AIAA JOURNAL
Vol. 32, No. 4, April 1994

Effects of Trailing-Edge Jet Entrainment on Delta Wing Vortices

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This paper examines the effects of trailing-edge jet entrainment on the streamwise vortices over a delta wing. Although studies have examined the effects of leading-edge suction and blowing on the burst location of delta wing vortices, very little research has focused on the effects of trailing-edge jet exhaust on the burst location. Using a 60-deg delta wing model in a water tunnel with dye to mark the vortex core, it was possible to visualize how the location of the vortex breakdown changes with trailing-edge jet velocity. This research has determined that at moderate angles of attack it is possible to delay the burst location up to 18% of the chord by increasing the flow velocity from the exhaust ports. In addition, at higher angles of attack, the trailing-edge jets stabilized the asymmetric separated vortices by reattaching the flow and moving the burst location aft on the wing.

Nomenclature

V_r = trailing-edge jet velocity ratio, V_{jet}/V_∞
V_∞ = freestream velocity
V_{jet} = jet exit velocity

Introduction

DELTA wing vortex dynamics and the effects on aircraft performance have become an important research topic in recent years. The most significant aerodynamic aspect of delta wings at moderate and high angles of attack is the formation of leading-edge vortices. These streamwise vortices are formed as the flow separates at the leading edge and rolls over the upper surface. At high angles of attack, approximately half of the lift generated on a delta wing is a result of these vortices There are several variables that influence delta wing vortex dynamics. Some of these variables include angle of attack, leading-edge geometry, wing thickness, sweep angle, and freestream conditions. The most significant feature that can be influenced by these variables is the bursting process of the vortices.

Several theories governing vortex bursting have been proposed.[1-4] As the flow separates, it curls over the leading edge to form a well-defined vortex. The flow in core of the vortex accelerates as it travels downstream and can reach values as high as three times the freestream velocity.[3] At some point downstream, the core velocity will stagnate, and the vortex will burst. If the angle of attack is increased sufficiently, the vortex burst location will move upstream over the wing with a highly turbulent, wakelike flow replacing the organized flow of the vortex and its core.

In the study by Sarpkaya,[3] he identifies three types of vortex breakdown. The most common form of vortex breakdown is the spiral breakdown. After some distance, the flow along the vortex core rapidly decelerates until it reaches a stagnation point. At this bursting location, the core will deviate from its centerline and form a helixlike structure with a diameter much larger than the original core. The spiral structure will usually complete three rotations before it breaks down into the wakelike flow.[4] The flow in the center of the spiral will be in an upstream direction between the stagnation point and the wake region. A second and third type of breakdown identified by Sarpkaya are the bubble and the double helix. These types of breakdown are not as prevalent as the spiral breakdown.

It should be noted that at low angles of attack the burst location may be well behind the trailing edge of the wing. As angle of attack is increased and the burst location moves forward of the trailing edge, the lift generated by the vortices will decrease. In addition, at very high angles of attack or with high wing sweep angles, the shedding of the vortices may not always be symmetrical and/or may be separated. As a result of this asymmetry, the forces on either side of the wing will not be equal. The oscillation of the vortices from one side of the wing to the other can induce the phenomenon of wing rock.

To control delta wing aerodynamics, several studies have looked at the effects of suction and blowing on the leading-edge vortices. The study done by Visser et al.[5] examined the effects of blowing near the leading edge and back to 30% chord. They found that the blowing was most effective when located nearest the leading edge. Another study was conducted by Magness et al.[6] that examined the influence of suction as well as blowing. The suction was applied from a tube located at a distance of 0.95 chord, measured along the centerline, and placed out near the leading edge under the burst vortex core. The blowing was introduced to the flow from a port on the surface of the wing typically near the apex. It should be noted that most of the previous studies involved small amounts of mass flow out of the ports, primarily directed at boundary-layer control. A study by Roos and Kegelman[7] examined the effects of a suction wand downstream of the trailing edge. They found the vortex burst location could be changed, but for the specific cases evaluated, only small changes in the integrated forces on the delta wing were measured.

The work presented in this paper examines a different aspect of delta wing vortex control. Whereas previous studies have primarily used boundary-layer blowing/suction, this study concentrates on the effects of large amounts of mass injection through trailing edge jets. It is proposed that the entrainment from jets, or engines, at the trailing-edge of the wing can be used to control the leading-edge vortices. Thus, the influence of the trailing-edge jets on vortex bursting and asymmetry was examined for a delta wing at various angles of attack.

