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Low - Speed Characteristics of Waverider Wings

by

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LOW-SPEED CHARACTERISTICS OF WAVERIDER WINGS

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SUMMARY

This paper reports on low-speed wind tunnel studies of a series of simple delta-like shapes which might form the basis of future hypersonic aircraft.

The nature of the vortices formed above these wings was investigated by oil-flow experiments, smoke visualisation and flow surveys. Some of the vortices could only be described as broken and had a stagnation point at the centre. Nevertheless, the vortices still had a strong circulation and a high static suction.

The force characteristics were typical of current slender wing designs in spite of the anomalous vortices. The large shift of the aerodynamic centres of the hyperbolic planforms when changing from hypersonic to low-speed flight may prove embarrassing.

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*Replaces R.A.E. Technical Report 69051 - A.R.C.31344.

CONTENTS

1 INTRODUCTION

Hypersonic waverider aircraft[1] show considerable promise of providing really long ranges in the future[2]. However one of the characteristics which may prove crucial in the design is the large shift of the aerodynamic centre when changing from hypersonic to subsonic flight. A series of models was designed to provide some guidance on the limitations imposed by considerations of low-speed performance on the choice of cone-flow waverider planform shapes from the inherently large range possible.

Present thoughts are in terms of delta-like shapes for all the waverider types, with basically sharp leading edges. Cruise considerations dictate values of slenderness ratio, s/ℓ = semispan/length, between 0·2 and 0·3, which is not too small for satisfactory low-speed qualities and is in the order of slenderness of current supersonic transport designs. The models used in the present investigation were designed at a time when it was thought that the nose might have to be blunted, in an attempt to investigate the effect of planform nose shape on wings of constant slenderness. The models are simplified forms of waverider wings having plane under-surfaces, triangular cross-sections and a blunt base for a trailing edge. A single, fully representative model of a waverider with camber and thickness distribution obtained from conical shock and expansion theory[3] completed the series.

The tests involved six-component force measurements, as well as oil-flow and smoke flow visualisation tests aimed at establishing the nature of the separated flow field. Studies were made of the velocity distribution through the vortex cores on some of the wings, in particular to establish the nature of an unusual 'vortex-breakdown' demonstrated by smoke on the more blunt-nose planforms.

The tests were performed in the 13ft × 9ft low-speed wind tunnel at R.A.E. Bedford during 1965 and 1966.

2 MODEL GEOMETRY AND EXPERIMENTAL DETAILS

Figs.1 and 2 show the planform shape and thickness distribution respectively of the wing models and Tables 1 and 2 give numerical details of the planforms. Models A and B were intended as reference models to relate the results of the current tests with flat plate results and are simple deltas having leading edge sweeps of 65° and 70°. The remainder of the series have the same slenderness as the 65° delta and differ only in planform shape

(Models C, D and E have zero sweep at the nose which increases to 67·5°, 70° and 72·5° respectively at the trailing edge; models H, G and F have constant sweep at the trailing edge of 70° with a pointed apex of sweeps 20°, 40° and 60° respectively. The equations of the segments used to define the planform are conics (the intersection of a plane with a cone) of the form:-

$$y^2 + Py + Qx + Rx^2 = 0 \quad .$$

Numerical values of P, Q and R are listed in Table 1. The cross sections of this series of models are triangular with a plane underside, a triangular base at the trailing edge and sharp leading edges. Real waveriders will differ from this geometry, but it is expected that the leading edge would be of small radius and the exit of the engine (jet or rocket) would be large and not running full at low speeds.

Fig.3 shows the fully representative model of a cone-flow designed wave-rider wing. It should be noted that the fin arises automatically from the concepts used in designing the upper surface and apart from a slope discontinuity on the upper surface the wing can quite definitely be regarded as a slender wing at low speeds.

Six-component force measurements were made and these were reduced to coefficient form in stability axes system using the planform area, root chord and span as the reference dimensions. The reference centre was arbitrarily chosen as the centroid of the cross section at 50% root chord from the apex for the series of wings and at 50% root chord along the ridge line on the cone-flow design.

Oil flow experiments using the method of Ref.4 were made on all the wings to investigate the nature and stability of the flow. Examples are shown in Fig.4 for wing D and for various wings in Fig.5. The nature of the vortices at low incidences was investigated on wing E and the results are shown in Fig.6.

The nature of the vortex on wing D at an incidence of 16° was investigated by a five-tube pitot-static yawmeter probe. Velocity surveys of the flow were made in a plane normal to the wind at 40% root chord, presented in Fig.14, and in vertical traverses through the vortex centres at 2%, 10%, 20%, 40% and 70% root chord, presented in Figs.12 to 14. A vertical traverse was

also made on Wing A at 40% root chord and similar flat plate delta wing for the purposes of comparison.

Smoke injected at the apex of the wing, in the manner of Ref.5, was used in order to measure the position of vortex breakdown and to reveal the character of the vortex. This technique was also used as an adjunct to the velocity surveys to ensure that the traverse gear did not greatly disturb the vortex and that the smoke did not disturb the vortex.

3 NATURE OF THE FLOW

Figs.4 and 5 show typical surface flow patterns on various waverider wings some of which can be classified as slender in shape and behaviour. The patterns show that the vortex system at large angles of incidence, when α is greater than the base angle, is unified. Changes in incidence do not change the form of the system, but alter the strength and to some extent the position of the vortex. In particular the true horseshoe vortex of the Norman wings is most gratifying when, a priori, a mixed flow of a bubble and part-span vortices may have been expected.

However at low angles of incidence when the vortices are weak the 'Norman' wings have part-span vortices as shown by the examples in Fig.6. It is expected that the distribution of thickness would have a significant effect at these incidences which are within the angle subtended by the base at the apex.

An interesting aspect of the 'Norman' wings is the nature and early occurrence of vortex breakdown. Smoke injected near the apex gives an indication of the character of the wing vortices and some examples are shown in Fig.7. Normally when smoke is injected into the apex of a slender wing the smoke remains in a tubular region surrounding the vortex core[5]; vortex breakdown is indicated by the diffusion and spread of smoke away from the tube as in Fig.7. In the 'Norman' wings the smoke tube was absent at zero sideslip and a 'woolly' diffuse collection of smoke existed in the whole of the vortex. Analyses of the position of vortex breakdown at large angles of sideslip, such as Figs.8 and 9, show that at zero sideslip the vortex has a broken or conjugate state over the whole of the vortex.

