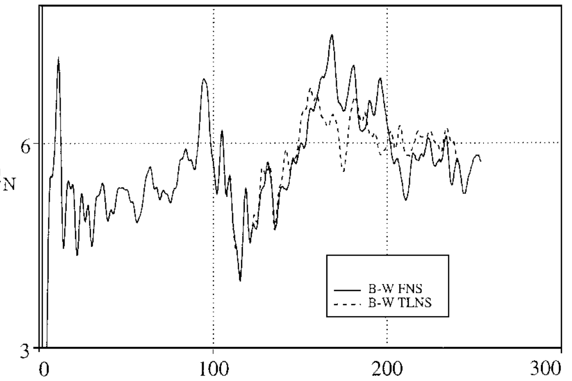
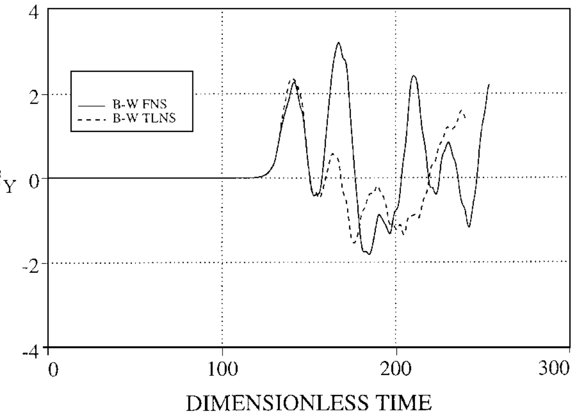


a) **Normal-force coefficient**



b) **Side-force coefficient**

Fig. 3 Time history; $\alpha = 60$ deg.

path of evolution. Such behavior of asymmetric solutions is discussed fully in Ref. 15.

Conclusions

All three codes tested (FS TLNS, BW TLNS, and BW FNS) gave virtually the same results for all three angles of attack (10, 40, and 60 deg) as long as the flow was symmetric.

When the disturbance was placed asymmetrically upstream of the apex of the body, differences between the FNS and TLNS solutions were found. These differences increase as the angle of attack increases.

It is conjectured that the two codes (and also the FS TLNS), pick up different paths of evolution of the (symmetric) convectively unstable flowfield. The added terms and small differences in programming amplified differently the effect of the asymmetric disturbance and acted together as a new, different disturbance.

Acknowledgment

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Diamond, Cropped, Delta, and Double-Delta Wing Vortex Breakdown During Dynamic Pitching

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Introduction

RECENT interest in high angle of attack aerodynamics has refocused attention on delta-shaped wings. Vortices are formed at nonzero angles of attack as flow separates along the leading edges of a delta-shaped wing. Very low pressure is associated with these leading-edge vortices, and they can account for up to 30% of the total lift at moderate angles of attack.[1] For example, lift continues to increase until about a 40-deg angle of attack on a 76-deg swept delta wing.[2] In comparison, symmetric two-dimensional airfoils typically stall out at around a 10- to 15-deg angle of attack. Unfortunately, there are limits to the benefits produced by these delta wing vortices. As the angle of attack is increased, there is a sudden breakdown in vortex structure. This phenomenon, also known as vortex bursting, results in a sudden stagnation in core axial flow and an expansion in radial size.[3] Once this occurs, lift is no longer enhanced aft of the burst point. Thus, the development and subsequent breakdown of leading-edge vortices is crucial to the performance of delta wing aircraft. There have been a number of attempts to control delta wing vortices including the use of blowing,[4,5] suction,[6,7] flaps,[8–10] and canards.[11,12] The reader is referred to Lee and Ho[13] for a more complete review on delta wing vortices.

As the angle of attack is increased on delta wings, the unburst part of the leading-edge vortices becomes shorter. Under dynamic conditions, there is a hysteresis or phase lag in the vortex burst location.

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For example, the vortex burst location is further aft compared to the static case (at a given α) under pitch-up motion and further forward under pitch-down motion.[14] This phase lag is larger as the pitch rate is increased.[14,15] Thus, fast pitch-up and slow pitch-down is desired to delay vortex breakdown.

It is well known that the sweep-back angle on a delta wing affects development and breakdown of the leading-edge vortices. For example, full-stall angle of attack (under static conditions) occurs at 27 deg on a 55-deg swept delta wing, whereas it is 38 deg on a 65-deg swept delta wing and 54 deg on a 75-deg swept delta wing.[16] Thus, high sweep-back angles provide enhanced lift until high angles of attack. This principle is used on modern-day fighter aircraft with strakes used in front of the main wing to form a double-delta shape. In this case, the strakes provide enhanced lift in addition to the main wing. A number of unique delta wing shapes were also investigated by Gatlin and McGrath.[17] However, all of these studies on the effect of delta wing shape were conducted under static conditions. Under dynamic conditions, investigations on only the basic shapes such as the delta[12,14,15] and double-delta[18] wings have been conducted. Modern-day military aircraft often use novel wing shapes to incorporate stealth technology. Furthermore, enhanced performance at high angles of attack and under unsteady conditions may be required of these military aircraft. Thus, a series of experiments were conducted on the effect of different delta wing shapes on vortex breakdown under dynamic pitching conditions.

