

Fluidic Fence Flow Control on a 30° Swept Wing in Compressible Freestreams

Evan J. McFadden¹ and Jeffrey P. Bons²
The Ohio State University, Columbus, OH 43235, USA

A 30° swept wing with a NACA 643-618 airfoil cross-section was evaluated in four different freestream conditions with Mach numbers increasing from 0.05 to 0.7 using computational fluid dynamics simulations. Active flow control (AFC) through a streamwise row of vortex generating jets was applied at 70% span, blowing inboard to obstruct the development of spanwise flow and increase lift outboard of the control location. The effectiveness of the AFC was evaluated at $\alpha = 5^\circ$ and 10° as freestream Mach number increased and the AFC mass flow coefficient was held constant. Increases to lift coefficient were reduced at higher Mach numbers, but the ratio of change in lift coefficient and the AFC momentum coefficient remained roughly constant. The fluidic fence caused decreased pressure coefficients on the outboard wing sections, but this region of decreased pressure coefficient moved aft on the chord with increasing Mach number. Mach 0.7 is higher than the critical Mach number of the wing and produced interesting interplay with the AFC, as the suction surface shock moved forward on the inboard wing section but moved aft on the outboard wing section.

I. Nomenclature

a	= speed of sound, $(\gamma RT)^{0.5}$
A_{AFC}	= total exit area of actuators
A_{ref}	= wing planform area, bc_{eff}
b	= wing semispan
BR	= jet blowing ratio, $(\rho_{AFC} V_{jet})/(\rho_\infty V_\infty)$
c	= true chord, normal distance from leading to trailing edge
C_D	= drag coefficient, $D / (\frac{1}{2} \rho_\infty V_\infty^2 A_{ref} \cos^2 \Lambda)$
c_{eff}	= effective chord, streamwise distance from leading to trailing edge, $c/\cos(\Lambda)$
C_f	= skin friction coefficient, $\tau_w / (\frac{1}{2} \rho_\infty V_\infty^2)$
C_l	= pressure-integrated section lift coefficient, Eq. 5
C_L	= lift coefficient, $L / (\frac{1}{2} \rho_\infty V_\infty^2 A_{ref} \cos^2 \Lambda)$
C_M	= pitching moment coefficient, $M / (\frac{1}{2} \rho_\infty V_\infty^2 A_{ref} c_{eff} \cos^2 \Lambda)$
C_p	= pressure coefficient, $(P - P_\infty) / (\frac{1}{2} \rho_\infty V_\infty^2)$
C_Q	= mass flow coefficient, Eq. 2
C_μ	= momentum coefficient, Eq. 3
C_π	= power coefficient, Eq. 4
M	= Mach number, V/a
$\dot{m}_{AFC}$	= total mass flow supplied to the wing for AFC
N	= mesh cell count
n_{jets}	= number of actuators used for AFC
P	= static pressure
P_0	= total pressure
PR_{AFC}	= total pressure ratio applied to active flow control, $P_{0AFC}/P_{0\infty}$
R	= ideal gas constant for air
r_{jet}	= radius of actuator

¹ Graduate Research Assistant, Department of Mechanical and Aerospace Engineering, AIAA Student Member

² Professor, Department of Mechanical and Aerospace Engineering, AIAA Associate Fellow

Re	= chordwise Reynolds number, $\rho_\infty c V_\infty \cos(\Lambda)/\mu$
V_{jet}	= actuator exit velocity from continuity, $\dot{m}_{AFC}/(\rho_{AFC} A_{AFC})$
VR	= jet velocity ratio, V_{jet}/V_∞
V_∞	= freestream velocity
α	= wing angle of attack
γ	= heat capacity ratio for air
Λ	= leading-edge sweep
μ	= air dynamic viscosity
ρ	= air density
τ_w	= wall shear stress

II. Introduction

The use of swept wings has become nearly universal, as swept designs for wings, strakes, tails, and more are applied on commercial, defense, and general aviation aircraft. This is because swept wings experience lower drag forces by effectively reducing the thickness of the wing [1]. They are also capable of providing higher levels of control to the aircraft with further aft placed control surfaces [2]. Sweeping a wing changes the suction surface flow field significantly by introducing spanwise-oriented flow and vortex structures that can be critical to the lift production of the wing. The separation pattern on the wing is also different from rectangular wings, in that stall is typically initiated at the wing tip and propagates inboard with increased angle of attack. This could render control surfaces ineffective for the aircraft, as they are typically located in the region where stall begins. Therefore, these swept wing flow features must be understood and controlled throughout the entire mission profile of the aircraft.

During any given flight of an aircraft, it may experience a wide range of freestream conditions, including (but not limited to) takeoff speed, cruise speed, high-speed maneuvers, and low-speed approaches. These changing freestream conditions can be characterized by a range of Reynolds numbers and Mach numbers. It has been documented that these different conditions can change the strength, trajectory, and role of the suction surface flow features in producing lift. In 1964, Harper and Maki theorized that swept wings would be much more sensitive to changes in Reynolds number, as the wing's performance can be characterized by the flow components normal to the leading edge, and low Reynolds number effects quickly arise [3]. Also, the Reynolds number can significantly alter the trajectory and size of leading-edge vortices (LEV) on wings with large leading-edge radii [4]. The foundational concept of swept wings was to increase the wing's critical Mach number to expand the operating envelope of an aircraft. On two-dimensional airfoils, the lift coefficient at higher subsonic Mach numbers can be predicted with the Prandtl-Glauert correction as described in Eq. 1:

$$C_{L_{M>0}} = \frac{C_{L_{M=0}}}{\sqrt{1-M_\infty^2}} \quad (1)$$

When applied to three-dimensional, unswept wings, the change of these performance coefficients with Mach number is not as severe, but they still increase. For low aspect ratio swept wings, the relation with Mach number is weaker due to the flow being characterized by the components normal to the leading edge [5, 6]. In the flow over a 30° swept Glauert-Goldschmied hump, Seifert and Pack found that the suction peak increased significantly with Mach number, and separation bubbles were seen to elongate with compressibility effects [7]. Jones and Cohen similarly report stretching of the swept wing flow field in the chordwise direction, which makes a wing in compressible flow resemble a wing of lower aspect ratio and higher sweep in incompressible flow [8]. However, the work of Kirkman suggests that the compressible swept wing flow can be captured as a velocity scaling of the incompressible solution rather than a geometric scaling of the wing [9]. Some questions remain, however, about how the character and role of leading-edge vortices change on moderately swept wings with increasing Mach number.