Further support for this contention is shown by the flow studies on wing D at zero sideslip in a transverse plane and in vertical traverses through the centre of the vortex. The results, plotted in Figs.10 to 14,

demonstrate unusually low kinetic pressures and total heads in a large region in the middle of the vortex. The profiles Figs.10 to 13, have a remarkably similar shape at all points along the vortex line, that is, a unified vortex development.

Because of the possibility of the traverse gear disturbing the vortex a comparison of kinetic pressure profiles of three wings is shown in Fig.14. This figure suggests that the gear does not upset the vortex and that the vortex on wing D could be regarded as having an abnormally large vortex core.

4 LONGITUDINAL CHARACTERISTICS

The lift and pitch curves shown in Figs.15 and 16, are very similar to those found on current slender wing aircraft designs both in magnitude and form. Delta wing A provides a typical illustration of the effect of vortex breakdown, above an incidence of 20° there is a loss of non-linear lift at the trailing edge resulting in a marked reduction of lift curve slope and longitudinal static stability (pitch-up). It is remarkable that no other wing of this series shows these characteristics although it is known that the vortices are 'broken' within the range of the measurements.

Fig.17 correlates the aerodynamic centres at $C_L = 0$ and $C_L = 0{\cdot}5$ with the centre of area in the manner first suggested by G.H. Lee. This type of analysis works well for slender wings of ogee delta and gothic planform, and works equally well for the waveriders. The problem of balancing these waveriders is a difficult one, since the high-speed aerodynamic centre is approximately at the centre of area which is rearward of the low-speed centres.

5 LATERAL CHARACTERISTICS

Except for the delta wing A the lateral behaviour of the simplified series of waverider wings are all similar to the 'Norman' wing D. The variations of rolling moment and yawing moment coefficients with side-slip for wing D are shown in Fig.18. In spite of all the doubts about the formation of full vortices at low incidences and the 'broken' vortex at high incidences the characterstics are very close to linear.

The later cone-flow design of waverider is closer to current slender wing designs, but in this case the lateral characteristics are non-linear (Fig.19). The non-linearities are caused by vortex breakdown, which occurs at values of incidences and sideslip expected of a conventional slender wing. The

derivatives for the cone-flow design, Fig.21, are dependent on whether a mean or a slope is used because of the non-linearity but comparison with Fig.20 shows the different behaviour with change in incidence from that of wing D.

Stability and fin effectiveness of all the wings tested are quite adequate to judge by current slender wing designs and would not present a designer with any abnormal problems, except for vortex breakdown occurring on wings approaching current slender wing planforms.

6 CONCLUSIONS

The low-speed characteristics of waverider wings of the type considered should not present any more difficulties to the designer than those of current slender wing designs.

The horseshoe shaped vortex flow over the waverider wings with round-nosed planforms has the very diffuse core of a 'broken' vortex yet still has a strong circulation and a large static suction. This vortex flow is worthy of more study from a theoretical and experimental standpoint.

Table 1

MODEL PLANFORM GEOMETRY

Planform co-ordinates were obtained from equation of the form:

$$y^2 + Py + Qx + Rx^2 = 0$$

where x is measured along the centre-line from the nose and y is measured perpendicular to the centre-line.

Model	s/ℓ	Leading-edge sweep at nose	Leading-edge radius at nose	Leading-edge sweep at tail	P	Q	R
A	0·4663	——	65° DELTA	——			
B	0·3640	——	70° DELTA	——			
C	0·4663	0	1·358 in	67·5°	0	−0·4860	−0·16885
D	"	0	2·862 in	70°	0	−0·9545	−0·12200
E	"	0	4·224 in	72·5°	0	−1·4084	−0·07661
F	"	60°	-	70°	+0·43808	−1·2036	−0·11752
G	"	40°	-	70°	+1·53186	−1·82559	−0·10632
H	"	20°	-	70°	109·71264	−63·34259	+1·00080

Table 2

PLANFORMS OF WAVERIDER WINGS

Ordinate	Model semispan (inches)							
	A	B	C	D	E	F	G	H
0	0	0	0	0	0	0	0	0
6·0	2·798	2·184	4·855	6·225	7·312	3·392	4·926	5·706
9·0	4·197	3·276	6·318	7·837	9·070	5·035	6·732	7·390
12·0	5·596	4·368	7·701	9·289	10·604	6·642	8·361	8·948
15·0	6·995	5·460	9·041	10·647	12·000	8·216	9·873	10·369
18·0	8·394	6·551	10·354	11·942	13·301	9·755	11·302	11·716
21·0	9·793	7·643	11·649	13·193	14·534	11·261	12·668	13·011
24·0	11·191	8·735	12·932	14·413	15·714	12·734	13·985	14·266
27·0	12·590	9·827	14·206	15·607	16·848	14·175	15·263	15·490
30·0	13·989	10·919	15·474	16·781	17·957	15·583	16·509	16·690
33·0	15·388	12·011	16·736	17·940	19·034	16·960	17·729	17·870
36·0	16·787	13·103	17·995	19·086	20·087	18·305	18·925	19·033
39·0	18·186	14·195	19·250	20·222	21·121	19·619	20·103	20·183
42·0	19·585	15·287	20·502	21·348	22·137	20·903	21·264	21·321
45·0	20·984	16·379	21·752	22·467	23·139	22·156	22·410	22·449
48·0	22·383	17·471	23·000	23·579	24·127	23·380	23·544	23·568
51·0	23·782	18·562	24·247	24·686	25·105	24·573	24·668	24·680
54·0	25·181	19·654	25·492	25·788	26·071	25·737	25·779	25·785
57·0	26·580	20·746	26·736	26·885	27·029	26·872	26·883	26·885
60·0	27·979	21·838	27·979	27·979	27·979	27·979	27·979	27·979

