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Delta Wing Vortex Control via Recessed Angled Spanwise Blowing

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A novel vortex control technique, known as recessed angled spanwise blowing, has been investigated in a water tunnel on a beveled 60-deg delta wing. Three pairs of blowing ports, located on the suction side of the wing and beneath the vortex core, were canted upward in the spanwise direction such that the injected flow is parallel to the beveled edge. Flow visualization experiments were performed using dye injected into the leading-edge vortices near the wing apex with the vortex burst location visually observed. Blowing coefficient values up to 0.1 were used in the experiments, although the effectiveness of blowing at a single chord location remained the same above blowing coefficients of 0.05. Maximum improvement in vortex breakdown location of 15% chord was obtained at an angle of attack of 22 deg and blowing coefficient of 0.05. Blowing from a port downstream of the natural burst location delayed vortex breakdown, whereas blowing upstream of the natural burst prompted vortex breakdown at the blowing port. Blowing ports at 41% chord had the greatest effect in delaying vortex breakdown. These observations are explained via Rayleigh's stability criterion for circular flow.

Nomenclature

C_μ = blowing coefficient
c = root chord length
$\dot{m}_j$ = blowing mass flow rate
q = freestream dynamic pressure
Re = Reynolds number, Vc/ν
r = radial distance from vortex core
S = wing planform area
V = freestream velocity
V_j = blowing fluid velocity
v = tangential velocity
w = axial velocity
x_b = chordwise burst location
x_n = chordwise natural burst location
x_p = blowing port location
α = angle of attack
β = blowing angle
Δx_b = net improvement in burst location, $x_b - x_n$
ν = kinematic viscosity

Introduction

THE flow over highly swept wings such as delta planforms has been studied extensively in the past.[1–3] Delta wings differ from high AR conventional wings since a sizable portion of lift at high angles of attack is generated by a pair of vortices present on the leeward side of the wing. These vortices are formed by the coalescence of smaller discrete vortical parcels being shed regularly from the separated leading-edge shear layer.[4] The low pressure in the cores of these tightly coiled bound vortices creates "vortex lift," which is distinguished from the lift due to potential flow. Smaller secondary vortices of opposite sign also form underneath the primary vortices due to the separation of the surface boundary layer. At high angles of attack, the cores of leading-edge vortices tend to "burst" or break down. Although vortex breakdown has been the subject of several review articles,[5–7] the phenomenon is still not well-understood. The breakdown is characterized by the rapid deceleration of the axial velocity in the vortex core, accompanied by an abrupt expansion of the core size. The increase in the core pressure after the breakdown reduces the lift contributed by these vortices. Lift coefficient measurements reveal a strong correlation with the chordwise position of breakdown. For example, the maximum lift coefficient of delta wings occurs at an angle of attack at which the vortex breakdown is at the trailing edges.[2] Additionally, the burst location and stability of the vortices affect the pitch and roll moments. The burst location has been observed to oscillate in a random fashion about some fixed position, which complicates the measurement of flow characteristics in the burst region. Leibovich[6] noted that the dominant period of these oscillations was approximately 2 Hz.

A feature of delta wings that makes them highly desirable for the subsonic, high-angle-of-attack regime of the flight envelope, is the ability to generate lift at large angles of attack. Aircraft performance can be further enhanced if the forward progression of vortex breakdown with increasing α is delayed. Therefore, control of vortices has been pursued by a number of investigators in order to improve the characteristics of high-performance aircraft during takeoff/landing and extreme maneuvers. Vortex control also can result in augmentation of roll maneuverability by asymmetrical destruction or strengthening of the vortices.

The majority of vortex control techniques discussed in the literature utilize steady injection or "blowing" of fluid either along or at the leading edge of the wing. Recently, unsteady blowing techniques, inspired by the regular shedding of the leading-edge shear layer, have been employed for vortex control as well.[8–10] The previous schemes for vortex control will be discussed first, followed by the steady blowing technique developed in the present study.

Vortex core blowing (VCB), which is illustrated schematically in Fig. 1a, attempts to delay vortex breakdown by increasing the momentum of the vortex core. This is accomplished by injecting a stream of fluid directly into the vortex core along the vortex axis. The result is an energized vortex with increased axial velocity. Although Malcolm and Skow[11] demonstrated qualitatively that this method is moderately effective, the physical limitations of aligning a blowing port external to the flow in the direction of the vortex axis makes this technique impractical. Additionally, the flow over the wing can be disturbed by an external blowing system.

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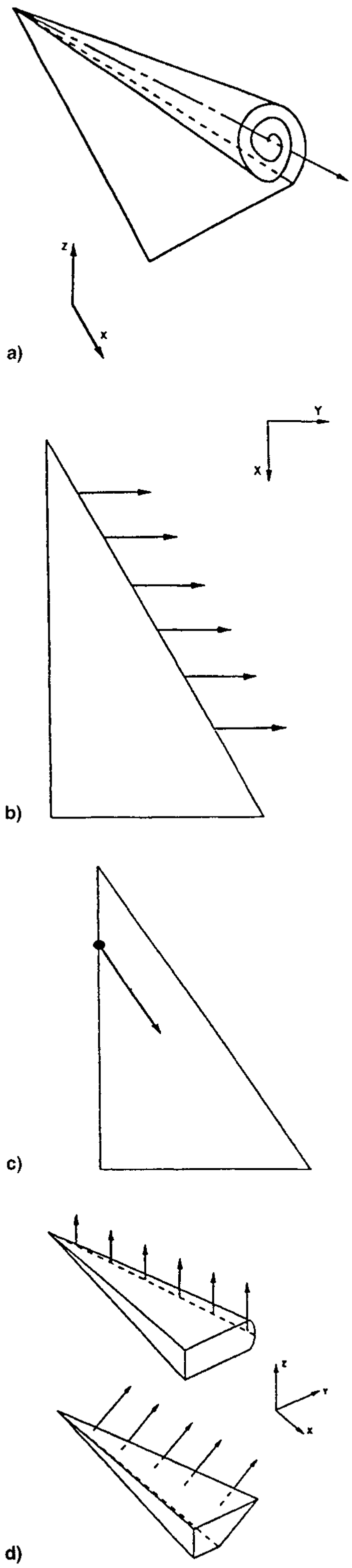

Fig. 1 Vortex control techniques: a) VCB, b) SWB, c) PLEB, and d) TLEB.

