Vortex Breakdown on Slender Sharp-Edged Wings

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Systematic wind-tunnel investigations of vortex breakdown have been conducted on sharp-edged delta and modified delta wings with sweep angles from 45° to 85° at Reynolds numbers of about 1×10^6, utilizing a schlieren system for flow visualization. Vortex breakdown positions are presented as a function of angle of attack and sweep. Lift measurements generally compare favorably with Polhamus' leading-edge suction analogy. Drag because of the lift is predicted quite satisfactorily as the streamwise component of normal force for all models tested. Effects of vortex breakdown on pitching moments are presented and discussed. Tests of the modified delta wings show that vortex breakdown is influenced much more strongly by planform changes near the apex than changes near the trailing edge.

Nomenclature

BD	= vortex core breakdown
c	= wing local chord
$\bar{C}$	= wing mean geometric chord, $\int c^2 dy/s$
C_o	= wing reference chord (usually centerline)
C_L	= wing lift coefficient, lift/qS
C_D	= wing drag coefficient, drag/qS
C_{D_0}	= drag coefficient at zero lift
C_M	= wing pitching moment coefficient about $\frac{1}{4}$ mean aerodynamic chord, moment/$qS\bar{C}$
K_p, K_v	= constants in Polhamus' lift equation
q	= dynamic pressure
S	= wing planform area
TE	= trailing edge
α	= angle of attack

Introduction

LEADING-edge vortex flow at low speeds has the subject of increased interest in recent years. Polhamus[1] has provided a technique which enables accurate prediction of the additional vortex lift. The phenomenon of vortex core breakdown has been recognized as a limiting feature of such analyses. Poisson-Quinton and Erlich[2] have published an experimental vortex breakdown boundary for delta wings with sweep angles less than 75°. Correlations of vortex breakdown data and force measurements, however, have been lacking.

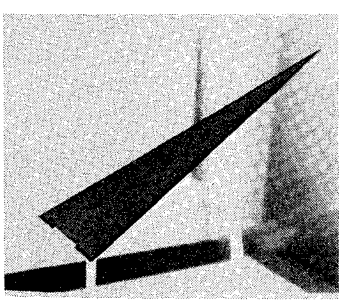

Fig. 1 Model installation.

The primary purpose of the present research was to provide a rather complete parametric investigation of vortex breakdown for sharp-edged delta wings, and to obtain force measurements from these same models in the same test facility in order to correlate force and flowfield characteristics in the most direct manner possible. A secondary purpose was to investigate certain modified-delta planforms in order to determine which factors have the greatest influence on vortex breakdown.

Models

Since vortex core breakdown is associated with angles of attack greater than 10°, it was felt that planform geometry was of primary importance. For this reason only uncambered, untwisted wings were tested. Thirteen delta wings

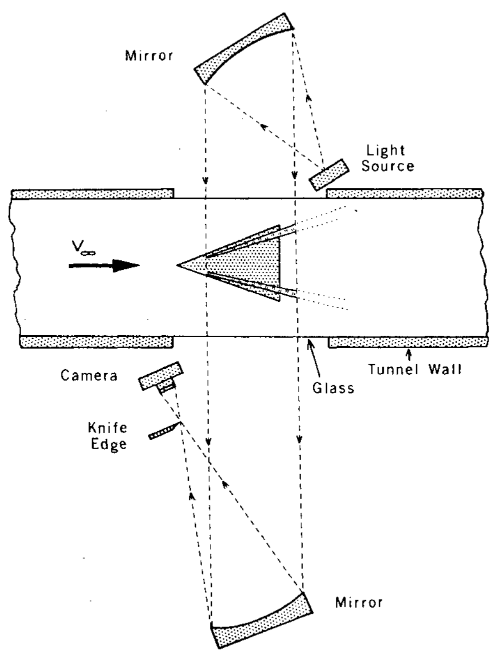

Fig. 2 Schlieren system.

