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Vortex Breakdown Control by Delta Wing Geometry

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The principal objective of the work has been to examine the reasons for the variation of vortex breakdown position in results from various investigators on delta wings of equivalent sweep. Flow visualization has been used to determine the position of the vortex breakdown over a series of delta wings, carefully constructed to be geometrically identical to those of previous investigators. The results obtained were virtually identical to those found in the original investigations. Support interference, tunnel effects, and Reynolds number were found to have little effect. The detail geometry of the wings, particularly the apex, is found to be the most important factor in determining the position of vortex breakdown. This conclusion has implications for the design of future experiments on vortex breakdown, and also on theoretical or computational models of the problem. A systematic series of tests were conducted to examine this effect on vortex breakdown position in order to control the aerodynamic forces. A small apex flap was found to provide about 1% chord movement in vortex breakdown position for a 1-deg change in flap angle.

Nomenclature

b = wingspan
c = chord length
d = thickness of wing
Re = Reynolds number
w = tunnel width
x/c = dimensionless chord length
α = angle of attack
β = yaw angle
θ = apex flap angle of attack
Λ = sweep angle
σ = chamfer angle normal to leading edge

Introduction

A DELTA wing is a basic configuration for supersonic flight. Modified versions of delta wings are used in both military and civil aircraft designs. The separated vortical flow, which occurs over these wings in subsonic flight, provides lift and maneuverability well beyond what would be expected if the flow remained attached. However, at a sufficiently high angle of attack, the vortices undergo a sudden expansion known as vortex breakdown. Once the angle of attack is large enough for the vortex breakdown to have crossed the trailing edge, the wing experiences a substantial change in the local pressure field, producing a decrease in the lift curve slope and an increase in the pitch-up moment. At sufficiently high angle of attack the whole of the vortex flowfield has undergone breakdown, so that a gross separation without concentrated vortex features exists over the wing. The general nature of the flow regimes over a delta wing is shown in Fig. 1, as defined by the results of Wentz and Kohlman (W&K),[2] which indicates the limiting conditions of the flow as a function of wing incidence and sweep angle. A fuller discussion of the parameters controlling the boundaries shown in Fig. 1 will be given later in this article.

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Many investigations have been made into the behavior of vortex breakdown over these wings.[1–5] All have found similar trends, in that the breakdown is a sensitive function of angle of attack and sweep angle, and that it is essentially unaffected by Reynolds number, so long as the wing leading edge is sharp. However, serious anomalies are to be found within the literature when one considers in detail the angle of attack at which vortex breakdown appears and the subsequent movement up and down the wing. A figure summarizing results for the first appearance of vortex breakdown at the trailing edge of the wing was presented by Erickson,[6] and is shown here as Fig. 2. This demonstrates that the results from different investigators on wings with the same sweep show considerable variation. Various factors have been suggested to account for this effect including wind-tunnel factors, differing flow visualization methods, and the interference of support systems. One other possible effect, that of Reynolds number, can be seen from Fig. 2 not to have any obvious systematic effect on the results.

These differences in published data remain as the breakdown moves up the wing, as can be seen in Fig. 3. Here, the results of the breakdown position against angle of attack, for nominally identical conditions, are compared for two sets of investigators. Although the trends are similar, the differences in chordwise location remain significant. Hence, there is no universally agreed location for the vortex breakdown on a

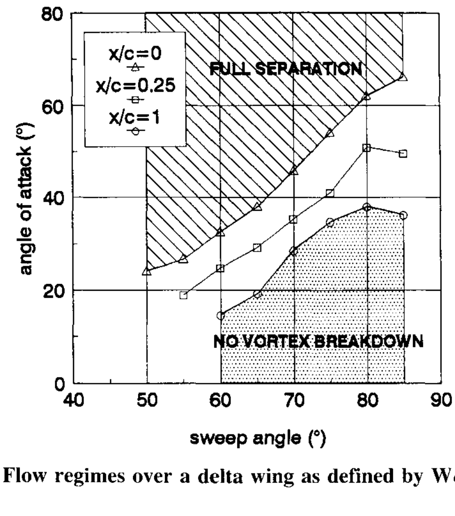

Fig. 1 Flow regimes over a delta wing as defined by W&K data.