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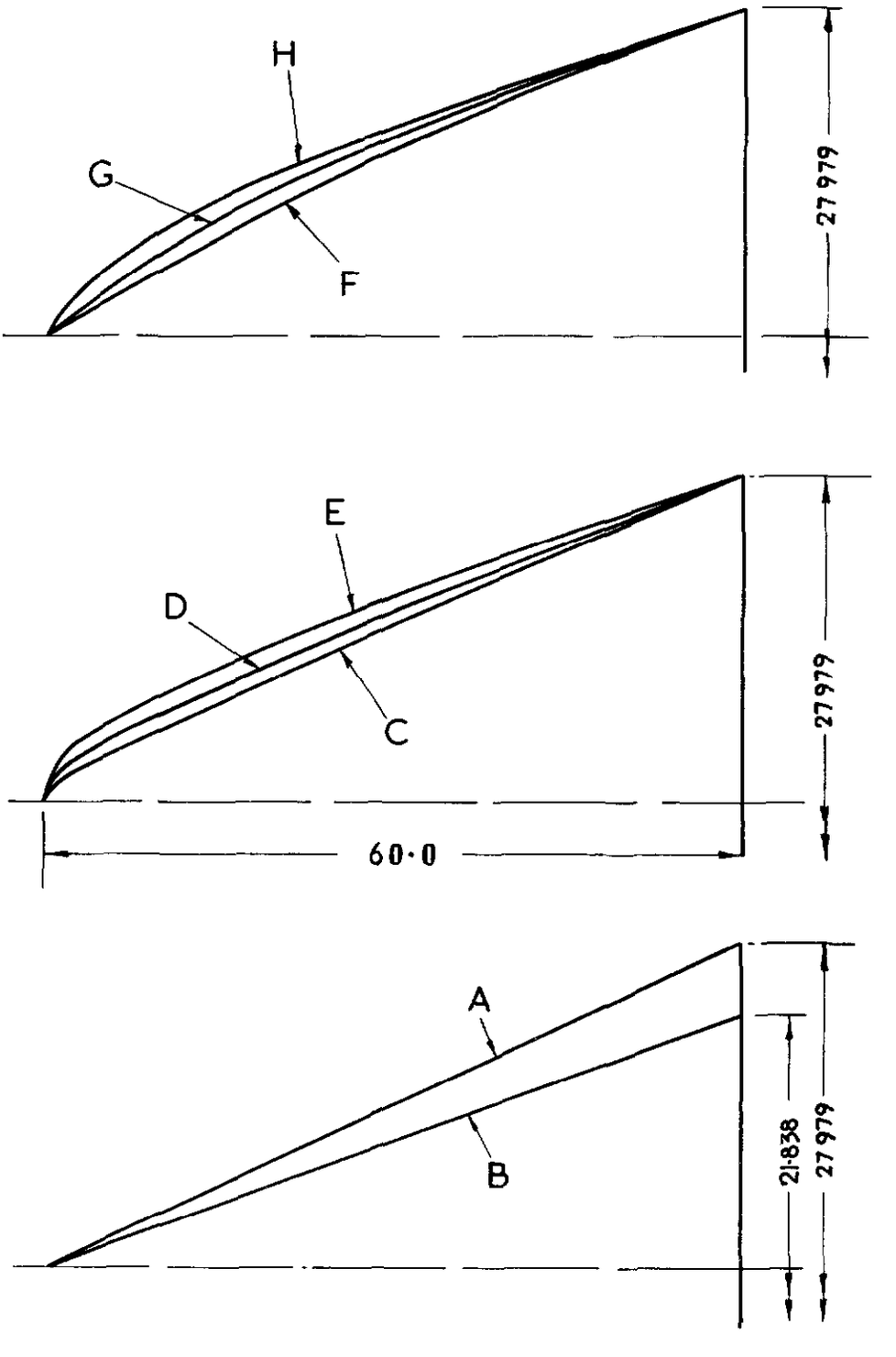
5	R.L. Maltby P.B. Engler R.F.A. Keating	Some exploratory measurements of leading-edge vortex positions on a delta wing oscillating in heave. A.R.C. R & M 3410 (1963)



