DRAG REDUCTION OF BLUNT TRAILING-EDGE AIRFOILS

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Abstract: Wind tunnel experimentation and Reynolds-averaged Navier-Stokes simulations were used to analyze simple, static trailing-edge devices applied to an FB-3500-1750 airfoil, a 35% thick airfoil with a 17.5% chord blunt trailing edge, in order to mitigate base drag. The drag reduction devices investigated include splitter plates, base cavities, and offset cavities. Splitter plate lengths between 50% and 150% of the trailing-edge thickness and plate angles (±10°) were investigated and shown to influence the lift and drag characteristics of the baseline airfoil. Drag reductions on the order of up to 50% were achieved with the addition of a splitter plate. The base cavity demonstrated possible drag reductions of 25%, but caused drastic changes to lift, primarily due to the method of device implementation. The offset cavity was shown to improve on the drag reductions of the splitter plate, while also eliminating unsteady vortex shedding prior to airfoil stall.
1 INTRODUCTION

Blunt trailing-edge airfoils have been proposed to address the need for thick airfoil sections necessary to meet the structural and volume requirements of various aerodynamic systems, including blended wing-body aircraft, unmanned aerial vehicles, and wind turbine blades, while reducing the well-documented separation sensitivity of airfoils with maximum thickness-to-chord ratios greater than 25% [1,2]. Without some sort of separation control technique, such as vortex generators, boundary-layer suction, or a blunt trailing edge, thick airfoils generate steep adverse pressure gradients, which lead to premature flow separation from the upper surface with even small perturbations [3]. Several studies have investigated these so-called “thick” airfoils and show that blunt trailing-edge airfoils have significantly improved lift performance compared to similar sharp trailing-edge airfoils [2-8]. The use of a blunt trailing-edge, however, introduces base drag and possible vortex shedding, which in most cases is undesirable.

In order to improve the performance characteristics of blunt trailing-edge airfoils, some form of drag mitigation is necessary. Past studies have investigated several options for bluff body drag reduction [9-13], but most of this research is directed toward two-dimensional axisymmetric bodies aligned with the flowfield [14]. Limited research has been conducted for bodies at incidence to the flow and even less study has been conducted for asymmetric lifting bodies, such as blunt trailing-edge airfoils. In the present study, the results of a coupled computational fluid dynamics (CFD) and wind tunnel experimentation study are presented for simple, static, trailing-edge attachments applied to a blunt trailing-edge airfoil in two-dimensional flow.

2 METHODS

In the following section, the airfoil and the basic devices selected for the present study are presented. Next the experimental and computational methodologies are introduced. The configurations described below were analyzed using wind tunnel experiment and computational fluid dynamics for two-dimensional flow. This approach was taken to help speed up analysis time and determine the feasibility of using CFD as a design tool for drag reduction of blunt airfoils.

2.1 Geometry

The baseline airfoil used in the present study was an FB-3500-1750 airfoil, a 35% thick variant of the FB airfoil series [15] with a 17.5% chord trailing-edge thickness, shown in Fig. 1. For the present study, simple and effective drag reduction techniques were desired. For these reasons, the drag reduction devices applied to the FB-3500-1750 in this study were limited to fixed geometric modifications to the trailing-edge, namely splitter plates, base cavities, and offset cavities, as illustrated in Fig. 2.

The drag of the FB-3500-1750 can be reduced using simple trailing edge devices, like those shown in Fig. 2. Splitter plates have been shown to reduce the base drag of axisymmetric bluff bodies [9, 16, 17] by acting to separate the shear layers developed by the upper and lower surfaces, thereby reducing the vortex structure on the trailing edge. The application to lifting bodies, however, is largely unknown. The work of Tanner [11, 14] indicates that a splitter plate length equal to the trailing-edge thickness is sufficient for drag reduction. In the present study, several splitter plate parameters were investigated, including length, angle, and edge shape.

Base cavities have also been investigated as drag reduction treatments to bluff bodies [12]...
Figure 2: Trailing edge devices investigated include (a) simple splitter, (b) base cavity, and (c) offset cavity.