Spanwise blowing (SWB) attempts to energize the vortex by ejecting high-momentum fluid in a spanwise direction from ports along the leading edge, as shown in Fig. 1b. The intent of SWB is to increase the vortex strength by increasing the vorticity of the free shear layer. Wind-tunnel tests on a 70-deg sweep delta wing were conducted by Trebble[12] using SWB, resulting in a 17% improvement in lift at 12-deg angle of attack and at a blowing coefficient of $C_\mu = 0.10$. This improvement, however, resulted in increased drag. Moreover, vortex breakdown was observed at lower angles of attack in comparison with the wing without blowing. Both effects can be attributed to a larger span perceived by the oncoming flow.

Parallel leading-edge blowing (PLEB), depicted in Fig. 1c, consists of injecting fluid parallel to the leading edge. Although this technique is often referred to as spanwise blowing, it is significantly different from the technique described above, in that the blowing ports are located at the wing root (usually on the fuselage) above the wing surface. Anglin and Satran[13] performed static and wind-tunnel free-flight testing on two fighter models using this technique. Their results indicated a 20% improvement in the lift coefficient at an angle of attack of 15 deg and $C_\mu = 0.08$. They stated that PLEB enhances or creates leading-edge vortices, improving lift performance at moderate angles of attack. Asymmetric application of PLEB produced large rolling moments. Furthermore, the drag coefficient can be reduced by lowering the effective angle of attack required to attain a similar lift coefficient on a wing without blowing. Bradley and Wray[14] and Seginer and Salomon[15] also observed similar results utilizing PLEB.

According to Lee and Roberts,[16] the injected flow in PLEB acts like a line sink creating suction on the upper surface of the wing, pulling the vortex back to the wing and reattaching it to the surface. This flow strengthens the vortex, thereby delaying breakdown. The stability of the wing was also improved by reducing the wing rock common to delta wings in this flight regime. A drawback of PLEB is the significant bleed momentum required to attain the desired effects.

Tangential leading-edge blowing (TLEB) uses slots located on the leading edge to inject fluid tangent to the wing's leading-edge bevel or normal to the wing surface (in a rounded geometry), as shown in Fig. 1d. The phenomenon of Coanda jet attachment to convex surfaces is the basis for TLEB on rounded leading-edge wings. By being able to affect the crossflow separation point on rounded leading-edge delta wings, the location (with respect to the wing surface) and strength of the vortices can be controlled.[17,18] This technique has a strong stabilizing effect on the vortices and lift is increased for even small amounts of blowing. Experimental results from Ref. 18 reveal that TLEB can improve the lift coefficient by 30%. Similar to SWB, the placement of blowing ports on the leading edge of a wing causes limitations in practice.

In the present effort, a novel vortex control technique, recessed angled spanwise blowing (RASB), is investigated. RASB is essentially a variation of SWB with canted blowing ports recessed away from the leading edge, as shown in Fig. 2. The blowing fluid is injected in the spanwise direction from the top surface of the wing, parallel to the sharp leading-edge

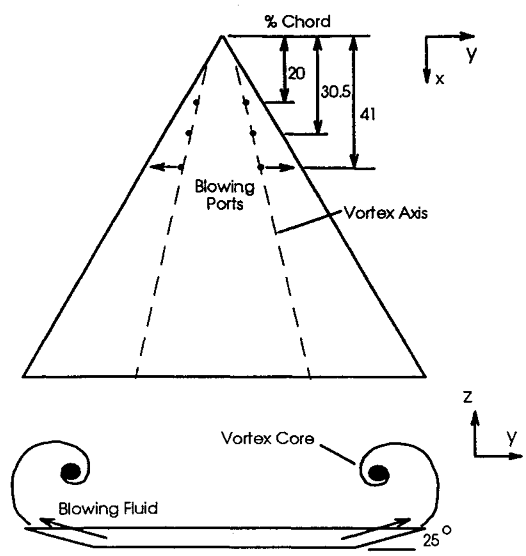

Fig. 2 Schematic of RASB.

bevel. The ports were canted 25 deg as a compromise between normal blowing, which tends to displace the vortex cores away from the wing surface, and tangential blowing, which is difficult to implement in thin wings. Three pairs of blowing ports were located on the top surface of the wing outward of the observed vortex location at 20, 30.5, and 41% chord. Blowing in this manner not only reduces the risk of vertically displacing the vortex away from the wing surface and, thus reducing lift prematurely, but it also appears to be more practical than blowing schemes located on the leading edge. The intent of the momentum injection in this scheme is on increasing the stability of the vortex, thus delaying vortex breakdown. From Rayleigh's stability criterion for circular flows, a vortex is stable to axisymmetric disturbances when its circulation increases monotonically in the radial direction.[19] It is expected that the vortex circulation could be manipulated and the stability of the vortex core would consequently be increased.

