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Measurements of Vortex-Breakdown Position at Low Speed on a Series of Sharp-Edged Symmetrical Models

by

P. B. Earnshaw

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SUMMARY

Measurements have been made at low speed of vortex-breakdown positions on a series of five, symmetrical wings, using a Schlieren system to detect the position of breakdown. The results suggest that the modification of a delta planform to incorporate streamwise tips has little effect on breakdown position when this is forward of the modified tip.

Examination of the large differences between these measurements and those from other sources suggests that the influence of cross-sectional shape even on nominally thin wings may be larger than expected and merits further investigation.

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1 INTRODUCTION

Since little information is available on the relation between slender-wing geometry and the occurrence of vortex breakdown, a series of experiments having planform as the primary variable has been performed in the 4 ft × 3 ft low-turbulence wind tunnel. Following R.F.A. Keating of R.A.E. Bedford, who demonstrated in August 1963 that a Schlieren system could be used to detect vortex breakdown at low speeds, this technique has been used as a breakdown indicator. It possesses an obvious advantage in that there is evidently no risk of interference with the vortex development, nor is there any restriction to very low wind speeds as is the case with some smoke visualisation techniques. At the speeds used in the present tests, the Schlieren system responded only to density gradients near the axis of the vortex and the abrupt disappearance of these gradients was identified as breakdown. Other techniques detect different flow characteristics. For example, with smoke at moderate speeds, breakdown is generally identified with the rapid expansion of the outer vortex field, or, when using tufts, with the appearance of flow reversal or high turbulence.

In the present state of knowledge, it is difficult to define vortex breakdown more precisely than as a catastrophic change of vortex structure. It cannot be argued therefore that all possible forms of breakdown would be detected by one particular technique. Thus, apart from the degree of interference with the flow, the only remaining characteristic that might support a preference for one technique over another would be its resolution. Here, in the author's experience, the Schlieren technique shows a clear advantage over smoke techniques at moderate speeds, tufts and (at least in some cases) over condensation trails. The technique is therefore well suited to study the effects of small changes in model geometry on the occurrence of vortex breakdown.

Because of conflicting results obtained in earlier work with thin delta wings[1,2,3], care has been taken in the present tests to eliminate features that might restrict this generality. The models - a series of five wings sharing two apex angles - were designed to have the same, smooth, symmetrical chordwise-section, ensuring zero vortex strength at zero incidence. The Reynolds number based on centre-line chord differed slightly between the five wings but in view of the insensitivity of breakdown position to Reynolds number variation[1,2], the 15% change through the series seems unlikely to produce any significant effect. Distributed roughness was applied to each model to eliminate possible disturbances due to movement of the transition from laminar to turbulent secondary separation, which transition is indicated on the smooth wing by the kink in the secondary separation line. In consequence, there is reason to believe that differences in breakdown position on different wings of the present series are likely to be governed almost wholly by differences in planform.

2 APPARATUS AND TESTS

The tests were carried out in the R.A.E. 4 ft × 3 ft low-turbulence wind-tunnel at 100 ft/sec. Five sting-mounted models of 4% thickness-chord ratio and the same, smooth, symmetrical section were used. The planforms are shown in Fig.1. They comprise:- two delta wings of 65° and 70° sweepback angles: a third wing whose forward 50% chord has straight leading-edges of 65° sweep but having streamwise tips giving a span-length ratio equal to that of the 70° delta: a fourth wing similar to the third but stretched to give an initial sweep of 70°: a fifth wing whose initial 35% chord has straight leading-edges of 70° sweep but having the tip shape and therefore span-length ratio of the third wing.

Each model has had distributed roughness applied to the forward 10% of the upper surface, together with two strips of roughness radiating from the apex at spanwise positions dictated by the vortex positions at the lowest incidence considered. Surface flow patterns indicated the minimum length of these strips that was necessary to move the 'kink' in the secondary separation line to the apex. This kink is a result of transition from laminar to turbulent secondary separation with its attendant outward shift in the secondary separation line. The lower incidence case is the critical one since the 'kink' moves forward with incidence. This procedure then avoids any disturbance generated by unsteadiness of such a 'kink'.

