C.P. No. 1018

C.P. No. 1018

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Measurements of the Effects of Thickness on Vortex Breakdown Position on a Series of Sharp-Edged Delta Wings

by

P. B. Earnshaw

LONDON: HER MAJESTY'S STATIONERY OFFICE

1968

PRICE 3s 6d NET

U.D.C. 532.517.43 : 533.693.044 : 533.6.071.31 : 533.6.013.6

C.P. 1018*
February 1968

MEASUREMENTS OF THE EFFECTS OF THICKNESS ON VORTEX BREAKDOWN POSITION ON A SERIES OF SHARP-EDGED DELTA WINGS

by

P. B. Earnshaw

SUMMARY

Measurements have been made of vortex breakdown position on a series of symmetrical delta wings of 70° sweep angle but differing thickness distribution using a schlieren system to detect the breakdown. The results demonstrate that the angles of incidence necessary to achieve a given position of breakdown over the wing can differ by at least as much as 5° from a thin wing to a wing of 8% thickness-chord ratio. The tests also show the breakdown position to have a weak dependence on Reynolds number.

*Replaces R.A.E. Technical Report 68050 - A.R.C. 30405.

CONTENTS

1 INTRODUCTION

In an earlier series of measurements[1] of vortex breakdown position on slender wings, the assumption was made on planning the tests that the thickness distribution of the models was unlikely to have any significant influence on the results. In view of the 4% thickness-chord ratio, smooth symmetrical section, and sharp leading-edges, this seemed a not unreasonable assumption to make. But a comparison of these results with those from other sources which was made in Ref.1 suggested that even for thin wings, the thickness distribution might have some measurable effect on the results even though the overall trend in the influence of planform should be undisturbed. Since it seemed clear that the schlieren technique could distinguish much smaller differences between the breakdown characteristics of different wings than had been needed for the earlier measurements, tests have been made on a further series of models aimed at assessing the magnitude of the thickness effect.

The results show this to be easily measurable - as much as five degrees difference in incidence to attain a given breakdown position between the thinnest and thickest wings on which results were obtained. However, in the course of the tests, anomalies in the results suggested that the influence of Reynolds number and possibly also Mach number could not be ignored. It seemed worth while therefore to establish whether within the small range obtainable, such an influence could be isolated. This in fact proved to be at the limit of resolution of the technique, at least in its existing state, but it is felt nevertheless that the results do indicate a significant variation in breakdown position with variation in Reynolds number. No measurable influence of compressibility could be detected at the low wind speeds used in the tests.

2 APPARATUS AND TESTS

The tests were carried out in the R.A.E. 4ft × 3ft low turbulence wind tunnel, mainly at a wind speed of 100 ft/s. A series of sting-mounted, sharp-edged, symmetrical delta wings all of 70° sweep angle were tested. With the exception of the thinnest wing, Wing 1, which was a 'flat-plate' metal model of 1.7% thickness-chord ratio, symmetrically chamfered to an included angle of 30° on all edges and having a centreline chord of 10.95 inches, the models tested to investigate thickness effect were all of 21 inches chord and constructed from wood with a centre section of epoxy resin and fibreglass so that a good quality leading edge could be maintained. Details of the thickness distributions are given in Fig.1 but to summarise, Wing 2 is constructed to the same design as the 70° delta of the earlier tests[1] having 4% thickness-chord ratio, Wing 3 has this thickness distribution scaled by a factor of 2, and Wing 4 resembles Wing 3 but with the region of high thickness reduced so that while the thickness-chord ratio is approximately 4%, the thickness distribution in the neighbourhood of the edges remains that of Wing 3. Two further models 12% and 16% thick respectively, scaled from Wing 2, were tested but for reasons discussed in Section 3, no results were recorded.

In order to investigate Reynolds number and compressibility effects, Wing 5 of 12 inches chord scaled down from Wing 2 was tested at 100 ft/s and 180 ft/s. This was compared with results from Wing 2 at 100 ft/s and, not wholly satisfactorily, at 60 ft/s.