As technology around active flow control (AFC) continues to be refined, it remains important to make these techniques as robust and “marketable” as possible to aircraft designers. This can be done by reporting their sensitivities, strengths, and costs over a wide range of flight conditions or scenarios. Separation control on a 30° swept wing with a streamwise row of vortex generating jets (“fluidic fence”) has been studied in several publications [10, 11, 12, 13]. These studies reported on the sensitivities to spanwise location (60% to 80%), number of jets (5 to 20 jets), unsteady actuation (up to 150 Hz), freestream Reynolds number (10^5 to 10^6), and (de)activation of the AFC. The fluidic fence is effective in increasing lift production by up to 15% and delaying the stall angle by up to 12°. These enhancements are due to obstruction of spanwise flow and the straightening of suction surface streamlines immediately outboard of the control location. Placing the fence further inboard leads to higher magnitudes of lift enhancements, but outboard placement maintains control of the tip flow, delaying stall to higher α . This control technique is most effective when the baseline wing is experiencing significant trailing-edge separation ($\alpha > 12^\circ$) and eventually full

leading-edge separation ($\alpha > 18^\circ$). As Reynolds number is increased, the laminar separation features are attenuated, and baseline performance improves. This results in less spanwise flow development, and the application of the fence has a smaller benefit.

Though these studies evaluated many parameters of the flow control technique, they were all performed in incompressible freestreams. These parameters were investigated with low-speed wind tunnel experiments as well as computational fluid dynamics simulations. Since swept wings were designed for higher subsonic Mach numbers, it follows that this swept wing AFC technique should also be evaluated in these conditions. Thus, this study looks to characterize the performance of the fluidic fence on the 30° swept wing in compressible freestreams. The fluidic fence is tested at freestream Mach numbers of 0.051, 0.30, 0.50, and 0.70. The lowest Mach number listed here reproduces results of previous work by McFadden et al. [10]. The wing is set at $\alpha = 5^\circ$ and 10° for each freestream Mach number at which both the baseline and controlled wings are simulated. Compared to the other studies which focused on high angles of attack, these lower angles of attack are more reasonable flight conditions for a vehicle flying at higher subsonic Mach numbers. As reported by experiments of McFadden et al. at $M = 0.051$, the baseline wing produced lift coefficients of 0.619 and 1.041 at $\alpha = 5^\circ$ and 10° , respectively [10]. With 2% momentum coefficient (C_μ), AFC increases lift performance by 6.9% and 4.0% at these angles of attack. The boundary layer was not tripped at the wing leading edge in experiments, which produces laminar separation bubbles at these low angles of attack. The simulations of this study assumed fully turbulent boundary layer flow and did not model the laminar to turbulent transition. Therefore, lift and drag coefficients as reported from simulations are higher than the experimentally observed values.

III. Methodology

A. Test Article

The geometry used for this study is a 30° swept wing with the cross-section defined along the true chord (c) as a NACA 64₃-618 airfoil. As depicted in Fig. 1, the wing has a semispan of 0.254 m, and a true chord length of 0.1016 m. With no taper, the wing planform area is 0.0298 m² and has a full-wing aspect ratio of 4.33. This geometry has been the test bed for several iterations of fluidic fence flow control studies in the 15"x15" low-speed wind tunnel at Ohio State University [14, 10, 15, 11]. In this study, the 30° swept wing is equipped with a streamwise row of 20 vortex generating jets (VGJs), as published by McFadden et al. for control of the separated flow near the wingtip at moderate to high angles of attack [10]. The 20 VGJs have diameters of 1 mm and are spaced by 5 diameters along the effective chord (c_{eff}) at 70% semispan. The jets are pitched 30° off the local wing surface curvature, and they are skewed 60° from the freestream direction toward the wing root (as indicated with thin red arrows in Fig. 1). The leading-edge jet is pitched 30° off the leading-edge surface but is skewed 90° from the freestream due to geometric constraints.

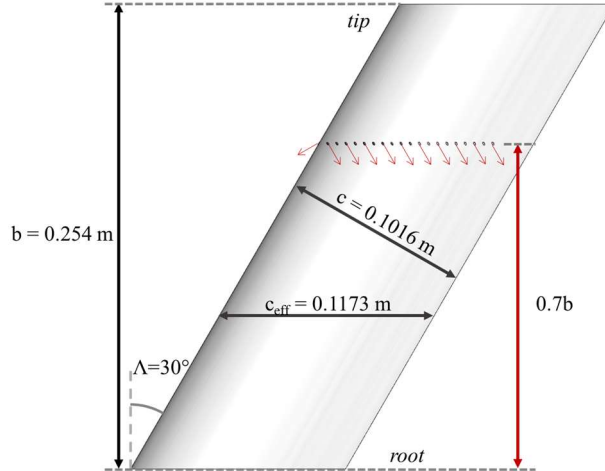


Fig. 1 Diagram of 30° swept wing geometry with AFC applied at 70% semispan.

B. Computational Methodology

Computational fluid dynamics (CFD) simulations informed the effect of a compressible freestream on fluidic fence flow control on the 30° swept wing. These Reynolds-Averaged Navier Stokes (RANS) simulations were performed

with NASA's Fully Unstructured Navier Stokes 3D (FUN3D) finite-volume solver. Computations were performed on NASA's Advanced Supercomputing Division Pleiades Supercomputer. The negative Spalart-Allmaras one equation turbulence model was employed with corrections for rotation and curvature (SA-neg-RC) [16, 17]. Riemann-invariant farfield boundary conditions were applied 100 chord lengths away from the wing in a rectangular domain to model the wing in free flight, and a symmetry boundary condition was applied on the face at the wing root. Total pressure boundary conditions set 4 VGJ diameters beneath the wing surface were applied for control of flow through the VGJs. All other walls in the domain were treated as viscous, no-slip walls with the first cell off the wall characterized by a y^+ value less than 5. A Hierarchical Adaptive Nonlinear Iteration Method (HANIM) adaptively controlled the Courant-Friedrichs-Lewy (CFL) number to accelerate iterative convergence [18].

An adaptive mesh refinement (AMR) tool called Sketch-to-Solution (S2S) was incorporated to solve the flowfield and refine the mesh in an iterative procedure that encourages faster solution times, smaller meshes, and more refined flow features [19]. The adapted grid RANS approach has proven effective in AIAA's High Lift Prediction Workshops (HLPW) in achieving higher levels of agreement between solutions of complex problems and avoiding the "multiple solution" problems sometimes experienced with fixed-grid RANS simulations, even with expertly crafted meshes [20]. For this study, 1000 iterations of the flow solver were computed for each iteration of mesh adaptation. For the first two mesh adaptations, the number of cells in the mesh did not change, but the grid points were moved to areas in the domain needing more resolution. On every third mesh adaptation, S2S doubles the number of grid points and also moves them within the domain. S2S performs both surface and volume refinements based on gradients in the Mach number. This procedure provides a necessary balance between refining the features in the flow and limiting the size of the mesh that is produced. The flow solution is interpolated onto each newly adapted mesh to minimize computation time. Each mesh in the adaptation cycle demonstrated iterative convergence by computing less than 1% variation in the lift force, drag force, pitching moment, and AFC mass flow rate over the last 10% of flow solution iterations. The meshes produced at the end of the S2S workflow for each case in this study contained approximately 180 million tetrahedral cells. The mesh convergence plot in Fig. 2 depicts the evolution of the solution with all 19 adapted meshes until mesh convergence is achieved (no significant change in the quantities of interest with the mesh size doubled).