Experimental Method

The experiment was conducted in the 2×3 ft water tunnel located at Wichita State University, National Institute for Aviation Research. The facility is a closed-loop water tunnel capable of attaining a maximum flow velocity of 1.0 ft/s. The facility has excellent optical access, providing two side views, a bottom view, and an end view.

Figure 1 shows a sketch of the four different wing shapes that were tested. All four shapes have a sweep-back angle of 76 deg at the wing apex and a root chord length of 9 in. The sweep-back angle of the aft one-third of each wing is different, corresponding to diamond, cropped, standard delta, and double-delta shapes. Each wing is made of 0.063-in.-thick aluminum alloy, and both starboard and port sides are symmetrically beveled at a 45-deg angle. Each wing included reference grid lines perpendicular to the centerline at 5% chord intervals to help determine the vortex breakdown location. The aspect ratios for the diamond, cropped, delta, and double-delta wings are 0.66, 0.5, 1.0, and 3.0, respectively.

Dye-flow visualization technique was used in this experiment.[11,12] The videotaped flow behavior was carefully examined frame by frame, and the vortex breakdown locations were identified relative to the reference grid lines on the model. The vortex breakdown locations are expected to be accurate within 2–3% of the wing root chord by this method.[14]

A freestream velocity of $U_\infty = 0.4$ ft/s was used throughout the course of this experiment. This corresponds to a Reynolds number of $Re = 25 \times 10^3$ based on wing root chord ($c_r = 9$ in.). A dynamic test mount consisting of a rotating turntable was used to obtain the

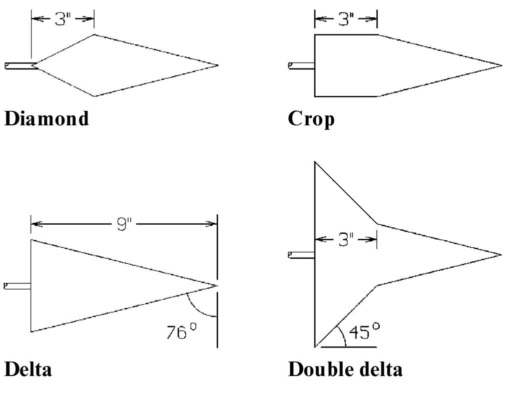

Fig. 1 Test model shapes.

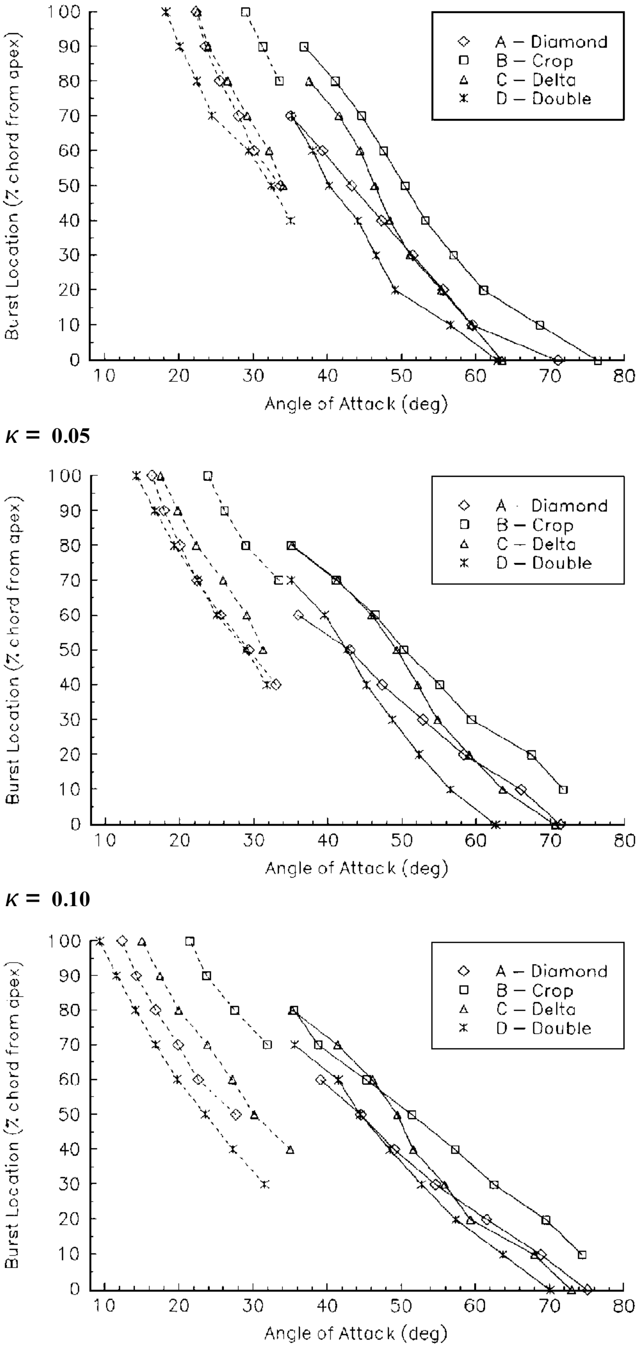

Fig. 2 Vortex burst locations for different pitch rates: ——, pitch-up and - - - -, pitch-down.

