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Effects of a Contoured Apex on Vortex Breakdown

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Introduction

STRONG streamwise vortices are a well-known feature of the flowfields above delta wings. The breakdown of these vortices at a high angle of attack is also commonly observed and results in a change in pressure distribution that affects the lift and, especially, the moment produced by the wing. It is probably not possible to avoid vortex breakdown entirely, but in any case the phenomenon should be delayed and controlled.

Although it is an oversimplification, it is useful for physical purposes to think of a vortex embedded in a pressure field generated by the delta wing. Vortex breakdown is sensitive to the exact nature of the vortex structure and to the flowfield (or pressure gradient) in which the vortex is embedded. Mathematical studies on the breakdown of symmetrical isolated vortices show that the vortex can be completely described by the radial profiles of total pressure and of streamwise vorticity. Reduced total pressure occurs in the core of the vortex because the fluid has undergone a history of frictional forces. Likewise, the process by which the vortex was formed must give the core fluid a vorticity profile.

The object of the research was to modify the total pressure or the vorticity distribution in the vortex and observe the effect on the location of the breakdown. The idea is that the core of the vortex is formed from fluid that passes near the leading edge. Adding friction at this point results in core fluid that has a lower total pressure than the main flow. On the other hand, additional vorticity is imparted to the vortex if the fluid crosses the leading edge at a higher angle of attack or, equivalently, a higher sweep. Contouring the planform in the region of the apex in principle alters the vorticity distribution in the vortex core.

It should be pointed out that in many cases a double delta produces two vortices: one from the apex and one from the intersection of the leading edges. These two vortices interact as has been documented in several studies. The concept employed here is distinctly different. The modifications to the delta are intended to be so slight that they alter the vorticity distribution in the main vortex, but do not produce a distinct second vortex.

Background

The recent review by Escudier[1] shows that vortex breakdown is a very active research area. Vortex breakdown was first observed by Peckham and Atkinson[2] in 1957. Causal theories are still in a stage of development as evidenced by the articles of Leibovich[3] and Stuart.[4] In spite of this, much useful information is available. From the calculations of Grabowski and Berger,[5] it is known that bubble-like solutions of the Navier-Stokes equations exist. Sensitivity to pressure fields has been studied experimentally by Staufenbiel and Helming[6] and both experimentally and numerically by Délery et al.[7] This later work documents the insensitivity of numerical solutions of breakdown for vortex Reynolds numbers greater than 5×10^2. Aerodynamic researchers such as Earnshaw[8] have long noted the inviscid nature of vortex breakdown.

Test Program

The fluid in the core of a delta-wing vortex has previously passed the leading edge. There, the upper and lower flows merge at a slight angle to each other forming a sheet of vorticity. Fluid within the sheet comes from the boundary layers where viscous forces have reduced the total pressure. The rational for the present experiments is to modify the distribution of total pressure or vorticity that is introduced along the leading edge.

Extra friction was generated at the leading edge by wire protrusions extending into the flow so that more turbulence was introduced into the vortex sheet (Blowing at this location can introduce fluid with a higher total pressure than the freestream.) One wing had protrusions only at the apex, one for half span, and one for full span.

The freestream velocity can be decomposed into components along and normal to the leading edge. The angle of attack β of the normal component is

$$\tan\beta = \tan\alpha/\cos\Lambda$$

By changing Λ, the local effective angle of attack can be modified. Wings with different apex sweep angles that were set ahead of the basic delta by different distances were used to produce various vorticity distributions. A global measure of the effect of these modififcations of the vortex structure is the breakdown position as a function of the angle of attack. This was measured in a series of experiments.

Test Setup

A horizontal water channel with a cross section 40 cm wide and 18 cm deep was used for the tests. The channel had a free surface except in the vicinity of the model where an adjustable clear plastic plate was used to suppress waves. This was done primarily to improve the flow visualization; however, some opinion exists that surface waves can have minor effects on the test flowfield. Wings were pivoted 14 cm from the floor at roughly the midspan. At high angles of attack, wall interference effects were likely; therefore increments between configurations are more significant than absolute levels. Another reason to view the present results qualitatively is that Kegelman and Roos[9] have shown that breakdown position is somewhat sensitive to leading-edge shape.

For the current tests, the flow velocity was approximately 25 cm/s. This yields a test Reynolds number of 3.5×10^4. Although this is low from a wind tunnel or flight standpoint, it is generally agreed that the primary vortex and its bursting behavior are only slightly sensitive to Reynolds number. Wings were mounted in the water channel from the bottom. The support strut had a mechanism consisting of a worm gear and reducing gears driven by a wheel. A digital readout indicated the gear position to an equivalent of 280 counts/deg in angle of at-

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tack. Backlash in the system was estimated as less than 0.3 deg in angle of attack. Although this is not a significant amount for the present tests, changes in position were approached only in one direction.