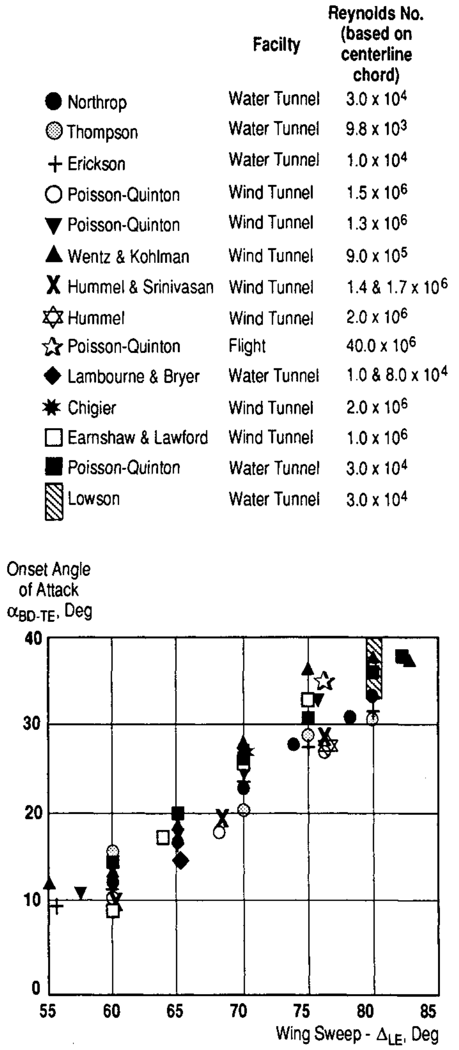

Fig. 2 Variation in the appearance of vortex breakdown.[6]

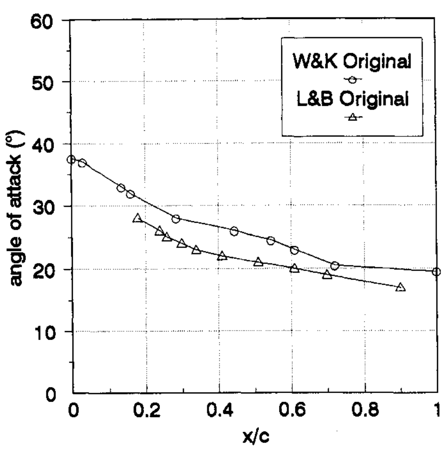

Fig. 3 Original data for two 65-deg delta wings showing variation in position of breakdown.

delta wing, as a function of angle of attack and leading-edge sweep. Also, there is no agreed explanation for the variations.

Vortex breakdown has also been the subject of many theoretical investigations, and more recently has been used as a model case for the development of Navier–Stokes computational solutions. These solutions have demonstrated the presence of vortex breakdown in locations that broadly correspond to experiment. However, as with previous inviscid models, precise correspondence with the detail of experiment is absent. This uncertainty in the position of the vortex breakdown, even for the simplest of delta wing models, has important implications for theory and computation of vortex flows in general.

Present Experiments

The present experiments were motivated by the observations of Lowson and Ponton[7] on symmetry breaking in vortex flows on slender bodies. They showed that the reported appearance of a third vortex on very low AR slender wings was almost certainly due to the finite thickness of the apex of such wings, which necessarily depart from idealized slender delta form near the apex. The experiments they reported incidentally demonstrated a significant variation in vortex breakdown position on otherwise similar delta wings as a function of plate thickness. This is shown in Table 1. The slender delta wings are of identical sweep. The essential difference was the thicker wing was made from 3.3-mm plate and the thinner wing from 1.3-mm plate (see Ref. 7 for further details). Table 1 shows that rather small effects near the apex of the wing cause around 5-deg variation in the angle of attack at which vortex breakdown appears at the trailing edge.

It was therefore postulated that the observed variation of vortex breakdown position on delta wings at nominally identical angles of attack and sweep could be due to detail differences in geometry between the various experiments. Examination of the original papers revealed wide variations in details of geometry such as thickness, leading-edge chamfers, leading-edge radius, etc. For example, the W&K wings were chamfered on both top and bottom surfaces, while all others were chamfered on the bottom surface only. Also, the Lambourne and Bryer (L&B) data was from an unusually thick wing. Hence, several delta wings, with geometries identical to those used in some published investigations, have been tested to see if their results were repeatable under similar conditions.

The idea that the apex geometry affects the vorticity distribution downstream, and hence the position of vortex breakdown, also led to an investigation on the effects of an apex flap and changes in apex sweep angle. This was conducted on a delta wing of 70-deg sweep.