For most of the tests, transition from laminar to turbulent secondary separation on the models was avoided by the use of a transition wire on the upper surface of the models applied spanwise at 10% chord downstream of the apex and two further wires radiating from the apex at spanwise positions dictated by the vortex positions at the lowest incidence considered. Since the transition at the secondary separation moves forward with increasing incidence, this procedure is sufficient to ensure that the transition is triggered by the wire within the whole incidence range considered, provided of course that the leading-edge vortices cover a large part of the wings as is the case here. This technique was adopted since it was found that although the use of the minimum necessary amount of distributed roughness, as used in the earlier tests gave, so far as could be determined, the same position of vortex breakdown, the breakdown itself was less unsteady when wires were used.

In an attempt to ensure the closest possible degree of similarity between the flow fields associated with Wings 2 and 5 at nominally the same Reynolds number, transition was allowed to remain free. Surface flow patterns indicated that similarity did appear to have been achieved under these conditions.

As in the earlier tests, vortex breakdown was detected by means of a schlieren system, angled slightly to distinguish between the two vortices, defining the breakdown position as the point where the vortex abruptly disappeared on the schlieren screen. Windows in the working section were replaced by $\frac{1}{8}$ inch perspex sheets. Since, in this wind tunnel, only small pressure differences exist between working section and observation room, these had adequate stiffness and permitted a good quality schlieren image with no evidence of stress pattern.

By far the most sensitive indication of yaw on the models was through asymmetry of the breakdown positions on the port and starboard sides of the wing. Throughout the tests, it was ensured that these positions differed by no more than 5% chord, their mean being taken as the correct value.

3 DISCUSSION OF RESULTS

3.1 Thickness effects

The variation of breakdown position with incidence for four wings at essentially the same Reynolds number is shown in Fig.2. Using the technique of Ref.2, a crude estimate of lift coefficient has been made to apply a tunnel constraint correction to these results giving a maximum increment of incidence of 1.5° for the larger wings and 0.35° for Wing 1. Although this correction, and the effective camber of the wings implied by the correction, is large, the influence of thickness distribution on the results is clear. Differences cannot be ascribed to a variation in sensitivity of the schlieren system between observations of the breakdown position on different models of the series. At least three positions of the system were needed for each wing. Continuity of the curves therefore implies that the breakdown position recorded is unaffected by slight variations in sensitivity of the optical system.

It will be seen in Fig.2 that in no case was it possible to record breakdown positions in the neighbourhood of the trailing edge. This results in part from the increasing gradient of the curves and also from the tendency of the flow to take up a stable asymmetric arrangement where breakdown in one vortex is downstream of the trailing edge while that on the other side is upstream. It remains possible therefore that on the thicker wings, 2,3,4, breakdown crosses the trailing edge at the same incidence. Nevertheless at higher incidences, there is a clear movement of the breakdown downstream as the thickness increases.

Beyond remarking that the position of vortex breakdown appears to be a function of the distribution of thickness across the whole wing rather than simply in the neighbourhood of the leading edge or the centre-line, little can be deduced with any confidence. It is however perhaps worth noting some degree of similarity in the geometry of Wings 1 and 4. Although Wing 1 is simply a chamfered flat plate, both the thickness-chord ratio and leading-edge angle are approximately a half of those of Wing 4 which is flattened over the centre section of the wing. The same relationship obtains between Wings 2 and 3. Without wishing to draw too firm a conclusion from these similarities, one may nevertheless note a grouping of the breakdown curves into pairs. If this is valid, behaviour near the trailing edge is less untidy than at first sight appears on the basis only of thickness-chord ratio.

As remarked earlier, some tests were also made with wings of 12% and 16% thickness-chord ratio. For these wings however, it was found impossible to detect the existence of vortices before breakdown. It will be realised that the optical system is capable only of detecting density gradients above a given strength and therefore above a given incidence. It must be concluded therefore either that breakdown first occurs below an incidence at which the vortices would become visible or that the structure of the unbroken vortices on the thicker wings is so changed that they are no longer visible even at high incidences. Both possibilities exist because on wings of such extreme thickness, it was not possible to position the schlieren system so that a view along the surface of the model in the neighbourhood of the apex could be obtained.