A Schlieren system, angled to distinguish between the vortices, was used as a breakdown detector. Noted breakdown positions were then measured wind-off and normal to the wing surface, assuming the vortex centre-line to be at 65% semi-span. As the angle of the optical axis was approximately 3°, no appreciable error was introduced by this procedure (see Fig.4).

3 DISCUSSION OF RESULTS

As used in these tests, the Schlieren system showed the leading-edge vortices as thin lines which terminated abruptly at vortex breakdown. Previously[4], a small feather tuft has been used as a simple detector of a rapid transition to high turbulence with intermittent forward flow, which was taken as breakdown. In the present tests, an initial check was made that both techniques were consistent. Good agreement was found when the two techniques were used simultaneously. However, the introduction of the tuft-probe moved the breakdown position by 10-15% of centre-line chord forward of the position given by the Schlieren system alone.

The variations of breakdown position with incidence for the five wings are plotted in Fig.2. As force measurements for these wings are not known, a crude estimate of C_L, using Ref.4 as a basis for extrapolation, was made in order to apply a tunnel-constraint incidence correction. The maximum value of the correction amounted to 1·5°. This value is uncomfortably large since it cannot be expected to be very accurate at high incidences and also suggests that there may be an appreciable induced camber on the models. Nevertheless, this correction is still well within the range of differences between results from this and other sources.

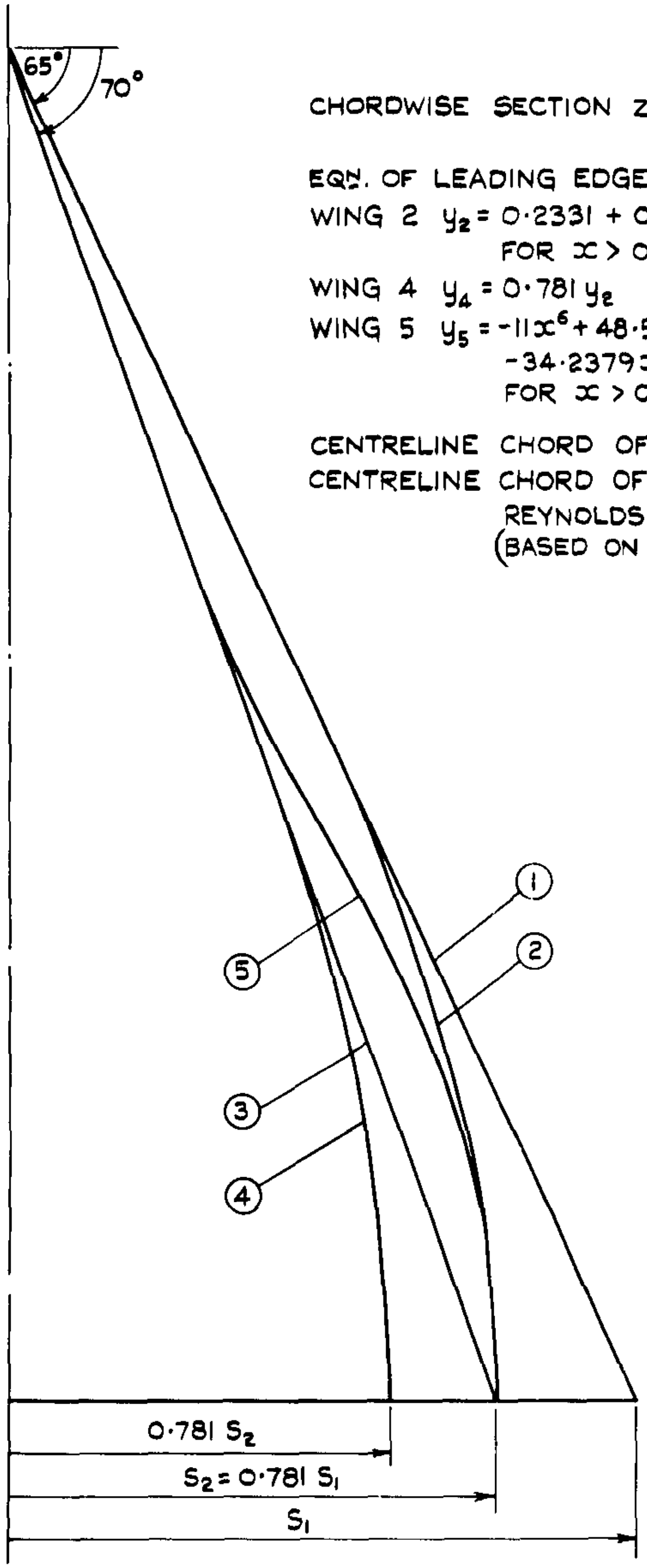
Fig.2 shows that wings 1 and 3 have behaviour closely similar to wings 2 and 4 respectively for higher incidences. This suggests that breakdown position is strongly dependent on leading-edge sweep angles over the forward part of the wing and that span-length ratio which is the same for wings 2,3, and 5 has only little influence. It is true that the modification of the tip shape of wing 1 in order to produce wing 2 has changed the breakdown behaviour towards that of wing 3. Nevertheless the change is greatest only at the lower incidences and is relatively minor when compared with the changes produced by apex modifications. This is apparent on wing 5 where the breakdown position has moved a long way from wing 2 towards wing 3, both at low and at high incidences.