Dimensions in inches

Fig.1 Wave-rider wing planforms

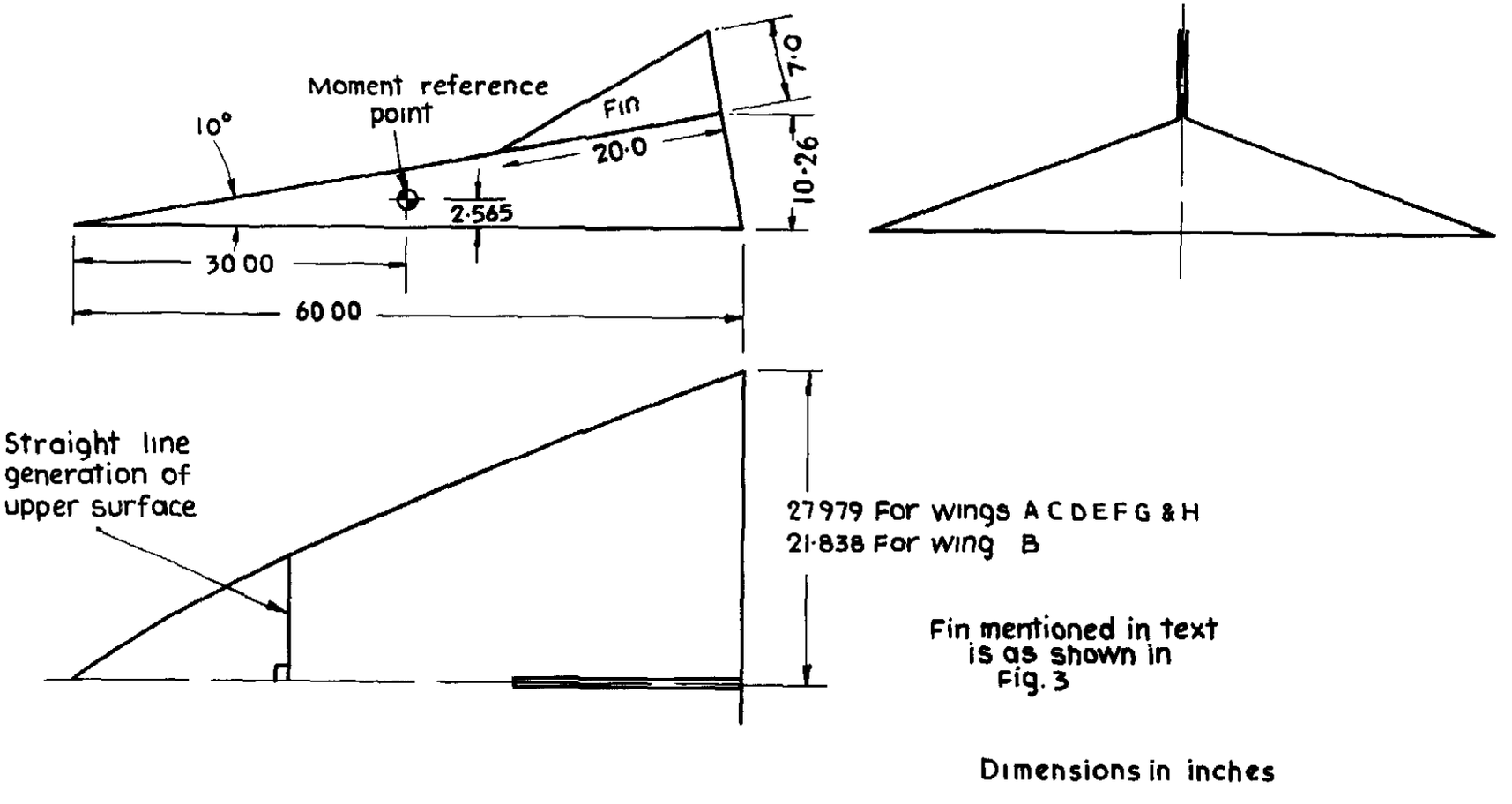


Fig.2 Model geometry

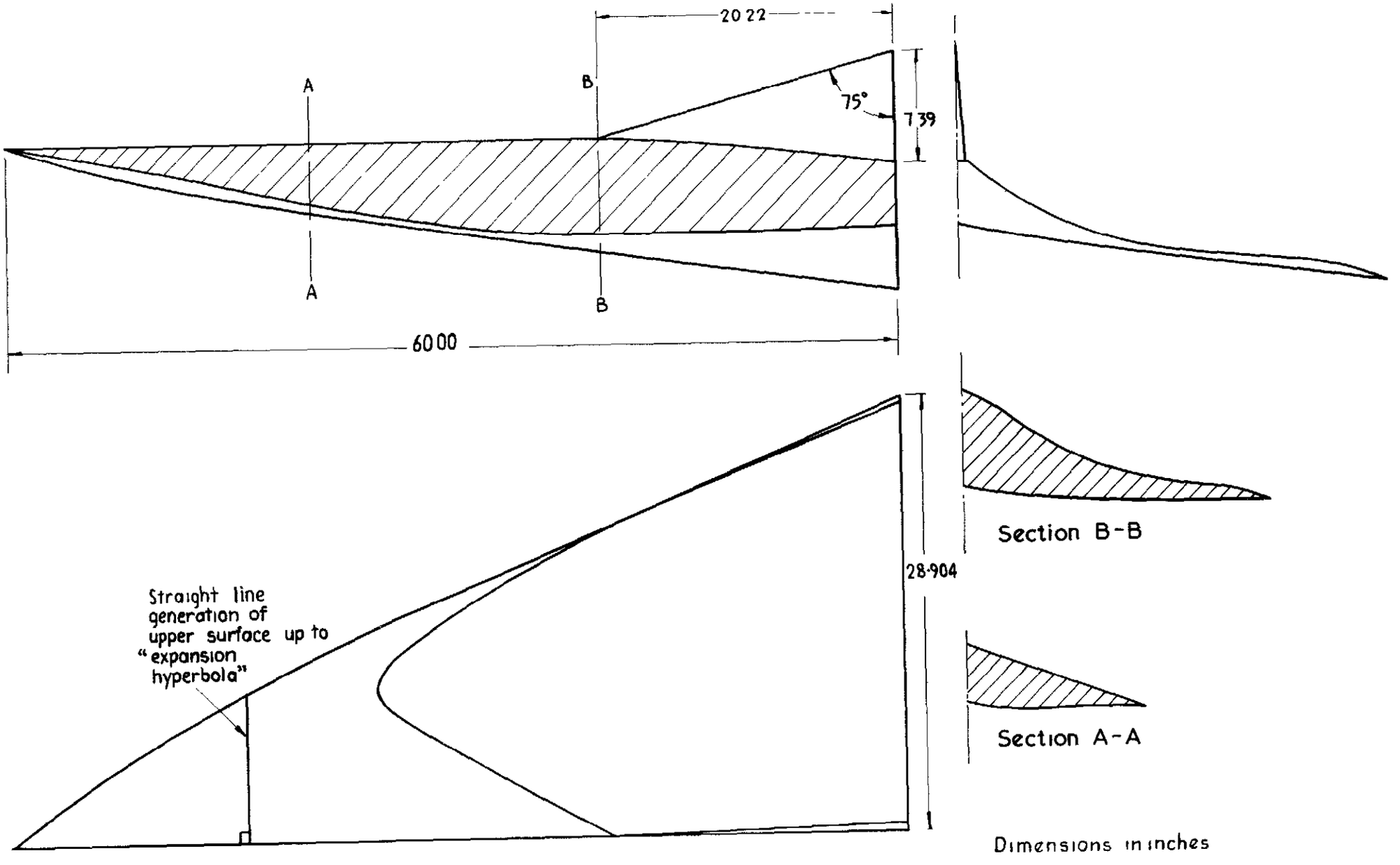
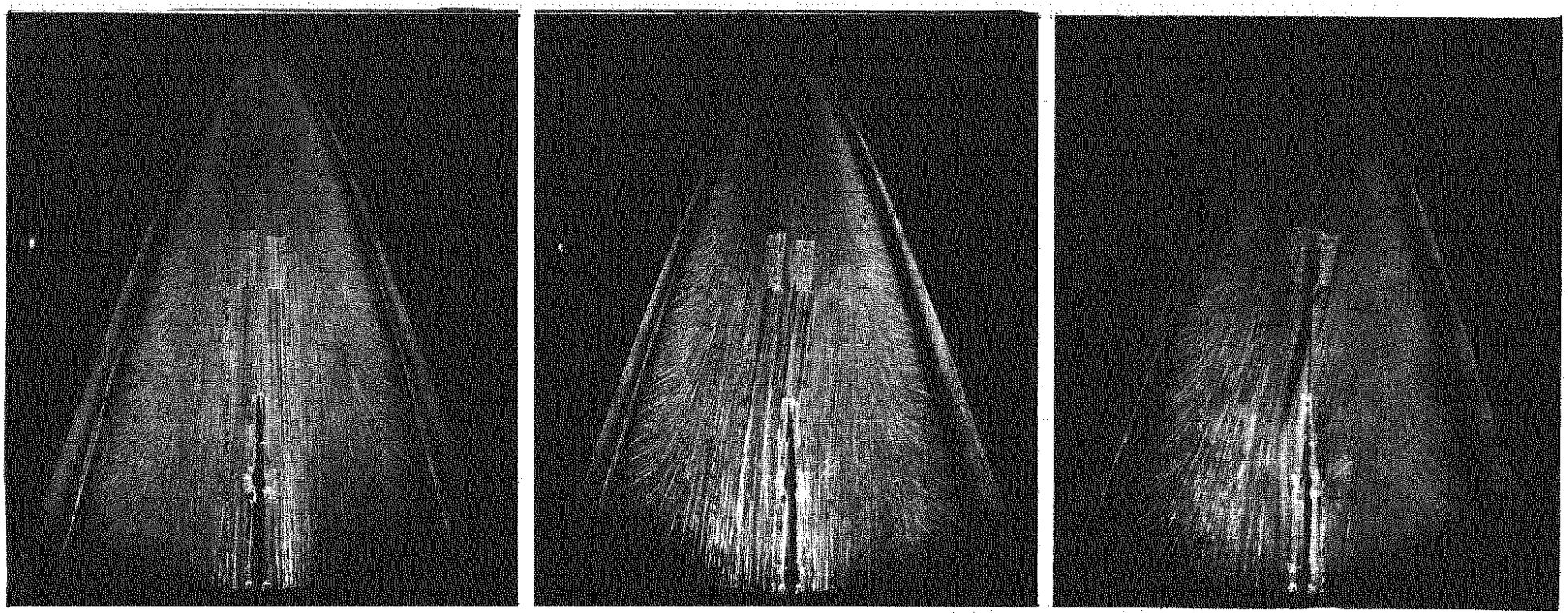