3.2 Reynolds number variation

In making the tests on Wing 1, measurable movements of breakdown position were detected when raising the wind speed from 100 ft/s adopted for the other models to 200 ft/s needed to obtain the appropriate Reynolds number, although at both speeds the secondary separation was turbulent and would not therefore move significantly as Reynolds number increased. Even at such low speeds, the possibility of compressibility effects must be borne in mind since velocities along the axis of a vortex before breakdown well over four times that of the free stream have been measured[3] in one case. In order to investigate this point further therefore, Wing 5, a scaled-down model of Wing 2, was tested at speeds of 100 ft/s and 180 ft/s and Wing 2 itself was again tested at 60 ft/s so that similar Reynolds numbers were obtained at different Mach numbers. Initially, to avoid difficulties in ensuring similarity of transition on the models, no trip wires were attached.

At the higher Reynolds number, Fig.3 shows that good agreement is obtained between the two models over most of the incidence range although, in the neighbourhood of the trailing edge, there is some divergence between the two sets of results. At the lower Reynolds number, agreement is only fair but it must be pointed out that at 60 ft/s, the schlieren system is on the limit of its usable range for such small models.

These tests with the exception of the runs at 60 ft/s were repeated with transition wires attached to the models. The most directly comparable results are those with the wires scaled in approximately the same ratio as the models at a fixed Reynolds number. As can be seen in Fig.4, agreement is excellent throughout the incidence range. On reducing the Reynolds number, it was found necessary to increase the diameter of the wires in order to ensure transition. The weak variation with Reynolds number is therefore no longer a clear-cut issue particularly since the use of these same large wires at the higher Reynolds number appears to lead to a slight rearward movement of breakdown from the small wire situation. However this movement which is hardly outside the experimental scatter of results is in the opposite sense to the effect of Reynolds number so that it seems fair to assume that the latter does have an influence even when the secondary separation is everywhere turbulent. It seems clear also that in this range at least, compressibility has a negligible influence compared with that of Reynolds number.

At first sight, it might be thought that since Reynolds number is known to affect the structure of a leading-edge vortex fairly strongly only in the outer turns of the vortex sheet and in the viscous sub-core, the mechanism leading to breakdown has its origin in or near one of these regions. However it will be realised that the influence of Reynolds number on breakdown, on the evidence of the present tests over admittedly a very small range, is weak. It remains possible therefore that weak Reynolds number effects on the flow field as a whole such as might be produced by changes in the wing boundary layer could lead to the weak dependence noted.