Experimental Apparatus

The experiments were carried out in the Worcester Polytechnic Institute (WPI) free surface water tunnel. The flow passes through turbulence management screens and honeycomb, and is then accelerated through a 7:1 contraction before entering the 60 × 60-cm test section. The test section is fabricated from transparent acrylic to allow for optical access from all sides. A port for viewing the flow from the downstream end of the test section is also present. Since the experiments are conducted in water, the results are applicable to subsonic incompressible regimes such as takeoff and landing. A 60-deg delta wing with a sharp leading edge and 25-deg bevel was used to match the detailed study of O'Neil et al.[3] Vortex breakdown over the wing occurs at relatively low angles of attack for this configuration. The aluminum wing had a 30.5 cm span, 26.4 cm root chord length, and 1.9 cm thickness, resulting in a thickness-to-chord ratio of 7.2%, and an AR of 2.3. Angles of attack ranging from 14 to 32 deg were studied. The solid blockage ratio varied between 2.7% of the test section area at $\alpha = 14$ deg and 5.9% at $\alpha = 32$ deg, comparable to other investigations.[3] The effects of blockage ratio variation on vortex burst location is expected to be within our measurement uncertainty. Although baseline runs were conducted at freestream velocities of 30 and 49 cm/s, the experiments for this study were conducted at 38 cm/s. The Reynolds number based on root chord length was $Re = 1 \times 10^5$. Even though the primary vortex structure is largely unaffected at these Reynolds numbers, the secondary vortices are likely to be affected by the Reynolds number variations. In the present study, our main concern is with the structure of the primary vortices.

The wing was manufactured in two halves for ease of assembly. Internal channels were used to deliver the blowing fluid through a 90-deg bend to the angled blowing ports through the top of the wing. Experimental considerations required the wing to be mounted topside-down, which also facilitated measurement and photography. Additional particulars on the wing can be found in Fitzpatrick et al.[20]

The blowing port stations on the model were located at 20, 30.5, and 41% chord locations for ports 1, 2, and 3, respectively. The 0.32-cm-diam blowing ports were located on rays emanating from the vertex making an angle of 22 deg with the wing centerline. The blowing port locations were chosen to position one pair of ports as close as possible to the wing apex. The two additional blowing ports were located near the natural burst location at 18 and 22 deg. Below the 18-deg angle of attack, the vortex core is relatively weak, and the breakdown location is nearer to the trailing edge. The blowing system injected fluid from a pressurized diaphragm well tank. A flowmeter regulated flow to each of the blowing port pairs. The blowing velocity and mass flow rate $\dot{m}_j$ were derived from the flowmeter readings and could not be varied independently. All references to single-port blowing indicate a pair of symmetric blowing ports located at each chord station.

The widely accepted definition

$$C_\mu = \dot{m}_j V_j / qS$$

is used for the blowing coefficient. Two types of blowing were performed: 1) single-port blowing, where only one pair of blowing ports was used; and 2) three-port blowing, where all three pairs were set at the same volumetric flow rate and C_μ is an aggregate value for all ports. Maximum blowing coefficients of 0.15 and 0.38 were possible for single-port and three-port blowing, respectively. It is generally accepted that the power requirements for any value of blowing coefficient greater than 0.10 is prohibitive in practical application, with possible lower limits depending on the engine specifications. On the other hand, it is possible to tailor the engine for certain bleed requirements. In the laboratory experiments, our purpose was to study an order-of-magnitude range in blowing coefficient encompassing this practical limit.

The dye delivery system used a pair of internal 0.15-cm nominal internal diameter Teflon® tubes in the top half of the wing, 0.37 cm on either side of centerline, exiting near the leading edge at 0.6 cm from the apex of the wing. Dye was gravity-fed from small reservoirs through metering devices. A separate external reservoir system also allowed dye to be introduced directly into the blowing fluid.

Flow visualization images were recorded by a 35-mm SLR Cannon AE1P camera, as well as a video camera. The vortex burst location (average between left- and right-side values) was detected visually by the rapid dispersion of dye present in the vortex cores. Lines were drawn on the wing surface at 5% chord intervals for this purpose. Visually averaging the oscillating burst location was a source of uncertainty on the order of ±2.5% chord. Angle of attack was measured by a three-line sight using a metal protractor mounted on the end of the transverse sting support rod, resulting in errors on the order of ±0.5 deg. Blowing coefficient errors on the order of ±0.005 due to the flowmeter scale were noted.

Results

Baseline Testing

Baseline tests were completed in order to verify the experimental methods. Measurements of vortex breakdown location without blowing were made at various Reynolds numbers and angles of attack ranging from 14 to 30 deg. As mentioned earlier, the wing solid blockage ratio variation over

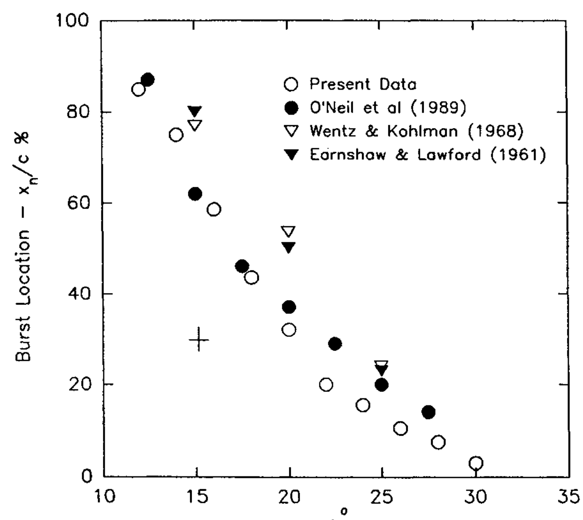

Fig. 3 Baseline (no blowing) vortex burst location; present data at $Re = 1.0 \times 10^5$.