It seems fair to assume that, in the absence of breakdown, the flow over the forward part of wing 1, 2, 3 and 4, apart from the viscous sub-core, is conical to the first order and that, on corresponding pairs of wings, it is similar. Since, on a delta wing, vortex breakdown does not occur simultaneously at all points along the vortex and scale effect is small[1,2], a slight modification of this primary flow, due to the presence of the trailing edge, must exist to allow breakdown to occur repeatedly at a particular chordwise position. The implication of the present results therefore is that the modification necessary to produce breakdown is a stronger function of trailing-edge position than of the planform shape of the rear part of the wing.

Finally a comparison is made in Fig.3 between the present results on the delta wings and those of Lambourne and Bryer[1], Elle[2], and Lawford[3]. Tunnel constraint corrections consistent with those of the present series have been applied. In fact, results for only two of the four conditions of test quoted

REFERENCES

No.	Author	Title, etc.
1	N.C. Lambourne D.W. Bryer	The bursting of leading-edge vortices - some observations and discussion of the phenomenon. A.R.C. R & M No.3282 April 1961
2	B.J. Elle	An investigation at low speed of the flow near the apex of thin delta wings with sharp leading edges. A.R.C. R & M No.3176 January 1958
3	J.A. Lawford A.R. Beauchamp	Low-speed wind-tunnel measurements on a thin sharp-edged delta wing with 70° leading-edge sweep, with particular reference to the position of leading-edge-vortex breakdown. A.R.C. R & M No.3338 November 1961
4	P.B. Earnshaw J.A. Lawford	Low-speed wind-tunnel experiments on a series of sharp-edged delta wings. Part 1. Forces, moments, normal-force fluctuations, and positions of vortex breakdown. A.R.C. R & M No.3424 March 1964



CHORDWISE SECTION $z = \frac{3\sqrt{3}}{50}x(1-x)\left(1-\frac{x}{2}\right)$

EQN. OF LEADING EDGE
WING 2 $y_2 = 0·2331 + 0·4663(x-0·5) - 0·496(x-0·5)^{2·278}$
FOR $x > 0·5$
WING 4 $y_4 = 0·781\ y_2$
WING 5 $y_5 = -11x^6 + 48·5224x^5 - 85·1382x^4 + 74·7491x^3$
$-34·2379x^2 + 8·1672x - 0·6989$
FOR $x > 0·35$

CENTRELINE CHORD OF WINGS 1,2,5 IS 18 INCHES
CENTRELINE CHORD OF WINGS 3,4 IS 21 INCHES
REYNOLDS NUMBER $\simeq 10^6$
(BASED ON CENTRE-LINE CHORD)