4 CONCLUSIONS

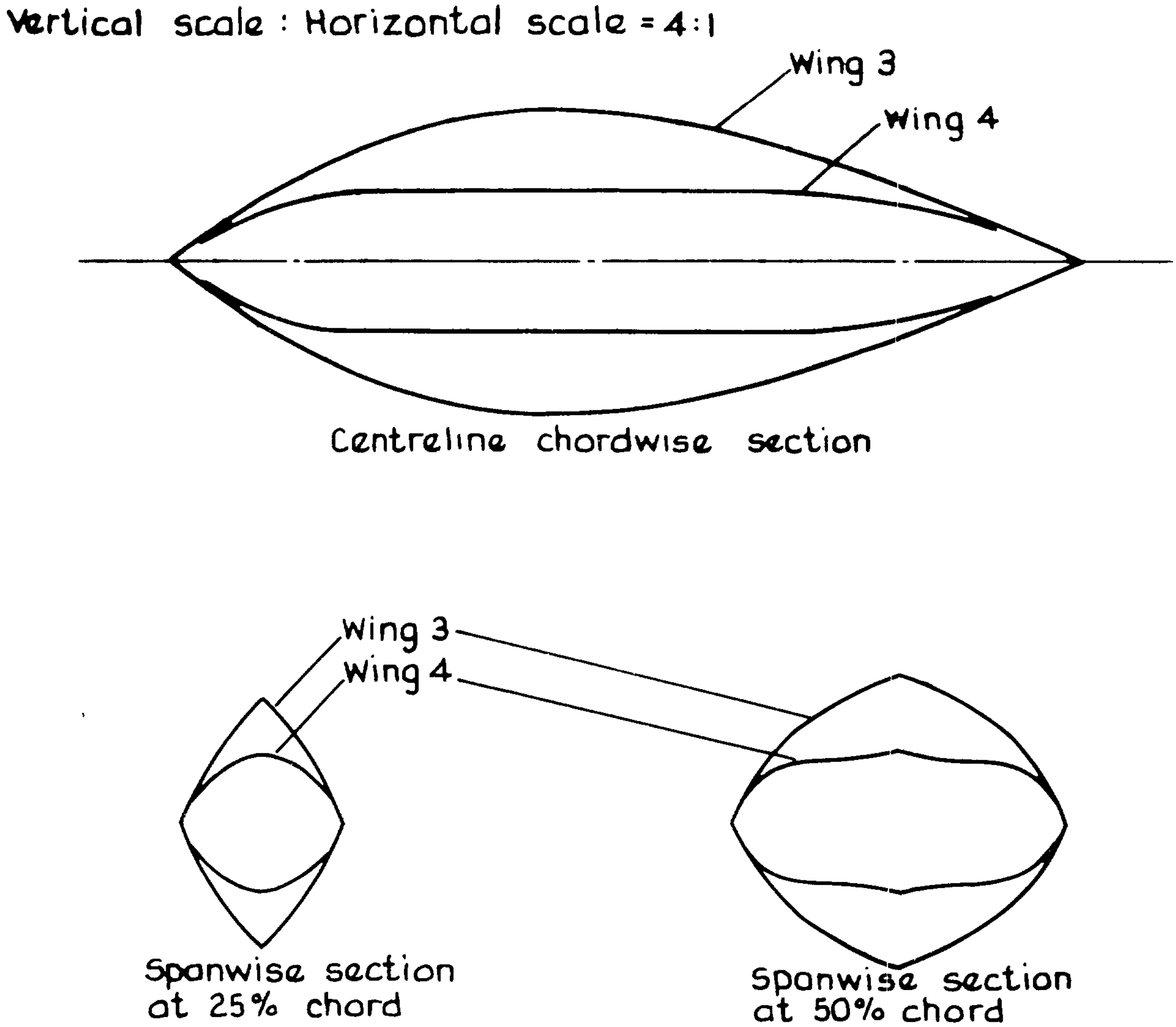
Measurements of vortex breakdown position on a series of delta wings, all of 70° sweep angle but with various thickness distributions, suggest that breakdown moves back towards the trailing edge as the wing is thickened. The effect is by no means negligible even for fairly thin wings. For example, as much as five degrees of incidence separates the thinnest wing (of 1.7% thickness-chord ratio) and thickest wing (8% thickness-chord ratio) to attain a given breakdown position. Furthermore, from the trend of the results, it seems possible that even the thinnest wing is still strongly influenced by thickness effects.

Too few models have been tested to be clear whether any significant movement will take place on still thicker wings. In tests on 12% and 16% wings, no vortex was detectable by means of the schlieren system at any point in the incidence range. This could mean that the trend is reversed and that breakdown occurs at very low incidences. However it is equally possible that density gradients in the vortices weaken rapidly as the thickness of the wing increases above 8%.

The tests showed also a fairly clear though weak dependence on Reynolds number in the small range covered, resulting in a rearward movement of breakdown as Reynolds number was increased. This however does not necessarily imply that the mechanism for breakdown is controlled by flow in the viscous regions of the vortex field.