Molezzi and Dutton [12] show that the primary drag reduction mechanism is caused by a displacement of the vortical wake structure away from the base. They show that the base cavity does not significantly alter the structure of the vortex street, apart from the displacement downstream from the base. Again, the cavity work presented in the literature is largely concerned with nonlifting bodies and needs to be investigated to determine viability under lifting conditions. In the present study, a cavity was added to the baseline airfoil by attaching two plates perpendicular to the trailing edge, see Fig. 2(b).

The offset cavity is a concept that combines the base cavity and splitter plate. Since the splitter plate acts to break up the vortical structure, and the base cavity acts to displace the structure away from the base, these drag reduction mechanisms may be combined in some useful way if two splitter plates are offset from the upper and lower surfaces, creating a base cavity of width less than the trailing-edge thickness, as shown in Fig. 2(c).

2.2 Experimental Methods

The Aeronautical Wind Tunnel (AWT) at the University of California, Davis is an open circuit, low-turbulence wind tunnel [18]. The wind tunnel has test section area dimensions of 0.86 m × 1.22 m (2.8 ft × 4 ft) and length of 3.66 m (12 ft). The test section is constructed with parallel sides, utilizing four tapered fillets to compensate for boundary-layer growth and to preserve constant pressure throughout the section. For a two-dimensional airfoil experiment, the airfoil model is mounted to a six-component pyramidal balance to measure lift. The precision of the balance is insufficient for airfoil drag measurement, however, prompting the use of a wake integral method [19–21].

The FB-3500-1750 airfoil model was constructed with a chord length of 0.203 m (8 in.), span of 0.838 m (33 in.), and maximum thickness of 0.071 m (35% chord). The model was tested at a chord Reynolds number of 666,000, selected to limit solid blockage, and to avoid exceeding load limitations of the pyramidal balance. Boundary-layer transition was fixed for all configurations using 0.25 mm zigzag trip-tape placed at 2% and 5% chord on the suction and pressure surfaces, respectively.

The trailing edge devices used in the experiment consist of metal plates attached perpendicular to the trailing edge of the FB-3500-1750 airfoil model, each with lengths equal to the model trailing edge thickness (17.5% chord). The device configurations investigated include the simple splitter and base cavity, shown in Fig. 2(a) and 2(b), respectively. To determine if plate edge-shape can affect device performance, three edge treatments were investigated including a non-serrated edge, and 90° and 60° serrated edges, as...

Figure 3: Edge treatments for the splitter and cavity used in experiment.
depicted in Fig. 3.

An uncertainty analysis for the present study has been conducted using methods described by Coleman and Steele [22]. Further information regarding statistical analysis for similar studies at the AWT may be found in Refs. [2, 20]. All error estimates are presented for a 95% confidence level. The lift values were determined to have error less than 1.5% up to maximum lift. The maximum uncertainty in drag was determined to be 3.35%, but in general was on the order of 1–2%.

The wind tunnel results presented in this paper have been corrected for wind tunnel wall effects using two-dimensional flow corrections, described in Barlow et al. [23]. The two-dimensional, potential flow-based corrections account for solid and wake blockage, and streamline curvature. A detailed discussion comparing wind tunnel wall corrections using potential flow and RANS methods for blunt trailing-edge airfoils is presented by Baker et al. [2], which indicates that the corrections in both cases are small and, for the most part, in agreement. The corrections of Barlow et al. were chosen because of the ease of implementation.

2.3 Computational Methods

The Reynolds-Averaged Navier–Stokes (RANS) code used in this project is OVERFLOW, a three-dimensional, compressible flow solver [24]. In this study, all computations are conducted with a central-difference, three-factor diagonal scheme. Artificial dissipation is added to the scheme for numerical stability using matrix dissipation [25]. Unsteady simulations were conducted for each case investigated, utilizing dual time-stepping to obtain second-order accuracy in time, with 10–15 subiterations per physical timestep such that the residual was reduced by approximately two orders of magnitude during each subiteration cycle.

Turbulent closure of the RANS equations is provided by the two-equation $k-\omega$ shear-stress transport (SST) model developed by Menter [26, 27]. This model is known for improved prediction of flows with strong adverse pressure gradients and separation [28], which is of particular importance in a blunt trailing-edge airfoil wake. Due to a lack of transition prediction capability in OVERFLOW, the laminar-turbulent transition location must be specified manually. This is accomplished by defining a laminar region over the airfoil leading edge in which the turbulence model production terms are disabled. In order to match experiment, the computational results presented in this paper were conducted with a laminar region specified between 2% and 5% chord on the suction and pressure surfaces, respectively.

