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Technical Notes

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Control of Vortex Breakdown over Highly Swept Wings

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I. Introduction

HIGH-ANGLE-OF-ATTACK aerodynamics plays a crucial role in the design of high-speed aircraft and aerospace vehicles with highly swept wings, such as delta wings. The greatest limitation to the performance of a delta wing aircraft is vortex breakdown. The jetlike velocity profile of the vortex, observed upstream of breakdown, is converted into a wakelike flow. As velocity decreases, pressure increases resulting in a loss of lift.[1] The role of the swirl ratio and adverse pressure gradient on the vortex stability were studied using global theoretical analyses.[2]

In the past few decades, many researchers have studied the leading-edge vortices of highly swept wings, and several different techniques have been developed in an attempt to delay breakdown. Some of these developments include canard wings, spanwise blowing, tangential leading-edge blowing, trailing-edge blowing, and along-core blowing.[3]

The present Note discusses along-core blowing, incorporating a jet of air directed down the core of the vortex. The majority of previous studies used jets that originated from the apex of the wing.[4,5] For all of these blowing configurations, a jetlike acceleration of the flow along the vortex core was observed upstream of vortex breakdown location, but the post breakdown region maintained its wakelike axial velocity profile.

II. Experimental Setup

A half-span model of a 60-deg delta wing mounted on half a cylindrical fuselage with a radius of 7 cm was tested on the wall of a low-speed wind tunnel at a Reynolds number of 2.6×10^5 (Fig. 1). The wing chord c was 34.3 cm, the wing thickness was 1.3 cm, the leading edge was sharp with a 30-deg bevel angle, and the wind-tunnel blockage ratio was 3.5%. The angle of attack was fixed at 15 deg for all tests except force measurements, where the angle was varied from 0 to 27 deg. The lift and drag measurements were performed using a force balance.

Jets are emitted from three 31-mm nozzles, with an L/D ratio of 12:1, that are located beneath the vortex core and at $x/c = 30$, 60, and 80%. The azimuthal angle is measured from an imaginary line directed straight upstream and is positive in the counterclockwise direction. Nozzles with pitch angles of 25, 35, and 45 deg measured from the surface of the wing were used.

Pressure is measured on the upper surface of the wing via 30 pressure taps. The pressure taps are located beneath the vortex at four chordwise positions: six at $x/c = 35\%$ and eight each at $x/c = 55$, 75, and 95%.

Contour plots of axial velocities measured by laser Doppler velocimetry (LDV) were generated for multiple chordwise planes. Each grid consisted of approximately 100 velocity points, which were an average of 2000 readings.

III. Results and Discussion

A. Characteristics of Flow Without Control

1. Flow Visualization

Visualization of the flow over the wing was created by illuminating smoke with sheets of laser light. Aligning the sheet along the length of the core, from above the wing and from the side, allows breakdown to be seen in a single image (Fig. 2). The core appears as a dark line flowing through the white smoke-filled vortex that stops at the breakdown location (~35% of the chord).

2. Velocity Measurements

Average axial velocity profiles were measured for cross sections of the vortex oriented orthogonal to the freestream (Fig. 3). Without flow control, velocities in the core are decelerated, and negative values are common as a result of recirculation behind the breakdown point. The velocity in the vortex core is decreased even at 35%, indicating an initiation of the vortex breakdown, and it continues to drop steadily toward the trailing edge with negative velocities at the aft end.