Experimental Setup

The model for these experiments was a 60-deg swept delta wing (Fig. 1). The leading edges of the wing were sharp with a 60-deg

Received June 21, 1993; revision received Oct. 11, 1993; accepted for publication Oct. 21, 1993; presented as Paper 94-0072 at the AIAA 31st Aerospace Sciences Meeting, Reno, NV, Jan. 10–13, 1994.

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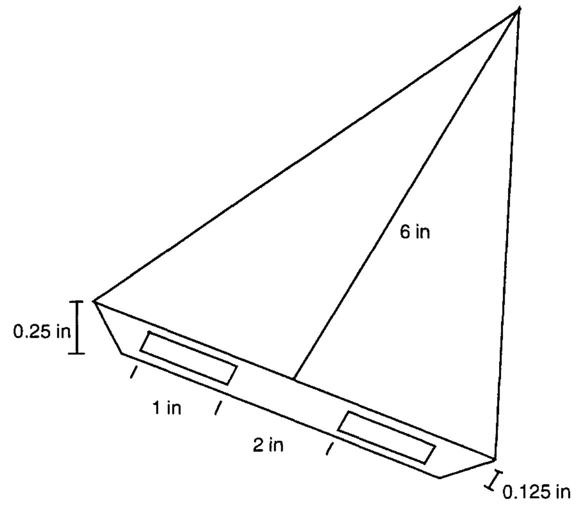

Fig. 1 Delta wing model with 60-deg sweep, 60-deg underside leading-edge bevels, and high-aspect-ratio rectangular trailing-edge jets.

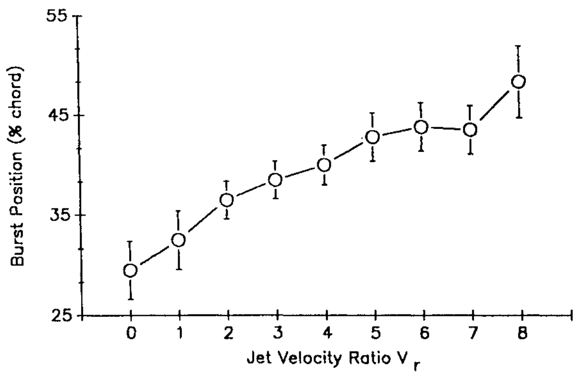

Fig. 2 Plot of burst location vs V_r for 20-deg angle of attack. Each point is an average of four data measurements with error bars for the standard deviation.

underside bevel. The jet exhaust ports were high aspect ratio (8:1) rectangular jets along the trailing edge of the model. This configuration was chosen due to geometrical similarity to the F-117 stealth fighter and because the 60-deg planform has been used in previous studies. An Eidetics 0.46 × 0.46 m water tunnel located in the United States Air Force Academy Aeronautics Laboratory was used for these studies. The water-tunnel velocity was set at 7.62 ± 0.3 cm/s. This provided a Reynolds number per unit foot of 2.07×10^4. To alleviate wake perturbations the model was sting mounted from the underside and an internal cavity, also ported from the underside of the wing, was used to supply the mass flow for the jets. To insure the flow would exit from the model parallel to the freestream, several thin-walled tubes were inserted into the exhaust ports. At this freestream velocity, trailing-edge jet to freestream velocity ratios V_r were varied from 0 to 8, in increments of 1.0. The chosen velocity ratios and trailing-edge jet exit areas are representative of actual aircraft parameters.

Flow visualization of the delta wing vortices was accomplished by staining the core of the vortex with dye. The dye was injected into the flow 1.6 mm from the apex on the underside of the leading edges. The dye streaklines were illuminated from the side and photographed with a 35-mm camera.

A transit was used to insure that the model was set up in the tunnel at 0 deg yaw, pitch, and roll. After the initial conditions were set, the model could be pitched by using a crescent traverse with an error of ± 0.05 deg in angle of attack. The angles of attack used for this study were 0, 10, 20, and 30 deg. For most combinations of V_r and angle of attack, the experiment was repeated so that two sets of data could be compared for repeatability. From these sets of data, measurements were made for the burst location, core position with respect to the centerline, and the spreading angle of the burst vortex.