Presented as Paper 69-778 at the AIAA Aircraft Design and Operations Meeting, July 14–16, 1969, Los Angeles, Calif.; submitted January 28, 1970; revision received July 22, 1970. This work was supported by NASA Grant 17-002-043 and by the National Science Foundation.

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a) α = 27.5° no breakdown

b) α = 32.5° breakdown

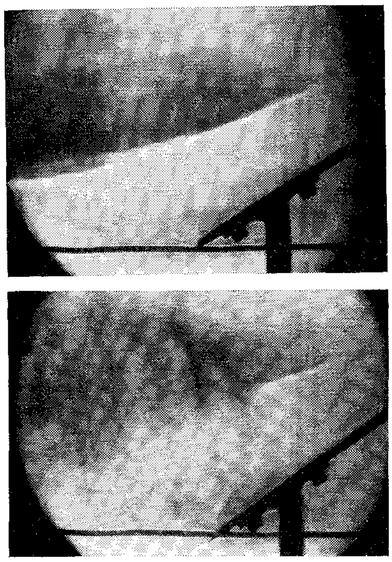


Fig. 3 Breakdown characteristic with smooth surface—72.5° delta.

were tested with leading edge sweep angles from 45° to 85°. Several modified delta planforms were also tested.

Models tested consisted of flat plate planforms fabricated from flat 0.10-in. aluminum sheet. Delta model leading edges and trailing edges were beveled to a 15° chisel point. Modified delta models utilized square edges, after comparison tests of square and chisel edges showed no substantial difference in force data or vortex breakdown. All models were fitted with No. 120 grit sandpaper on the upper surface to insure a turbulent cross-flow boundary layer.

Testing Techniques

All tests were conducted in the University of Kansas low-speed wind tunnel, a 3′ × 4′ closed return tunnel, at a Reynolds number of about 1 × 10^6. Models were mounted on a simple 2-point strut system (Fig. 1). Vortex breakdown observations were conducted utilizing a schlieren optical system (Fig. 2). The collimated beam was angled vertically a few degrees to distinguish right and left hand panel vortices, following the method suggested by Earnshaw.[3] Lift, drag, and pitching moment data were obtained for direct correlation with the flow visualization results.

a) α = 30.0° no breakdown

b) α = 32.0° breakdown

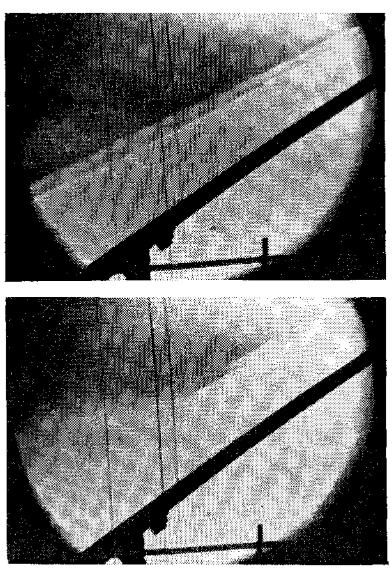


Fig. 4 Breakdown characteristic with rough surface—72.5° delta.

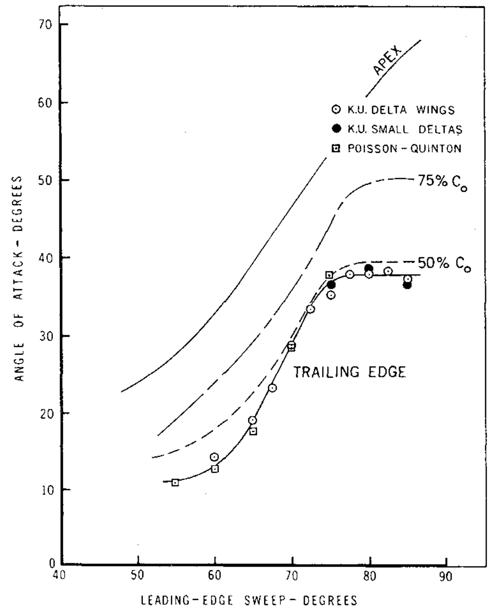


Fig. 5 Effect of sweep on vortex breakdown—delta wings.

