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Effects of Blowing on Delta Wing Vortices During Dynamic Pitching

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An experimental investigation was conducted in a water tunnel to identify the effects of apex blowing on two delta wing models undergoing constant pitch-rate motion. One wing was of 60-deg sweep and the other was of 76-deg sweep. Flow visualization methods were utilized to determine vortex burst locations for a range of pitch-up and pitch-down rates, apex jet strengths, and blowing directions. Results indicate, individually, that blowing direction on the 60-deg wing and blowing rate on the 76-deg wing have the greatest effect on vortex behavior under both static and dynamic pitch-up conditions. Vortex improvements, for any blowing direction or rate examined, are most dramatic during dynamic pitch-down conditions. In this case, the use of blowing resulted in the reformation of unburst vortices with significant length.

Nomenclature

C_μ = jet blowing coefficient, $m_j V_j / qS$
C_r = wing root chord
k = nondimensional pitch rate, $\alpha' C_r / 2V_\infty$
m_j = mass flow rate from jet
q = freestream dynamic pressure, $0.5\rho V_\infty^2$
R_e = Reynolds number, $V_\infty C_r / \nu$
S = wing area
V_∞ = freestream tunnel velocity
V_j = jet exit velocity
α = wing angle of attack, deg
α' = pitch-up or pitch-down rate, deg/s
ν = freestream flow kinematic viscosity
ρ = freestream flow density

Introduction

IDENTIFYING the behavior of vortical flows produced by highly swept leading-edge surfaces is important for understanding modern aircraft performance. Many current aircraft utilize strakes or delta wind planforms to generate vortices at moderate angles of attack. The presence of these vortical flows can greatly enhance vehicle performance. For example, vortices can account for up to 30% of the total lift generated by delta wing aircraft operating at moderate angles of attack.[1]

Unfortunately, the benefits produced by vortical flows diminish as the aircraft angle of attack increases to larger values due to the occurrence of vortex bursting. Vortex bursting occurs when instabilities develop and the core flow stagnates. Identification of methods which delay or avoid vortex bursting are desirable if modern aircraft are to obtain greater maneuverability.

Delta wing planforms have been the subject of much study due to their simple geometry and strong vortical flow development. Indeed, the position, strength, and persistence of delta wing vortices have been well-documented by many investigators under both static[2–4] (constant angle of attack) and, more recently, dynamic[5–8] (time varying angle of attack) conditions. In steady state one observes that the vortices become unstable and shorter, due to bursting, as wing angle of attack increases. As was previously mentioned, this result is undesirable since the wing aerodynamic capability diminishes when bursting occurs. During dynamic pitching maneuvers, both up and down, a vortex burst location hysteresis or time lag develops. In simple terms, the vortex burst location is different under dynamic as compared to static conditions. For example, compared to static conditions at a given angle of attack, the vortex burst location on the wing is further aft during pitch-up and further forward during pitch-down. The exact hysteresis behavior and magnitude roughly depends on the pitch range and rate experienced. Obviously, delayed bursting (longer vortex) during either pitch-up or pitch-down conditions is desired. Therefore, methods of achieving these goals are of notable interest.

Jet blowing has been shown to be an effective means for delaying vortex bursting and significantly improving the aerodynamic performance of delta wings under static conditions.[9,10] The exact performance increase one obtains depends on a number of factors, including notably the jet position, strength, and blowing direction. Unfortunately, no information on the performance of delta wings utilizing jet blowing during dynamic pitching conditions exist.

An experimental investigation was conducted in a water tunnel to identify the aerodynamic effect of jet blowing on two simple delta wing models undergoing ramp-type pitching motion. Flow visualization methods were utilized to track vortex bursting locations for a range of model pitch-rates, blowing coefficients, and jet directions.

Experimental Apparatus and Method

The experimental investigation was conducted in a 0.61 × 0.91 meter water tunnel facility located at the Wichita State University, National Institute for Aviation Research (NIAR). This is a horizontal axis closed loop tunnel which offers excellent optical access and flow visualization capabilities. Respective test speeds and Reynolds numbers ranging from 0–0.31 m/s and 0–18,290 (per meter) are possible. During the current investigation a flow speed of 0.12 m/s, corresponding to an approximate Reynolds number of 33,000 based on model root chord, was utilized. For the present work, the tunnel test

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section area was not fitted with a top boundary. As a result the tunnel was operating with a free surface much like a water channel.