Results

Vortex Burst Location

With the model at 0-deg angle of attack, the dye bled over the leading edge and spread into the upper surface boundary layer of the wing. There were no leading-edge vortices, and, in addition, no noticeable flow disturbances due to the dye injection were seen. The flow appeared to be relatively symmetric about the centerline. As V_r was varied from 0 to 8, no changes were observed.

At 10-deg angle of attack and V_r equal to 0.0, prominent leading-edge vortices were present. The burst location of these vortices was aft of the trailing edge, and again the flow appeared to be relatively symmetric. The bursting process followed that of the spiral mode, as discussed earlier. As V_r was increased to 8.0, no discernible changes in burst location were seen. It should be noted at this point that the burst location aft of the trailing-edge is probably dominated by the blunt finite trailing-edge thickness of the model, as it significantly affects the adverse pressure gradient in that region.

When the model was placed at 20-deg angle of attack, dramatic differences were seen in the bursting of the vortices. The burst location vs V_r is plotted in Fig. 2. Each data point shows the averaged measurements for the left and right burst locations in both sets of data. At $V_r = 0.0$, the burst location had an average value of 29% chord. As V_r was incremented, the burst location moved to 47% chord. Details of this process can be seen in Figs. 3a and 3b, which show the leading-edge vortex system at $V_r = 0.0$ and 8.0, respectively. In addition to the burst location movement, these photographs show relative symmetry between the left and right vortices and clearly depict the spiral breakdown mode.

As the angle of attack was increased to 30 deg and with $V_r = 0.0$, the vortex burst location moved to the apex of the wing. In addition, the completely burst vortices oscillated from one side of the wing to the other. This can be seen in Figs. 3c and 3d, which were taken at different times. The period of this oscillation was about 20 s. Although similar oscillations of burst vortices at the apex have been observed by co-workers, no documentation of this phenomenon could be found in the literature. At this time little insight can be given on the physical mechanism behind this process, although it could be speculated that small instabilities in the test facility, model imperfections, or model positioning could be responsible. As V_r was increased to 2.0 and 3.0, it appeared that the period of oscillation was increased and the burst vortices began to stabilize. By $V_r = 5.0$, small vortex cores were noticed on both sides of the wing (Fig. 3e). Also, these vortices were stabilized without any oscillation. The bursting location was extended to 17% of the chord and remained symmetric when V_r was increased to 8.0 (Fig. 3f).

Vortex Core Position

In addition to measuring the change of burst location as V_r was increased, two other variables were measured to determine how the vortex dynamics were affected by the trailing-edge blowing. The vortex core position was measured by the angle between the centerline of the wing and the vortex core. At both 10- and 20-deg angle of attack, where a vortex core could be seen, the angle was 17 ±1 deg. There was no positive correlation between small changes in the vortex core position and V_r. At 30-deg angle of attack and with V_r greater than 5.0, the vortex core angle was again measured to be approximately 17 deg.

Spreading Angle

The spreading angle is a measurement of the divergence of the burst vortex once it transitioned to a turbulent state. With spiral