FIG. 1 DETAILS OF MODELS

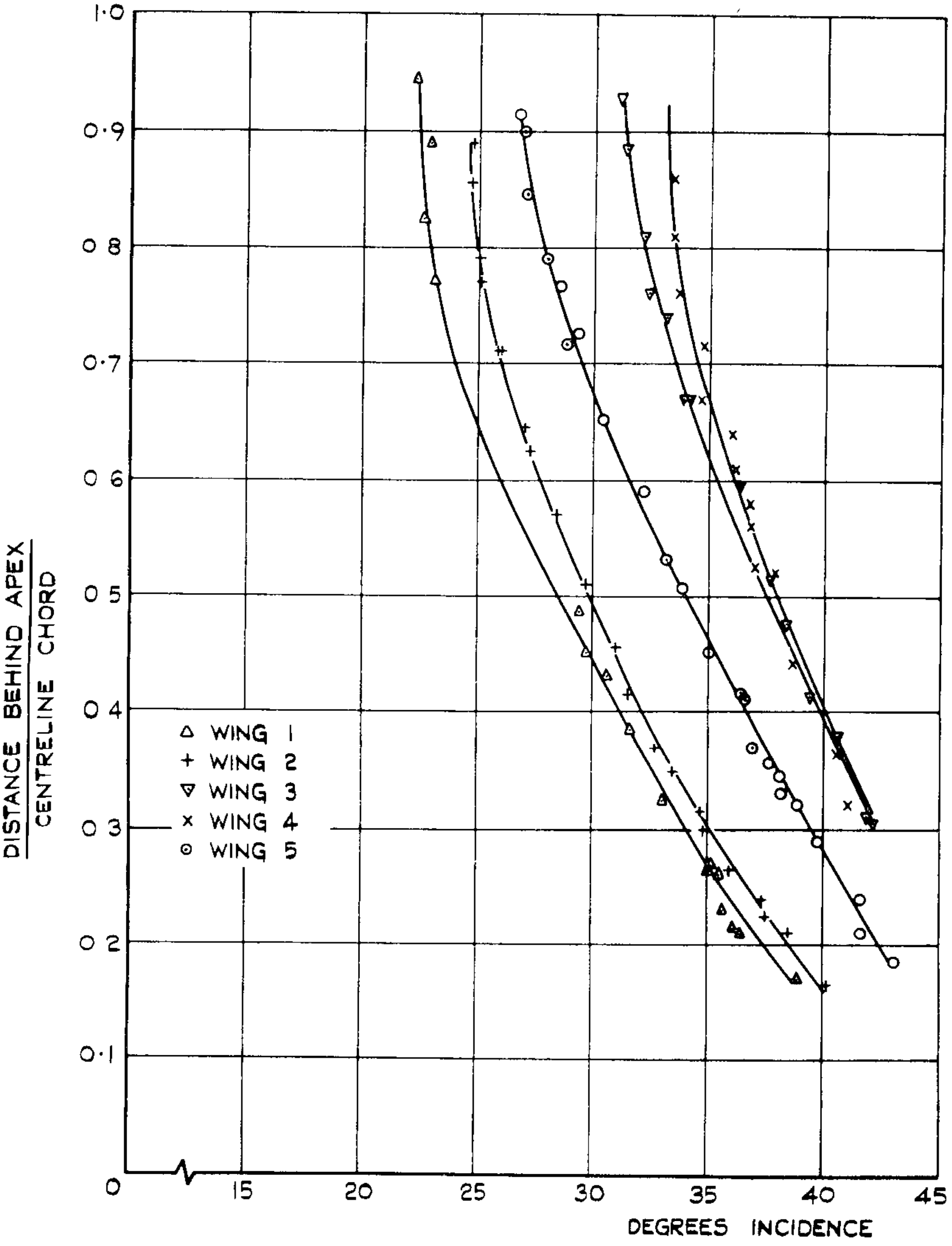


FIG 2 VARIATION OF BREAKDOWN POSITION