the boundary layer height difference discussed previously. Drag penalty is increased slightly as the MiTE is brought further from the trailing-edge. This is likely due to the smaller boundary layer height further from the trailing-edge on both the lower and upper surfaces. The \( h_f/c = 0.02 \), \( x_f/c = 1.0 \) case shown in Figure 4a shows heightened levels of drag for \( \alpha < 8° \). A closer examination showed that this was due to high amplitude unsteady shedding immediately downstream of the MiTE due to the large size of the MiTE and the small boundary layer height on the lower surface. At \( \alpha > 8° \), the shedding subsides. Figure 5 shows lift-drag polars for the same cases. It is clear that most of the drag increment seen in Figure 4 is due to increase in lift. Nonetheless, the drag per unit lift is greater for cases with MiTEs deployed which is consistent with previous findings (Refs. 7 and 8).

Figure 6 shows plots of pitching moment coefficient increment, \( \Delta C_{\text{pm}} \), evaluated at \( \alpha = 0 \) as a function of MiTE height at the same three chordwise locations as before. This increment is simply defined as the difference between the moment coefficient value at the given configuration and the neutral case moment coefficient. This quantity provides a good measure of aerodynamic authority for rotocraft applications. Here we note the same trends that we saw in the lift plots, i.e., asymmetry in effectiveness between upper
and lower surfaces, and generally greater effectiveness when the MiTE is closer to the trailing-edge. Furthermore, in Figure 6a, we see that the moment increment varies in a fairly linear fashion with respect to $h_f/c$. In Figures 6b and 6c, however, this is not true. A clear jump in effectiveness occurs between $h_f/c = 0.005$ and 0.01 on the upper surface in Figure 6b and on both surfaces in Figure 6c. The reason for this is illustrated by the Mach number contours shown in Figure 7. When the MiTE of $h_f/c = 0.005$ is placed at $x_f/c = 0.95$, the flow separation immediately downstream of the MiTE is able to extend all the way to the airfoil trailing-edge. When the same size MiTE is placed at $x_f/c = 0.90$, there is sufficient distance downstream of the MiTE to allow the flow to reattach. This reattachment tends to attenuate the moment authority created by the MiTE leading to the non-linearity.
Figure 5. Lift-Drag polars for select cases with MiTE placed at (a) \( x_f/c = 1.0 \), (b) \( x_f/c = 0.95 \), and (c) \( x_f/c = 0.90 \).

Figure 6. Moment increment at \( \alpha = 0 \) as a function of MiTE height at (a) \( x_f/c = 1.0 \), (b) \( x_f/c = 0.95 \), and (c) \( x_f/c = 0.90 \).
seen in Figures 6b and 6c. Overall, the most important result of this parametric study is shown by Figure 6c. Even with the MiTE placed at \( x_f/c = 0.90 \), a reasonable amount of authority is possible with a fairly small MiTE. For example, a MiTE placed there moving \( h_f/c = \pm 0.01 \) provides \( \Delta C_m \approx \pm 0.03 \) which is comparable to the moment authority provided by a conventional-size flap moving approximately \( \pm 2.3 \) degrees (Ref. 15). The drag coefficient increment is approximately 0.006 with the MiTE on the lower surface.

\[ \text{(a) } h_f/c = 0.005, \ x_f/c = 0.95 \]

\[ \text{(b) } h_f/c = 0.005, \ x_f/c = 0.90 \]

Figure 7. Mach number contours near the trailing-edge for two cases with the same MiTE height, \( \text{(a) } x_f/c = 0.95 \), and \( \text{(b) } x_f/c = 0.90 \). The separated region downstream of the MiTE extends to the trailing-edge in \( \text{(a) } \) but does not in \( \text{(b) } \).

WIND TUNNEL EXPERIMENTS

Prior to performing the parametric study discussed in the previous section, a brief validation study was conducted to confirm that the CFD methodology used provided adequate fidelity, however, this study was performed on airfoil shapes different from the VR-12 due to the limited data available at that time. In order to confirm the results of the parametric study, and examine other phenomena, a set of wind tunnel experiments on a model VR-12 blade equipped with an operational MiTE at \( x_f/c = 0.90 \) was performed.

The experimental apparatus consisted of a half-span, low aspect ratio VR-12 blade model as shown in Figure 8. An outer shell was fabricated using SLA and rigidly supported by a steel strut which connected directly to a six-component loads balance underneath the tunnel test section. The chord length of the model was 17 inches, and the half-span was 22 inches giving an overall aspect ratio of approximately 2.6. Three chordwise rows of pressure taps were placed at three points along the span of the airfoil. The points were distributed chordwise as shown in Figure 9.

Figure 8. Half-span model shown mounted in wind tunnel (left) and with pressure side cover removed (right).