Experimental Results—Delta Wings

Vortex Core Visualization

Visualizing vortices in a low-speed flow was found to be much easier than the authors had anticipated. The density gradients associated with a vortex core are sufficient to produce a rather distinct schlieren image as shown in the photos (Fig. 3). Furthermore, extremely high tunnel speeds were not required to make the vortices visible. Testing was conducted at an airspeed of about 130 mph, but vortices were easily observable at speeds as low as 40 mph. In one case (α = 32.5°) a coiling core associated with breakdown is visible, In other instances (Fig. 4) the coiling pattern did not appear.

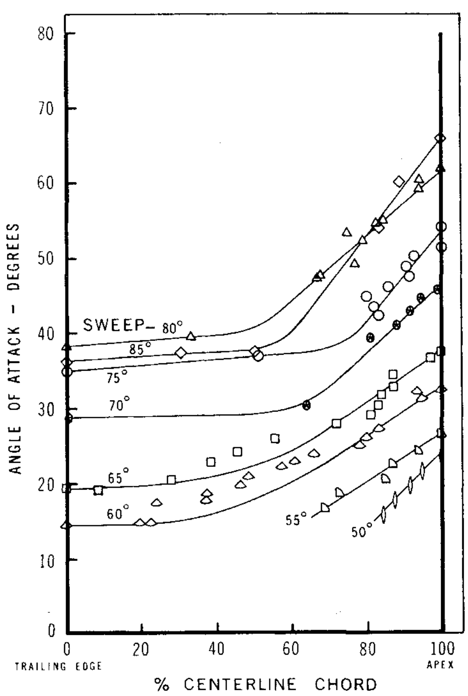
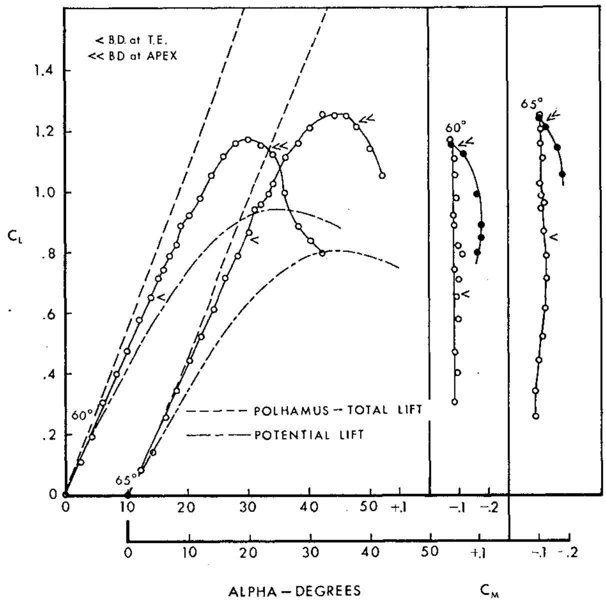
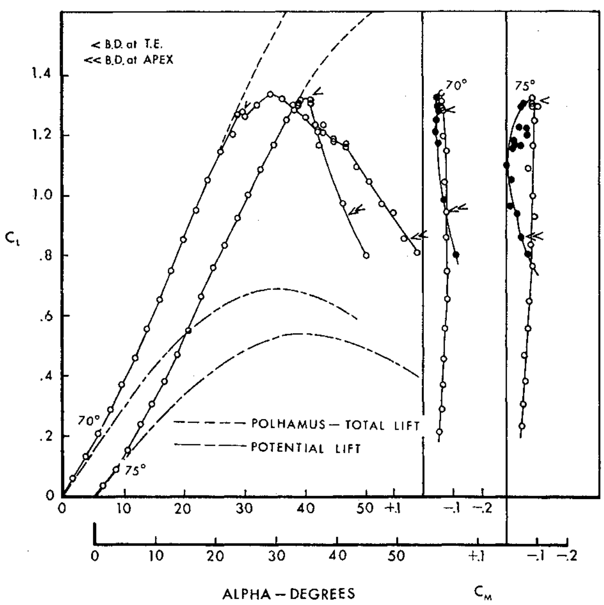