dynamic pitch motion.[14] The nondimensional pitch rate κ is based on the measured pitch rate $\dot{\alpha}$ (in rad/s), where[14]

$$\kappa = \dot{\alpha} c_r / 2U_\infty \tag{1}$$

Pitch-up and pitch-down tests were conducted for pitch rates of $\kappa = 0$ (i.e., static), 0.05, 0.10, and 0.15. For dynamic pitch-up tests, measurements were started at $\alpha = 15$ deg and continued past $\alpha = 90$ deg. For dynamic pitch-down tests, measurements were started at $\alpha = 40$ deg and continued until $\alpha = 0$ deg. The delta-shaped models were all pitched about the one-third chord (from apex) location.

Results and Discussion

Under static conditions (i.e., $\kappa = 0$), the double-delta wing had the earliest vortex breakdown among the four different shapes tested. The cropped wing had the longest unburst vortex at low-to-moderate angles of attack. This was not surprising because the sweep-back angle was large (i.e., 90 deg) in the aft one-third on the cropped wing. This effect persisted in the front part of the wing as well (until about a 50-deg angle of attack) even though all four wing shapes had the same sweep-back angle at the apex. Additional details of the static condition results are presented by Myose et al.[19]

Figure 2 compares the vortex breakdown locations for the four different wing shapes at a given pitch rate. The breakdown locations are given in terms of percentage of chord measured from the wing apex. Thus, a breakdown location of 0% corresponds to full stall where the leading-edge vortices are completely burst. The region below each curve corresponds to a condition where the vortex is not burst. It is desirable for this region to be as large as possible, because this is the area where enhanced lift from the vortical flow is still present.

The solid curves in Fig. 2 compare the pitch-up results. Like the static case, the double-delta wing had the earliest vortex breakdown location under pitch-up. Among the four shapes tested, the cropped wing had the longest unburst vortex. There appear to be two parallel sets of vortex breakdown curves. The first set, belonging to wings with aft sweep-back angles greater than or equal to 90 deg (i.e., cropped and diamond wings), have vortex breakdown curves that tend to be roughly linear with angle of attack. The second set, belonging to wings with aft sweep-back angles less than 90 deg (i.e., delta and double-delta wings), have vortex breakdown curves that tend to have a convex–concave shape.

The dashed curves in Fig. 2 compare the vortex breakdown locations for the four different wing shapes at a given pitch-down rate. The double-delta wing had the earliest vortex breakdown and the cropped wing had the longest unburst vortex. The slower ($\kappa = 0.05$ and 0.10) pitch-down results appear to show two parallel sets of vortex breakdown curves. The first set of curves is concave and belongs to wings with aft sweep-back angles greater than or equal to 90 deg. The second set of curves has a slight kink and belongs to wings with aft sweep-back angles less than 90 deg.

Although not shown here, the longest unburst vortex during pitch-up was obtained at the fastest pitch rate.[19] Conversely, the slowest pitch rate provided the longest unburst vortex during pitch-down. This is consistent with the results of previous studies on delta wings under dynamic conditions.[12,14,15]

Summary

The effect of delta wing shape on leading-edge vortex breakdown was investigated in the 2 × 3 ft water tunnel at Wichita State University. In this experiment, the aft one-third of a 76-deg swept delta wing was modified to obtain diamond, cropped, standard delta, and double-delta shapes. The vortex breakdown location during dynamic pitch-up and pitch-down motion was observed by dye flow visualization. Among the four shapes tested, the cropped delta wing had the longest unburst leading-edge vortex during dynamic pitching and the double-delta wing had the earliest vortex breakdown.

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Concentration Measurements in Experimental Microbursts

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Introduction

ATMOSPHERIC microbursts have been recognized as a cause of aircraft accidents for more than 15 years.[1] Since that time, observational, numerical, and experimental studies have investigated microburst behavior and structure.[2–4] Recent studies have employed small-scale laboratory experiments to examine the propagation behavior and vortex dynamics of atmospheric microbursts.[5,6] Microbursts were simulated by releasing small volumes of heavy fluid into a less dense ambient. For sufficiently large Reynolds numbers, experimental and atmospheric microbursts behaved similarly. Specifically, the large-scale structure, propagation velocity, and maximum velocity could be interrelated by choosing length and time scales based on the appropriate equations of motion.

Whereas knowledge of the velocity field can be invaluable in identifying and surviving a microburst, knowledge of the temperature field can provide a useful secondary tool. Because microbursts are driven primarily by evaporational cooling, microburst occurrences are typically associated with a local decrease in temperature.[4] Further, it is expected that the greater the temperature drop, the stronger

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