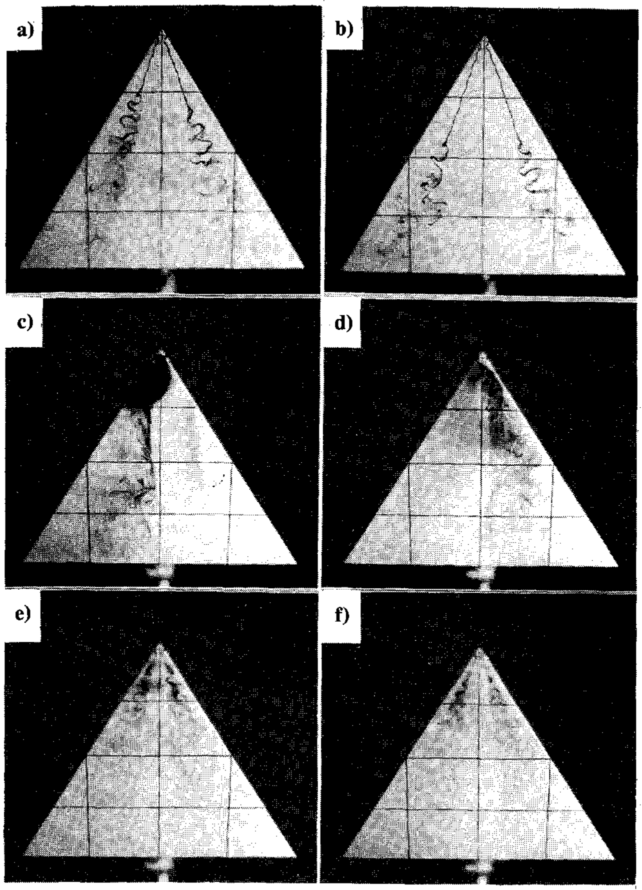

Fig. 3 Photographs of delta wing vortices where a) and b) show burst delay at 20 deg with increased V_r, c) and d) show oscillation of burst vortices at 30 deg, and e) and f) show stabilization and delay of burst as V_r increases: a) $\alpha = 20$ deg, $V_r = 0.0$; b) $\alpha = 20$ deg, $V_r = 8.0$; c) $\alpha = 30$ deg, $V_r = 0.0$, time 1; d) $\alpha = 30$ deg, $V_r = 0.0$, time 2; e) $\alpha = 30$ deg, $V_r = 5.0$; and f) $\alpha = 30$ deg, $V_r = 8.0$.

vortex breakdown, the angle could be measured using the burst location and the edges of the spirals. These data were only measured at 20 deg angle of attack, since it was not clearly defined at 10 deg where the burst location was aft of the trailing edge, or at 30 deg where the burst location was close to the apex. The values of the spreading angle varied from 24 to 32 deg, but again there was no positive correlation between these values and V_r.

Discussion

The results of trailing-edge jet entrainment on delta wing vortex kinematics demonstrate that it is possible to control vortex bursting and asymmetry. By increasing V_r to 8.0, the burst location of the leading-edge vortices was delayed by up to 18% of the chord. By delaying the burst location, a more cohesive vortex remains closer to the wing surface and thus should result in an increase in the lift. However, the total amount of vorticity generated at the leading edge does not change; it is simply redistributed from a cohesive vortex to a burst vortex that is spread over a broader extent. The distribution and rate of dissipation of the vorticity in the burst vortex would become factors in determining the amount of lift generated. In an aircraft environment at higher Reynolds numbers, the leading-edge vortices would exist in a fully turbulent fashion. Again, the bursting process will redistribute the vorticity over a much broader region, and the ability to change the burst location could affect aircraft performance and controllability. Without detailed measurements of the vorticity field, it is difficult to speculate at this time as to the actual effect on integrated lift or lateral stability.

Perhaps a more important result of jet entrainment on the leading-edge vortices is the ability to control the asymmetric nature of flow at high angles of attack. This was clearly demonstrated at 30-deg angle of attack where the flow was initially completely burst, separated, and asymmetric. Not only were the burst vortices reattached and extended over the wing, they were stabilized and became symmetric. This suggests a potential flow control methodology for the undesirable condition of wing rock. Although the current study did not show any appreciable change in the vortex core location or spreading angle due to jet entrainment, it may be possible to vary these characteristics by using asymmetric blowing or by changing the jet location and/or using differential and vectored thrust.

Modern delta wing aircraft fly in a dynamic environment that includes rapid changes in angle of attack and coupled rolling motions, which have been shown to affect vortex dynamics. The potential to control the resulting vortex-dominated flows with specifically programed thrust/engine settings alludes to performance enhancement with little or no penalty.

Conclusion

This study examined the effects of trailing-edge jet entrainment on the flow over delta wings. Using a 60-deg delta wing model with high-aspect-ratio trailing-edge jets and V_j/V_∞ ratios of 0.0–8.0, significant events were observed.

It has been shown that trailing-edge mass injection can be used to move the burst location of the leading-edge vortices back by up to 18% of the chord. Also, in addition to delaying the burst location, trailing-edge mass injection can be used to reduce the asymmetry, commonly found in the leading-edge vortices over delta wings at high angles of attack. By reducing the asymmetry, trailing-edge jet entrainment may provide a technique to prevent undesirable conditions like wing rock. The delayed burst location provided by the trailing-edge blowing could possibly result in higher values of lift. However, to determine the actual effects on lift, experiments employing force balances and/or surface pressure measurements need to be conducted.

Acknowledgments

The authors would like to acknowledge discussions concerning this study with A. Krothapalli at Florida State University and the technical assistance of J. Philp and R. Durmon at the United States Air Force Academy.

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