These experiments were conducted in the UTRC Pilot Wind Tunnel (PWT), a low-speed wind tunnel with a maximum speed of approximately 100 mph, and an octagonal 4 ft \( \times \) 6 ft test section. All experiments were conducted at approximately \( M_\infty = 0.12 \) and \( Re_c = 1.16 \times 10^6 \). Two sets of experiments were conducted: pressure profiles and loads balance measurements.

Figure 9. Chordwise locations of pressure taps at each spanwise station.

Figure 10 shows pressure profile results from the clean airfoil and \( h_f/c = -0.015 \). When the MiTE is applied on the upper surface, large changes in the pressure distribution occur in three areas: (1) pressure goes up on the upper surface just upstream of the MiTE, (2) pressure goes down on the upper surface just downstream of the MiTE, and (3) pressure goes down on the lower surface opposite to the MiTE. While (1) and (3) tend to cause a nose-up pitching moment, (2) counteracts that effect. This provides a very clear illustration of why MiTE effectiveness varies with \( x_f/c \). When the MiTE is at the trailing-edge, (2) does not exist, thus, the greatest authority occurs. As we move the MiTE away from the trailing-edge, (2) grows in size and influence causing a decline in effectiveness.

Several corrections were applied to the loads balance data in order to facilitate comparison to the two-dimensional (infinite aspect ratio) CFD results. Due to the low aspect ratio of the experimental model, lift coefficient values were corrected for three-dimensional effects using the Weissinger
method. Drag coefficients were corrected for induced drag. Finally, lift, drag, and moment coefficients were corrected to account for the fact that the MiTE does not span the entire blade. This correction simply involves scaling the increments in each coefficient with the fraction of blade spanned by the MiTE. The accuracy of this correction is confirmed in Ref. 7.

The most important result is shown in Figure 12. Here, we compare the moment increments between the experiments and the CFD. Values are taken at $\alpha = 0$ in order to minimize discrepancies due to three-dimensional effects. It is clear that the moment increments predicted by the CFD generally fall within the uncertainty of the experimental measurements. This confirms that the MiTE configurations examined in this work can provide the levels of aerodynamic authority found in the parametric CFD study.

One final issue was investigated in the wind tunnel experiments. As shown in Figure 13, long spanwise slots are present on the lower and upper surfaces of the blade which allow access for the MiTE to deploy. A set of data was collected to determine the potentially negative impact of

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**Figure 10.** Contours of pressure coefficient illustrating the effect of the MiTEs near the trailing-edge for one example case.

**Figure 11.** Comparison of lift and drag coefficients between experiments and 2D CFD for the clean airfoil and two cases with the MiTE deployed.
these slots upon the baseline airfoil performance. Figure 13 shows a lift-drag polar of the $h_f/c = 0$ configuration and the same configuration with the spanwise slots tightly sealed with thin Aluminum tape. Since no comparison is made here with 2D CFD, the results shown in Figure 13 are uncorrected for three-dimensional effects (and denoted with uppercase subscripts). Clearly, there is no appreciable degradation in performance due to the slots. Note that the slots used in this experimental model are approximately 0.17” in the chordwise direction which is substantially larger than the opening required to allow the MiTE to deploy.

3D unsteady Simulations

The overall results from the 2D steady simulations and wind tunnel experiments suggested that MiTEs have enough aerodynamic authority to be used for active rotor control. The goal of the next phase was to quantify the impact of MiTEs on a full rotor through a 3D unsteady simulation.

In order to simulate the motion of the MiTE, a new mesh was constructed for the VR-12 airfoil with a grid-block boundary at $x_f/c = 0.90$ to be used as a variable boundary condition to model an infinitesimally thin MiTE. Figure 14 shows a snapshot of the 2D grid highlighting the variable boundary condition area. The wall boundary condition at faces along this boundary were turned “on” and “off” at specific times to simulate a moving MiTE. The CFD simulations were performed using GENCAS, a generic multi-block unsteady Navier-Stokes solver developed at Georgia Tech. These simulations used Roe flux-differencing and the Spalart-Allamaras turbulence model. For the full rotor simulations, GENCAS is capable of applying elastic blade motions and performing hybrid Navier-Stokes/free-wake simulations. More details on GENCAS are available in Ref. 13.

Prior to the full rotor simulations, several 2D unsteady cases were run to demonstrate the variable boundary condition technique on the VR-12 geometry. A MiTE was simulated at $x_f/c = 0.90$, and oscillated sinusoidally between $h_f/c = \pm 0.01$ at several reduced frequencies with the airfoil $\alpha = 0$ and $M_\infty = 0.628$. The results for unsteady lift, drag and moment are shown in Figures 15 and 16. The horizontal lines in the plots show the values for steady-state simulations. As the frequency is increased, the amplitude of lift curves decreases and shows a reduction relative to the steady value. In contrast, the peak values in drag curves increase with frequency, as expected. As the frequency is reduced, the peak values approach the steady-state values. The moment coefficient peaks are unchanged with frequency and are very close to the steady-state values. This behavior of unsteady lift and moment with frequency is consistent with unsteady thin-airfoil aerodynamic theory (Refs. 18, 19, and 20).