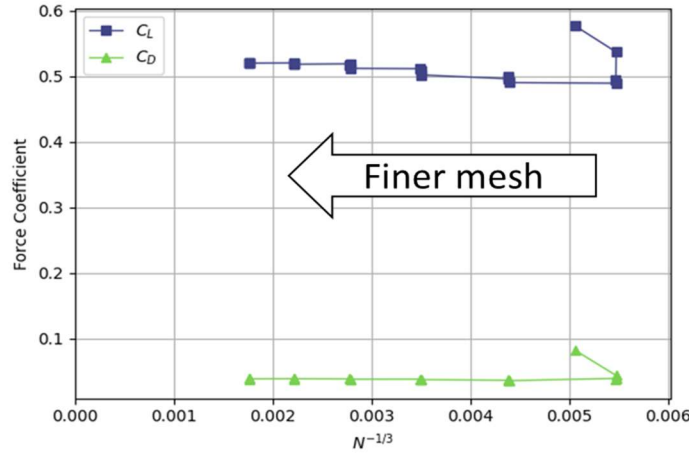


Fig. 2 Sketch-to-Solution AMR convergence showing lift and drag coefficients against a characteristic length ($N^{-1/3}$) for each mesh, finer meshes towards left of x-axis. $M = 0.05$, $\alpha = 5^\circ$, AFC off.

C. Test conditions

The purpose of this study is to vary the freestream Mach number to assess its impact on the performance of the fluidic fence. The freestream Mach numbers evaluated for this study are $M = 0.05$, 0.3 , 0.5 , and 0.7 . The angles of attack studied are $\alpha = 5^\circ$ and 10° . Though freestream Mach number is increased, freestream static pressure and temperature are held constant at 101.325 kPa (14.7 psi) and 300 K (80.33°F), respectively. This results in a higher Reynolds number at each freestream Mach number. Table 1 below documents the freestream conditions for each test point, with Reynolds numbers ranging from $1e5$ to $1.3e6$. McFadden and Bons documented the effect of changes to Reynolds number in incompressible freestreams on 30° and 45° swept wings [12]. As Reynolds number increased, turbulent boundary layer behavior discouraged separation regions, resulting in smaller enhancements from the flow control. In this study, a transition model is not used in the simulations, so the effect of Reynolds number is assumed to be much smaller than if laminar-to-turbulent transition occurred.

Table 1 Test matrix for each freestream setpoint.

	Setpoint 1	Setpoint 2	Setpoint 3	Setpoint 4
Mach	0.051	0.300	0.500	0.700
Pressure (kPa)	101.325	101.325	101.325	101.325
Temperature (K)	300	300	300	300
Velocity (m/s)	17.8	104.2	173.6	243.1
Reynolds Number	100,000	584,013	973,355	1,362,697
Angles of attack	5°, 10°	5°, 10°	5°, 10°	5°, 10°

The inlet flow specification for the VGJs is a ratio of total pressure from the AFC inlet to the freestream total pressure. As freestream Mach number increases for each setpoint, the freestream total pressure increases due to a constant freestream static pressure. Flow through the VGJs can be characterized by several different cost metrics, such as mass flow coefficient (C_Q), momentum coefficient (C_μ), and power coefficient (C_π), calculated with Equations 2-4, respectively. The total pressure ratio for Setpoint 1 was assigned to achieve a momentum coefficient of approximately 2%—a value used throughout several other VGJ fluidic fence studies. For the remaining setpoints, the objective was to hold mass flow coefficient (C_Q) constant because the pressure ratios required to maintain a constant momentum coefficient were unreasonably high. A constant mass flow coefficient translates to a constant blowing ratio between the AFC and the freestream. Table 2 below tabulates the total pressure ratio settings and associated cost metrics for each setpoint’s active flow control condition. Also included in this table is the velocity ratio, which was greater than unity for each setpoint in the test matrix.

$$C_Q = \frac{\dot{m}_{AFC}}{\rho_\infty U_\infty A_{ref}} \quad (2)$$

$$C_\mu = \frac{A_{AFC}}{A_{ref}} \frac{\rho_{AFC} V_{jet}^2}{\frac{1}{2} \rho_\infty U_\infty^2} \quad (3)$$

$$C_\pi = \frac{P_{0AFC}}{\frac{1}{2} \rho_\infty U_\infty^2} C_Q \quad (4)$$

Table 2 Active flow control conditions and cost metrics for each setpoint.

	Setpoint 1	Setpoint 2	Setpoint 3	Setpoint 4
Mach	0.051	0.300	0.500	0.700
PR _{AFC}	1.05	2.54	4.21	4.83
C_Q	0.0024	0.0027	0.0029	0.0028
C_μ	0.0223	0.0138	0.0074	0.0065
C_π	1.374	0.130	0.084	0.056
VR	4.62	2.54	1.26	1.14

IV. Results and Discussion

A. Baseline Results

Before AFC was activated on the wing, the uncontrolled performance was investigated at each freestream setpoint. It is best to understand the problems or dominant features in a given flow before employing active flow control so that the control technique can be targeted towards these issues. Presented in Fig. 4 are the suction surface streamlines and skin friction contours for the uncontrolled wing at the lowest Mach number ($M = 0.051$). Without the transition model included in the simulations, laminar separation bubbles that were observed in the experimental surface oil flow visualizations (SOFV) of McFadden et al. are not produced, as pictured on the right of Fig. 3 [10, 12, 21]. This leads to lift coefficients up to 12% higher for the simulations at $\alpha = 5^\circ$ and 10° than the previous experimental work, plotted in the left of Fig. 3. Instead, the suction surface demonstrates trailing-edge type separation, which is characteristic of a thick, cambered NACA 64₃-618 airfoil, exacerbated by the spanwise pressure gradient set up by the 30° wing sweep. The spanwise flow grows stronger further down the effective chord (Fig. 4), and the suction surface streamlines indicate entirely spanwise-oriented flow near 80% and 60% chord for $\alpha = 5^\circ$ and 10° , respectively. The effect of the wingtip vortex is indicated with the region of high skin friction near the wingtip (lightest color on contour bar), and the surface streamlines turn off the wingtip rather than traversing to the trailing edge.

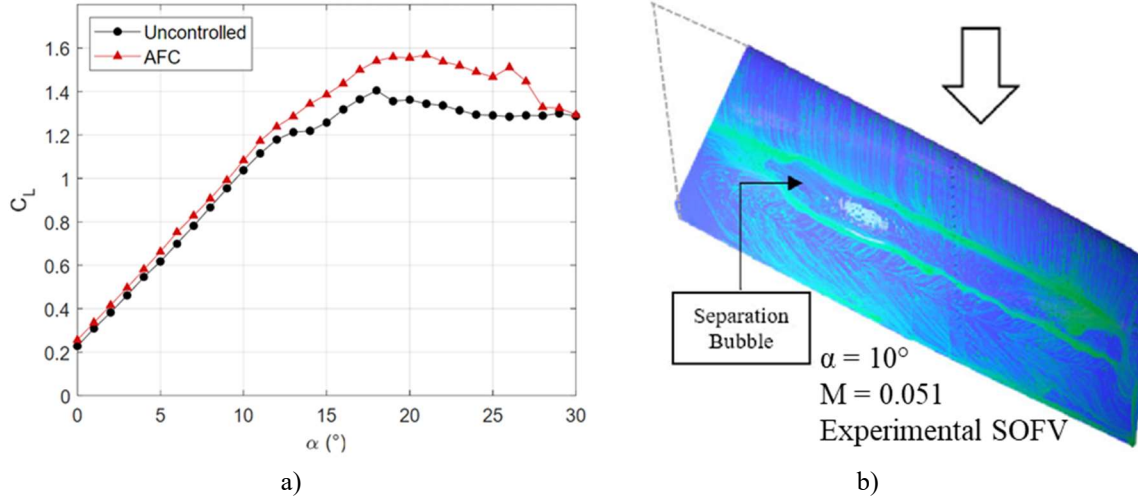


Fig. 3 Experimental results at $M = 0.051$ from McFadden et al. for (a) lift coefficient uncontrolled and AFC ($C_\mu = 2\%$) and (b) uncontrolled surface oil flow visualization at $\alpha = 10^\circ$, reproduced from [12, 21].