Experimental Setup

The delta wings in this survey were manufactured to a high degree of precision using the dimensions published in three previous investigations.[1–3] These are shown in Table 2 along

Table 1 Angle of attack for vortex breakdown at the trailing edge of two 85-deg delta wings[7]

Thick wing		Thin wing	
Standard	Inverted	Standard	Inverted
32 deg	31 deg	36 deg	37 deg

Table 2 Dimensions of the models used in the present experiments (all lengths in mm)

Λ, deg	c	d	σ, deg	Investigation
65	302	19	16	L&B
65	272	2.5	7.5[a]	W&K
70	349	2.5	7.5[a]	W&K
75	406	6.4	25	Payne
80	406	6.4	25	Payne
80	457	2.5	7.5[a]	W&K
85	406	6.4	25	Payne
70	441	12	20	Ref. 11
70	269	3.2	——	Ref. 10

[a]Half-wedge angle.

with the wings used in analyzing the effect of changes in apex geometry. All of the wings were tested in the 0.8 × 0.6 m closed return wind tunnel in the Department of Aerospace Engineering. The tunnel has a working range of 0–100 m/s and a contraction ratio of 12:1. It has been specifically designed to produce a turbulence level of less than 0.05%. The models were mounted on a parallel arm arrangement that allowed the incidence to be changed from outside the tunnel. The accuracy of the measured incidence was determined to be ±0.15 deg. The support system allowed a range of incidence of 0–80 deg and also ±2 deg of yaw. The experiments were conducted at the same Reynolds numbers as those quoted in the original investigations.

The principal flow visualization medium used was smoke, injected into the flow by a probe some chord lengths upstream of the wing. The smoke was generated by vaporizing a mineral-based oil at the tip of the probe. This created a plume of smoke that was directed at the apex of the wings. The entrained smoke allowed the vortices to be visualized, except at the center where the smoke particles are centrifuged out, producing a dark core. It was determined that the presence of the smoke probe had a negligible effect on the flowfield. This was done by seeding the tunnel to the extent that the dark cores of the vortices were visible without the plume of smoke being required. The results under these conditions were identical to those obtained with the smoke probe present.

A Spectra-Physics 5-W argon-ion laser, operating in all lines mode, was used to illuminate the flow by creating a light sheet via a small cylindrical lens. An optical bench setup provided beam steering to achieve a light sheet of specific height and chordwise position. The cylindrical lens could then be rotated to position it at any prescribed angle of incidence in the tunnel. For the purpose of tracking the vortex breakdown, it was inclined normal to the wing surface.

Vortex breakdown is an unsteady phenomenon that has a low-amplitude, high-frequency oscillation in the longitudinal direction. Hence, it is necessary to exercise some judgment in estimating its position. This was done by averaging the chordwise location where the dark core first begins to expand, and conversely, where the dark core first appears in the turbulent wake. For the wings of 75-deg sweep and less, this longitudinal oscillation covered no more than 6% of the chord. For the more slender wings the situation becomes more complex, with the breakdowns being known to travel large distances up and down the wing.[5] It has been suggested that there is a possibility of interaction between the two breakdowns since they are in close proximity to each other.

All the data presented in this article has proved to be very repeatable with errors, in terms of chordwise position, being less than 2%.

Results

The delta wings constructed for this survey covered a range of sweep angles from 65 to 85 deg. They are exact replicas of the models used by the three previous investigations, except for the L&B wing, which is a one-quarter scale version of the model used in their wind-tunnel tests. This was due to the original being too large for the test section of the low-turbulence wind tunnel. All the wings were tested under the same conditions as those stipulated in the original investigations.

Figure 4 shows a comparison of results for the 65-deg delta wings tested in the present experiments with the original data from W&K and L&B. Careful reproduction of the wing geometry has recovered the variation in vortex breakdown position found between the two tests.

The slight difference between the present data and the original data for the L&B wing, near the trailing edge, could be a result of the proximity of the tunnel walls in the original investigation. It has been suggested that this would produce an upwash effect, which would be greater at the trailing edge than at the apex.[8] The result is an effectively cambered wing that delays the onset of vortex breakdown and pushes it further down the wing for a specific angle of attack. It was decided to test this out by putting the L&B wing in the department's 0.6 × 0.6 m open-return wind tunnel, giving a b/w ratio of 0.47, compared with 0.35 for the low-turbulence tunnel. However, no effect of the reduced tunnel size was observed. The W&K comparison also varies slightly as the breakdown nears the apex. It was thought that this might be due to the forward strut being too near the apex on the underside of the wing. A further test with the struts further back showed no discernible variation.