REFERENCES

No.	Author	Title, etc.
1	P.B. Earnshaw	Measurements of vortex-breakdown position at low speed on a series of sharp-edged symmetrical models. A.R.C. C.P. 828 (1964)
2	P.B. Earnshaw J.A. Lawford	Low-speed wind-tunnel experiments on a series of sharp-edged delta wings. A.R.C. R & M 3424 (1964)
3	P.B. Earnshaw	An experimental investigation of the structure of a leading-edge vortex. A.R.C. R & M 3281 (1961)



Wing 1 Thickness - chord ratio 0·017 symmetrical chamfer 30° included angle

Wings 2 & 5 $z = \frac{3\sqrt{3}}{50} \; x(1-x)(1-\frac{x}{2}) \quad ; \quad 0 \leqslant x \leqslant 1$

Wing 3 $z = \frac{6\sqrt{3}}{50} \; x(1-x)(1-\frac{x}{2}) \quad , \quad 0 \leqslant x \leqslant 1$

Wing 4 $z = \frac{6\sqrt{3}}{50} \; x(1-x)(1-\frac{x}{2}) - 0{\cdot}544 \, x^2(1-x)^2(1-0{\cdot}824\,x) \; (1-y^2)^2 ; 0 \leqslant x, y \leqslant 1$