Flow visualization of the vortex and its breakdown was the main experimental objective. Fluorescent dye introduced at the apex of the wing through a hypodermic needle was the most effective method, however, in some cases hydrogen bubble wires placed in front of the wing were used. During a test, a videotape of the flow was recorded. Subsequent visual analysis of the recording at slow motion produced the average position for the vortex breakdown.

Wing Models

For the basic wing, a 65-deg delta with a 15-cm centerline chord was chosen. Previous literature on delta wings has shown that when the sweep angle is 65 deg or larger, the vortex rollup and breakdown follow a typical pattern. All wings were constructed from flat aluminum plate 3.175 mm (0.125 in.) in thickness giving $t/c = 0.0212$. The lower side was beveled at a 15 deg angle to a relatively dull leading edge.

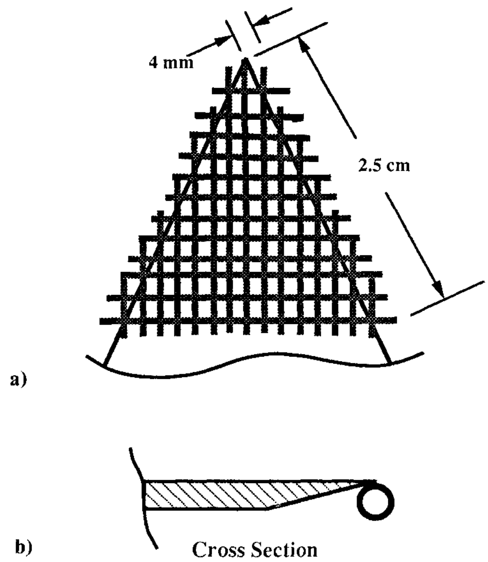

Fig. 1 Wings with increased friction: a) Wire mesh on apex region, b) wire spring along leading edge.

Modifications to the wing were of two types. The first group was designed to add friction and thereby reduce the total pressure of fluid in the vortex core. The first modification was to attach screen material to the top of the wing near the apex in such a way that it extended past the leading edge (see Fig. 1). The screen was 34 gauge (0.264 mm) copper-coated steel wire with a mesh $5.5 \times 5.5/\text{cm}^2$. The wire protruded 4 mm (0.0267 chord) perpendicular to the leading edge for a length of 2.5 cm (0.167 chord) along the leading edge. This configuration added friction to the fluid that formed the central core of the vortex. The Reynolds number of the wire was 6.1×10, based on the freestream velocity. This places the wires in the vortex shedding regime.

With the same purpose in mind, two configurations with a 3.17-mm (1/8-in.)-diam coil spring were also tested. In one configuration, the spring was attached along the leading edge for a distance of 50% of the chord, whereas in the second configuration 100% of the length was covered. A small gap of about 4 mm existed at the apex before the spring actually starts. The spring was 39-gauge wire wound in nominal 3.17-mm-diam coils. The Reynolds number of the spring wire was 4.8×10, again based on the freestream velocity. In the half-span configuration, there were 12 coils/cm, and when the spring was stretched for the full span, it had 5.9 coils/cm.

The second-phase modifications were intended to alter the tangential/longitudinal velocity profiles in the vortex by tapering the apex region of the wing. Six models were made by milling a piece of flat stock. A planview of the models is shown in Fig. 2. From a geometric standpoint, the basic 65-deg delta has an extension to the apex defined by the initial sweep angle Λ and the origin, a distance e in front. Initial sweep angles of 75, 77.5, and 80 deg were used, each in conjunction with extension lengths of 2.5 cm ($e/c = 0.167$) and 3.5 cm ($e/c = 0.233$). The two triangles thus formed were faired by a circular arc that was tangent to both leading edges and equidistant from the virtual intersection. For all models this distance was 2 cm. The radius of curvature of the fairing arc (for clarity omitted from Fig. 2) changes for each model.

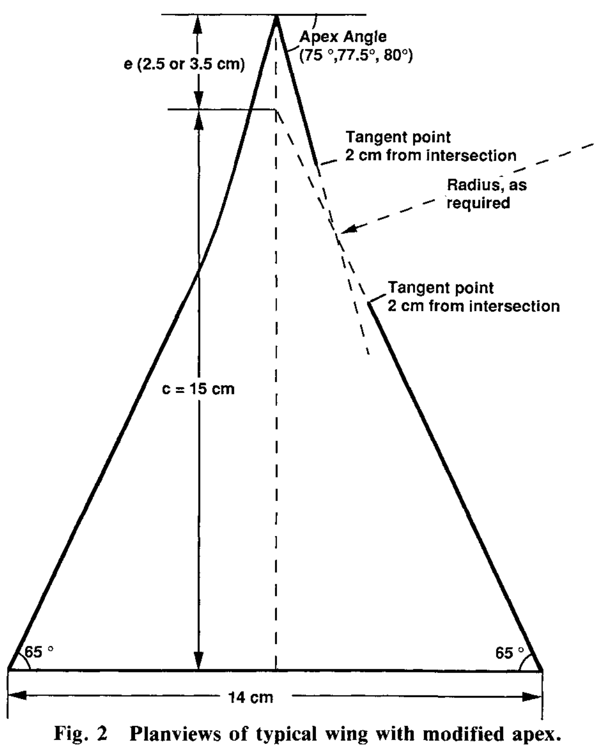

Fig. 2 Planviews of typical wing with modified apex.