The results for the W&K 70-deg wing are shown in Fig. 5. The comparison is good for vortex breakdown positions near the apex of the wing. However, there is some discrepancy in positions towards the back of the wing.

Two wings from the study of Payne,[3] with sweeps of 75 and 80 deg, were also tested. The 75-deg Payne wing was initially beveled with a 70-deg chamfer angle, producing a rather blunt leading edge. This meant that the apex region, which departs from the idealized slender delta form and is prismatic in shape, was only 2.7% of the chord length. This was compared with the original model, which had a sharper leading edge, of 25-deg chamfer angle, and hence, a 13.5% prismatic apex. The result was a delay of 4–5 deg in the appearance of breakdown (Fig. 6).

The comparison between the original data and that obtained in Bristol, for the original model dimensions, can be seen in Fig. 7. Again, as with the W&K 70-deg wing, there are differences in position near the trailing edge, and this time

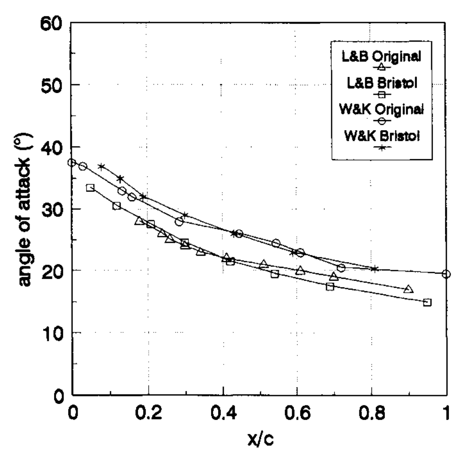

Fig. 4 Vortex breakdown movement for the 65-deg deltas of L&B and W&K.

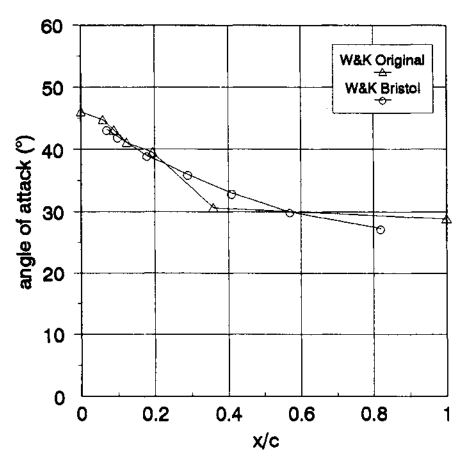

Fig. 5 Comparison of the data obtained for the W&K 70-deg delta.

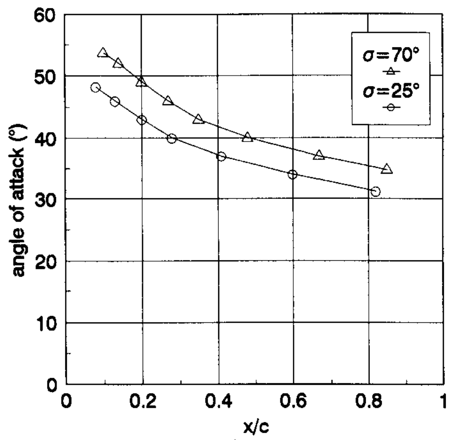

Fig. 6 Effect of chamfer angle on the position of vortex breakdown for 75-deg delta.

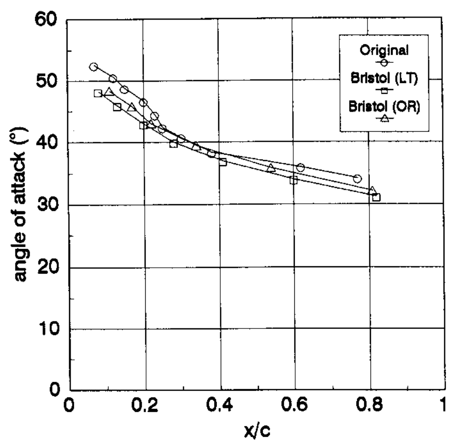

Fig. 7 Comparison between original data and Bristol data for 75-deg delta.

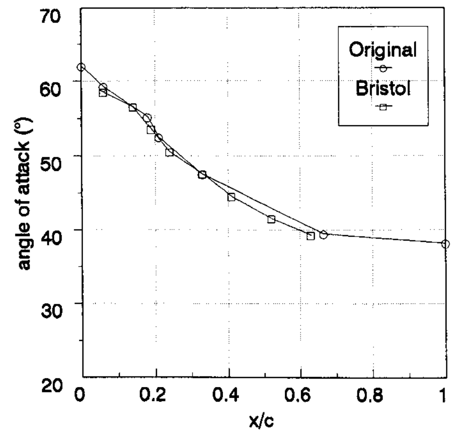

Fig. 8 Comparison of the averaged Bristol data with the original W&K 80-deg delta results.