Fig. 3 Cone-flow wave-rider wing model



$\alpha = 16°, \quad \beta = 0°$ $\alpha = 16°, \quad \beta = 4°$ $\alpha = 16°, \quad \beta = 8°$

Fig.4. Upper surface flow patterns of wing D at high incidences

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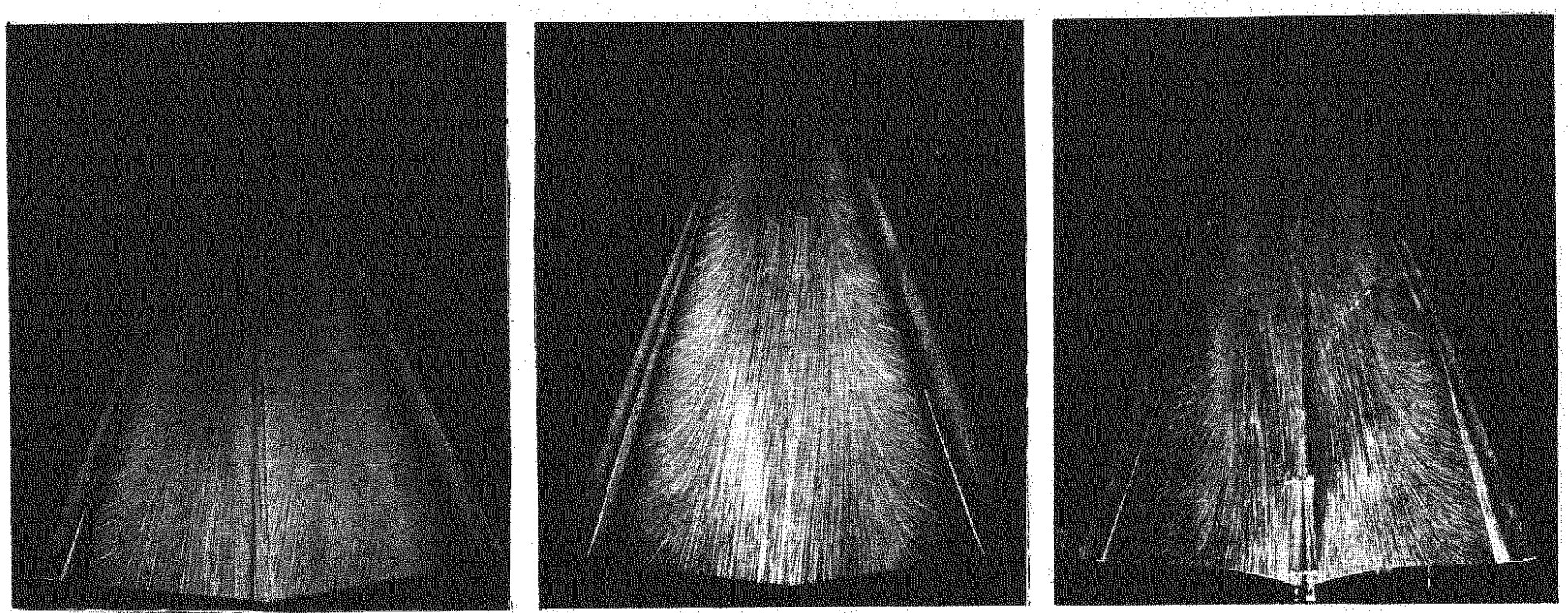
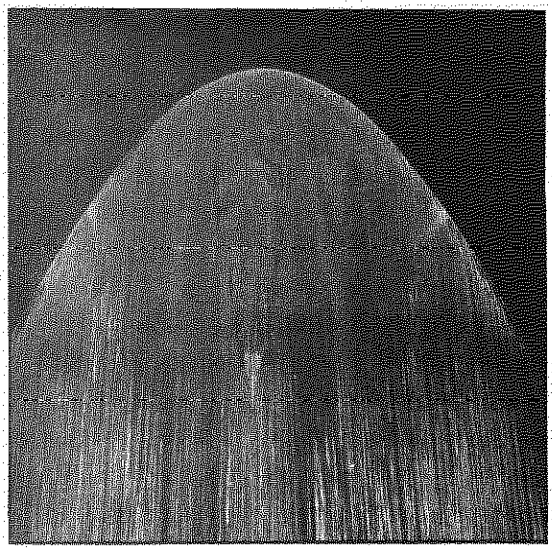


Wing A · $\alpha = 16{\cdot}8°$, $\beta = 8°$

Wing G $\alpha = 21°$, $\beta = 4°$

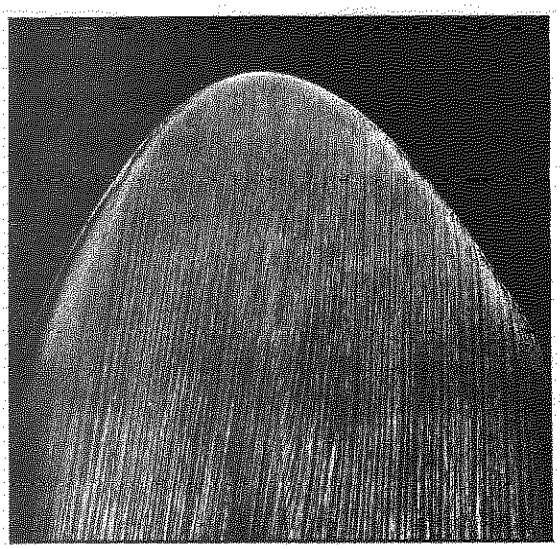
Cone-flow wave rider
$\alpha = 12{\cdot}4°$, $\beta = -5°$