Wing 1	10·95	Inches centreline chord
Wing 2	21	
Wing 3	21	
Wing 4	21	
Wing 5	12	

Fig. 1 Details of models

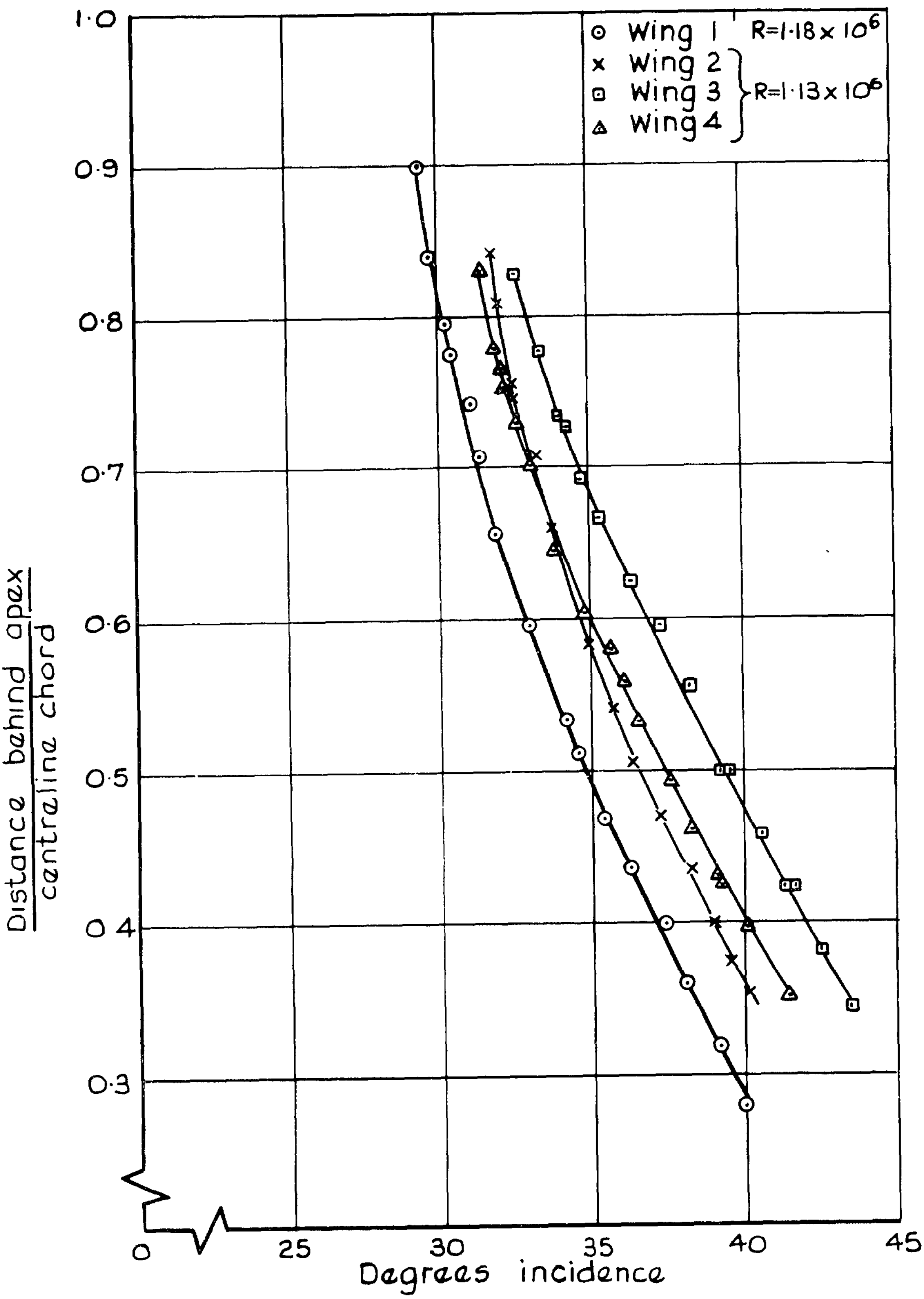


Fig.2 Influence of thickness distribution on vortex breakdown position