B. Flow Control

1. Flow over Wing Using Control Nozzle near Apex

a. Flow visualization. The first blowing arrangement to be studied is the combination of the $\theta_p = 35$ deg pitch angle nozzle at $x/c = 30\%$ at an azimuthal angle of $\theta_a = 157.5$ deg and $C_\mu = 0.013$, where $C_\mu = (A_{\text{Jet}}/S) \times (V_{\text{Jet}}/U_\infty)^2$. When the images with the flow control are compared to the baseline, the vortex remains tighter and

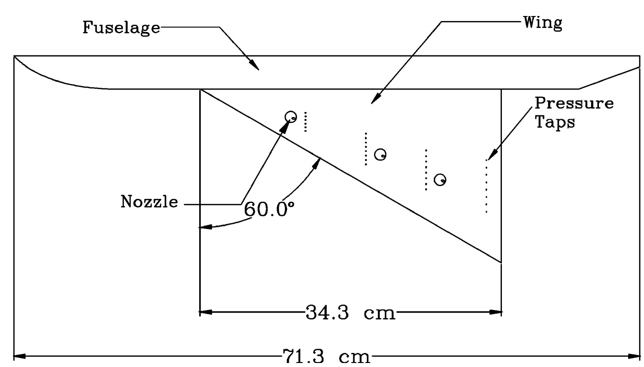

Fig. 1 Schematic of the model.

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more organized well downstream of the position where the baseline experiences breakdown (Fig. 4). Both cross sections show a vortex core that remains visible until near the trailing edge.

b. Velocity measurements. Figure 5 contains axial velocity plots with the flow control at four chordwise positions. At 35% of the chord, the jet is clearly visible as a distinct structure located at 11% of the local span above the surface of the wing and 48% of the local span from the fuselage. At this point, the velocity in the center of the jet is 3.5 times the freestream and the velocity in the core is still lower than the freestream. The merger occurs in less than 10% of the chord. Similar to the results observed in the flow visualization, plots of the velocity (Fig. 4) show the jet entering the core rapidly without disturbing the vortex.

By 55% of the chord, the jet and the vortex have merged into a single visible structure with a centerline velocity almost 2.5 times that of the freestream. Continuing downstream, the core velocity gradually decelerates but remains greater than the freestream velocity. At 95% of the chord, the core velocity is 1.6 times the freestream and no signs of stagnation are visible.

2. *Study of Flow over Wing Using Nozzle near Trailing Edge*

a. Flow visualization. Despite the fact that the downstream nozzle is located at 80% of the chord, the jet still has a significant effect on the flow over the entire surface of the wing by creating a low-pressure region near the rear of the wing. This

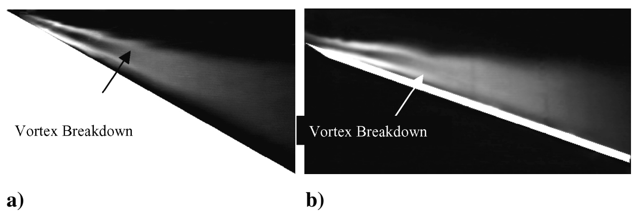

Fig. 2 Visualization of the vortex from a plane oriented along core and a) parallel and b) perpendicular to the wing.

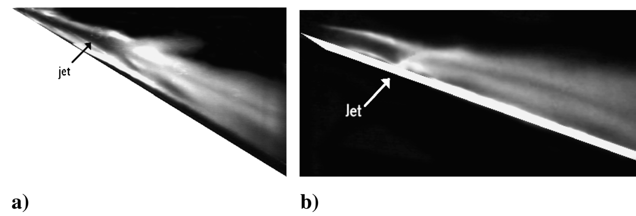

Fig. 4 Cross sections of leading-edge vortex with nozzle at *x/c* = 30%: a) horizontal and b) vertical.