Fig.5. Typical surface flow patterns on wave-rider wings at high incidences and at side-slip



$\alpha = 4°, \quad \beta = 0°$

$\alpha = 5°, \quad \beta = 0°$



$\alpha = 5°, \quad \beta = 8°$

$\alpha = 6°, \quad \beta = 12°$

Fig.6. Upper surface flow patterns of wing E, effect of side-slip at low incidences

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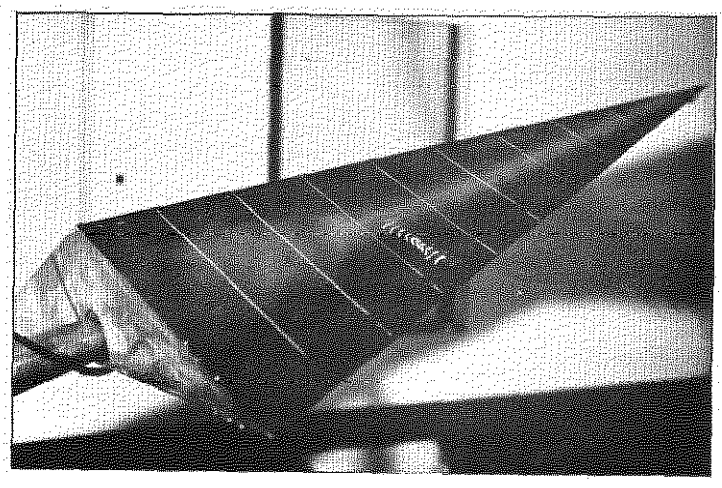
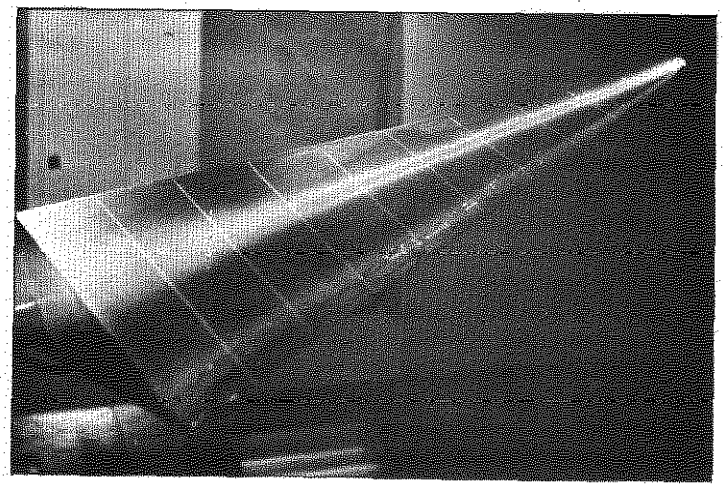
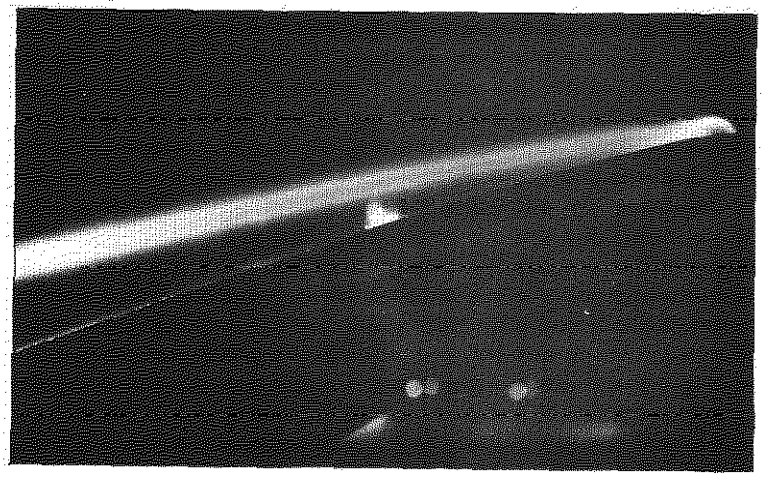


Wing A $\alpha = 23{\cdot}2°$, $\beta = 0°$, (Flash photo)