the angle-of-attack range is comparable to other investigations on delta wings. Only "bubble-type" vortex breakdown was observed in our experiments. Baseline runs were made at $Re = 7.9 \times 10^4$ and 1.3×10^5 in order to verify that the breakdown location is not Reynolds number dependent at high Re. Although our maximum Re is limited by the facility, previous studies[3] of vortex breakdown have shown that the burst location is independent of Reynolds number for the range of interest. The breakdown position, in terms of percent chord, is plotted against the angle of attack in Fig. 3. For $\alpha < 20$ deg, our data is compatible with the data in Ref. 3, to within our experimental uncertainty. The present baseline data fall below those in the previous experiments for $\alpha > 20$ deg, but are within the combined experimental error of the present and O'Neil et al.[3] studies. A well-defined burst was not detectable for $\alpha < 14$ deg.

The natural phenomenon of fore and aft "walking" of the vortex burst location was observed. Due to instabilities in the flowfield, the burst location tended to oscillate somewhat unpredictably along the vortex trajectory about a fixed chordwise point. This phenomenon was often coupled with an out-of-phase movement in the other vortex, particularly at high angles of attack. This vortex instability may have been caused by the pseudoconical shape that the flow initially sees near the tip of delta wing.[21] Due to the geometry of the wingtip, the relative thickness is high near the wing apex and the flow effectively perceives a triangular cross section near the apex, rather than a flat plate. Alternatively, slight imperfections in the apex region, or freestream turbulence (about 2%) may account for this phenomenon. When the present blowing scheme was employed, the oscillation amplitudes were reduced by approximately half, while the frequency of oscillation increased slightly.

Single-Port Blowing

All results for single-port and three-port blowing are presented for a chord Reynolds number of 1.0×10^5. Figure 4 shows the results of single-port blowing for each of the three pairs of blowing ports at various angles of attack between 18–32 deg, chosen to emphasize the regime where the burst is located in the first half of the wing. Testing below $\alpha = 18$ deg and above $\alpha = 32$ deg showed little improvement for all values of C_μ.

In general, blowing upstream of the natural burst location had the effect of degrading vortex stability and inducing breakdown. A slight aft movement of the burst location was