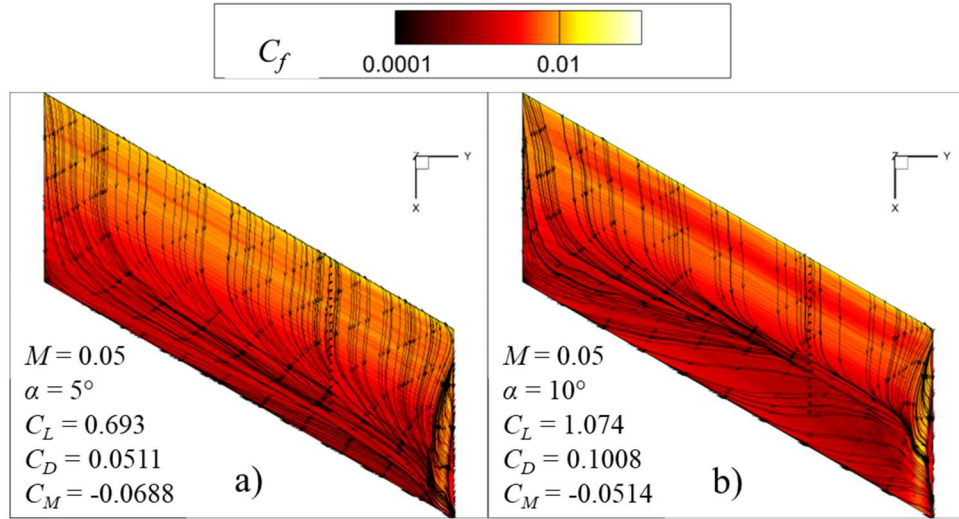


Fig. 4 Suction surface streamlines and skin friction coefficient contours of uncontrolled wing at $M = 0.05$ and $\alpha =$ (a) 5° and (b) 10° .

The flow visualizations in Fig. 5(a-f) depict the uncontrolled wing's suction surface flowfield with increasing Mach number for each setpoint. The surface streamlines upstream of the spanwise flow region are oriented more perpendicular to the leading edge (in line with true chord) as Mach increases to 0.7 (left to right in Fig. 5). While the spanwise flow development was gradual at $M = 0.051$, the spanwise turning occurs more rapidly with higher freestream Mach numbers. The $M = 0.7$ setpoints (Fig. 5c&f) exhibit much different behavior than the other setpoints, as a shock induces separation across most of the suction surface. The critical Mach number is exceeded, and the conventional spanwise flow separation pattern is not produced by the uncontrolled wing at this setpoint. The suction surface shock moves toward the leading edge at $\alpha = 10^\circ$, with nearly all the suction for lift being produced at the leading edge of the wing. There are significant losses in this flowfield which AFC is targeted to improve.

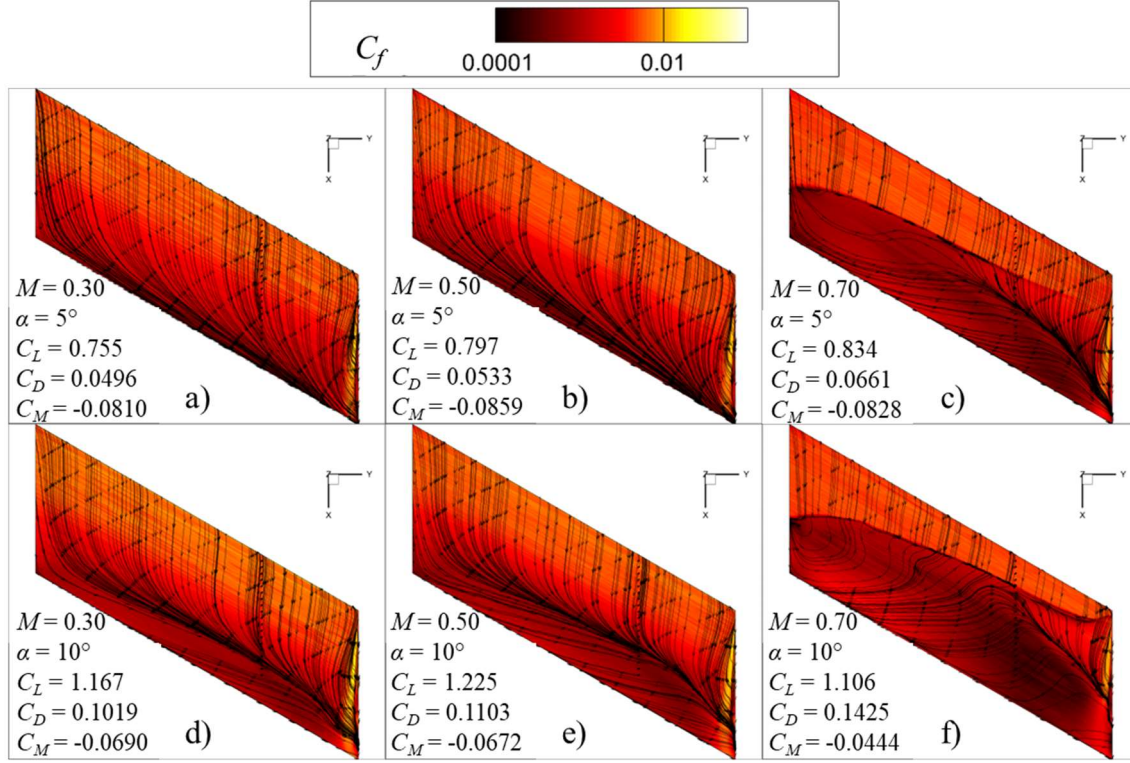


Fig. 5 Suction surface streamlines and skin friction coefficient contours of uncontrolled wing with increasing Mach number from $M =$ (left) 0.3 to (right) 0.7 and $\alpha =$ (top) 5° and (bottom) 10°.