All meshes used in this study were generated with the Chimera Grid Tools and OVERGRID codes [29]. The baseline airfoil and simple splitter plate configurations allowed for the use of O-grids, an example of which is shown in Fig. 4. For more complex topologies, e.g. offset cavity, a near-body airfoil O-grid was generated, which was overset with automatically generated offbody cartesian grids extending to the farfield, see Fig. 5. In each case, the grid domain extends approximately 50 chord lengths from the airfoil surface to ensure a return to free stream conditions in the farfield. The initial normal grid spacing at the airfoil surface corresponds to $y^+ \leq 1.0$. The airfoil surface grids have been generated using (on average) 450 surface points. In the surface normal direction at least 65 points were located within 1% chord of the surface to adequately resolve viscous effects in the boundary-layer. A freestream/characteristic boundary condition is imposed at the outer edge of the grid domain, and a no-slip condition is specified at the airfoil surface.

Most of the computational study was conducted at $Ma = 0.2$ and $Re = 666,000$ to closely match the reference conditions of the wind tunnel experimentation. The baseline airfoil and splitter plate (length = 100% $t_{TE}$) cases were also investigated at $Re = 5 \times 10^6$ in order
Figure 4: Example of an O-grid in the (a) farfield and (b) detail views for the FB-3500-1750 airfoil with simple splitter. Some axial and radial gridlines omitted for clarity.

Figure 5: Overset grid approach for the FB-3500-1750 airfoil with offset cavity in the (a) farfield and (b) detail view near the airfoil surface. Some axial and radial gridlines omitted for clarity.

to more closely resemble conditions faced by full-scale wind turbines and to help determine Reynolds number dependence.

The trailing edge devices investigated computationally include splitter plate lengths of 50%, 75%, 100%, and 150% $t_{TE}$. The 100% $t_{TE}$ splitter plate was also investigated at two angles ($\pm 10^\circ$) from centerline to determine the performance effects. The offset cavity concept was also studied for plate lengths equal to 100% $t_{TE}$ with each plate offset from the upper and lower surface by a distance of 25% $t_{TE}$.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The measured lift and drag characteristics for the single splitter plate configuration are presented in Fig. 6. The application of splitter plates to the FB-3500-1750 resulted in a moderate loss in maximum lift due to an earlier onset of stall compared to baseline, as shown in Fig. 6(a). The stall angle was increased by one degree for both serrated edge cases, compared to the untreated splitter plate edge. The drag of the baseline airfoil was reduced from approximately 0.1 to 0.05 in the linear lift regime, which is a reduction of 50% with the application of the splitter
Figure 6: Measured (a) lift curves and (b) drag polars for the FB-3500-1750 airfoil with a single splitter plate at \( Re = 666,000 \), transition fixed. Corrected for wind tunnel wall effects.

Figure 7: Measured (a) lift curves and (b) drag polars for the FB-3500-1750 airfoil with a base cavity at \( Re = 666,000 \), transition fixed. Corrected for wind tunnel wall effects.

plate. A comparison of the effects of plate edge treatment on drag reduction indicates that edge serrations slightly diminish the effectiveness of the device. The angle of the edge treatment, 90° or 60°, did not have an appreciable effect.

The base cavity also affected the lift and drag of the FB-3500-1750 airfoil, as shown in Fig. 7. In this case, the lift slope and the zero-lift angle of attack were increased compared to baseline, with only slight variations based on plate edge treatment (Fig. 7(a)). The change in zero-lift angle of attack is likely due to an effective reduction of airfoil camber, caused by the manner in which the cavity was applied to the airfoil, while the change in lift curve slope may be caused by an effective increase in airfoil chord. These effects were not present in the single splitter configuration due to the massive flow separation over the surface of the plate. The airfoil with base cavity experienced up to 25% less drag than the baseline airfoil, as shown in Fig. 7(b), however, this drag reduction was dependent on both angle of attack and edge treatment. As the angle of attack increased, the drag mitigation effect improved. Plate edge serrations tended to improve drag reduction, with a slight advantage to the 60° edge serrations.