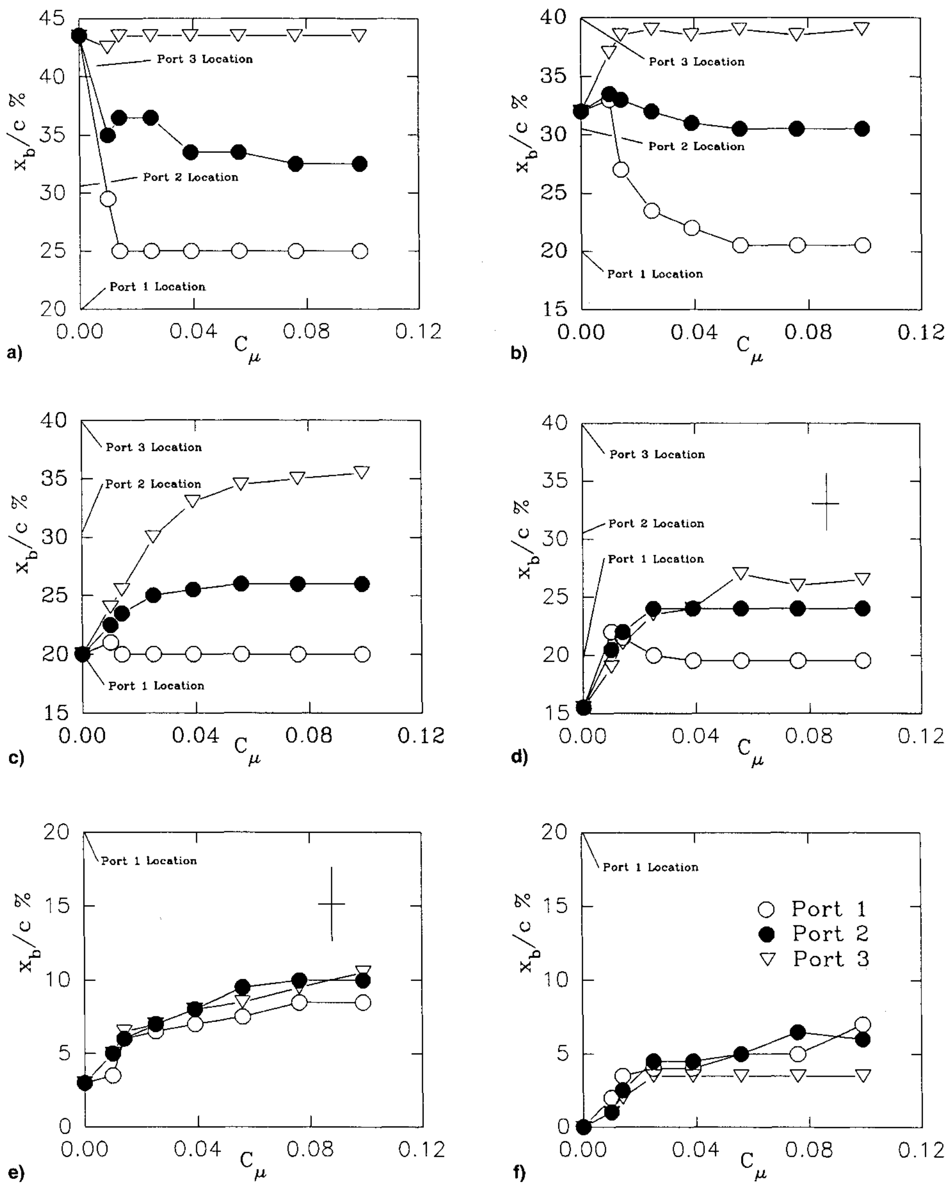

Fig. 4 Single-port blowing burst locations, $Re = 1 \times 10^5$. α = a) 18, b) 20, c) 22, d) 24, e) 30, and f) 32 deg. The error bars indicate the uncertainty in the measured data.

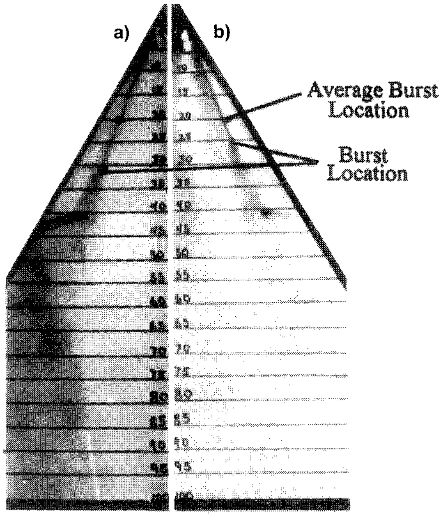

Fig. 5 Flow visualization of vortex burst locations for single-port blowing, α = 22 deg, $Re = 1 \times 10^5$: a) port 3 blowing, C_μ = 0.025 and b) no blowing.

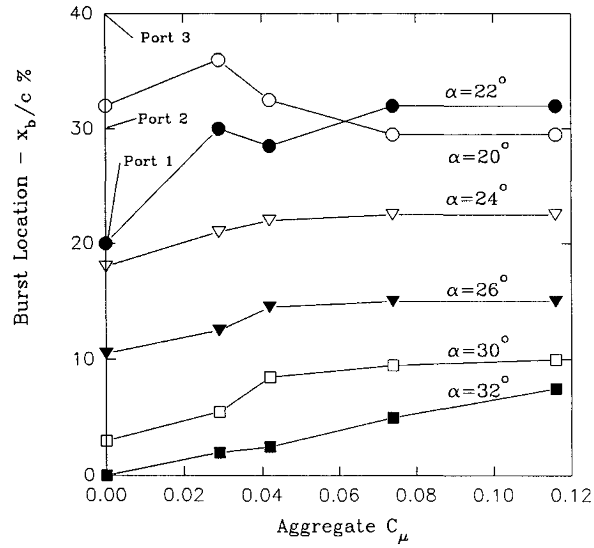

Fig. 6 Burst locations for three-port blowing, $Re = 1 \times 10^5$.

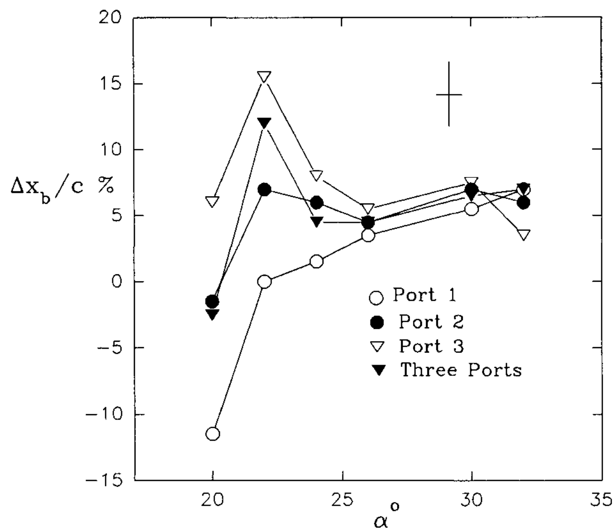

Fig. 7 Net improvement in burst location at C_μ = 0.10, single- and three-port blowing, $Re = 1 \times 10^5$.

seen for very low values of C_μ for ports 1 and 2 at 20-deg angle of attack. However, the burst location moved rapidly upstream, approaching the blowing port location with increasing C_μ. Figures 4a and 4b demonstrate this observation most dramatically. Contrary to the findings in Ref. 13, the first blowing port appeared to have a detrimental effect on the burst location for $\alpha < 22$ deg. Despite our earlier reasoning (in the Introduction), single-port blowing upstream of the natural burst location generally had a tendency to burst the vortex at the location of the blowing port. This is shown in Fig. 4a for ports 1 and 2 at α = 18 deg, and Fig. 4b for port 1 at α = 20 deg. Blowing from a port located at or near the natural burst location resulted in no change. This effect is indicated in Figs. 4a–4c for blowing from port 3 (α = 18 deg), port 2 (α = 20 deg), and port 1 (α = 22 deg), respectively. Port 1 blowing may still prove useful in inducing the breakdown of one vortex core in order to improve rolling and maneuverability.