As the Mach number is increased, the distribution of the lift force across the span also changes. Swept wings are known to exhibit decreasing section lift coefficients further out on the span [3]. Harper and Maki portray the wing sweep as beneficial for increasing the section lift coefficients of the inboard sections of the wing, beyond the maximum lift coefficient of that same airfoil on a 2D wing [3]. The section lift coefficient was estimated from the CFD simulations of this current study using Eq. 5 below. This calculation integrates the difference between the pressure coefficients (C_p) on the pressure (PS) and suction (SS) surfaces. Calculating C_l in this way neglects any viscous contribution to the lift force and applies thin airfoil theory, where the pressure forces on the pressure and suction surfaces are acting in directions perpendicular to the chord line.

$$C_l = \frac{L'}{\frac{1}{2}\rho_{\infty}V_{\infty}^2 \cos^2(\Lambda)c_{eff}} \approx \frac{\cos(\alpha)}{c_{eff} \cos^2(\Lambda)} \int_0^{c_{eff}} (C_{p_{PS}} - C_{p_{SS}}) dx \quad (5)$$

The spanwise lift distributions for the uncontrolled wing at each freestream setpoint and angle of attack are plotted below in Fig. 6. The total lift produced increases with Mach number, following the same logic as the Prandtl-Glauert correction for 2D flows. These spanwise lift distributions also reflect how the wingtip vortex strengthens with Mach number, resulting in more lift production near the wingtip until the outboard wing entirely stalls at $M = 0.7$ and $\alpha = 10^\circ$.

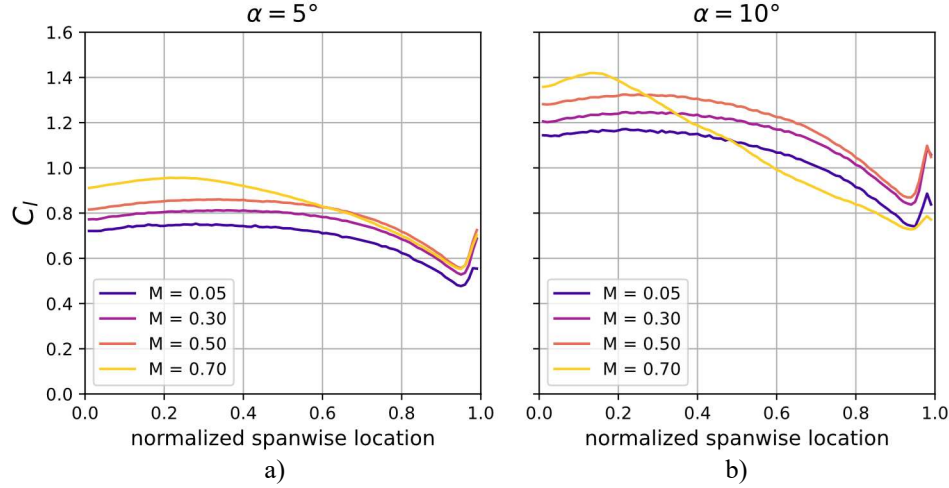


Fig. 6 Section lift distributions for uncontrolled wing at each freestream setpoint, $\alpha =$ (a) 5° and (b) 10° .

B. Active Flow Control Results

As observed in other publications by McFadden et al., the fluidic fence produces more lift on a 30° swept wing because it blocks the development of spanwise flow, straightens surface streamlines, and entrains higher momentum freestream flow on the wing outboard of the control location. These mechanisms contribute to lift enhancement at each setpoint in the test matrix. The plots in Fig. 7 detail the magnitudes of lift, drag, and pitching moment for each freestream Mach number and angle of attack (uncontrolled results in dashed lines, AFC results in solid lines). The drag rise due to compressibility effects is exhibited on the swept wing with and without control. Overall lift increases, but the lift increments (ΔC_L) decrease with Mach number. This is in part related to holding a constant mass flow coefficient across each setpoint instead of another AFC parameter, such as momentum coefficient or velocity ratio. For the uncontrolled case, pitching moment remains relatively constant with angle of attack since moments were taken about the $1/4$ chord location of the mean aerodynamic chord. Application of AFC contributes to more negative pitching moments, which is generally beneficial for longitudinal stability.

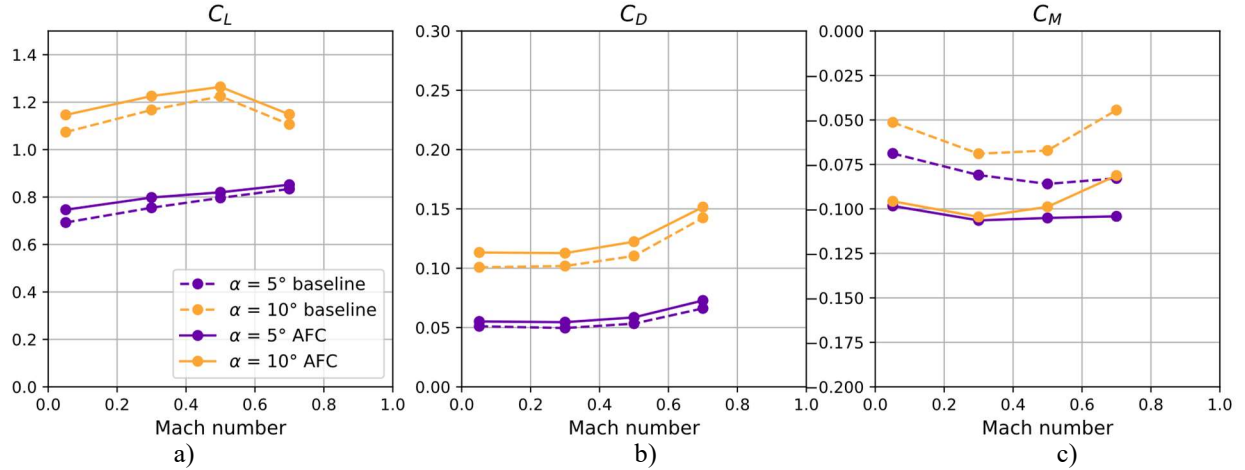


Fig. 7 Lift (a), drag (b), and pitching moment (c) coefficient comparisons for uncontrolled and controlled wings at varying Mach number.

The suction surface streamlines and skin friction contours of Fig. 8(a-f) illustrate the mechanisms of lift enhancement with AFC. The surface streamlines demonstrate more straightened flow outboard of the control location, traversing nearly to the trailing edge before developing some spanwise component. The surface streamlines also turn toward the jets, evidence that the jets entrain freestream flow even at these higher freestream Mach numbers. The inboard-directed blowing does not have much effect on the inboard flow pattern except for the local 10% span near the exits of the jets which form the fluidic fence effect. The shock-induced separation for freestream Mach of 0.7

experiences the most change with active flow control. Outboard of the streamwise row, the shock and separation are eliminated entirely at $\alpha = 5^\circ$ (Fig. 8c). At $\alpha = 10^\circ$, the shock still exists outboard of the row, but the flow remains attached for a much further extent of the effective chord downstream of the shock (Fig. 8f). The uncontrolled wing at this setpoint and angle of attack (Fig. 5f) showed a large region of low skin friction near the wingtip, representative of significant separation, which the fluidic fence has cleared.