Fig. 6 Vortex breakdown position—delta wings.



a) 60° and 65° delta wings

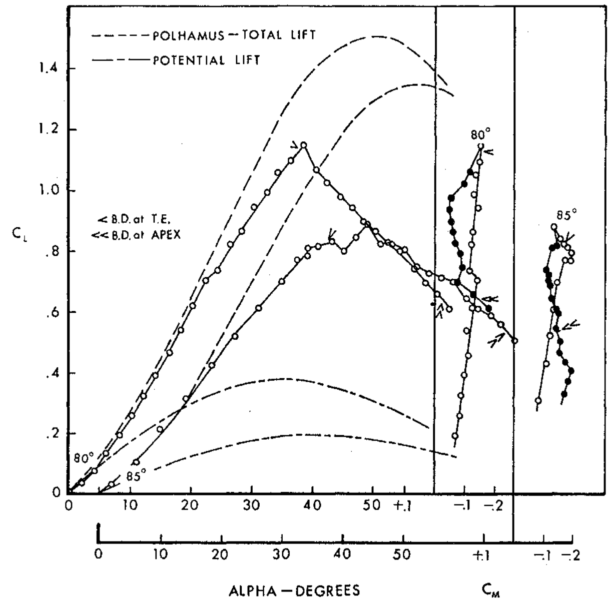


b) 70° and 75° delta wings

Initial Vortex Breakdown

Results of testing of the delta wings show the trend of increasing breakdown angle with increasing sweep for sweep angles less than 75° (Fig. 5). These results are generally in good agreement with the results previously published by Poisson-Quinton and Erlich.[2] In addition the present tests provide data for sweep angles greater than 75°, and show that in this range, the breakdown occurs at a constant angle of attack, independent of sweep. Since the new data represented a trend not evident in prior data for the very high sweep angles, there was some question as to its validity. The more slender models had a centerline chord dimension equal to half the tunnel test section height. To investigate the possibility that tunnel walls might be affecting the results, a series of smaller (half-size) models was tested. These data show excellent agreement with the data from the larger models, affirming the veracity of the larger model testing.

The abrupt change in trend of vortex breakdown vs sweep for sweep angles greater than 75° suggests the existence of a different limiting mechanism for breakdown with these very slender planforms. It was observed that vortex breakdown on these wings was quite sensitive to yaw. There was a definite tendency for the vortex from one wing panel to become displaced vertically above the other, with subsequent premature breakdown of the displaced vortex. A recent report by Bird[4] illustrates the unsymmetrical displacement. In the present tests, yaw adjustments of 0.1° or 0.2° were sufficient to restore the flow symmetry, and subsequently, the right- and left-hand panel vortices were observed to break down at angles of attack differing by 2° or less. In these cases, the average of the two angles of attack has been designated as the initial breakdown angle for the particular wing being tested.



c) 80° and 85° delta wings

Fig. 7 Lift and pitching characteristics—delta wings.

Chordwise Progression of Vortex Breakdown

In addition to the initial vortex breakdown boundary just described, measurements were made of vortex breakdown position vs angle of attack for each wing (Fig. 6). These data show that breakdown progresses rapidly forward at first, then more slowly with increasing angle of attack.

These trends are consistent with the fact that vortex breakdown is influenced by pressure gradients along the axis of the core (Refs. 3, 5, or 6). An adverse pressure gradient exists over the aft portion of the wing. Near the apex, on the other hand, the flowfield becomes nearly conical, with a pressure gradient approaching zero. Thus, the vortices would be expected to become much more stable as the breakdown position approaches the apex. Note that for the lower sweep (50° and 55°) wings, vortices were not visible at the trailing edge. Vortices were never observed on the 45° delta. Vortex lift is so small for the low sweep wings that knowledge of initial breakdown is probably not of great practical importance.

A cross plot of the vortex breakdown position data provides a useful design chart for predicting vortex breakdown position for delta wings (Fig. 5).