Blowing aft of the natural burst location appears to improve vortex stability, thus delaying breakdown. Blowing via port 3 appears to provide the best improvement in vortex breakdown location. The net improvement gradually diminished with increased α. Figures 4e and 4f indicate that all three ports improve the burst location, to within our uncertainty, equally for $\alpha \geq 30$ deg. A flow visualization for blowing via port 3 at C_μ = 0.025 and α = 22 deg is presented in Fig. 5. In Fig. 5, the burst location moved aft 7% chord. It should be emphasized here that the visualizations depict an instantaneous burst location and not the visually averaged value. Consequently, the vortex locations observed may differ from the average values in Fig. 4. In most cases little additional improvement is realized for $C_\mu > 0.05$, revealing the asymptotic nature of the burst location movement above this C_μ.

Three-Port Blowing

Three-port blowing results are shown in Fig. 6 for 22 deg $\leq \alpha \leq$ 32 deg and blowing coefficients up to 0.116. The most improvement in burst location is realized for α = 22 deg at low values of C_μ, with smaller improvements for other angles of attack. However, at higher values of C_μ, the rate of improvement diminishes for α = 22 deg, with performance actually degrading at higher values of C_μ for α = 20 deg. Blowing from port 1 was postulated to dominate the results at higher C_μ. This was verified by setting α = 20 deg, employing constant blowing out of port 3 at C_μ = 0.025 while gradually increasing the blowing out of port 1 to C_μ = 0.056. As the value of C_μ for port 1 was increased, the burst location gradually moved forward from 32% chord to the port 1 location at 20% chord.

The net improvement in burst location at C_μ = 0.10 as a function of α for both single- and three-port blowing is shown in Fig. 7. It is apparent that single-port blowing from port 3 for $\alpha \leq$ 30 deg results in the best improvement in burst location. Above this angle of attack, the enhancements due to port 3 become diminished. Port 1 and three-port blowing are marginally superior to the others for α = 32 deg. An additional effect of blowing was to move the vortex slightly off the wing, vertically, and outward in the spanwise direction. Both effects will tend to reduce delta wing lift and increase drag.

Discussion

It was initially believed that the blowing ports upstream of the natural burst location should have the greatest influence on improving the vortex behavior. However, since the blowing ports downstream of the burst location provide the desired improvement, it is hypothesized that utilizing RASB at locations downstream of the burst tends to stabilize the vortex core by increasing the circulation of the vortex at the appropriate radial location. According to the Rayleigh criterion for the stability of circular flow, the circulation must increase continually as the radial distance r from the vortex center increases.[19] This criterion remains true for a constant axial velocity and axisymmetric disturbances. Jones[22] showed that essentially the same argument holds for an arbitrary cylindrical flow subject to infinitesimal disturbances. More recently, Leibovich and Stewartson[23] have demonstrated an instability criterion for vortex cores when axial velocity as well as tangential velocity v are dependent on r. The applicability of stability arguments is confined to the region near the natural burst location where the tangential velocity profiles are approaching marginal stability. For chordwise locations far downstream of the natural burst location, it is doubtful that these arguments are valid and alternative mechanisms may be responsible for the burst location improvement. Based on these hypotheses, single-port blowing from ports placed closer to the natural burst location, on the downstream side, should have a larger influence on the burst location movement. It is easier to manipulate the tangential velocity profiles in the vicinity of the marginal stability, and therefore, it is expected that on a properly normalized basis, blowing closer to the natural burst location would be more effective.

In order to clarify the above statements, the net improvement in burst location Δx_b was normalized by the maximum possible burst location movement, $x_p - x_n$, at $C_\mu = 0.10$. This normalization assumes that the burst location can only move as far as the downstream blowing port. In Fig. 8, the normalized data were plotted against the distance from the blowing port to the natural burst location. This distance is equivalent to the maximum possible burst location movement. The data appear to fall on a single curve to within our experimental accuracy. One can then conclude that the normalized improvement in burst location is solely dependent on the distance between the blowing port and the natural burst location. Therefore, on a normalized basis, all ports are equally effective in moving the burst location downstream.

As the distance $x_p - x_n$ increases, the normalized net improvement decreases, justifying the arguments in the first paragraph of this section. For blowing ports near the natural burst location (i.e., small $x_p - x_n$), there is large normalized improvement in the burst location; however, the potential for absolute improvement in the burst location is small. On the other hand, blowing ports far away from the natural burst location have a large potential for absolute improvement. Yet at the same time, the normalized improvement is rather small.

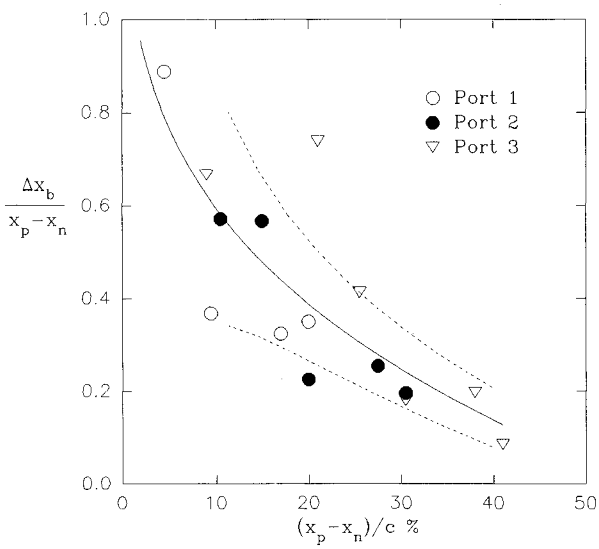

Fig. 8 Dependence of normalized improvement in burst location on the distance between the blowing port and the natural burst location for single-port blowing at $C_\mu = 0.10$. A power law curve fit to all of the data points is represented by the solid curve and the dashed curves depict the uncertainty band based on the error of $\pm 2.5\%$ chord in burst location measurement.