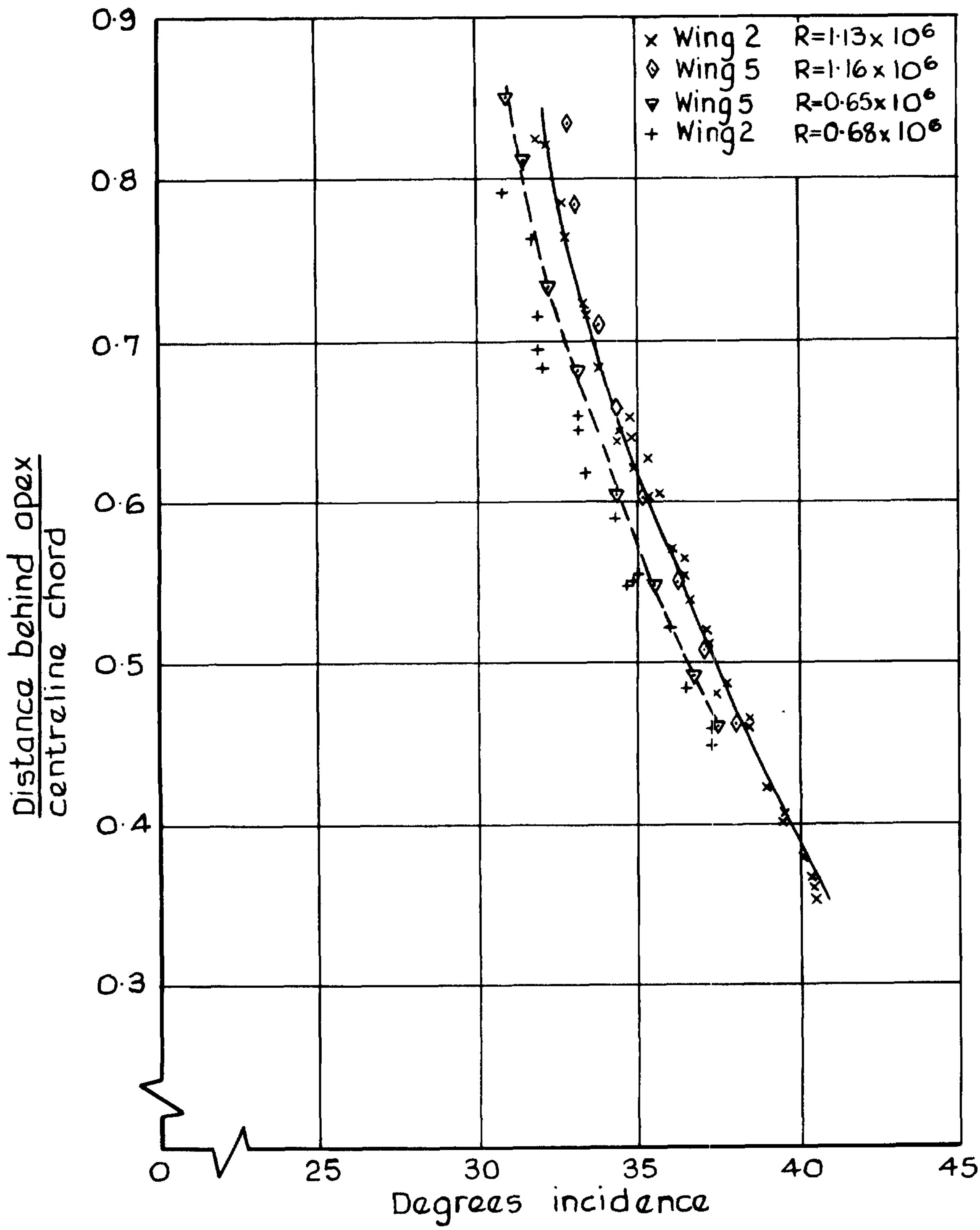


Fig.3 Influence of Reynolds number on vortex breakdown position with free transition

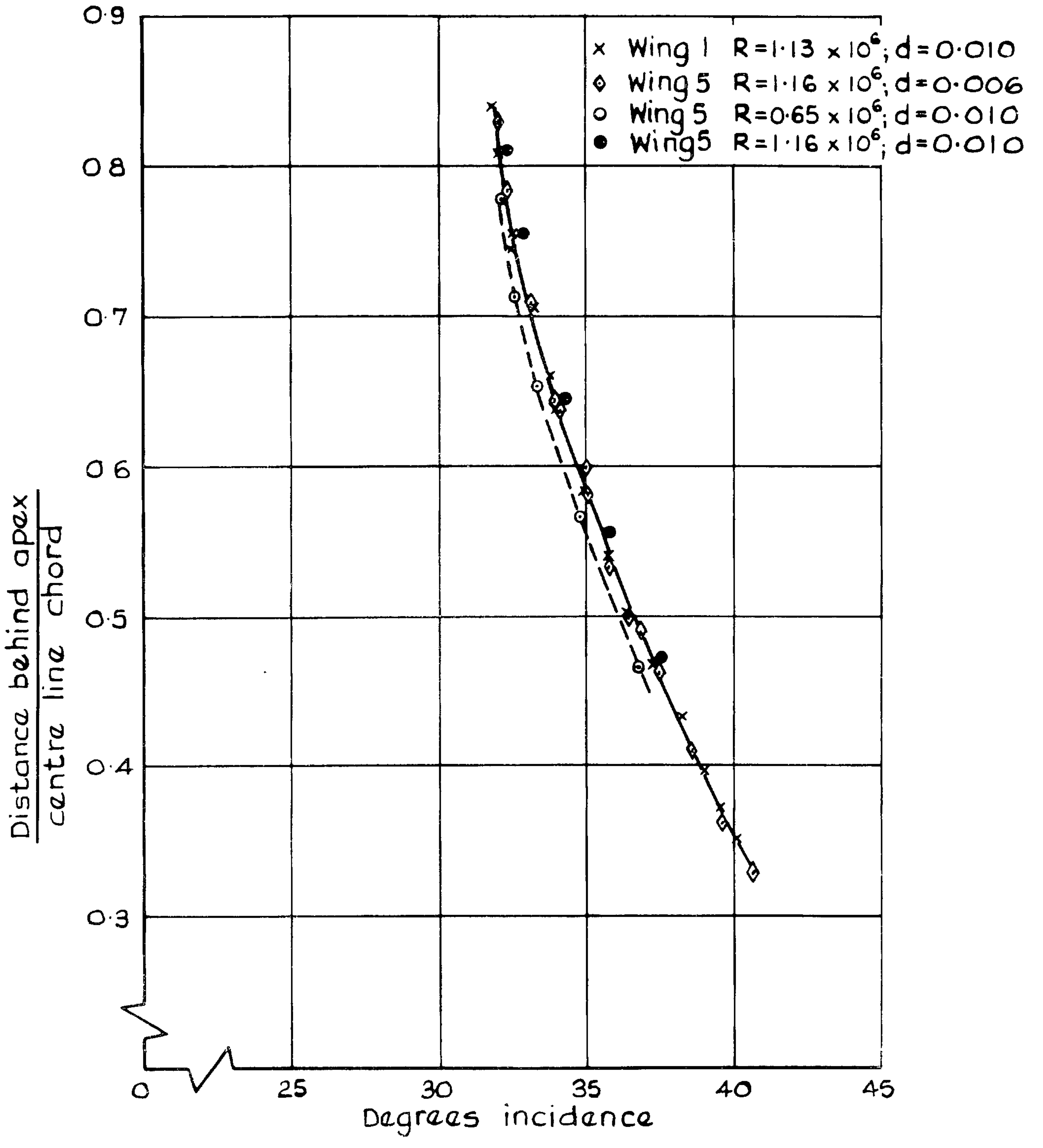


Fig. 4 Influence of Reynolds number on vortex breakdown position with fixed transition