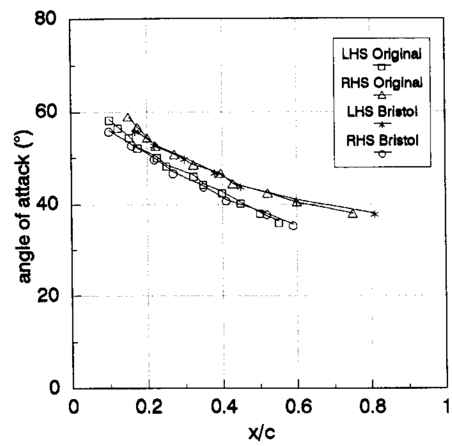

Fig. 9 Comparison of original and Bristol data for Payne 80-deg delta.

also near the apex. The wing was retested in the smaller open-return tunnel (OR), similar in size to the original tunnel used by Payne, and the position of breakdown moved downstream, in the process becoming more coincident with the original data. However, the variations at the apex and the trailing edge still remained.

The comparison of data for the 80-deg wings of W&K and Payne is shown in Figs. 8 and 9. The flowfield over the 80-deg wing is more complex than wings with lesser sweep angles in that there is a genuine difference in vortex breakdown position from side-to-side for these slender wings, originally observed by Lowson.[5] This complexity is accentuated by the position of the breakdown also being very sensitive to small changes in yaw angle, especially at high angles of sweep. This was documented by W&K who found changes as little as 0.1 deg in yaw make a significant difference in the flowfield. They used this fact to recover some kind of symmetry in the flowfield when the vortex breakdown first appeared on the wing. However, it was unclear from their paper whether this was done at every data point, since the original data for the W&K wing was presented as single data points at every angle of attack, or whether the breakdown positions were averaged. In the present experiments the data has been averaged and the comparison with the original data was extremely good.

In the case of the Payne results both the left and the right hand breakdown positions were documented. The wing was tested both for a symmetric alignment and two angles of yaw. It was found that the symmetric results were very similar to the results with 2 deg of yaw, with the negative yaw results showing an opposite trend in terms of left- and right-hand side breakdown positions. This suggested that the supposed symmetric case had slight positive yaw and this was confirmed when a further test with a smaller negative yaw angle produced similar results to the −2-deg case. This confirmed W&K's previous statement that small changes in the yaw angle make a large change in the flowfield. It also suggested that further increments in yaw, up to ±2 deg, do not have as great an effect. The results that best compared with the original data were the data for the slight positive yaw angle.

An 85-deg wing from Payne's study was also tested. The original data could not be reproduced in these experiments due to an asymmetry in the two vortices appearing at angles of attack as low as 30 deg. The appearance of this asymmetry, first reported by Lowson and Ponton,[7] was shown to vary with apex geometry. It has been found in the present tests that variations in tunnel speed from 3 to 20 m/s also affect the flowfield. The two vortices remain symmetrical longest, as the angle of attack is increased, at the lowest tunnel speed. The asymmetry could be induced over all three of the 85-deg wings tested merely by increasing the tunnel speed at a specific angle of attack. At the Reynolds number used in the Payne report, asymmetry occurred over the Payne 85-deg wing prior to vortex breakdown actually appearing over the wing. It was thought that the smoke probe upstream of the wings may have been influencing the flowfield. However, when tests were conducted with the tunnel fully seeded and the smoke probe no longer present, the asymmetry was still seen to occur.

Discussion

The previous results have demonstrated that the detail geometry of the wing plays an important part in the position of vortex breakdown. Angle of chamfer, plate thickness, and the chamfering technique (wedge or angle) all produce changes to the apex geometry, which will in turn produce significant variations in breakdown position, as can be seen for both the 65-deg deltas and through the modification to Payne's 75-deg delta. Careful reproduction of the wing geometry and testing under similar conditions has recovered previous data, for vortex breakdown position, on all the wings tested. The only exception is the 85-deg delta, which is discussed later.