Results

In Fig. 3 the results for the basic 65-deg delta are presented. The three curves represent tests that were done at different times after the model was removed and reinstalled in the channel. Test 3 was done approximately a year before tests 1 and 2. The scatter of about 2 deg is typical of the results achieved on any repetition of tests. These curves fall within the region of results published by others. All test runs have been done twice,

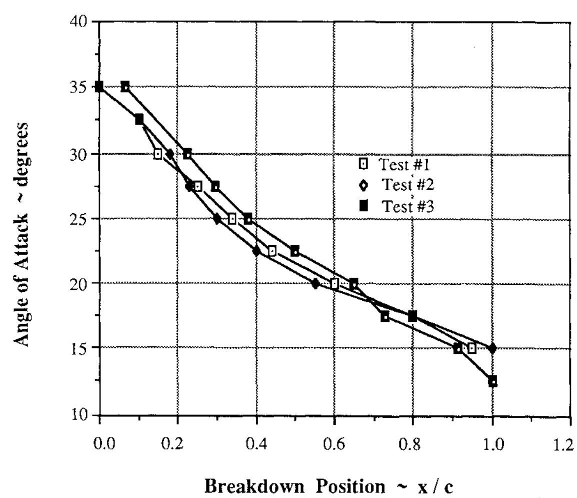

Fig. 3 Breakdown position for 65-deg basic delta.

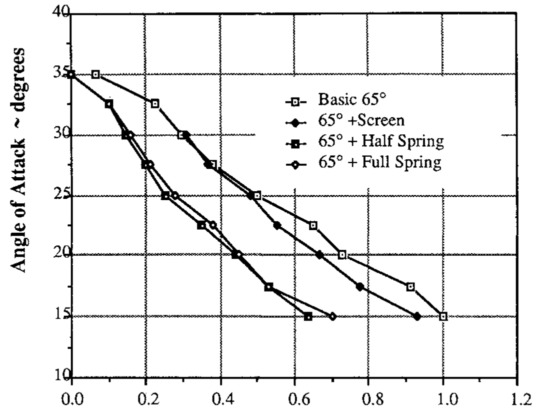

Fig. 4 Effect of decreased total pressure on breakdown position.

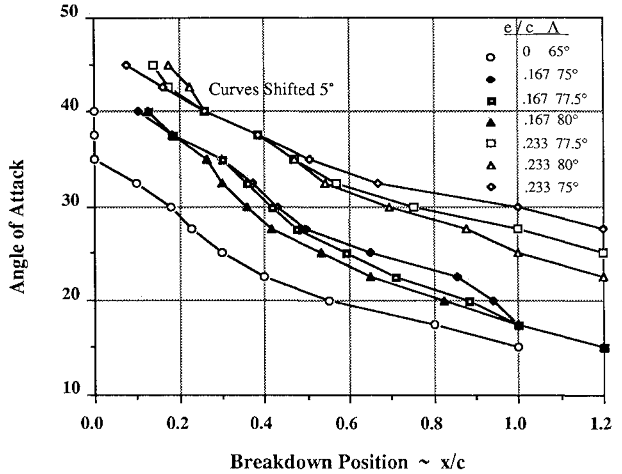

Fig. 5 Effect of extension length on breakdown position. Note curves shifted 5 deg upward for $e/c = 0.233$.

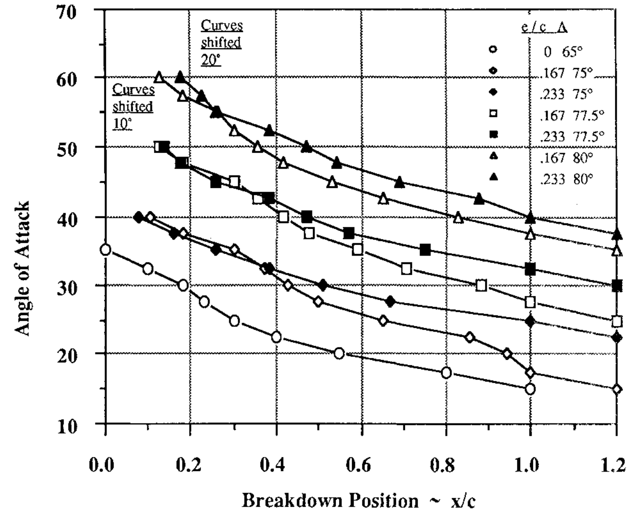

Fig. 6 Effect of initial sweep angle on breakdown position. Note curves shifted 10 deg upward for $\Lambda = 77.5$ deg and 20 deg upward for $\Lambda = 80$ deg.