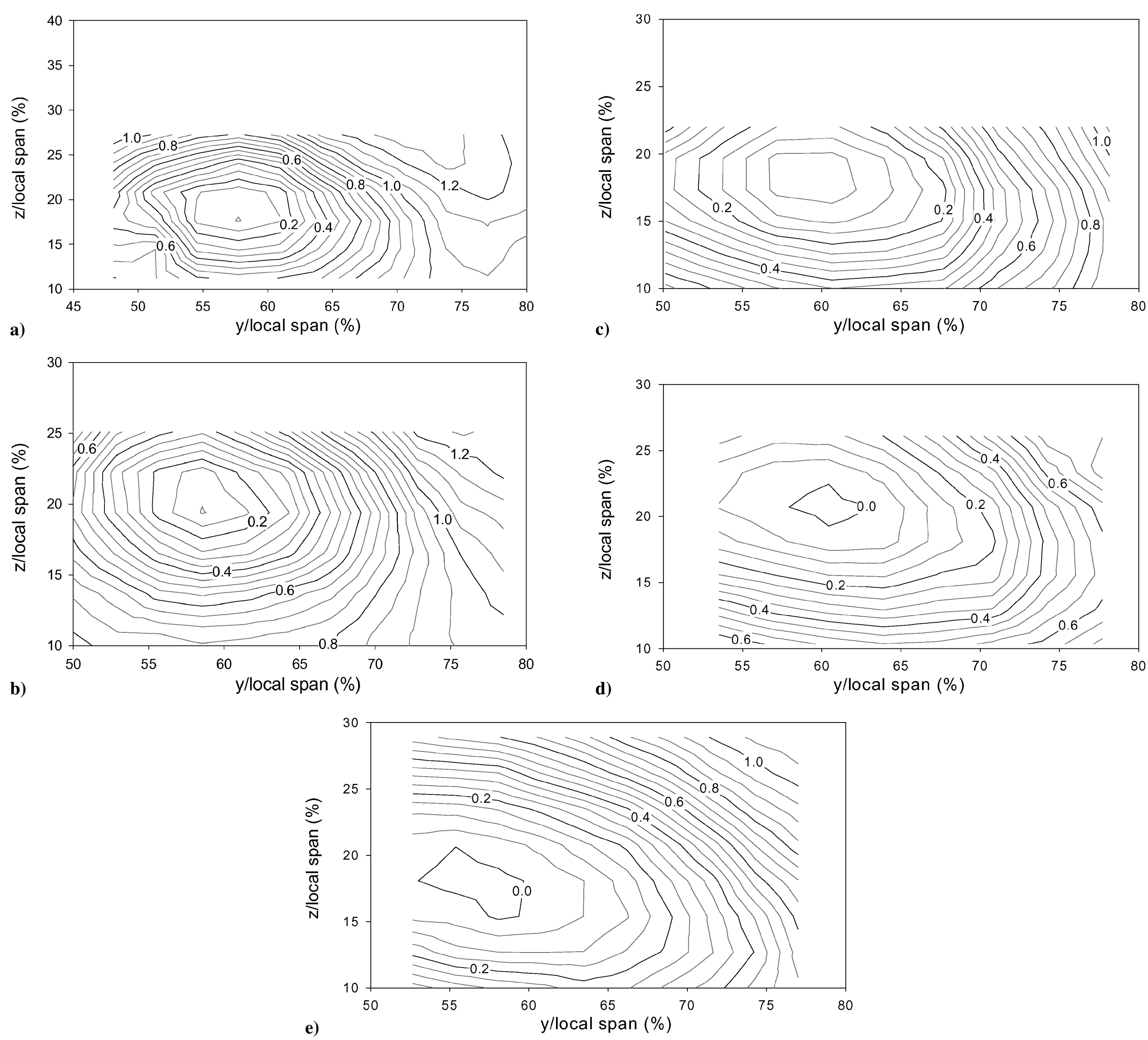

Fig. 3 Axial velocities at 15-deg angle of attack for *x/c* = a) 35%, b) 40%, c) 55%, d) 75%, and e) 95%.