The largest discrepancy for the results obtained was near the trailing edge of the W&K 70-deg wing. It may be noted that a recent paper by Delery[9] brought together a considerable number of results for vortex breakdown positions over 70-deg wings (Fig. 10), which suggested that the W&K results, indicated by the solid line, may be untypical. All the results for vortex breakdown at this kind of sweep angle show a more gradual movement up the wing. It is thought that the W&K data, which suggests this particularly rapid movement of vortex breakdown position with angle of attack, may be unrepresentative.

This effect was also apparent in the comparison of the original Payne 75-deg results, although deviations from the original data were no more than 5% in chord length at the trailing edge. Slight variations near the trailing edge, compared with the data obtained in Bristol, were due to a rapid movement in vortex breakdown position observed in the original investigation. The data obtained in Bristol also varied slightly from the original results near the apex, due to an anomaly in the original data near $x/c = 0.25$, although the error was no more

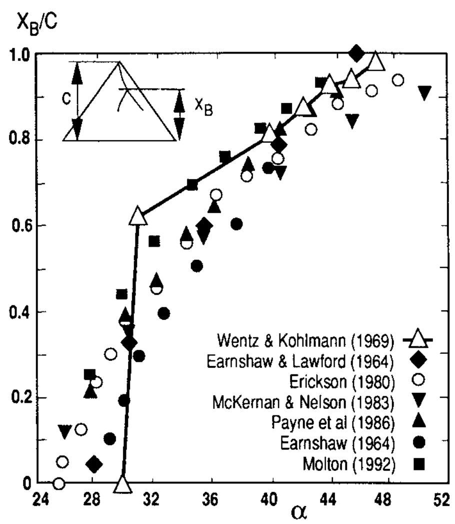

Fig. 10 Comparison of W&K data with several other surveys on 70-deg deltas.

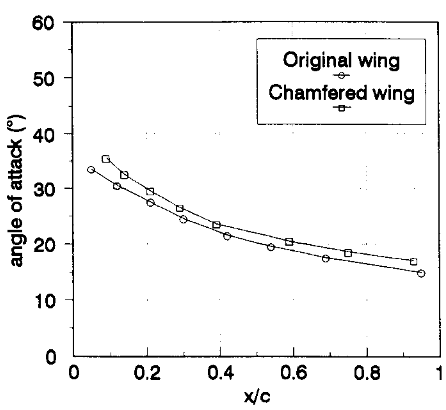

Fig. 11 Effect of chamfering the trailing edge of the L&B 65-deg delta.

than 2% in this case. It is apparent that any differences between data obtained in Bristol and that of the original investigations tends to be caused by sudden variations in chordwise movement of the original data. These have not been observed in the data obtained in this survey.

A further issue is whether the geometric changes at the apex or the trailing edge are of the most significance in determining the breakdown position. Hence, an experiment was performed on the L&B 65-deg wing, modifying it by adding a chamfer to the trailing edge. The effect was to delay the onset of breakdown and to push it down the wing, compared to the original data, for all angles of attack (Fig. 11). This latter result was surprising in that the modification has had a significant upstream effect. However, due to the thickness of the wing and the angle of chamfer, the amount of wing actually altered extended 22% of the chord length from the trailing edge. Also, the chamfering allowed the windward and leeward flowfields to merge smoothly, unlike the discontinuous straight edge prior to the modification. Hence, this large trailing-edge change could well effect the external pressure gradient over the whole wing. The effect on vortex breakdown position, though, was less than that due to the changes in apex geometry, as in the two sets of original 65-deg data and the Payne 75-deg data.

It is believed that the key effect in determining the vortex breakdown position is the apex shape. The strength of the vorticity shed near the apex of the wing will be directly affected by the variation in the shape. The vorticity shed from the apex forms the center of the vortex core, hence, the effect of detail geometry changes is to cause variations in the vorticity distribution at the center of the core. It is well established that changes to vorticity gradient can have serious effects on the stability of fluid flows. This provides a candidate mechanism to explain the effects on the position of the breakdown due to changes in apex geometry.

An attempt has also been made to assess the possible effects of those factors mentioned in the Introduction. Only one kind of flow visualization has been utilized in this survey. However, W&K's investigation used the schlieren method and L&B, although using smoke, did not have the benefit of laser light sheet illumination. As already shown, there is no apparent difference in results. Support systems differed for the L&B and Payne investigations. The L&B wing was sting-mounted and Payne's was mounted by a single strut. The two-strut system used in this survey does not seem to have affected the results. Wind-tunnel factors have already been mentioned, but they only appear to have slight effects on the breakdown position for the cases studied. Reynolds numbers have been varied by an order of magnitude in the present tests and no change has been observed in the vortex breakdown position.