Then, at any given α, there may be an optimum location for blowing in order to maximize the absolute improvement in the burst location. It appears that port 3 is nearest this optimum location over the α range studied for the three blowing port configurations. The data point resulting from port 3 blowing at $\alpha = 22$ deg, which falls outside the uncertainty range in Fig. 8, is not well-understood at present.

For blowing ports upstream of the natural burst location, if the circulation profile is altered such that it becomes unstable and susceptible to natural disturbances, premature vortex breakdown can be induced. This scenario is possible if a blowing port delivers momentum to (or creates circulation at) a point in the vortex where v (or $2\pi rv$) increases in an appropriate manner. This is thought to be the reason for the detrimental effects of blowing from port 1 until the burst location has moved upstream of it at high α. This reasoning is corroborated by the measurements of Visser and Nelson.[24] They found that prior to the burst, circulation around the vortex core did not decrease in the radial direction, while after the burst, circulation reached a maximum prior to decreasing. The previously described hypothesis could be verified by detailed experimental measurements of rotational velocity around the vortex core with and without blowing.

If the Rayleigh's criterion is adopted, an optimum spanwise blowing location on the wing can be found for each angle of attack and leading-edge sweep. This location, between the leading edge and the vortex trajectory, could be approximated once the tangential velocity profile of the vortex core is known. We believe placing blowing ports spanwise inboard of the vortex trajectory would inherently be destructive to the vortex when using the RASB geometry. In this case, the blowing will create opposite signed vorticity in the vortex. A blowing port inboard of the vortex core produces an opposite sign torque to the vortex circulation.

The observed effects of RASB, when employed upstream of the natural burst, could also be explained in a different manner. Blowing upstream of the burst effectively increases the swirl angle of the vortex, defined as $\tan^{-1}(v/w)$, by inducing a higher rotational velocity in the core. If RASB is able to increase the swirl angle to the critical value, near 50 deg,[25] the outcome will be premature bursting. Additionally, the induced velocities will tend to reduce the pressures in the local area, contributing to the adverse pressure gradient causal in vortex breakdown. However, when blowing is applied downstream of an already burst vortex, the swirl angle has already reached its critical value and further increasing the swirl angle should not have any effect on this aspect of the burst characteristics. As a result, this line of reasoning cannot explain the vortex burst location modifications when RASB is applied downstream of the burst. The physical mechanisms hypothesized could be further verified with measurement of the velocity field, and comparison of the circulation profile around the vortex core as RASB is implemented.

It is expected that improvements in the burst location, by as much as 15% chord, would translate to higher lift coefficients at any α. Previous investigations of vortex control schemes have generally observed such a trend.[3,13,18] However, the fact that the vortices are slightly displaced vertically from the surface of the wing will result in a lowering of the potential lift coefficient gains. Moreover, the vertical component of momentum from blowing will tend to reduce the lift coefficient by an amount proportional to $C_\mu \cos \alpha \sin \beta$, where β is the angle of blowing with respect to the wing. In the present geometry where $\beta = 25$ deg and 20 deg $\leq \alpha \leq 30$ deg, the loss-of-lift coefficient by this mechanism is expected to be about 2%. Although the streamwise component of the blowing fluid momentum would tend to slightly augment the forward thrust, the penalties of reduced engine mass flow would have to be taken into account.

The most useful application of RASB may come from controlling aerodynamic moments as opposed to simply increasing the lift coefficient. Employing asymmetric blowing, where a blowing port on one side of the wing is upstream of the natural burst location while another blowing port on the opposite side of the wing is downstream of the natural burst location, would be effective in improving roll characteristics. In this manner, the premature bursting of the vortex on one side is accompanied by delayed breakdown on the opposite side. Furthermore, appreciable yawing moments may be created by the momentum resulting from applying RASB from ports on one side of the wing only.

Lastly, a comparison of RASB and TLEB performance is warranted. While both blowing methods achieve their optimum performance (in terms of the burst location) at similar blowing coefficients ranging from 0.01 to 0.05, the effective range of α in RASB appears to be smaller than that in TLEB. On the other hand, RASB may be easier to implement in practice since only a few well-placed blowing ports are required. Blockage of blowing ports in real applications is less likely to occur with RASB than with TLEB since the ports are away from the leading edges. As with asymmetric blowing from TLEB,[26] RASB can be utilized to affect the vortex on one side of a wing to alter the aerodynamic moments.

Conclusions

In summary, implementing RASB on a 60-deg delta wing achieved moderate improvement in vortex breakdown by moving it to a location farther aft along the wing chord. Between 18- and 32-deg angles of attack, blowing at 20 and 30% chord locations upstream of the natural burst tended to move the burst location forward, blowing downstream of the natural burst tended to move it closer to the blowing port, and blowing at the burst location had little effect. Single-port blowing from port 3 produced the best absolute improvements, by as much as 15% chord, at moderate angles of attack and blowing coefficients on the order of 0.05. Increasing the blowing coefficient beyond a certain value did not generally result in further improvement of the burst location. On a normalized basis, all three ports are equally effective. It is hypothesized that by placing a blowing port at the proper location on the wing, the radial distribution of circulation around a burst vortex can be manipulated to render the vortex stable. Conversely, blowing upstream of the natural burst location will create a local maxima in the circulation profile and make the vortex unstable. Lift coefficient is expected to increase with the downstream movement of the burst location at a given angle of attack. However, there are slight penalties due to the vertical component of bleed momentum. Also, thrust losses, caused by the reduction of engine mass flow due to the bleed air requirement, must be accounted for. Finally, force-balance measurements should be undertaken to verify the anticipated changes in lift, drag, and moment coefficients, and RASB should be tested on aircraft models to verify its effectiveness.