Models

Two delta wing models of 60- and 76-deg sweep, and 2.31 and 1.00 aspect ratio respectively, were made from 1.27-mm-thick aluminum. The root chord for the 60-deg wing was 0.27 and 0.31 m for the 76-deg sweep wing. All edges were sharp and symmetrically beveled. The 60-deg sweep wing was beveled at 5.7 deg and 76-deg sweep wing was beveled at 11.3 deg. Each model was held by a 9.5-mm-diam sting which was connected to the wing lower surface trailing edge. A grid, for referencing vortex burst locations during experiments, was painted on each wing upper surface.

Dynamic Model Mount

Models were positioned in the tunnel test section on a unique mount which allows for dynamic high angle-of-attack testing. Figures 1a and 1b show a simple schematic diagram of the mount as positioned within the tunnel. As can be seen, test models are mounted on a sting support connected to the edge of a rotating turntable, which is in turn enclosed and held by a 19.05-mm-thick splitter plate mounted next to the tunnel side wall. Turntable position is controlled by a motor driven belt which allows for 360-deg of rotation at continuously variable rates up to (α') 30 deg/s. Ramp type, or constant angular rate of change, model pitch-up, or pitch-down motion could therefore be produced. During this investigation, the models were rotated about the 50% chord location at five nondimensional pitch-up and pitch-down rates. Model angle of attack was identified by a pointer and index marks on the turntable and splitter plate, respectively. Model yaw angle was set to zero prior to all testing. Lighting and flow visualization is not adversely effected, since the mount is made primarily of Plexiglas®.

The 60- and 76-deg sweep models occupied at 90-deg angle of attack, respectively, 7 and 4% of the tunnel test section area. The exact effect of blockage on the measured results were not identified or predicted. However, no noticeable effects of model blockage or motion on the tunnel approach flow were observed. The test section flow speed remained constant, within the accuracy of the facility speed indicator (0.003 m/s), during pitching motion of the model.

Flow Visualization Method

As has been mentioned previously, model vortex behavior was identified for all test conditions using flow visualization methods. Specifically, a 1.58-mm (outside) diameter stainless steel tube was positioned along the wing upper surface centerline such that dye was introduced, near the apex, into the starboard (right) wing vortex core. By injecting dye at a very slow rate into the core flow, one can observe the development of instabilities or flow stagnation and thus identify the occurrence of vortex bursting. A videotape recorder was used to record the vortex behavior at all times during tests. The videos were later reviewed and bursting locations were identified relative to grid lines drawn on each model. This method is assumed to provide vortex bursting location accuracy within about 2–3% (based on the root chord length).

Jet Blowing Technique

A pressurized supply system, fitted to the water tunnel facility, provided water for producing jet flows during the blowing tests. A jet was introduced by a 3.17-mm (outside) diameter Tygon tube positioned to blow in one of two directions next to and tangent to the wing surface. Only a single jet, instead of two, was used to minimize potential adverse aerodynamic interference effects associated with running more jet lines to the wing apex region. In light of this concern, a Tygon tube was carefully routed from the wing lower surface over the port (left) leading edge to either the center or starboard (right) upper surface 10% chord location. An appropriately bent 1.58-mm-diam steel tube held the Tygon tube such that it would not move relative to the wing during dynamic tests. Figure 2 shows a simple close-up diagram of the nozzle installation on the front, approximately 15%, of the wing model.