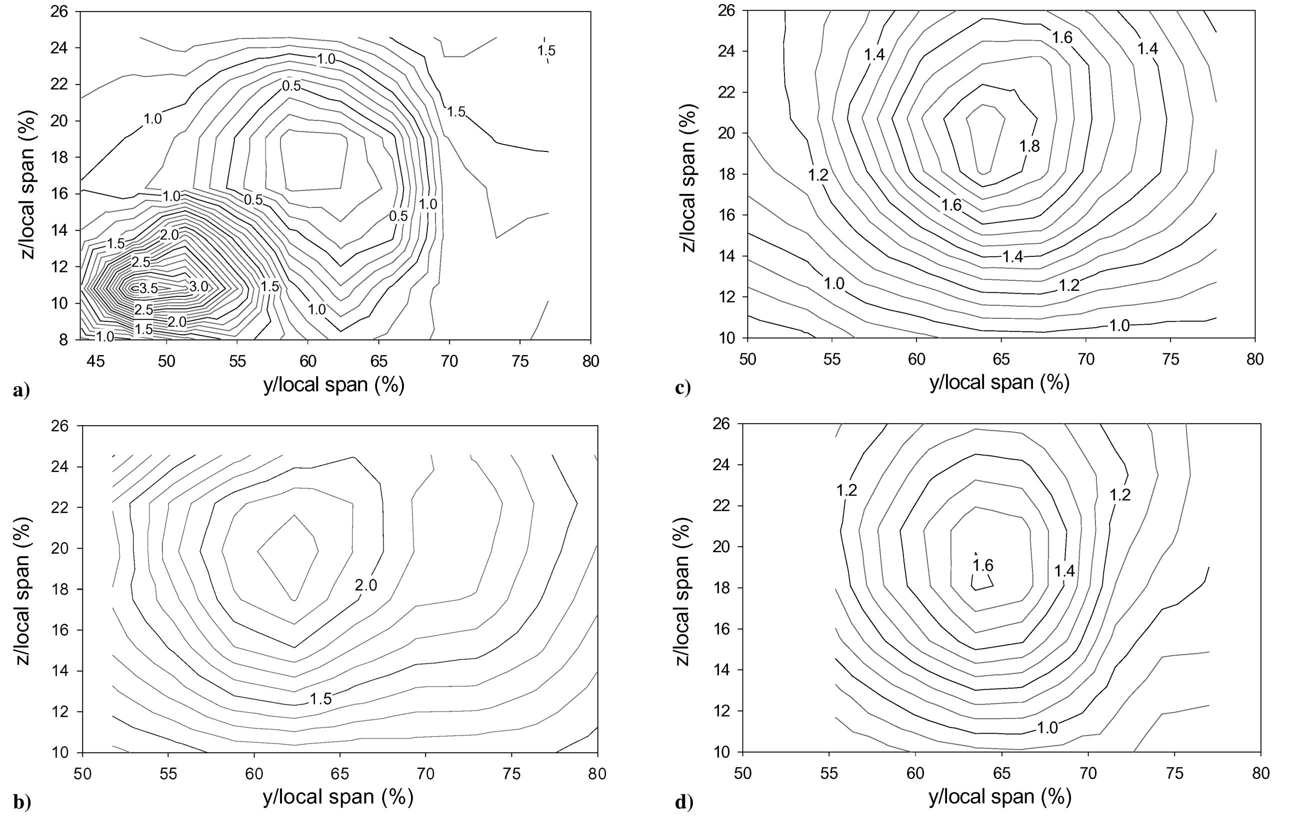

Fig. 5 Axial velocities in vortex with nozzle located at $x/c = 30\%$, $C_\mu = 0.013$, $\theta_a = 157.5$ deg, and $\theta_p = 35$ deg at $x/c =$ a) 35%, b) 55%, c) 75%, and d) 95%.

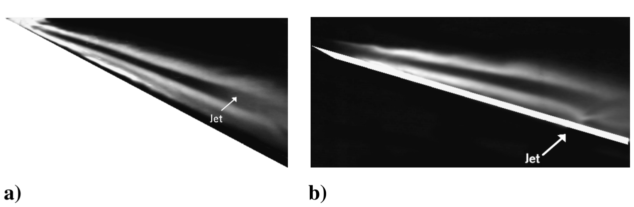

Fig. 6 Cross sections of leading-edge vortex with nozzle located at $x/c = 80\%$, $C_\mu = 0.013$, $\theta_a = 168.75$ deg, and $\theta_p = 25$ deg: a) horizontal and b) vertical.

helps to alleviate the adverse pressure gradient and delay vortex breakdown.