Following the present experiments, it is now possible to be a little more specific about the effects on vortex breakdown appearance for changes in detail model geometry. The present experiments suggest that vortex breakdown will tend to move up the wing if 1) wing thickness is increased or 2) chamfer angle is decreased. The sum of these effects can be up to 5–7-deg variation in angle of attack for a given vortex breakdown position.

The present experiments also show little effect on vortex breakdown position from 1) Reynolds number, 2) strut position, or 3) smoke probe (at least in present experiments). Increased tunnel blockage was found to move the vortex breakdown downstream. This was consistent with the findings of Ref. 8, although the effects were small for the cases studied here.

Figure 12 shows a revised version of Fig. 1, in which a uniform trend in the delta wing flow regimes has been observed, over the range of sweep angles tested. Figure 12 is based on the present results for the W&K wings. The results in the present test series for the 75- and 80-deg Payne wings, and also for the 65-deg L&B wing, have been added to the

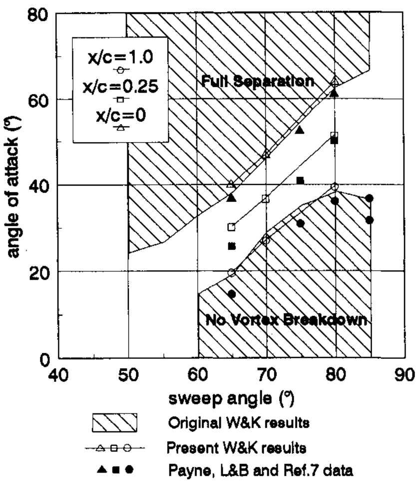

Fig. 12 Comparison of the present results with the original W&K flow regimes.

figure (solid points). These points demonstrate the systematic effect that variations in wing thickness and chamfer angle can have on the onset of the various flow regimes. The exception to the general trends has been the 85-deg wing, which behaves in a nonlinear fashion, with respect to the onset of the flow regimes. The results for the appearance of vortex breakdown, obtained by Lowson and Ponton,[7] over the two 85-deg wings referred to in Table 1, have also been added to Fig. 12. It can be seen, as with the original W&K data in Fig. 1, that the 85-deg data does not follow the expected trend. However, as can be seen from Table 1, the appearance of vortex breakdown is still in agreement with the suggested effect of wing thickness. Results for this case are subject to three major confusing features: 1) the large effects of yaw (discussed previously), 2) the substantial asymmetries often observed, and 3) the potential appearance of a third vortex near the apex. Any of these effects may have caused the results to vary from the norm. It is believed that the regions outlined in Fig. 12 are reasonably representative of the broad trends.

Control of Vortex Breakdown Position

A further issue of interest is the possibility of using the apex geometry as a means of flow control. The variation in apex vorticity provides a mechanism to change the location of vortex breakdown as required. This could be a useful source of moment of high angles of attack. Figure 13 shows the effects of a systematic series of tests on a small 70-deg delta plate fitted with a 25% "apex flap," which can be set at an angle to the wing as desired.[10] The dimensions for the model are shown in Table 2. It can be seen that the effects of even quite small variations in apex flap angle cause significant variations in vortex breakdown position.

From the control point of view the principal interest is the effect of small apex flap motions. It can be seen that the apex flap produces a reasonably systematic effect on vortex breakdown position. This could be used at high angles of attack to produce changes in pitching moment, or by differential action, a useful rolling moment.

The tests have been repeated with a smaller flap, of 10% chord, on a 70-deg wing used in previous research at Bristol[11] (see Table 2). It was hoped that the vortex breakdown would prove very sensitive to vorticity distributions at the core center, so that effectiveness could be maintained with a smaller flap. The results are given in Fig. 14. This shows that the hope was partially fulfilled, in that a reduction in flap chord of more than half has resulted in only a modest reduction in effectiveness, for small apex deflections. For this case the flap produces just under a 1% chord vortex breakdown movement

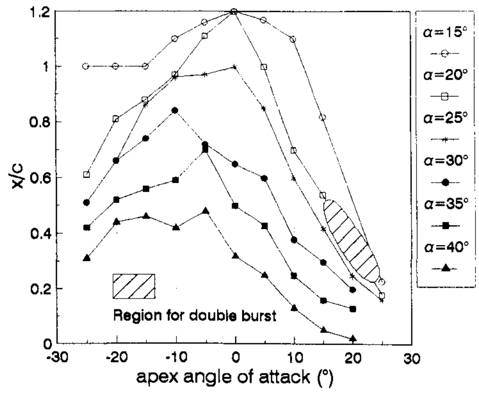

Fig. 13 Effect of 25% apex flap for a 70-deg delta wing.