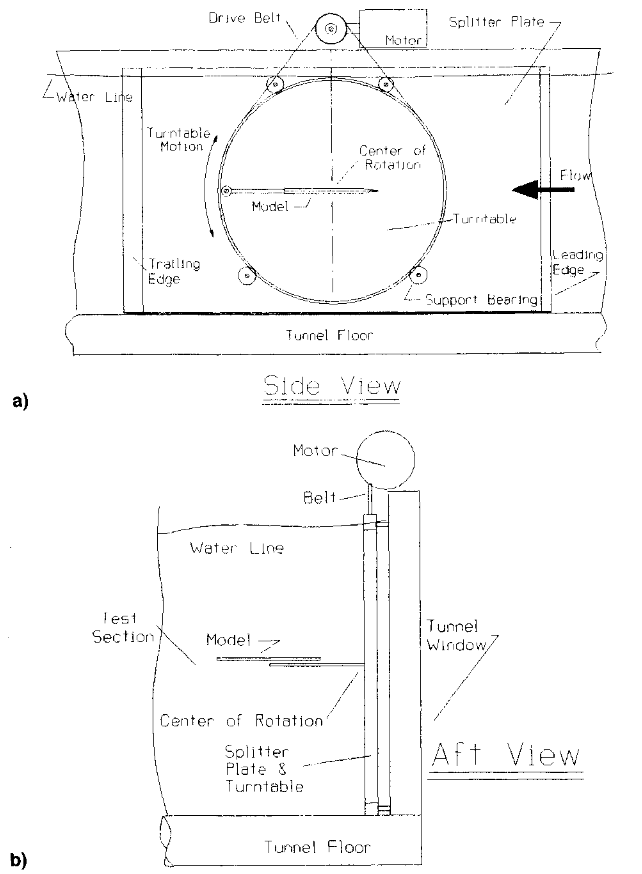

Fig. 1 Diagram of dynamic model mount installation within water tunnel test section.

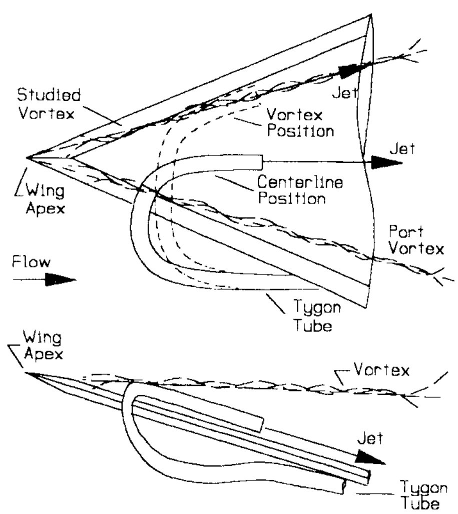

Fig. 2 Schematic of jet nozzle positions, for centerline and vortex blowing directions. (Only front 15% of model shown.)

As Fig. 2 also shows, two blowing directions were examined. In the centerline position the jet blew along the model centerline, and in the vortex position the jet blew in a direction parallel to the leading-edge vortex. In both cases, the jet was positioned to blow directly next to and tangent to the model surface. Three blowing rates or coefficients (C_μ) were used during the investigation.

As was noted previously, only the behavior of the starboard leading-edge vortex was recorded during the experiments. Cursory flow visualization experiments performed under static conditions with the jet line installed, but not operating, indicated that the port vortex character was not adversely affected for either the centerline or vortex jet nozzle positions. Unfortunately, the effect of blowing or pitching motion on the port side vortex could not be identified due to the difficulty of routing a second dye line for visualization purposes.

Test Procedure

The vortex behavior of each model, at a flow speed of 0.12 m/s, was observed for a wide range of operating conditions. Nondimensional pitch-up and pitch-down rates of $k = 0.0$, 0.05, 0.10, 0.15, and 0.20, and blowing coefficients of $C_\mu =$ 0.00, 0.04, and 0.06 were utilized. Only constant pitch-rate motion, up and down, was investigated. Sinusoidal or other motion types were not examined. As was mentioned earlier, jet blowing along the vortex axis and model centerline directions were also studied.

The angle-of-attack (α) range examined in static and dynamic tests differed. During static ($k = 0.0$) conditions, vortex burst location measurements were obtained at 5-deg increments from 0 to 90 deg. However, during dynamic pitch-up conditions an angle-of-attack range from 15 to 90 deg was used. The initial angle of 15 deg was utilized since at this angle relatively strong vortices existed over each wing. During pitch-down tests, an angle-of-attack range from 40 to 0 deg was selected for testing. The 40-deg initial angle value was selected arbitrarily. For this case (as will be shown) the 60-deg wing had a completely burst vortex and the 76-deg wing had a partially unburst vortex.

Results

Flow visualization experiments were conducted on both delta wing models for the dynamic pitch-rate, blowing coefficient, and angle-of-attack ranges previously identified. The following sections describe the behavior of the vortical flow, with emphasis on vortex burst location identification. More detailed information can be found in Ref. 11. It should be noted that in all figures showing results, the vortex burst point is either at or downstream of the wing trailing edge when the burst location is plotted as 100%.