The vortex core in the planform view of Fig. 6a is very well defined. Because the jet is located toward the rear of the wing, the vortex is left undisturbed over the majority of the wing. The core remains stable all of the way to the jet, at which point it collapses.

As shown in Fig. 6b, the jet passes through the core of the vortex, causing immediate breakdown at 80% of the chord. The jet has a beneficial effect on the vortex upstream of the nozzle but causes breakdown at the point where it intersects the vortex. Perhaps moving the jet to the trailing edge would allow the vortex to remain organized over the entire surface of the wing.

b. Velocity measurements. The velocities in the vortex core with the jet blowing from 80% of the chord are shown in Fig. 7. At 35% of the chord, the velocity profile has a definite jetlike profile and the velocity in the core is nearly twice the freestream compared to a near zero velocity with no control (Fig. 3a). By 55% of the chord, the centerline velocities have substantially decelerated, indicating the onset of vortex breakdown.

At 95% of the chord, the jet is visible and it is clearly separate from the core. Unlike the optimum blowing condition from the nozzle at $x/c = 30\%$, the jet emitted from $x/c = 80\%$ never merges with the core. Nonetheless, it delays breakdown and accelerates the flow over the entire surface of the wing. Although Fig. 6 could indicate a full recovery of the vortex core over the entire chord, the velocity measurements show that the core flow was accelerated relative to the no-control conditions, but still maintained a wakelike profile downstream of 55%.

3. *Comparison of Pressure and Forces*

a. Pressure measurements. Figure 8 shows the pressure coefficient $Cp(-) = (P_\infty - P)/(\frac{1}{2}\rho U_\infty^2)$ distribution over the model of the upstream and downstream blowing conditions compared to the baseline. Each curve shows an increase in the negative pressure coefficient directly beneath the vortex.

The vertex nozzle (Fig. 8a) shows substantial increase in the negative pressure coefficient beneath the vortex at $x/c = 30$, 50, and 70%. At $x/c = 90\%$, there is still a slight improvement over the baseline, but the benefits of the jet have diminished this far downstream of the nozzle.

The aft nozzle (Fig. 8b) produces gains in the negative pressure coefficient that are largest toward the rear of the wing. Although the drop in pressure is not as great as that seen at $x/c = 35\%$ in Fig. 8a, the larger area affected results in a similar increase in lift. The pressure coefficients at 35% of the chord are still considerably lower than the baseline value at the same location.

b. Force measurements. Lift and drag curves were generated to test the performance of the blowing at a wider range of angles of attack. In addition to the experimental data, theoretical lift and drag curves developed in Ref. 6 are included (Fig. 9).

The arrangement for the upstream nozzle is $\theta_a = 157.5$ deg and $\theta_p = 35$ deg. The blowing momentum is 0.016, which was found to be optimum for this orientation of the jet. The configuration of the rear nozzle is $\theta_a = 168.75$ deg, $\theta_p = 25$ deg, and $C_\mu = 0.023$. The combination of the two nozzles use each nozzle simultaneously under the same configurations used previously.

All three blowing arrangements show steady improvements in the lift coefficient over the baseline for attack angles larger than 8 deg. At 15-deg angle of attack, the nozzle at 30% of the chord shows 15% improvement over the baseline. At 16 deg, there is a sudden loss in performance and the lift gain over the baseline is small. Beyond