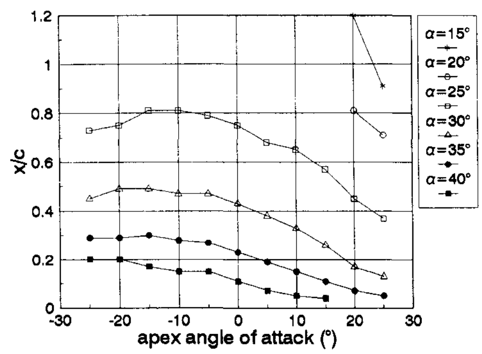

Fig. 14 Effect of 10% apex flap for a 70-deg delta wing.

per degree over most positions of vortex breakdown on the wing.

The apex flap results for both the 70-deg deltas presented here proved to be highly nonlinear for large flap deflections. In the case of the 25% apex flap further increases in negative flap deflection, beyond 10 deg, did not result in a downstream movement of the vortex breakdown and, if at all, the breakdown began to move upstream. At larger positive flap angles more complex effects occurred. The most interesting is the result shown for apex flap angles of around 20 deg for modest wing angles of attack, depicted in Fig. 13 by the shaded area. Under these conditions the burst vortex on the apex flap reformed as a concentrated unburst vortex on the wing. The reformation of a previously burst vortex is unexpected and could have wider fluid dynamic interest.

Large negative flap angles produced similar behavior in the case of the 10% apex flap, although movement back upstream was not so pronounced. Downstream movement of the breakdown for the 10% flap tended to be at a slower rate than for upstream movement for positive flap deflections. No double burst could be found for the 10% apex flap. It was interesting to note that for both the apex flaps investigated, concentrated vortex structures were found over the flaps at combined angles of attack, which would suggest full separation. This suggests that the flowfield over the main wing has a significant upstream effect on the apex flap, preventing a fully separated flowfield where one would be expected.

The effects of changes in apex geometry, in terms of sweep angle, were also considered. These tests were conducted on the wing used for the 10% apex flap tests. The sweep angle was changed by ±5 deg at the 10% chord position. For the 75-/70-deg delta the breakdown moved downstream in comparison with the original wing (Fig. 15). The 65-/70-deg delta varied little from the original results, although there was a slight upstream movement. Thompson[4] conducted a thorough survey on a number of sweep combinations, although the change in sweep for most of his tests occurred at the half-chord position. The nearest comparable result was for a 70-/

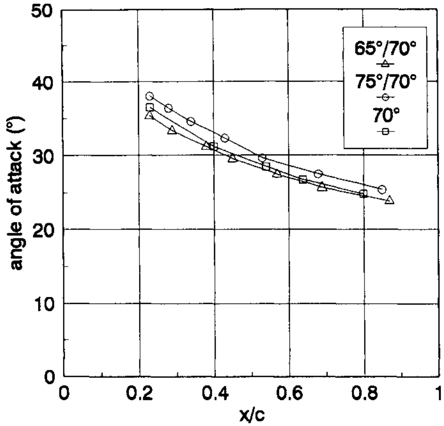

Fig. 15 Effect of variation of apex sweep on the position of vortex breakdown.

60-deg wing, which changed in sweep at 20% chord from the apex. There was a downstream movement of the breakdown similar to that which occurred for the 75-/70-deg wing in Fig. 15. The results for the 65/70 deg show that, as with the variation in apex angle of attack, changes in apex sweep angle produce a nonlinear effect on the flowfield. The conclusion of these apex tests was to add two further conditions for the upstream movement of the vortex breakdown, which are if 1) apex sweep is reduced and 2) apex incidence is increased.

Conclusions

1) It has been demonstrated that the variation of vortex breakdown position over a slender delta wing from various investigations at the same sweep and angle of attack is principally due to changes in detail model geometry, particularly the geometry of the apex.

2) Previously published results for the behavior of vortex breakdown have been successfully reproduced by using models of the exact geometry used in prior investigations.

3) The effects on vortex breakdown position due to variations in geometry far outweigh those due to support interference, methods of flow visualization, wind-tunnel factors, and changes in Reynolds numbers.

4) It has been shown that a small apex flap can be used to control the position of vortex breakdown on a delta wing.

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