Lift and Pitching Characteristics

Polhamus (Ref. 1) has given a theoretical equation for calculation of lift for wings of the type tested, as follows:

$$C_L = K_p \sin\alpha \cos^2\alpha + K_V \sin^2\alpha \cos\alpha \quad (1)$$

(total lift = potential lift + vortex lift)

where K_p and K_v are determined by conventional lifting surface theory. In the presentation of the experimental results, a line representing the "potential lift" term in Eq. (1) is presented, as well as a line representing the total Polhamus lift. The difference between the lines is thus the theoretical vortex lift.

For the 60° and 65° deltas (Fig. 7a), the experimental results show that less than theoretical lift is produced. Both lift and pitching characteristics show little change with initial breakdown on these wings. Polhamus pointed out that the leading-edge suction analogy is apt to overpredict vortex lift for wings of moderate sweep, since the vortices produced by such wings do not stream perpendicular to the trailing edge and cannot, therefore, produce full suction lift. If the wing planform trailing edge were perpendicular to the vortex core, the full vortex could be effective. As illustrated in the sketch (Fig. 8a) for highly swept deltas, the additional area required becomes vanishingly small. Therefore, the theory should be more accurate for the more highly swept wings.

For the 70° and 75° delta wings (Fig. 7b), the agreement between theoretical and experimental lift is excellent. Furthermore, the initial vortex breakdown points, as indicated on the curves, mark clearly the onset of deviation from the theory. Thus, the vortex breakdown measurements, in conjunction with the Polhamus theory, provide an excellent means for predicting lift for these configurations. These trends were found to hold quite well for wings with sweep angles ranging from 70° to 77.5° (see Ref. 7 for more detailed results of the present tests). The characteristic pitch-up of delta wings with sweep angles in this range occurs prior to vortex breakdown (Fig. 7b).

For wings with sweep angles from 80° to 85°, a progressive deviation of experimental results from theory is noted prior initial breakdown (Fig. 7c). This is in the range of leading-edge sweep angles for which initial vortex breakdown is independent of sweep, as noted earlier. Maltby and Peckham[8] have shown that for very slender wings at high angles, the vortex sheets from the two sides may meet at the centerline, eliminating the region of reattached streamwise flow usually found on the upper surface. This effect is illustrated in the sketches of the cross-flow vortex sheets (Fig. 8b). Recent tests by Matz[9] at Wichita State University confirm that sheet contact occurs prior to vortex core breakdown. At angles of attack above initial contact, the vortex cores are forcibly displaced upward. Such displacement would be accompanied by a reduction in vortex lift.

In extreme cases (very slender wings and bodies), the vortex sheets may "tear" from each side. The tearing mechanism is not usually symmetric and often results in one vortex core becoming vertically displaced above the other. From a practical standpoint, the onset of vortex sheet tearing probably limits the useable angle of attack range for such wings because of the rolling moments associated with the unsymmetrical flowfiedls.

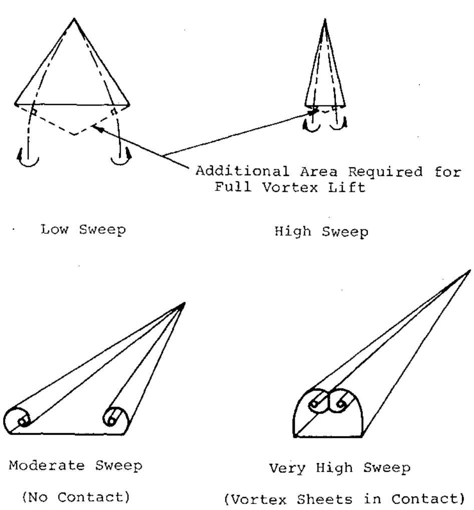


Fig. 8 Limitations of vortex lift theory.