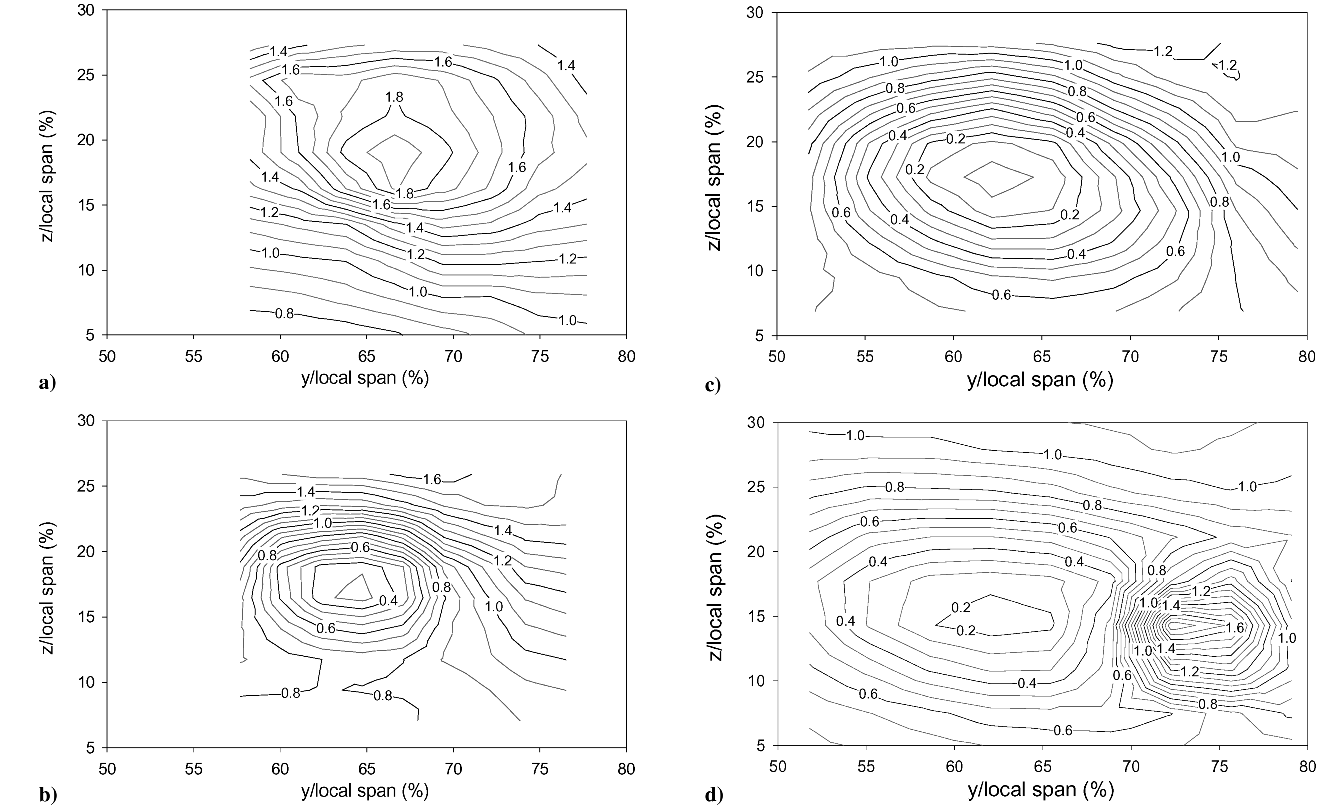

Fig. 7 Axial velocities in the vortex with the nozzle located at $x/c = 80\%$, $C_\mu = 0.013$, $\theta_a = 168.75$ deg, and $\theta_p = 25$ deg at $x/c =$ a) 35%, b) 55%, c) 75%, and d) 95%.