Static Conditions, No Blowing

Figure 3 shows a plot of vortex burst locations (in percent chord) vs angle of attack for each wing under static or zero pitch-rate conditions without jet apex blowing. As expected, the vortex burst points move forward as angle of attack increases and the 76-deg sweep wing shows a longer unburst vortex than the 60-deg wing at any given angle. Unfortunately, below 15 deg, angle-of-attack identification of a vortex burst location for the 60-deg wing was difficult, since the exact behavior of the vortex was difficult to identify using the dye visualization technique. In contrast, the 76-deg wing vortex character was very easy to observe at such small angles of attack.

Dynamic Conditions, No Blowing

Figures 4 and 5 show the effect of the nondimensional pitch-up rate on vortex burst position for both wings, without apex jet blowing. As can be observed in Figs. 4 and 5, a vortex burst lag or delay develops as the pitch-rate increases. The basic curve describing the burst location, vs angle of attack, for the 60-deg wing (Fig. 4) moves laterally to higher angles as the k increases. In fact, pitching at $k = 0.20$ produces a 20-deg delay in wing vortex bursting position when compared to static conditions. The general behavior of the burst vs angle-of-attack curves (Fig. 5) for the 76-deg sweep wing is slightly different than that observed for the 60-deg wing. Differences are most noticeable for the two highest pitch-rates and at larger angles of attack. Complete bursting of the 76-

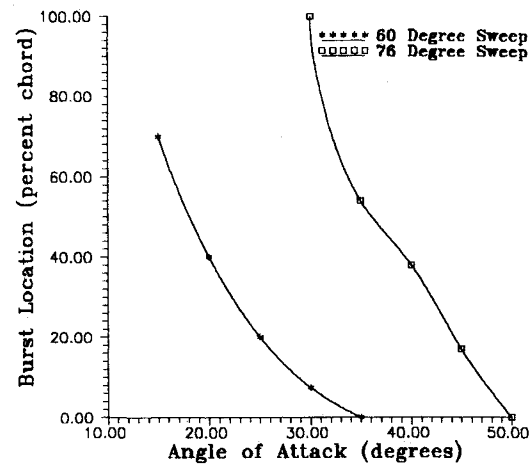

Fig. 3 Static burst locations for 60- and 76-deg delta wings.

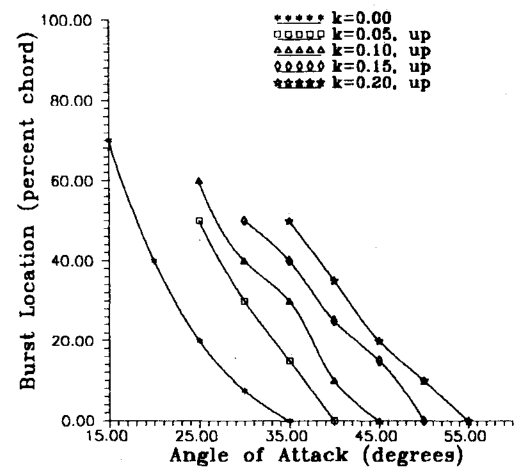

Fig. 4 Burst location for 60-deg wing, pitch-up from 15 deg.

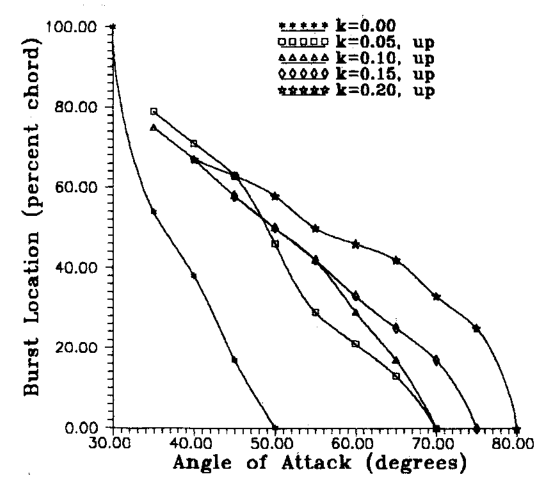

Fig. 5 Burst location for 76-deg wing, pitch-up from 15 deg.

deg wing vortex is delayed, for the highest pitch-rate ($k = 0.20$), by 30 deg when compared to the static condition ($k = 0.0$). Unfortunately, pitch rate effects at low angles of attack are difficult to identify since differences are within the previously stated 2–3% error bounds associated with the measurement method utilized.