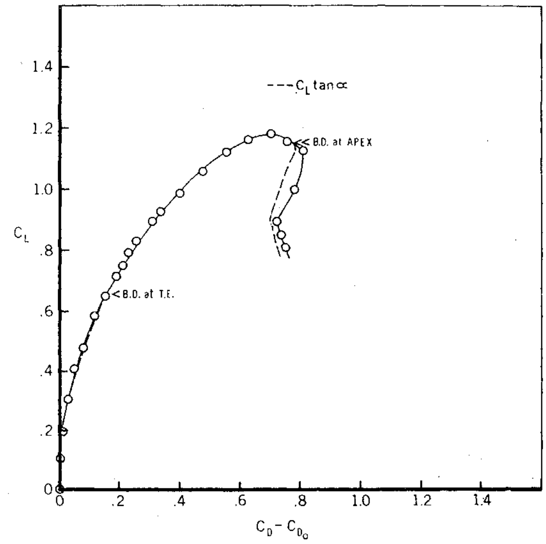


Fig. 9 Typical drag due to lift—60° delta wing.

The lift loss resulting from parallel vortex displacement would presumably not be abrupt, but rather gradual reduction in the proportion of vortex lift actually achieved relative to the theoretical amount. Although it is not possible to say if or when vortex sheet contact occurred in the present tests, it seems plausible that the systematic lift loss noted on the 80° and 85° wings above a critical angle (but prior to initial breakdown) might be due to such a phenomenon.

Drag Due to Lift

The drag due to lift data from all wings tested have been compared with theoretical values based upon zero leading-edge suction given by the following equation:

$$C_D - C_{D0} = C_L \tan\alpha \qquad (2)$$

The appropriate *experimental* C_L vs α data have been used in this equation. Such a comparison (Fig. 9) shows excellent agreement, indicating the validity of assuming a pure normal force (i.e., no leading-edge suction). Similar agreement was found to exist for all models, including the modified delta wings described in the following section. From the present results, it is clear that adequate lifting theories will lead to accurate induced drag prediction, as indicated by Polhamus' recent report on this subject (Ref. 10).

Experimental Results— Modified Delta Wings

In order to ascertain more fully the effects of planform variations on vortex breakdown, a series of modified delta models was tested.

Diamond and Arrow Wings

Vortex breakdown measurements for 70° delta, diamond, and arrow planform wings demonstrate that variations in trailing-edge geometry have a negligible affect on breakdown (Fig. 10).

Lift characteristics for these wings provide interesting examples of some limitations of Polhamus' theory. The arrow wing develops less lift than theoretical, while the diamond wing exceeds theoretical lift (Fig. 11). Both of these effects are attributable to the influence of the vortex lift over the aft portions of the wings.

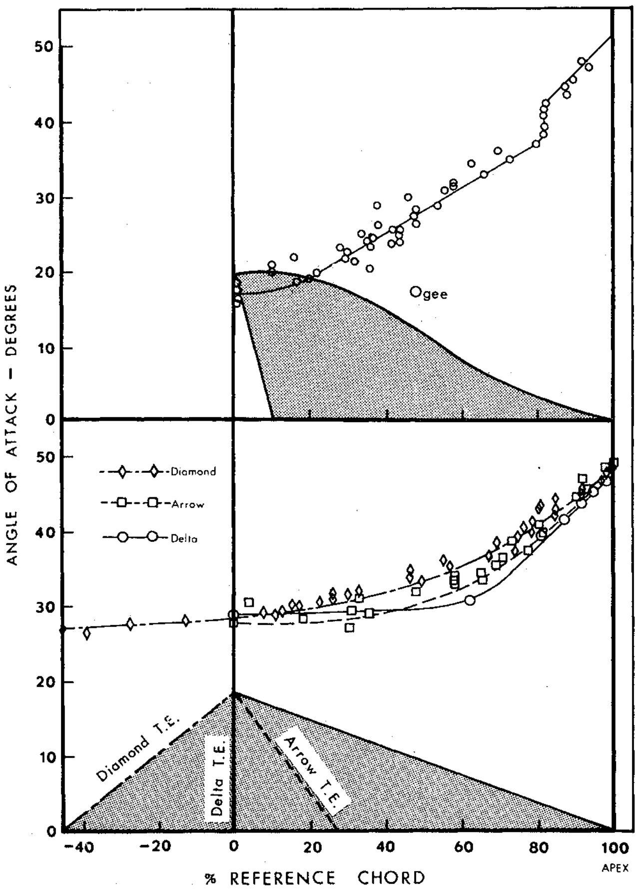
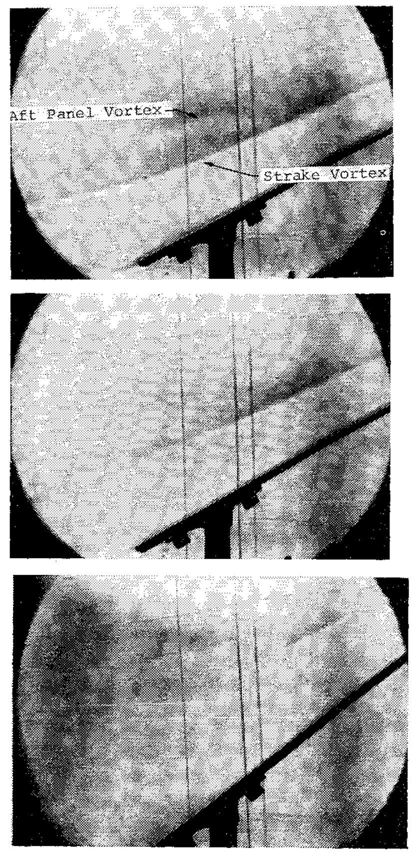