Wing C $\alpha = 23{\cdot}2°$, $\beta = 5°$



Wing E $\alpha = 21{\cdot}0°$, $\beta = 10°$

Fig.7. Smoke visualisation of vortices on wave-rider wings

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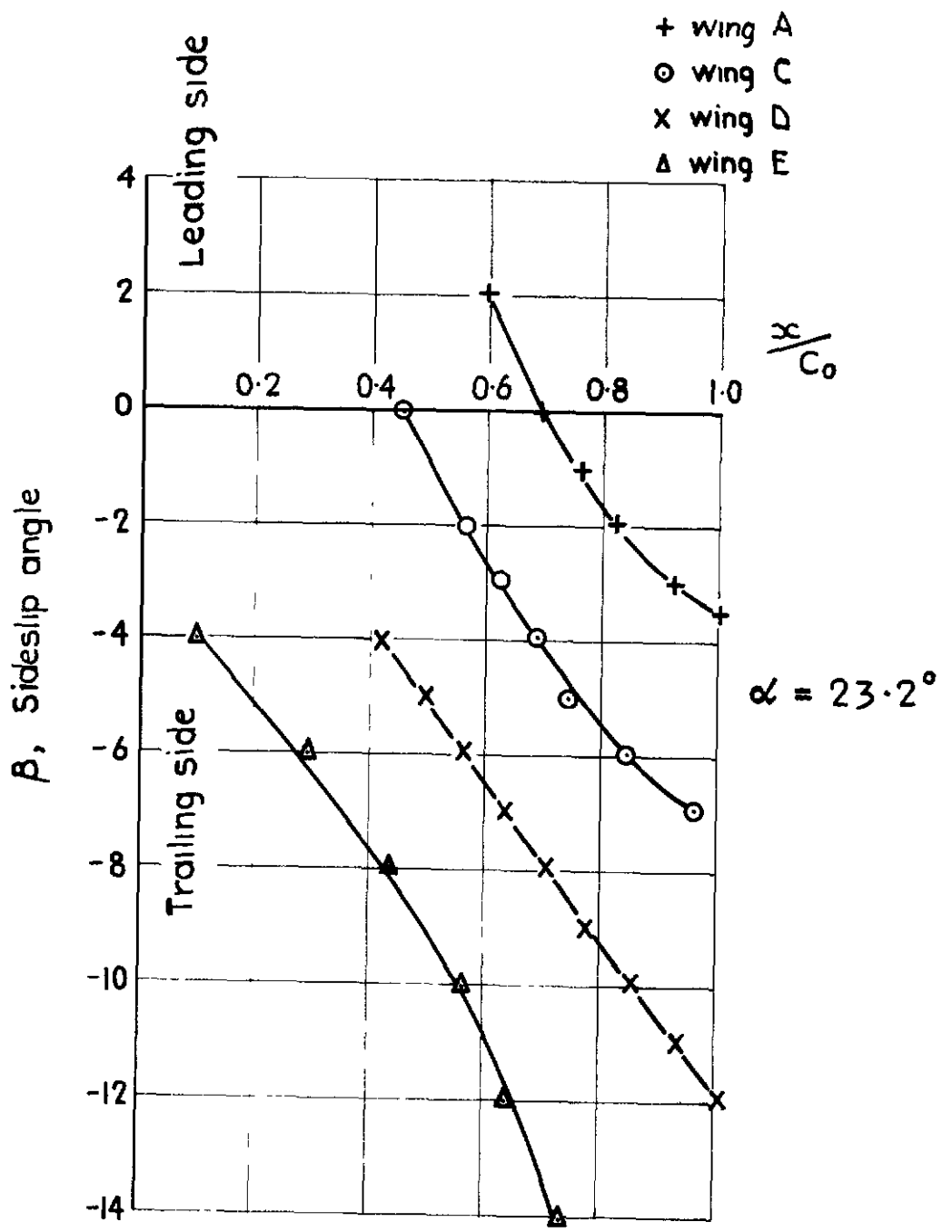