When pitching the wings downward, from an initial angle of attack of 40 deg, downstream motion of the vortex burst point was notably delayed. Figure 6 shows the 76-deg wing vortex behavior during pitch-down conditions. Interestingly, the vortex burst location moved aft only for the two lowest pitch-down rates examined. The burst location remained fixed for the two highest pitch rates. Comparison of dynamic and static results indicates that a shorter unburst vortex exists over the 76-deg sweep wing during pitch-down motion. Results for the 60-deg wing were not obtained since no length of unburst vortex developed during the pitch-down motion. The pitching motion (downward) simply occurred faster than the burst point could move downstream.

Static Conditions, with Blowing

Figures 7 and 8 identify the effect of two wing apex blowing coefficients and directions, under static ($k = 0.0$) conditions, for both wings. For the following plots, the words "center" or "vortex" and "at 0.04 or 0.06" indicate, respectively, jet blowing direction and rate. For example, "center, at 0.06" means the jet was blowing tangent to the surface along the model centerline at $C_\mu = 0.06$.

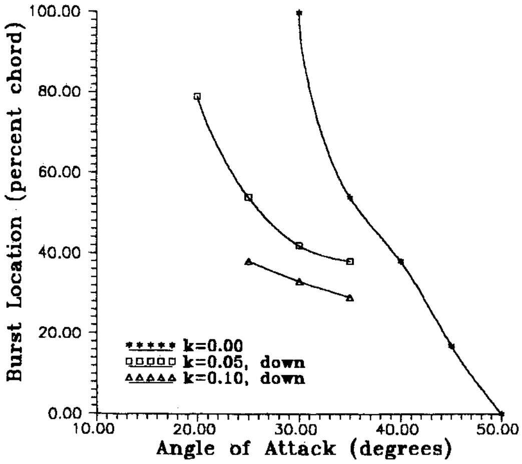

Fig. 6 Burst location for 76-deg wing, during pitch-down from 40 deg.

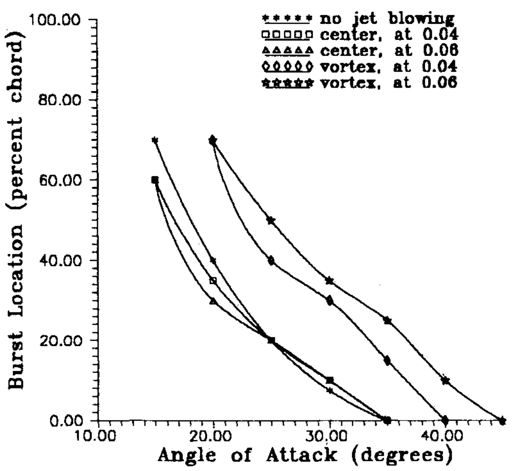

Fig. 7 Comparison between blowing cases for 60-deg wing ($k = 0.0$).

As can be seen in Fig. 7, blowing parallel to the 60-deg wing vortex appears to produce the greatest increase in unburst vortex length as model angle of attack is increased. For model centerline blowing cases, an apparent initial degradation and then a slight improvement in vortex bursting behavior is noted as angle of attack increases. The significance of these last results are difficult to access however, since the differences are close to and within the stated error bounds (2–3% chord) of the measurements. As can be seen, the direction of blowing, as opposed to blowing rate, appears to have more impact on the 60-deg wing vortex behavior (for the cases examined in this investigation).

Figure 8 shows that centerline blowing on the 76-deg wing, at the highest rate, provides the greatest vortex burst delay improvement. Interestingly, the other blowing directions and rates also show a reasonable bursting delay over the no-blowing case. However, blowing rate, as opposed to direction, appears to have more impact. Results for the vortex blowing direction, at the highest blowing rate, are seen to approach results for the centerline case over the 40–50-deg angle-of-attack range. This effect could be due to the fact that for the higher sweep wing there is relatively little difference between the jet centerline and vortex blowing directions. Blowing rate may have more effect on the vortex behavior of the 76-deg wing as a result.