The measured performance of FB-3500-1750 airfoil, with and without trailing edge devices, is presented in Fig. 8. The addition of the simple splitter plate increased the lift-to-drag ratio.
of the baseline airfoil from a maximum of approximately 16.3 to 22.0, representing a 35% improvement. The subtle decrease in drag mitigation with the application of plate edge serrations, described above and shown in Fig. 6(b), resulted in a 12% loss in performance compared to the untreated splitter plate configuration. The base cavity also improved the performance of the airfoil, as presented in Fig. 8(b) but only at moderate angles of attack. At 0° and 4°, the application of the base cavity hurt performance. The mixed performance of the cavity configurations is likely caused by the chosen implementation of the cavity. The plates were added to the airfoil post-construction to eliminate the need for multiple models. Future investigations should seek to apply the cavity by removing material from the trailing-edge, while leaving the surface definition of the baseline airfoil intact.

**Figure 8**: Measured $L/D$ performance for the (a) simple splitter and (b) cavity applied to the FB-3500-1750 airfoil at $Re = 666,000$, transition fixed. Corrected for wind tunnel wall effects.

### 4 COMPUTATIONAL VALIDATION AND REYNOLDS NUMBER DEPENDENCE

A comparison of the computational and experimental results for the baseline airfoil and airfoil with 100% $t_{TE}$ splitter is presented in Fig. 9. The calculated lift matches very well with experiment, except the stall angle of attack is overpredicted compared to experiment. This problem is more acute for the baseline airfoil. Fig. 9(b) shows that the drag calculations are in excellent agreement with experiment for the splitter plate configuration, but agree poorly for the baseline airfoil. This trend may best be explained by the vortical wake structure for the baseline airfoil, and the lack thereof for the splitter plate configuration shown in Fig. 10. The Kármán vortex street is clearly evident for the baseline case, but is absent for the airfoil with a splitter plate. The unsteady vortical wake present in the baseline airfoil computations is probably qualitatively correct, but it is likely that the vortices’ strengths were over-predicted due to the artificial restriction of the flow to two-dimensions.

In the present study, the majority of cases were examined at Reynolds numbers equal to 666,000 in order to match experiment. In most full-scale applications, however, the Reynolds number is typically much larger. Blunt trailing-edges applied to the inboard section of modern utility-scale wind turbines, for example, encounter Reynolds numbers on the order of $5 \times 10^6$. To determine the effect of Reynolds number, the baseline airfoil and airfoil with splitter plate were examined at $Re = 666,000$ and $Re = 5 \times 10^6$. The results of this analysis, presented in Fig. 11, indicate that the lift curve slope is virtually independent of Reynolds number, but the maximum lift is predicted to increase for increased Reynolds numbers. The drag prediction was
unchanged for the splitter plate case in the linear lift regime, as shown in Fig. 11(b). There was
a slight Reynolds number effect for the baseline airfoil, with a moderate increase in drag for the
higher Reynolds number case. These results indicate that the computational methods presented
in this paper are applicable to a broad range of Reynolds numbers and that the drag reduction
techniques work at full-scale conditions.

5 COMPUTATIONAL RESULTS AND DISCUSSION

The experimental results have shown the simple splitter to be a good drag reduction device
for the FB-3500-1750 airfoil. Determining the effect of splitter plate length is necessary and is
a candidate for computational study due to the relative ease of generating several computational
grids versus manufacturing multiple splitter plates for experiment. Splitter plate lengths varying
from 50% $t_{TE}$ to 150% $t_{TE}$ were investigated computationally. The results of this investigation
are shown in Fig. 12. Splitter length had a dramatic affect on $C_{l_{max}}$ and, to a lesser extent, on
lift curve slope. As the plate length increased, $C_{l_{max}}$ tended to drop precipitously. The length of
the splitter plate had little to no effect on drag in the attached flow regime for all cases except
the 50% $t_{TE}$ plate length, as shown in Fig. 12(b). In this case, for instance, the drag coefficient
at 0° incidence was 0.0738, compared to 0.0495 for the 100% $t_{TE}$ splitter plate.
Figure 11: Computational (a) lift curves and (b) drag polars for the FB-3500-1750 airfoil, with and without splitter plate ($L = 100\% t_{TE}$), at Reynolds numbers of $666 \times 10^6$ and $5 \times 10^6$, transition fixed.