Fig. 10 Vortex breakdown position—modified delta wings.



a) α = 24.4° no breakdown

b) α = 28.7° aft panel breakdown

c) α = 35.6° strake vortex breakdo wn

Fig. 12 Vortex breakdown—75°/65° double-delta wing.

These trends are also evident in the pitching moment characteristics of the three wings, which show that adding area at the trailing edge (diamond) controls the unstable pitch-up tendency of the basic delta, while removing area (arrow) aggravates the destabilizing tendency.

Double-Delta Wings

Because of the interest in recent years in double-delta planforms for supersonic and hypersonic airplane designs, two double-delta models were tested. These models have forward panel leading-edge sweep angles of 75° and 80°, respectively, and a common aft panel sweep of 65°. These models were designed to have the same aspect ratio (1.60) in order to investigate further whether aspect ratio is more important than sweep in determining vortex breakdown.

Vortex breakdown characteristics for the double-delta wings are quite different than for simple deltas. The schlieren photos for these configurations are particularly interesting since they show the interaction between two distinct vortex cores. The aft panel vortex core, having less strength, coils in a helical fashion about the apex panel vortex (Fig. 12). Similar wind-tunnel observations have been made with the water vapor condensation vortices reported by Sacks, Lundberg, and Hanson.[11] In the present investigations, it was observed that the aft panel vortex disappears at higher angles of attack, apparently as a result of breakdown. The forward panel vortex remains visible, without breakdown for another 4°–6° for both double-delta wings tested.

It was found that the strake vortex has a definite stabilizing influence on the aft panel vortex flowfield.

This observation concurs with the conclusion reached by Earnshaw[3] that apex sweep is more important than sweep near the trailing edge in influencing breakdown.

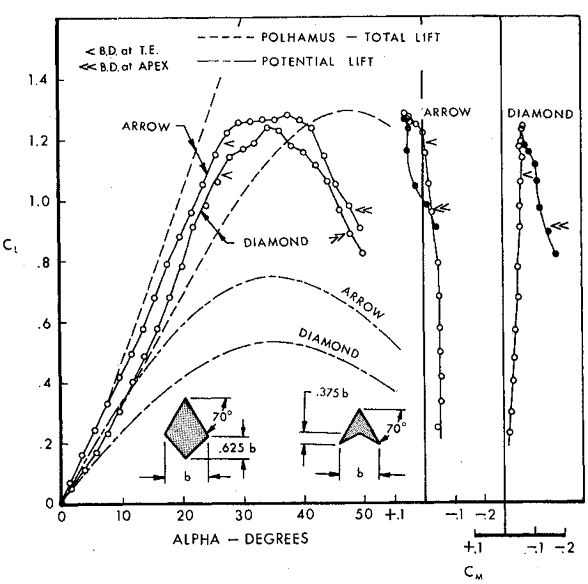


Fig. 11 Lift and pitching characteristics—70° arrow and diamond wings.