Acknowledgments

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References

[1]Earnshaw, P. B., and Lawford, J. A., "Low-Speed Wind-Tunnel Experiments on a Series of Sharp-Edged Delta Wings," Aeronautical Research Council, R&M 3424, 1964.

[2]Wentz, W. H., and Kohlman, D. L., "Vortex Breakdown on Slender Sharp-Edged Wings," *Journal of Aircraft*, Vol. 8, No. 3, 1971, pp. 156–161.

[3]O'Neil, P. J., Roos, F. W., Kegelman, R. M., Barnett, R. M., and Hawk, J. D., "Investigation of Flow Characteristics of a Developed Vortex," Naval Air Development Center Rept. 89114-60, Warminster, PA, May 1989.

[4]Gad-el-Hak, M., and Blackwelder, R. F., "The Discrete Vortices from a Delta Wing," *AIAA Journal*, Vol. 23, No. 6, 1985, pp. 961, 962.

[5]Hall, M. G., "Vortex Breakdown," *Annual Review of Fluid Mechanics*, Vol. 4, 1972, pp. 195–218.

[6]Leibovich, S., "The Structure of Vortex Breakdown," *Annual Review of Fluid Mechanics*, Vol. 10, 1978, pp. 221–246.

[7]Escudier, M., "Vortex Breakdown: Observations and Explanations," *Progress in Aerospace Sciences*, Vol. 25, No. 2, 1988, pp. 189–229.

[8]Gad-el-Hak, M., and Blackwelder, R. F., "Control of the Discrete Vortices from a Delta Wing," *AIAA Journal*, Vol. 25, No. 8, 1987, pp. 1042–1049.

[9]Gu, W., Robinson, O., and Rockwell, D., "Control of Vortices on a Delta Wing by Leading-Edge Injection," *AIAA Journal*, Vol. 31, No. 7, 1993, pp. 1177–1186.

[10]Meyer, J., and Seginer, A., "Effects of Periodic Spanwise Blowing on Delta-Wing Configuration Characteristics," *AIAA Journal*, Vol. 32, No. 4, 1994, pp. 708–715.

[11]Malcolm, G. N., and Skow, A. M., "Flow Visualization Study of Vortex Manipulation of Fighter Configurations at High Angles of Attack," AGARD CP-413, June 1987.

[12]Trebble, W. J. G., "Exploratory Investigation of the Effects of Blowing from the Leading Edge of a Delta Wing," Aeronautics and Research Council, R&M 3518, April 1966.

[13]Anglin, E. L., and Satran, D., "Effects of Spanwise Blowing on Two Fighter Airplane Configurations," *Journal of Aircraft*, Vol. 17, No. 12, 1980, pp. 883–889.

[14]Bradley, R. G., and Wray, W. O., "A Conceptual Study of Leading-Edge-Vortex Enhancement by Blowing," *Journal of Aircraft*, Vol. 11, No. 1, 1974, pp. 33–38.

[15]Seginer, A., and Salomon, M., "Performing Augmentation of a 60-Degree Delta Aircraft Configuration by Spanwise Blowing," *Journal of Aircraft*, Vol. 23, No. 11, 1986, pp. 801–807.

[16]Lee, K. T., and Roberts, L., "Controlled Vortical Flow on Delta Wings Through Unsteady Leading Edge Blowing," NASA Paper 90-16712, Jan. 1990.

[17]Wood, N. J., Roberts, L., and Lee, K. T., "The Control of Vortical Flow on a Delta Wing at High Angles of Attack," AIAA Paper 87-2278, Aug. 1987.

[18]Wood, N. J., and Roberts, L., "Control of Vortical Lift on Delta Wings by Tangential Leading Edge Blowing," *Journal of Aircraft*, Vol. 25, No. 3, 1988, pp. 236–243.

[19]Rayleigh, L., "On the Dynamics of Revolving Fluids," *Proceedings of the Royal Society of London, Series A 93*, 1916, pp. 148–154.

[20]Fitzpatrick, K., Johari, H., and Olinger, D., "A Visual Study of Recessed Angled Spanwise Blowing Method on a Delta Wing," AIAA Paper 93-3246, July 1993.

[21]Stahl, W. H., Mahmood, M., and Asghar, A., "Experimental Investigations of the Vortex Flow on Delta Wings at High Incidence," *AIAA Journal*, Vol. 30, No. 4, 1992, pp. 1027–1032.

[22]Jones, J. P., "On the Explanation of Vortex Breakdown," *Proceedings of the IUTAM Symposium on Vortex Breakdown*, Univ. of Michigan, Ann Arbor, MI, 1964.

[23]Leibovich, S., and Stewartson, K., "A Sufficient Condition for the Instability of Columnar Vortices," *Journal of Fluid Mechanics*, Vol. 126, Jan. 1983, pp. 335–356.

[24]Visser, K. D., and Nelson, R. C., "Measurements of Circulation and Vorticity in the Leading-Edge Vortex of a Delta Wing," *AIAA Journal*, Vol. 31, No. 1, 1993, pp. 104–111.

[25]Bossel, H. H., "Stagnation Criterion for Vortex Flows," *AIAA Journal*, Vol. 6, No. 6, 1968, pp. 1192, 1193.

[26]Wood, N. J., Roberts, L., and Celik, Z., "Control of Asymmetric Vortical Flows over Delta Wings at High Angle of Attack," *Journal of Aircraft*, Vol. 27, No. 5, 1990, pp. 429–435.