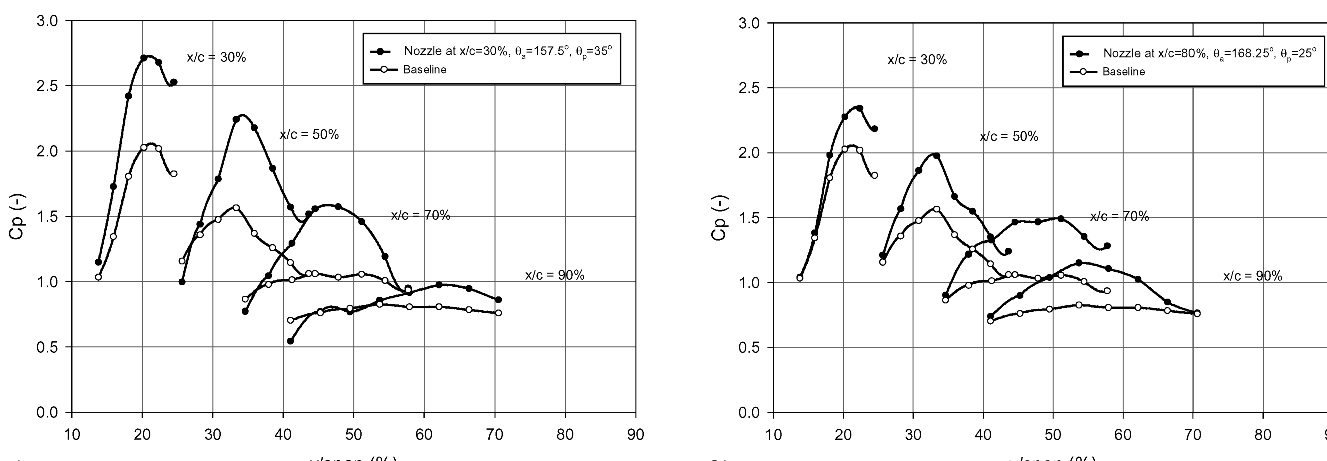

Fig. 8 Pressure distributions for blowing arrangements: a) vertex and b) trailing edge.

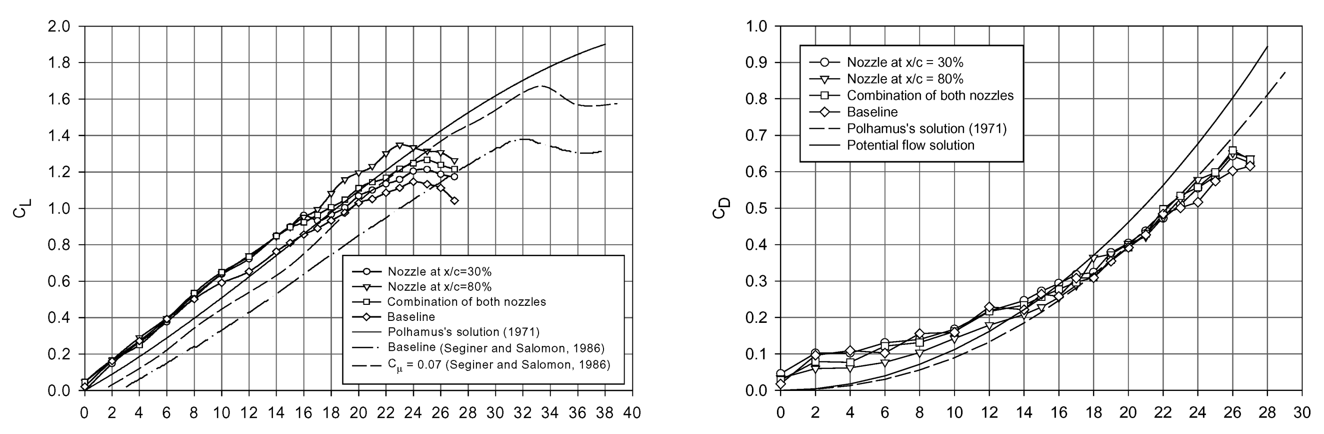

Fig. 9 Various blowing arrangements: a) lift and b) drag curves.

17 deg, the upstream nozzle begins to slowly regain an advantage in lift over the baseline. Stall is reached at 25 deg, which is 1 deg after the baseline stalls. At this point, the wing with the flow control experiences 7% greater lift than the baseline. The downstream nozzle experiences continued gains in performance over the baseline with increasing angle of attack. Stall occurs at 23 deg, which is actually 1 deg earlier than the baseline. The maximum lift was 1.9, an increase in lift of 22% over the baseline.