Dynamic Conditions, with Blowing

For purposes of brevity, only the $k = 0.05$ pitch rate (up and down) results will be discussed in the following section. The other pitch-up or pitch-down (k) rates examined in the investigation produced similar trends. Detailed results for the other cases can be found in Ref. 11.

The vortex burst behavior for both wings with blowing, at a nondimensional pitch-up rate of $k = 0.05$, is shown in Figs. 9 and 10. As can be seen in Fig. 9, blowing parallel to the 60-deg wing vortex core results in the best vortex behavior. Blowing at $C_\mu = 0.04$ produces the greatest improvement over the largest angle-of-attack range. However, blowing along the model centerline results in a notable unburst vortex length reduction when compared to the no-blowing case. As was noted for static conditions, the direction of blowing appears more important for the 60-deg wing. Figure 10 shows that blowing in either the vortex or centerline direction improves the vortex burst behavior of the 76-deg sweep wing over virtually all angles of attack. Again, as was seen for the 76-deg wing under static conditions, blowing at the highest rate in either direction appears to produce the best potential performance improvement.

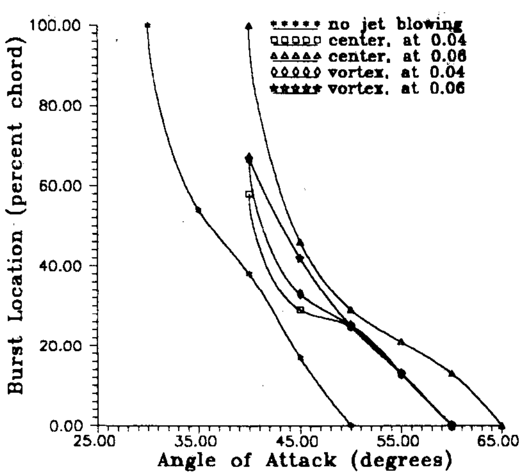

Fig. 8 Comparison between blowing cases for 76-deg wing ($k = 0.0$).

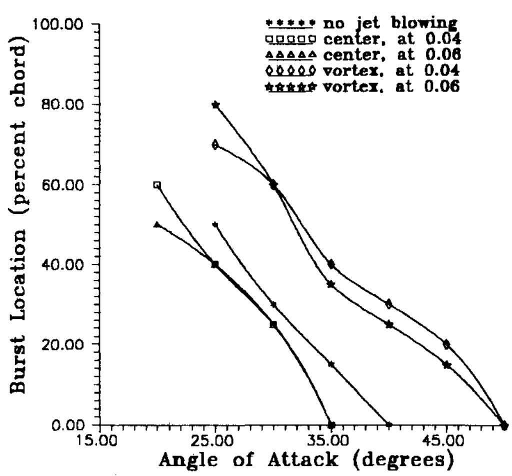

Fig. 9 Effects of blowing during pitch-up for 60-deg wing ($k = 0.05$).

The 60- and 76-deg delta wing vortex behavior during pitch-down conditions with jet blowing is shown in Figs. 11 and 12. As was discussed earlier, without blowing, the 60-deg wing vortex would not re-establish itself in an unburst form for any of the pitch-down rates examined. Significantly, in the current case Fig. 11 shows that the wing vortex burst location moves aft as a result of blowing in either the centerline or vortex directions. Jet blowing in the vortex direction, at either rate tested, has the greatest effect. Figure 12 similarly indicates

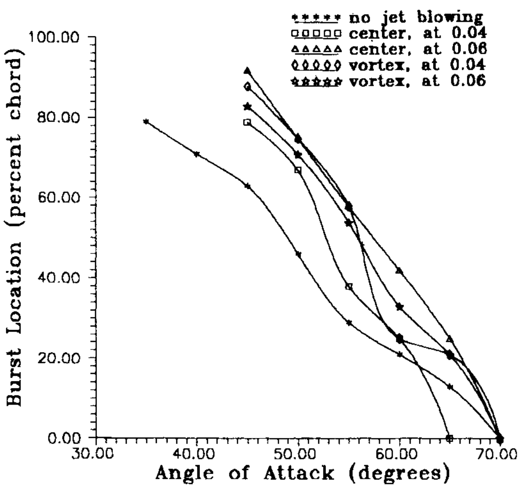

Fig. 10 Effects of blowing during pitch-up for 76-deg wing (k = 0.05).