Ogee Wing

Because of the recent interest in ogee planforms, such as the Anglo-French Concorde and USSR TU-144 supersonic transports, an ogee model was tested. The planform for this model was selected to match the outboard panel of a modified F5D tested by the NASA Ames Research Center.[12] This planform has also been the subject of extensive flow visualization studies (Refs. 13 and 14). It was hoped that force and flow visualization data from this model could be correlated with data from the sources previous.

With this planform a single continuously curved vortex is formed on each side. A plot of vortex breakdown position

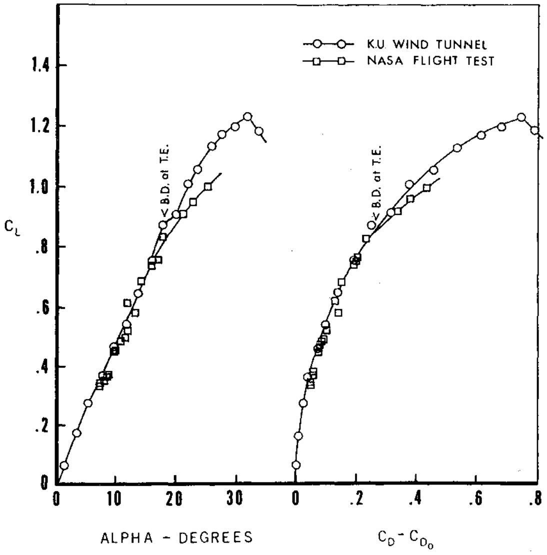


Fig. 13 Lift and drag comparisons with flight test data—ogee wing.

as a function of angle of attack for the ogee wing shows a number of interesting characteristics associated with the ogee planform (Fig. 10). First, initial breakdown occurs at 17.5°, a much higher angle of attack than would be anticipated for the basic aft panel alone. This substantiates the trend noted with the double-delta wings.

Second, the forward progression of vortex breakdown is at a much lower rate than for delta wings. This is apparently a direct result of the wing sweep increasing as the apex is approached. Thus, the vortices become much more stable near the highly swept apex.

Ogee Wing—Comparisons with Flight Test

A comparison between this model and flight test is afforded by the results obtained by NASA Ames Research Center with the modified F5D airplane (Ref. 11). As noted earlier, the ogee wing of the present tests was designed to match the outboard panel of this aircraft. The lift and drag results from flight tests compare quite favorably with the present ogee wing results (Fig. 13).

Based upon tuft observations and statements made in the reference concerning buffeting of the airplane, it appears that initial vortex breakdown occurred on the airplane at an angle of attack between 15° and 18°. The present wind-tunnel results (Fig. 10) show initial breakdown at about 17.5°.

From the comparisons of lift and drag results, as well as breakdown observations, it is evident that rather good force correlations are possible between full scale flight tests (Reynolds number $\simeq 20 \times 10^6$) and rather small scale wind-tunnel models (Reynolds number $\simeq 1 \times 10^6$).

Conclusions

1) Initial vortex breakdown and forward progression of breakdown have been defined for delta wings having sweep angles up to 85°. 2) Polhamus' leading-edge suction analogy for vortex lift has been verified, with some limitations. 3) For modified deltas, apex sweep has a dominant influence on vortex breakdown. Trailing-edge sweep, on the other hand, has a negligible effect. 4) While vortex breakdown does produce a nose-up moment, the pitch-up tendency of delta wings at moderate C_L is not because of the vortex breakdown. 5) Drag because of the lift of models with full leading-edge separation is given as the streamwise component of a pure normal force. 6) Force and moment measurements of an ogee wing compare favorably with flight test results at a 20 times larger Reynolds number.

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