Despite specifying a smooth sinusoidal MiTE motion, in Figure 15, where no sub-iterations between time-steps are used, small bumps appear in the lift time history, just after the peak values. These bumps were shown to be related to
Figure 15. Lift, drag, and moment coefficients as a function of time for several reduced frequencies of sinusoidal MiTE actuation $h_f/c = \pm 0.01$ and $\alpha = 0$ with no sub-iterations.

Figure 16. Lift, drag, and moment coefficients as a function of time for several reduced frequencies of sinusoidal MiTE actuation $h_f/c = \pm 0.01$ and $\alpha = 0$, with 5 sub-iterations per time-step.
Figure 17. Lift-drag polars for the same cases shown in Figures 15 and 16. Top plot used no-sub-iterations, bottom plot used 5 sub-iterations.

boundary condition technique were far out-weighed by the relative ease that this technique provided for simulating the MiTE motion. If necessary, the magnitude of these oscillations could likely be reduced through grid refinement near the MiTE or further modification to the algorithm, such as using an interpolation scheme to provide more continuous updating of the boundary condition.

Finally, several 3D unsteady hybrid CFD/free-wake rotor simulations were performed using GENCAS. Snapshots of the grid used for these simulations are shown in Figure 18. A MiTE was placed on each blade across 10% of the rotor radius (0.6R to 0.7R) and was deployed $h/c = \pm 0.01$ sinusoidally at 4 cycles per revolution. A UH-60A blade geometry was used with one small modification. The portion of the blade spanned by the MiTE was replaced with a VR-12 airfoil to be consistent with the previous simulations. A test case showed that this change in the baseline geometry had
very little impact on the aerodynamic characteristics of the blade for the conditions considered here. Figure 19 shows a comparison of the integrated aerodynamic loads in the z-direction from GENCAS compared to NASA/Army UH-60A Airloads Program flight counter 9017 data (high thrust, moderate speed, see Ref. 21). Blade motions were specified based on a converged GT-Hybrid/DYMORE simulation. The baseline and five cases with different phase shifts were run as shown in Table 1. The MiTE height motion is given by the equation 0.01sin(2πf₁t-ψ), where f₁ corresponded to a 4/rev (4P) actuation frequency. Note that case 4 is a special case where the MiTE was actuated only on the lower surface. The integrated aerodynamic loads in the z-direction were extracted from the simulation and compiled in Figure 20. Clearly, there are significant changes in the spectral content of the integrated aerodynamic loads. Most notably, case 5 shows an 80% decrease in 4P content compared to the baseline. Since the blade motions were specified in these simulations, it is not possible to deduce what the change in vibratory loads is, however, this result shows that there is promise that MiTEs could be used to reduce 4P rotor vibrations. Full aeroelastic simulations are planned for the next phase of this work which will provide better indications.

Table 1. Phase shifts of MiTE deployment used in the 3D simulations presented. Case 4 was a special case with MiTE deployment on only the lower surface.

| Case  | 24.5° | 14° | 0° | 0 (LS) | 7.5° |
|-------|-------|-----|----|--------|------|

Figure 20. Spectral amplitudes of integrated aerodynamic loads for the baseline and five phase shifts in $h_f/c = \pm 0.01$ MiTE deployment.

CONCLUDING REMARKS

The work presented here strongly indicates that Miniature Trailing-Edge Effectors (MiTEs) have adequate aerodynamic authority for active rotor control. The results of a 2D CFD analysis which was validated through wind tunnel experiments indicated that a moment increment of ±0.03 was achievable with a MiTE conveniently located 0.10 chords upstream of the trailing-edge and actuated to heights of ±0.01 chords. This configuration was applied to 3D unsteady CFD analysis of a rotor with specified blade motions which showed that a 4/rev deployment of a MiTE with a spanwise length of 0.10 rotor radii can achieve an 80% reduction in 4P integrated aerodynamic loads in the vertical direction. In the next phases of this work, a fully coupled CSD/CFD simulation is planned in order to properly account for the aeroelastic response of the blades.

In addition to aerodynamics, several other factors will ultimately affect the overall benefits which can be achieved with MiTEs. As with other active rotor technologies, an appropriate actuator must be designed, suitable feedback and control strategies must be devised, and the overall size and weight of the final design must be minimized. These and other risks must be addressed in future work.

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