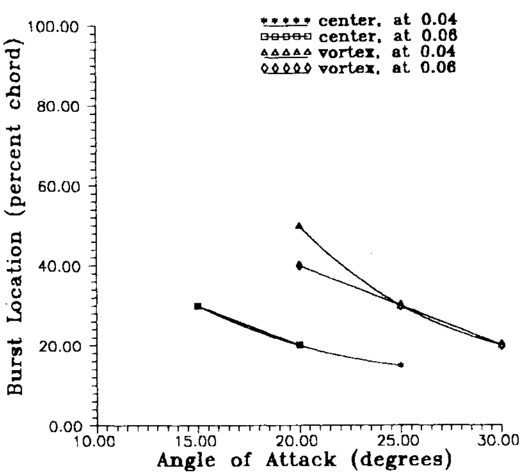

Fig. 11 Effects of blowing during pitch-down for 60-deg wing (k = 0.05).

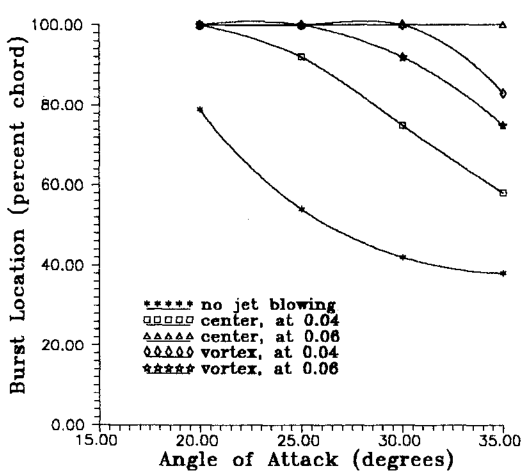

Fig. 12 Effects of blowing during pitch-down, for 76-deg wing (k = 0.05).

that blowing in any direction improves the 76-deg sweep wing vortex burst behavior. Blowing along the 76-deg wing centerline at the highest rate results in a significant improvement in vortex behavior during pitch-down when compared to no jet conditions. As was noted at the start of the Results section, the vortex burst point is either at or downstream of the wing trailing edge when the burst location is plotted as 100%.

Conclusions

An experimental investigation was undertaken to identify the effect of jet blowing on delta wing vortex behavior during dynamic motion. A range of pitch-up and pitch-down rates, jet blowing rates, and blowing directions were examined for delta wings of 60- and 70-deg sweep. The following conclusions, based on the investigation results, are offered:

1) As has been previously observed by other investigators, dynamic pitch-up motion produces a vortex burst delay. The delay in vortex burst point movement forward is greatest at the highest pitching rates.

2) For the dynamic pitch-down rates examined, aft movement of the vortex burst location occurred only for the 76-deg sweep wing and only at the two lowest pitch-down rates.

3) Under static (k = 0.0) conditions, blowing tangent to the wing surface and parallel with the 60-deg wing vortex core and the 76-deg wing centerline resulted in the greatest unburst vortex length. However, the effect of blowing direction appeared more important for the 60-deg wing and the effect of blowing rate appeared more important for the 76-deg wing.

4) Blowing parallel to the 60-deg wing vortex core and along the 76-deg wing centerline at the highest rate provided the greatest improvement in vortex behavior under dynamic pitch-up conditions. As was noted for the static conditions, blowing direction is more important for the 60-deg wing and blowing rate is more important for the 76-deg wing.

5) Other blowing directions, rates, and nozzle positions will likely produce different results under dynamic conditions. Further investigation in this area is warranted.

6) Blowing, at any rate, or in any direction examined, improved aft movement of the vortex burst point notably during dynamic pitch-down conditions. Blowing parallel to the 60-deg wing vortex core and along the 76-deg wing centerline produces a significant improvement in unburst vortex reformation during pitch-down conditions.

7) As has been noted, blowing and flow visualization was performed only on the starboard wing vortex. The exact behavior and impact of the port vortex on the results was not identified. The impact of the jet and dye visualization lines on the port vortex behavior under static conditions appeared minimal. Unfortunately, the experimental apparatus and method utilized did not allow for identification of port vortex effects during blowing or dynamic tests. It is conceivable that the behavior of the starboard vortex was modified by the behavior of the port vortex. Further investigation into these potential effects should be pursued.

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