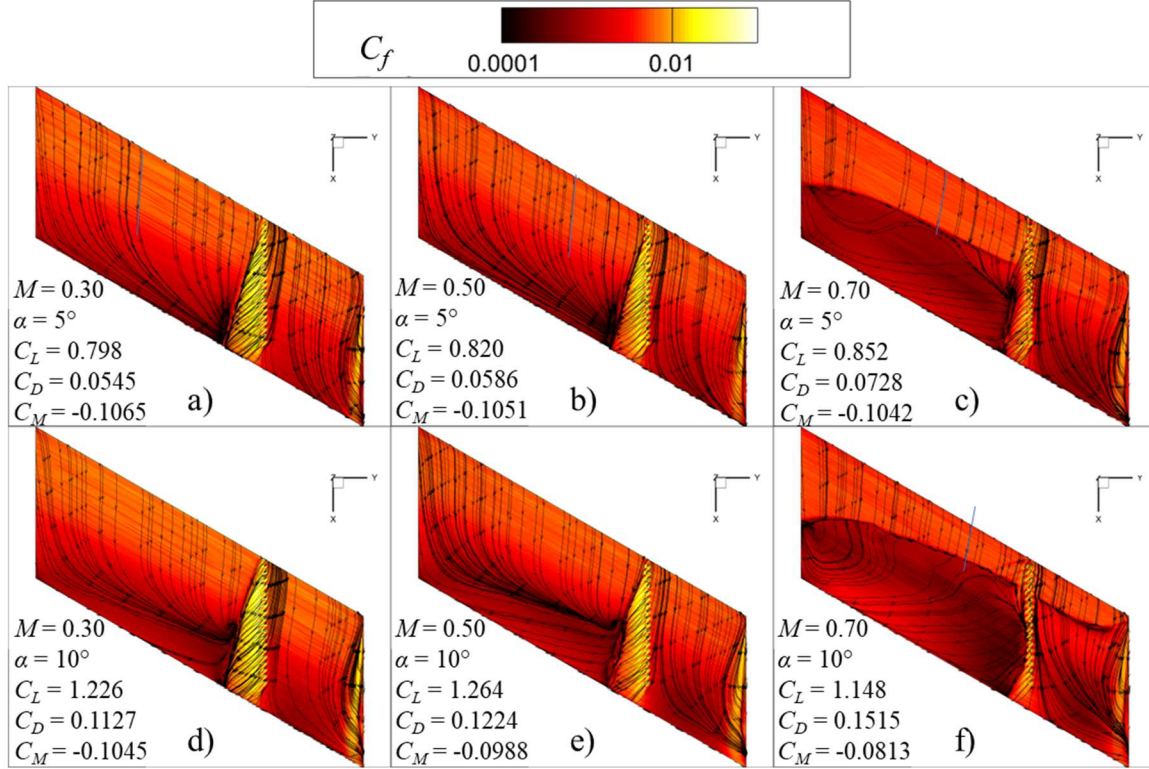


Fig. 8 Suction surface streamlines and skin friction coefficient contours of AFC wing with increasing Mach number from M = (left) 0.3 to (right) 0.7 and α = (top) 5° and (bottom) 10° , $C_Q \approx 0.0027$.

All the visualizations in Fig. 8 indicate enhancements to lift outboard of control, and this is reflected by improvements to the spanwise lift distributions in Fig. 9. The lowest setpoint experiences the highest lift improvements, but a similar pattern in lift improvement is observed with increasing Mach. The section lift coefficients immediately inboard of the control location (indicated by the vertical dotted line) are decreased, but this is due to the opposing flow directions of the inboard blowing AFC and the spanwise oriented suction surface flow. Physical fences experience a similar loss immediately inboard of a passive control fence [3]. The lift enhancement immediately surrounding the jets ($0.65 < z/b < 0.75$) decreases with Mach, and the inboard losses become much larger for the highest freestream setpoint. This is due to the disruption to the shock formation on the inboard wing and can be seen with the change in pressure coefficient on the suction surface due to AFC actuation in Fig. 10. The blue regions indicate the AFC is decreasing the pressure coefficient (increasing lift), and the red regions indicate increased pressure coefficient. As Fig. 9 indicates, the changes to inboard section lift coefficient are small for most cases, so only the outboard 50% span of the wing is depicted. This elucidates exactly where the AFC is providing enhancements to lift performance. It can be seen in Fig. 10 that the area of pressure reduction appears to decrease with increasing Mach up to 0.5, on both sides of the fluidic fence. This pressure reduction also moves further aft on the effective chord. At $M = 0.7$ (Fig. 10d&h), the AFC is disrupting the location and effect of the suction surface shock. There are red streaks indicating increased pressure at the location of the shock, and these streaks extend all the way to the wing root (not shown). This signals that the AFC is moving this shock forward, and this is reflected as decreased inboard performance in the spanwise lift distributions of Fig. 9. Conversely, the blue streak on the outboard section indicates clearing of the shock features entirely (Fig. 10d) or moving the shock downstream (Fig. 10h) with pronounced flow enhancements downstream of this shock. This is why the wing experiences large performance benefits on the outboard wing section at $M = 0.7$, not monotonically following the trend of the first three freestream setpoints (Fig. 9).

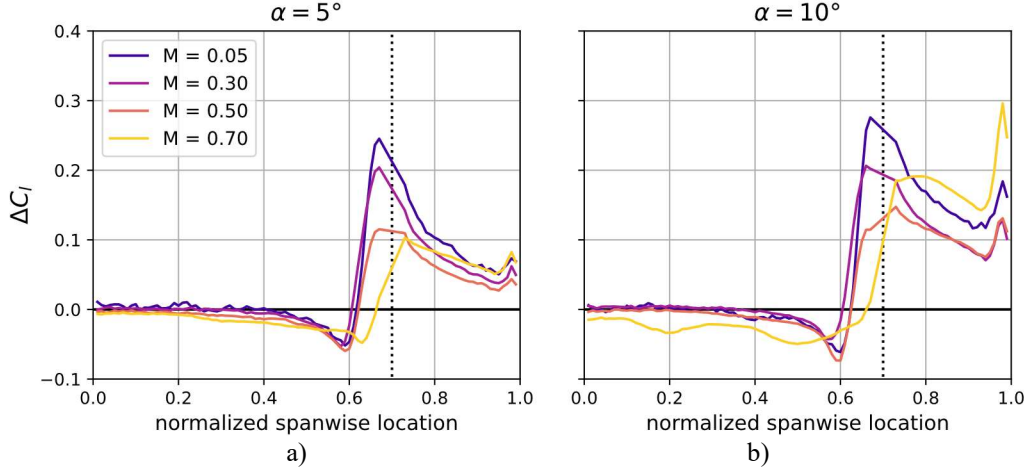


Fig. 9 Changes to section lift coefficients with AFC for $\alpha =$ (a) 5° and (b) 10° with increasing Mach number.