WITH INCIDENCE

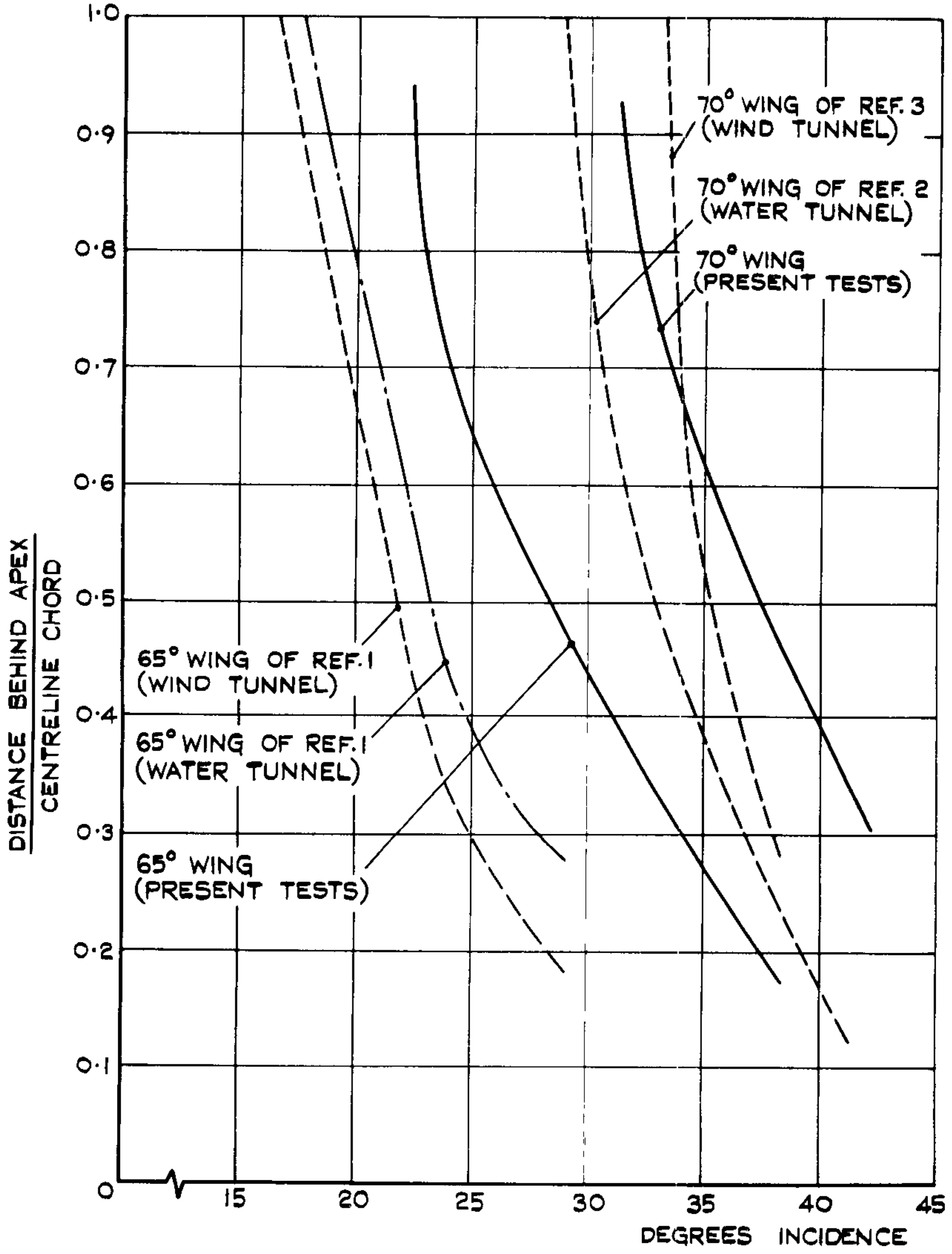
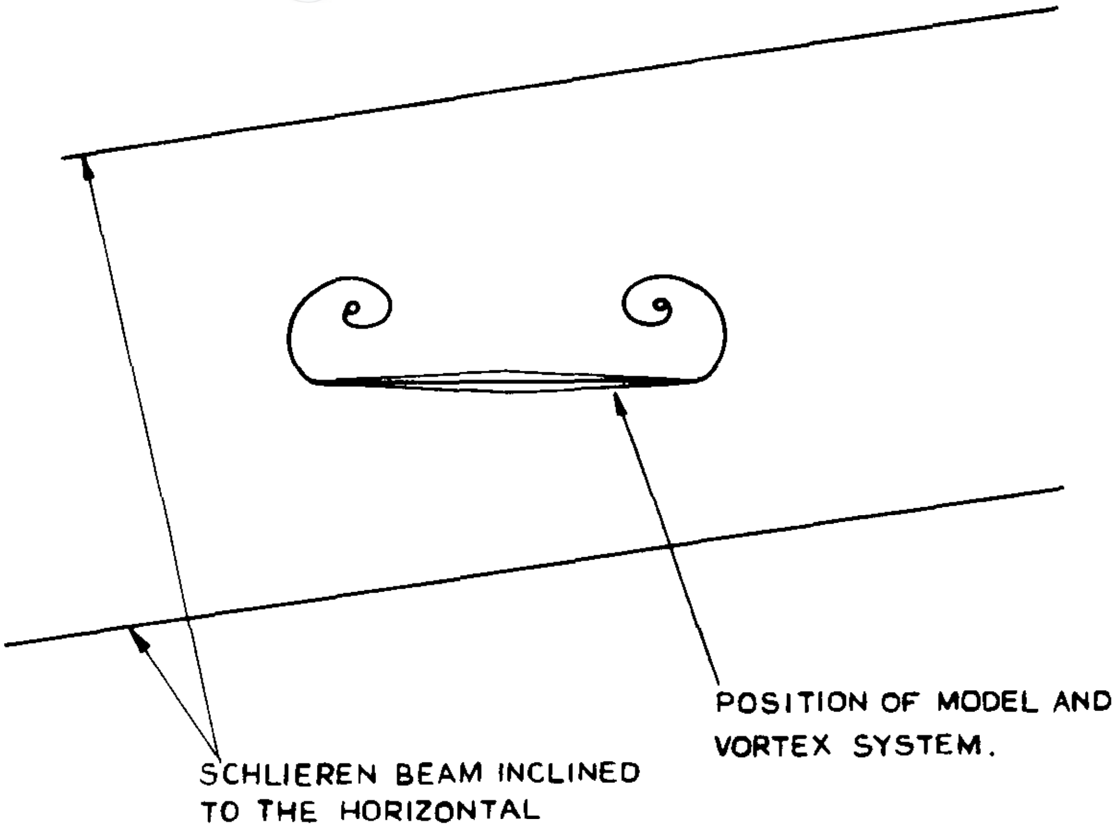