The combination of the two nozzles generates nearly a perfect average between the two individual nozzles. The combination does not experience as drastic a loss in performance as the upstream nozzle at 16 deg. Some loss in performance does occur around 16 deg, and the performance is not quite as good as the downstream nozzle for the higher attack angles. Stall occurs at 25-deg angle of attack. This blowing configuration generates a 12% advantage in lift over the baseline. For the most part, there is no significant change in drag for the different blowing conditions. Blowing from the downstream nozzle shows some decrease in drag for attack angles less than 15 deg.

IV. Conclusions

Tests were performed to control the leading-edge vortex breakdown location on a delta wing by blowing a small jet into the vortex along the vortex core at the wing vertex, wing trailing edge, or both. Visualization of the flow over the wing using the vertex-blowing configuration showed that the jet entered the core smoothly and rapidly. As a result, vortex breakdown at 15-deg angle of attack was delayed from its natural position of approximately $x/c = 35\%$ to near the trailing edge. The location of this jet at 30% rather than the usual location of along-the-core injection near the apex is important for effective control because the leading-edge vortex should be allowed to develop to a certain level before the control jet is injected into its core. Otherwise, the jet entrainment is not as efficient and is more sensitive to exact orientation. Axial velocity measurements showed a jetlike profile at $x/c = 95\%$ with a core velocity of 1.6 times the freestream, unlike some previously reported results that showed recovery of wakelike profile of the controlled vortex. Pressure measurements showed lower pressure coefficients on the upper surface of the wing. At 30% of the chord, the pressure coefficient was 35% lower than that of the baseline, resulting in 15% more lift than the baseline.

The high-velocity jet provides additional momentum to the flow in the core preserving the jetlike profile of the vortex core over the entire length of the wing. This provides the core with the energy needed to maintain stability against the adverse pressure gradients that are naturally present on the suction surface of the wing, pushing breakdown farther downstream.

The trailing-edge blowing arrangement yielded a well-defined core, which was present until at least 80% of the chord with a jet momentum of 0.023. Velocity measurements showed that the jet increased the axial velocity over the entire surface of the wing, not only in the core but near the surface as well. The jetlike profile persisted only for a short distance downstream of the initial breakdown location, and a wakelike profile developed, though with a higher axial core velocity compared to no control.

The rear nozzle induces a low-pressure region at the rear of the wing, creating a more favorable pressure gradient along the wing with stronger axial flow in the vortex, and delays breakdown. This mechanism is different from that observed in trailing-edge blowing, which achieves the alleviation of adverse pressure gradient by increased entrainment. This technique proves to be less sensitive to changes in the blowing conditions and flight conditions, making it more suitable for practical applications.

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References

[1] Leibovich, S., "The Structure of Vortex Breakdown," *Annual Review of Fluid Mechanics*, Vol. 10, 1978, pp. 45–88.

[2] Rusak, Z., and Lamb, D., "Prediction of Vortex Breakdown in Leading Edge Vortices Above Slender Delta Wings," AIAA Paper 98-2860, June 1998.

[3] Mitchell, A. M., and Delery, J., "Research into Vortex Breakdown Control," *Progress in Aerospace Sciences*, Vol. 37, No. 4, 2001, pp. 385–418.

[4] Kuo, C. H., Lu, N. Y., and Lin, D. C., "Evolution of Vortical Structure over Delta-Wing with Transient Along-Core Blowing," *AIAA Journal*, Vol. 35, No. 4, 1997, pp. 617–624.

[5] Mitchell, A. M., Molton, P., Barberis, D., and Gobert, J. L., "Control of Vortex Breakdown by Along-the-Core Blowing," AIAA Paper 2000-2608, June 2000.

[6] Polhamus, E., "Prediction of Vortex-Lift Characteristics by a Leading-Edge Suction Analogy," *Journal of Aircraft*, Vol. 8, No. 4, 1971, pp. 193–199.

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