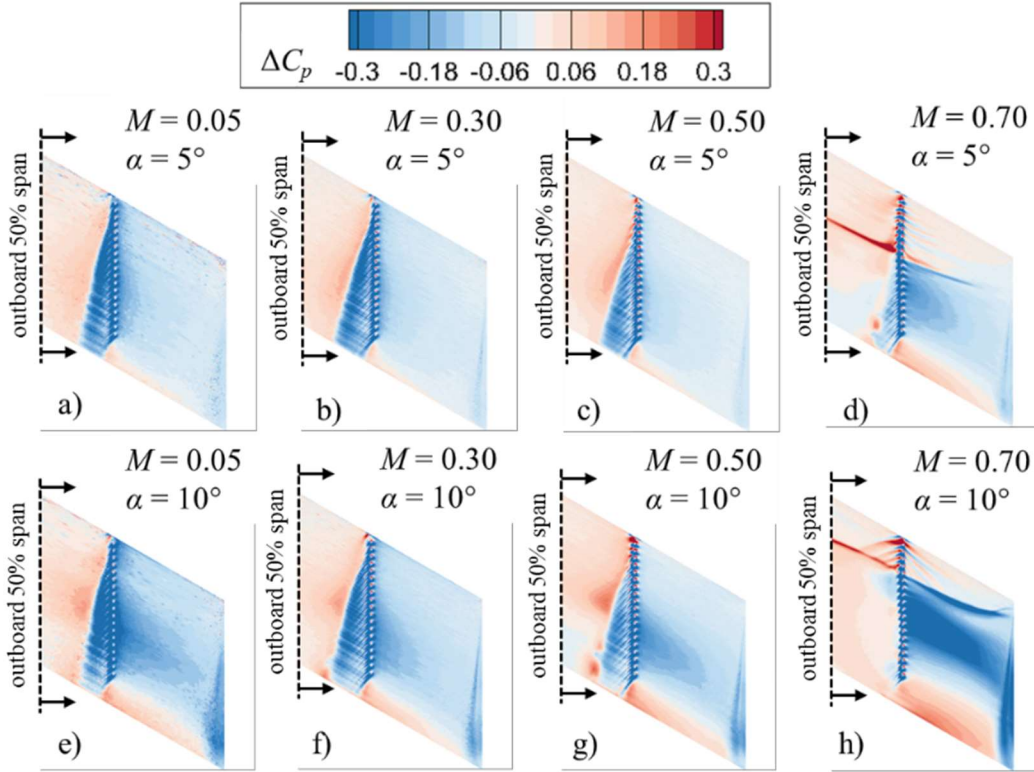


Fig. 10 Local changes in pressure coefficient on the outboard half of wing due to AFC for each freestream setpoint, Mach increasing left to right, $\alpha =$ (top) 5° and (bottom) 10° , $C_Q \approx 0.0027$.

Although the mass flow coefficient was held constant between each freestream setpoint, the other AFC cost metrics (such as C_μ , C_π , and $\dot{m}$) vary according to Table 1 and can be used to normalize the effect of control. The changes in each aerodynamic coefficient of interest are plotted in Fig. 11 normalized by the momentum coefficient (C_μ). Since the momentum coefficient should be treated as a vector, this normalization should not be compared to different flow control techniques or locations but is valuable in comparing the same AFC approach in different freestream conditions. The change in lift coefficient (ΔC_L) with respect to momentum coefficient is roughly constant with freestream Mach. This is the only AFC cost metric normalization that demonstrated consistent behavior across the Mach number ranges, as $\Delta C_L/C_Q$ and $\Delta C_L/C_\pi$ varied widely. The large increase in $\Delta C_L/C_\mu$ at $M = 0.7$ is due to the significant disruption to the shock formation on the outboard wing section. McFadden et al. varied the number, skew, and spanwise location

of the jets in the streamwise row for optimization on a 45° swept wing [22]. Their optimization function was $\Delta C_L/C_\mu$, and they were able to produce magnitudes of 11.9 and 22.8 for the 45° swept wing at $\alpha = 15^\circ$ and 20° , respectively. The lower angles of attack of 5° and 10° have less separation than $\alpha = 15^\circ$ and 20° , and therefore it is not surprising that this performance metric is much lower, averaging $\Delta C_L/C_\mu = 2.9$ and 4.6 for each α . The drag increases due to actuation and can be a concern for implementation at high flight speeds. This should be considered when determining a use case for this form of control. The pitching moment, however, can be decreased strongly with momentum coefficient at higher Mach numbers and could be effective in rapidly maneuvering a vehicle. This is due to the flow enhancements at higher Mach numbers found on further aft portions of the wing. Increased control surface effectiveness at higher Mach is also anticipated because of these enhancements.

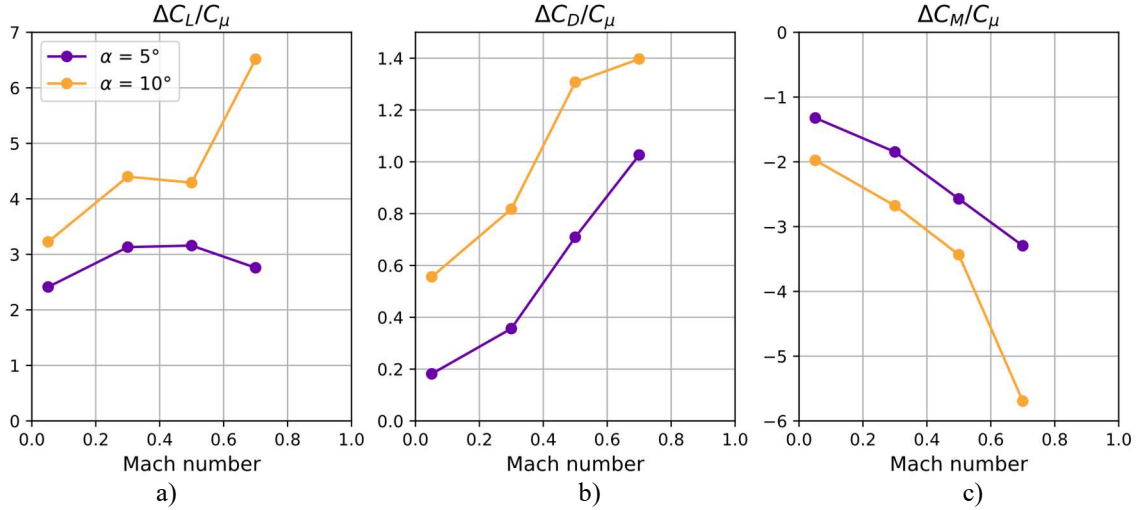


Fig. 11 Scaling of changes to aerodynamic coefficients (C_L , C_D , C_M) with momentum coefficient (C_μ).