The surface pressure data for the splitter plate length study, shown in Fig. 13, can be used to explain the lift and drag trends described above. The application of the simple splitter reduces the amount of pressure recovery that occurs in the wake by increasing the base pressure at the trailing edge, hence reducing the pressure drag. The amount of base pressure increase is dependent on splitter plate length, with greater increases for larger plate lengths. The base pressure increase forces a steeper pressure recovery on the upper surface of the airfoil, which results in increased likelihood of flow separation and earlier onset of stall. The splitter plates also change the suction peak on the upper surface. For each case, the suction peak diminishes with increasing plate length. For the 50\% $t_{TE}$ length, the suction peak was actually greater than baseline.

The computational results presented in Fig. 14 show the effects of splitter plate angle on lift and drag performance of the FB-3500-1750 airfoil. These results indicate splitter plate angle does not influence drag reduction, but can impact the lift curve slope and maximum lift. Interestingly, the upward deflected plate ($+10^\circ$) incremented the lift while the downward

Figure 12: The effect of splitter plate length on computational (a) lift and (b) drag polars for the FB-3500-1750 airfoil, with and without splitter plate ($L = 100\% t_{TE}$), at $Re = 666,000$, transition fixed.
deflected plate (−10°) caused lift decrement, which is the opposite effect of a flap. This behavior can be explained in part by the surface pressure plots presented in Fig. [15]. The base pressure for all plate angles are similar, with a slight drop in base pressure for the upward deflected plate. There is more pressure loading on the downward deflected plate than for either of the other angles, which caused a drop in the suction peak for the downward deflected plate. The upward deflected plate has a pressure peak nearly the same as the baseline airfoil, which is greater than the 0° and −10° plates.

The offset cavity concept, using two plates of length 100% $t_{TE}$, each offset by 25% $t_{TE}$ from the corners of the trailing-edge (see Fig. 2(c)), was investigated computationally. Figure [16] shows the effect of this concept on lift and drag. The base cavity caused a slight reduction of $C_l$ in the linear lift regime, compared to the simple splitter case, but did not result in a loss in $C_{l_{max}}$. The base cavity did cause improved drag reduction compared to the splitter plate configuration. The loss in lift is primarily the result of a decreased suction peak on the upper surface. Applying the offset cavity to the FB-3500-1750 airfoil caused the unsteady wake structure present for the baseline airfoil (Fig. 10(a)), to become steady with several standing vortices surrounding the plates as shown in Fig. 17. In fact, while in each case investigated the devices mitigated vortex shedding considerably and, in some cases, resulted in steady flow, the offset cavity configuration

![Figure 13: Surface pressure data for the splitter plate length study at $\alpha = 8^\circ$ and $Re = 666,000$, transition fixed.](image)

![Figure 14: The effect of splitter plate angle ($L = 100\% \ t_{TE}$) on computational (a) lift and (b) drag polars for the FB-3500-1750 airfoil at $Re = 666,000$, transition fixed. Angle defined + for upward deflection.](image)
was the only case for which steady flow existed for all angles of attack prior to stall.

From the above computational analysis, both plate length and angle were determined to influence the performance of the splitter plate concept. The offset cavity also proved to be an interesting case, especially considering the improved drag reduction compared to splitter plates. The $L/D$ performance of the three most promising configurations, namely the 75\% $t_{TE}$ splitter, the $+10^\circ$ plate angle with length 100\% $t_{TE}$, and the offset cavity, are shown in Fig. 18. All three of these devices improve the performance of the baseline airfoil considerably. The question of “which device is best?” is a complicated one, and is dependent on the desired application, due to the influence of the devices on lift. The simple splitter plate caused the least changes to the lift characteristics compared to the baseline airfoil, but had a lower $(L/D)_{\text{max}}$ compared to the angled splitter and offset cavity devices. The offset cavity case resulted in steady flow for all angles of attack prior to stall, which may reduce fatigue loading and noise.