Table 1 Virtual intersection position

Λ, deg	e/c	x_{int}/c
75	0.167	0.255
	0.233	0.318
77.5	0.167	0.151
	0.233	0.211
80	0.167	0.101
	0.233	0.141

but for clarity only one set will be shown in subsequent graphs.

Tests where the total pressure in the vortex was reduced are shown in Fig. 4. The wire screen near the apex had no effect when the breakdown was near the apex and only a slight effect when it was near the trailing edge. The wire spring for either the half or full span of the leading edge gives the same decrease, up to 7 deg, in the angle for breakdown at a given position. Unfortunately, the breakdown position did not move onto the last quarter chord of the wing where a difference might have been observed. In any event, for aerodynamic purposes, this is an unfavorable modification.

Wing modifications that alter the vorticity have two parameters: the initial sweep Λ, related to the increase in core vorticity, and the amount of apex extension e, related to the size of the core region with increased vorticity. The results will be presented in two ways. For constant initial sweep angle, Fig. 5 shows the effects of changing the apex extension distance. For constant apex extension distance, Fig. 6 shows the effects of changing the initial sweep angle. Note that the chord and position origin for all graphs is that for the basic 65-deg delta.

In interpreting the figures, it is useful to know the location of the virtual intersection of the initial delta and the basic delta. This is given in Table 1 in terms of the coordinates of the figures.

For all sweep angles, the figures show that the longer extensions increase the angle of attack for breakdown to occur at a specific point.

As the vortex breakdown position moves toward the apex, the curves always come together. For extremely high angles of attack, one expects that the initial sweep angle is dominant and the behavior will be the same as that for a wing of that sweep angle. Because of the coordinated used in these plots, the actual apex of the wing is at -0.167 for one extension and -0.233 for the other. Thus, it is anticipated that the curves should cross and have the same trends as these negative numbers are approached. The crossing can be seen to happen in Fig. 5, however the data does not extend high enough to see the complete trend.

It is instructive to reorganize the data into plots where the extension length is the same, and the initial sweep angle is varied. This is done in Fig. 6. The curves for all angles cluster together at about the quarter-chord position. At this point, the breakdown has been delayed by about 7.5 deg compared to the basic delta. For the breakdown located at the trailing edge, the situation is somewhat different. The highest curves are for the lower initial sweep angles. Furthermore, the curves for $e/c = 0.233$ are higher than those for $e/c = 0.167$. The highest curve, that for $\Lambda = 75$ deg, is about 10 deg higher than the curve for the basic delta.

The geometric parameters, initial sweep angle Λ and apex extension distance e, are very convenient for construction; however, they may not be the best for viewing the breakdown process. Different combinations of Λ and e lead to quite different values of x_{int} as shown in Table 1.

One early proposal for a single criterion for vortex breakdown was that the ratio of swirl velocity to longitudinal velocity exceeded a certain number. This ratio usually has its largest value in the outer portion of the vortex core. Assuming that this is the most sensitive part of the vortex structure leads one to look for the origin of these fluid particles. For example, consider when the vortex breakdown is at the trailing edge. Where do the streamlines of the outer core fluid pass when they cross near the leading edge? Obviously the answer is some distance down the leading edge. This line of argument would suggest that x_{int} and Λ are more significant from a physical standpoint. Unfortunately, the limited number of tests conducted in this study do not allow an extensive test of this hypothesis. From Table 1, one can see that all $\Lambda = 75$-deg wings have high x_{int}, and all 80-deg wings have low x_{int}.

Summary

A basic 65-deg delta wing was modified with the intent of changing the vortex breakdown behavior. Leading-edge modifications that decreased the total pressure or increased the vorticity in the vortex core were tested. The following was learned:

1) Decreases in total pressure in the core caused earlier vortex breakdown.

2) The extent of the pressure decrease, as indicated by the length of leading edge over which additional friction was produced, is not important. Results for half-span treatment are nearly the same as for full-span treatment.

3) An apex extension of a greater sweep angle than the basic delta increases the core vorticity and delays vortex breakdown.

4) The largest delay obtained in the present tests was 10 deg for a 75 deg apex extended 0.233 chord in front of the basic delta.

5) For a given extension position, increasing the apex sweep angle reduces the effect on bursting.

6) From the limited data taken, it is postulated that vortex breakdown at the trailing edge is more sensitive the leading-edge conditions at one-third to one-half span.

Acknowledgments

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