V. Conclusions

The lift performance of a 30° swept wing was enhanced with a streamwise row of 20 vortex generating jets at increasing freestream Mach numbers. Mass flow coefficient for the active flow control was held constant across each freestream setpoint, and the effects of a compressible freestream on the mechanisms of control were explored. It was found that the effectiveness of the control was decreased at higher freestream Mach numbers, when the trailing edge type separation pattern occurs on the uncontrolled wing. This resulted in roughly constant $\Delta C_L/C_\mu$ from Mach 0.05 to 0.5. The flow control obstructed the development of spanwise flow and was effective in decreasing the pressure coefficient on the suction surface for regions outboard of the control location. However, this region of decreased pressure coefficient became smaller and moved further aft on the chord as the Mach number increased. The highest freestream setpoint exceeded the critical Mach number of the wing at both angles of attack, and this resulted in a shock that induced large-scale flow separation. Application of the fluidic fence shifted this shock forward on the inboard wing section, reducing lift performance on this half of the wing. Outboard of control, the shock was cleared entirely for $\alpha = 5^\circ$, and at $\alpha = 10^\circ$, the shock moved downstream with the shock-induced separation significantly improved. This is a promising result for further use of active blowing control at high speeds to reduce the effect of shock-induced separations via freestream entrainment.

Acknowledgments

This research is partially supported with funding from the National Aeronautics and Space Administration (NASA) Advanced Air Vehicles Program (AAVP) fellowship opportunity, under the Advanced Air Transport Technology (AATT) project. The authors would like to thank program mentors from the Flow Physics and Control Branch at NASA Langley Research Center. The authors would like to thank John Henry Korth and Bil Kleb for their guidance in setup, running, and debugging the Sketch-to-Solution cases. The views expressed in the paper are those of the authors and do not reflect the official policy or position of the Department of Defense, NASA, or U.S. Government.

VI. References

- [1] Anderson, J., Fundamentals of Aerodynamics, 6th ed., New York: McGraw-Hill, 2017, pp. 792-801.
- [2] Stinton, D., The Design of the Aeroplane, BSP Professional Books, 1983, p. 142.
- [3] Harper, C. W. and Maki, R. L., "A Review of the Stall Characteristics of Swept Wings," NASA TN D-2373, 1964. <https://ntrs.nasa.gov/citations/19640014908>.
- [4] Poll, D. I. A., "Spiral Vortex Flow Over a Swept-Back Wing," *The Aeronautical Journal*, vol. 90, no. 895, pp. 185-199, 1986. <https://doi.org/10.1017/S0001924000015670>.
- [5] Raymer, D. P., Aircraft Design: A Conceptual Approach, 6th edition, Playa del Rey, CA: American Institute of Aeronautics and Astronautics, 2018.
- [6] Fisher, L. R., "Approximate Corrections for the Effects of Compressibility on the Subsonic Stability Derivatives of Swept Wings," NACA-TN-1854, 1949. <https://ntrs.nasa.gov/citations/19930082527>.
- [7] Seifert, A. and Pack, L. G., "Sweep and Compressibility Effects on Active Separation Control at High Reynolds Number," in *38th AIAA Aerospace Sciences Meeting*, Reno, NV, 2000. <https://doi.org/10.2514/6.2000-410>.
- [8] Jones, R. T. and Cohen, D., High Speed Wing Theory, Princeton, NJ: Princeton University Press, 1960.
- [9] Kirkman, J. J., "Transonic Flow Around Swept Wings: Revisiting Von Karman's Similarity Rule," Master's thesis at Arizona State University, 2016. <https://core.ac.uk/download/pdf/79584303.pdf>.
- [10] McFadden, E. J., Brandt, P. J. and Bons, J. P., "Swept-Wing Active Flow Control with a Streamwise Row of Vortex Generating Jets," *AIAA Journal*, vol. 61, no. 3, pp. 1142-1150, 2023. <https://doi.org/10.2514/1.J062302>.
- [11] Spens, A., McFadden, E. J. and Bons, J. P., "Active Flow Control of a Swept Wing using Unsteady Fluidic Fence Techniques," in *AIAA SciTech 2023 Forum*, National Harbor, MD, 2023. <https://doi.org/10.2514/6.2023-1238>.
- [12] McFadden, E. J. and Bons, J. P., "Leading-Edge Sweep and Reynolds Number Variation for Fluidic Fence Active Flow Control," in *AIAA SciTech Forum*, Orlando, FL, 2024. <https://doi.org/10.2514/6.2024-1318>.
- [13] Brandt, P. J., McFadden, E. J. and Bons, J. P., "Dynamic Response of Swept Wing Aerodynamics to Active Flow Control through Vortex Generating Jets," in *AIAA Aviation 2022 Forum*, Chicago, IL, 2022. <https://doi.org/10.2514/6.2022-3888>.
- [14] Hussain, A. and Bons, J. P., "The Effect of Active Boundary Layer Fence Spanwise Location on Swept Wing Performance," in *AIAA Aviation Forum*, Dallas, TX, 2019. <https://doi.org/10.2514/6.2019-3684>.
- [15] Walker, M. M. and Bons, J. P., "The Effect of Passive and Active Boundary-Layer Fences on Swept-Wing Performance at Low Reynolds Number," in *2018 AIAA Aerospace Sciences Meeting*, Kissimmee, FL, 2018. <https://doi.org/10.2514/6.2018-0793>.
- [16] Allmaras, S. R., Johnson, F. T. and Spalart, P. R., "Modifications and Clarifications for the Implementation of the Spalart-Allmaras Turbulence Model," in *Seventh International Conference on Computational Fluid Dynamics (ICCFD7)*, Big Island, HI, 2012. https://www.iccfd.org/iccfd7/assets/pdf/papers/ICCFD7-1902_paper.pdf.
- [17] Shur, M. L., Strelets, M. K., Travin, A. K. and Spalart, P. R., "Turbulence Modeling in Rotating and Curved Channels: Assessing the Spalart-Shur Correction," *AIAA Journal*, vol. 38, no. 5, pp. 784-792, 2000. <https://doi.org/10.2514/2.1058>.
- [18] Wang, L., Diskin, B., Nielsen, E. J. and Liu, Y., "Improvements in Iterative Convergence of FUN3D Solutions," in *AIAA SciTech 2021 Forum*, Virtual Event, 2021. <https://doi.org/10.2514/6.2021-0857>.
- [19] Kleb, W. L., Park, M. A., Wood, W. A., Bibb, K. L., Thompson, K. B., Gomez, R. J. and Tesch, S. H., "Sketch-to-Solution: An Exploration of Viscous CFD with Automatic Grids," in *AIAA Aviation 2019 Forum*, Dallas, TX, 2019. <https://doi.org/10.2514/6.2019-2948>.
- [20] Park, M. A., Alauzet, F. and Michal, T., "HLPW-4/GMGW-3: Mesh Adaptation for RANS Technical Focus Group Workshop Summary," *Journal of Aircraft*, vol. 60, no. 4, pp. 1219-1237, 2023. <https://doi.org/10.2514/1.C037192>.

- [21] McFadden, E. J., Brandt, P. J. and Bons, J. P., "The Effect of Spanwise Location of a VGJ Fluidic Fence on Swept Wing Performance," in *AIAA Aviation 2022 Forum*, Chicago, IL, 2022. <https://doi.org/10.2514/6.2022-3468>.
- [22] McFadden, E. J., Brandt, P. J. and Bons, J. P., "VGJ Fluidic Fence Configuration Analysis for 45° Swept Wing," in *AIAA Aviation Forum and ASCEND 2024*, Las Vegas, NV, 2024. <https://doi.org/10.2514/6.2024-3756>.