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment, Farnborough. Dd.135645. K.3.

A.R.C. C.P. 1018
February 1968

532.517.43 :
533.693.044 :
533.6.071.31 :
533.6.013.6

Earnshaw, P.B.

MEASUREMENTS OF THE EFFECTS OF THICKNESS ON VORTEX BREAKDOWN POSITION ON A SERIES OF SHARP-EDGED DELTA WINGS

Measurements have been made of vortex breakdown position on a series of symmetrical delta wings of 70° sweep angle but differing thickness distribution using a schlieren system to detect the breakdown. The results demonstrate that the angles of incidence necessary to achieve a given position of breakdown over the wing can differ by at least as much as 5° from a thin wing to a wing of 8% thickness-chord ratio. The tests also show the breakdown position to have a weak dependence on Reynolds number.

A.R.C. C.P. 1018
February 1968

532.517.43 :
533.693.044 :
533.6.071.31 :
533.6.013.6

Earnshaw, P.B.

MEASUREMENTS OF THE EFFECTS OF THICKNESS ON VORTEX BREAKDOWN POSITION ON A SERIES OF SHARP-EDGED DELTA WINGS

Measurements have been made of vortex breakdown position on a series of symmetrical delta wings of 70° sweep angle but differing thickness distribution using a schlieren system to detect the breakdown. The results demonstrate that the angles of incidence necessary to achieve a given position of breakdown over the wing can differ by at least as much as 5° from a thin wing to a wing of 8% thickness-chord ratio. The tests also show the breakdown position to have a weak dependence on Reynolds number.

DETACHABLE ABSTRACT CARDS

A.R.C. C.P. 1018
February 1968

532.517.43 :
533.693.044 :
533.6.071.31 :
533.6.013.6

Earnshaw, P.B.

MEASUREMENTS OF THE EFFECTS OF THICKNESS ON VORTEX BREAKDOWN POSITION ON A SERIES OF SHARP-EDGED DELTA WINGS

Measurements have been made of vortex breakdown position on a series of symmetrical delta wings of 70° sweep angle but differing thickness distribution using a schlieren system to detect the breakdown. The results demonstrate that the angles of incidence necessary to achieve a given position of breakdown over the wing can differ by at least as much as 5° from a thin wing to a wing of 8% thickness-chord ratio. The tests also show the breakdown position to have a weak dependence on Reynolds number.

A.R.C. C.P. 1018
February 1968

532.517.43 :
533.693.044 :
533.6.071.31 :
533.6.013.6

Earnshaw, P.B.

MEASUREMENTS OF THE EFFECTS OF THICKNESS ON VORTEX BREAKDOWN POSITION ON A SERIES OF SHARP-EDGED DELTA WINGS

Measurements have been made of vortex breakdown position on a series of symmetrical delta wings of 70° sweep angle but differing thickness distribution using a schlieren system to detect the breakdown. The results demonstrate that the angles of incidence necessary to achieve a given position of breakdown over the wing can differ by at least as much as 5° from a thin wing to a wing of 8% thickness-chord ratio. The tests also show the breakdown position to have a weak dependence on Reynolds number.

C.P. No. 1018

Published by
HER MAJESTY'S STATIONERY OFFICE
To be purchased from
49 High Holborn, London W.C.1
423 Oxford Street, London W.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
258-259 Broad Street, Birmingham 1
7-11 Linenhall Street, Belfast 2
or through any bookseller

C.P. No. 1018

S.O. CODE No. 23-9018-18