FIG. 3 COMPARISON OF BREAKDOWN MEASUREMENTS ON DELTA WINGS MEASURED IN DIFFERENT TUNNELS



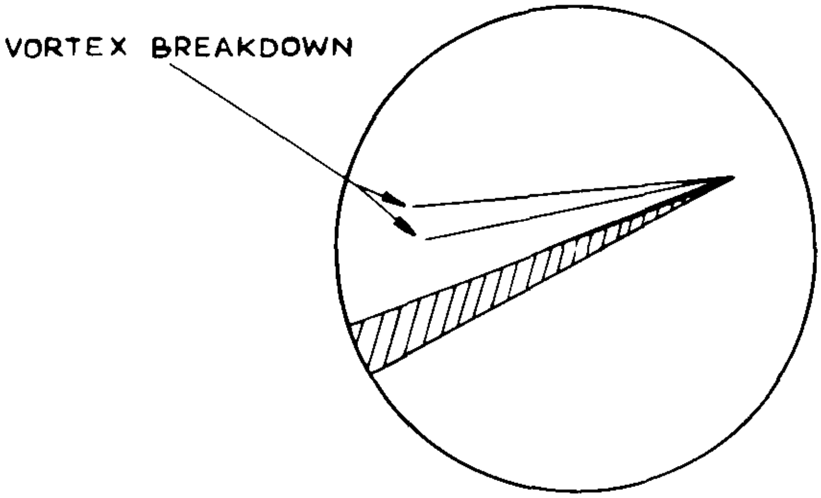


DIAGRAM SHOWING PATTERN ON
SCHLIEREN SCREEN

FIG. 4 DETAILS OF SCHLIEREN SYSTEM

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