6 CONCLUSIONS

The results from the experimental and computational analysis presented above show that simple, static devices can be added to a blunt trailing-edge airfoil to mitigate drag. Wind tunnel experimentation agrees well with simulated results for cases with limited vortex shedding.

Figure 15: Surface pressure data for the airfoil with splitter plates at various plate angles at $\alpha = 8^\circ$ and $Re = 666,000$, transition fixed.

Figure 16: Comparison of the baseline with splitter plate and offset cavity on (a) lift and (b) drag polars for the FB-3500-1750 airfoil at $Re = 666,000$, transition fixed.
Figure 17: Calculated pressure contours with instantaneous streamlines for the FB-3500-1750 airfoil at $Re = 666,000$ and $8^\circ$ incidence with offset cavity, transition fixed. Trailing-edge flow detail shown at right.

Figure 18: Promising calculated device performance compared to the baseline FB-3500-1750 airfoil at $Re = 666,000$, transition fixed.

The baseline FB-3500-1750 computations predict higher $C_{l_{max}}$ and drag values than measured. Several contributing factors lead to these discrepancies, including turbulence modeling, limiting the flow structure to two-dimensions in simulation, and the use of over-sized trip tape in experiment. Flow in the wind tunnel, even though designed to be two-dimensional, has inherent three-dimensional flow structures in the vortical wake of a blunt trailing-edge airfoil. The trip height may be excessive for the test conditions presented, with the corresponding trip-related momentum loss possibly triggering premature flow separation. These structures act to diminish the strength of the vortices, which is not captured in two-dimensional simulations. The results do indicate, however, that the computational methods employed in this study can be used as a design tool to investigate drag reduction devices, since overall the splitter plate simulations agree well with wind tunnel experiment for both lift and drag.

The wind tunnel experimentation investigated splitter plates and cavities applied to the baseline airfoil. Plate edge treatments of $60^\circ$ and $90^\circ$ serrations were also investigated to see if any change in performance resulted. The results of this analysis show that a single splitter plate applied to the FB-3500-1750 airfoil caused a 50% drag reduction in the linear lift regime, with only minor losses to lift performance. Plate edge treatments tended to mitigate the loss in lift, while also slightly reducing the drag benefits.

The results of the experimental base cavity study are less conclusive. Some drag reduction occurred, on the order of 25% compared to baseline, with the application of the cavity. These results, however, were accompanied by a decrease in lift performance in the linear lift regime.
The primary cause of the changes in lift are a result of the method of device attachment. In this study, the cavity was applied using two plates mounted perpendicular to the airfoil trailing edge. This caused an effective reduction in camber and an increase in chord length compared to the baseline airfoil. This was not encountered for the splitter plate case, because of the massive flow separation engulfing the single plate. Future studies should apply the cavity by excavating into the trailing-edge, not adding to it.

The computational study was used to investigate parametric studies of length and angle for the splitter plate. The results of this study indicate splitter length does not impact drag reduction capabilities of the device, unless the device becomes too short. In this case, the drag reduction was the same for lengths of 150% $t_{TE}$, 100% $t_{TE}$, and 75% $t_{TE}$, but diminished significantly for the 50% $t_{TE}$ case. The primary reason to determine the proper length plate applied to a lifting body is for the lift effect. As plate length increased, the maximum lift and lift curve slope decreased. The computations showed plate angle did not have an effect on drag, but did change the lift. An upward plate deflections caused an increase in lift, while a downward deflection decreased lift, which is opposite of the flap effect.

The offset cavity can be considered to be two splitter plates attached to the trailing edge. In the present study, the plates were offset from the upper and lower surface of the airfoil by 25% $t_{TE}$. The results of this study show that the offset cavity is a viable drag reduction technique for blunt trailing edge airfoils, resulting in greater drag reductions than the simple splitter plate. The offset cavity did cause a slight reduction in lift at lower angles of attack, but did not affect $C_{l_{max}}$. The offset cavity also resulted in steady flow for all angles of attack investigated, which could reduce fatigue loads and noise.

Future studies will continue the work presented in this article. Namely, more wind tunnel investigations will be performed to further validate the computational method. Once this validation is complete, a thorough numerical optimization study should be conducted to determine the proper design of a blunt trailing-edge airfoil integrated with a trailing-edge device similar to those presented in this study.
REFERENCES