Fig.8 Position of vortex breakdown on norman wings

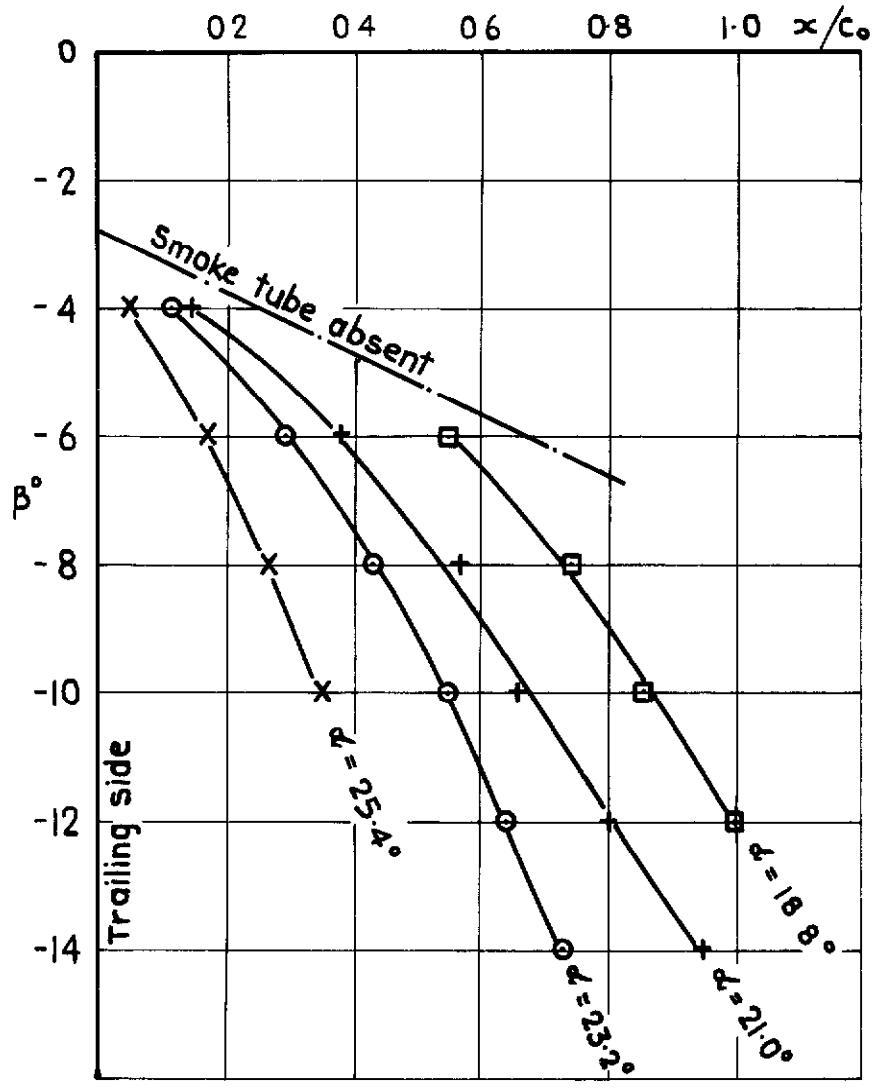


Fig.9 Position of vortex breakdown on wing D

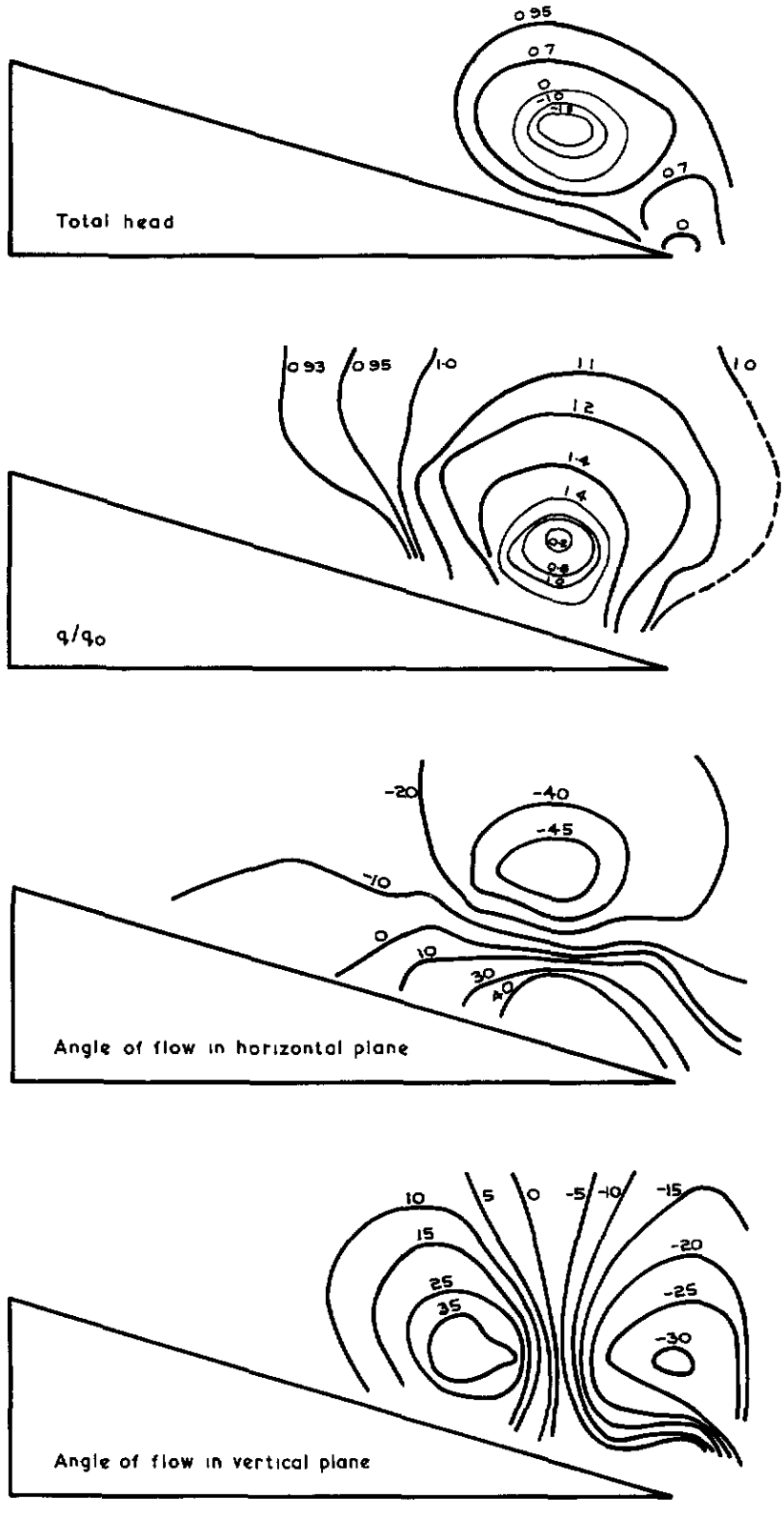


Fig. 10 Flow contours on wing 'D' in a plane at 40% root chord, $\alpha = 16^\circ$

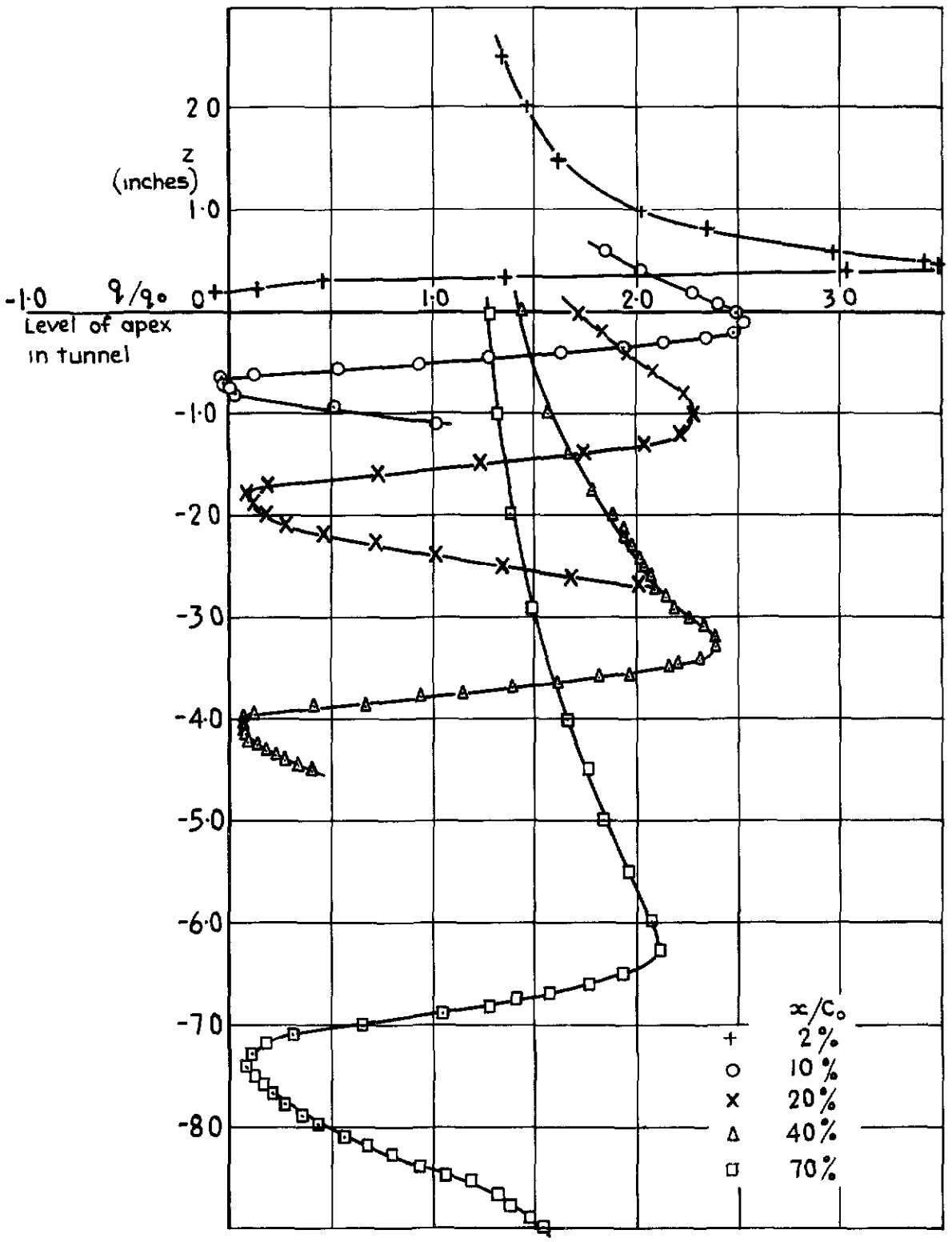


Fig. 11 'q' profiles in vertical traverses through vortex centres of wing D at $\alpha = 16^{\circ}$

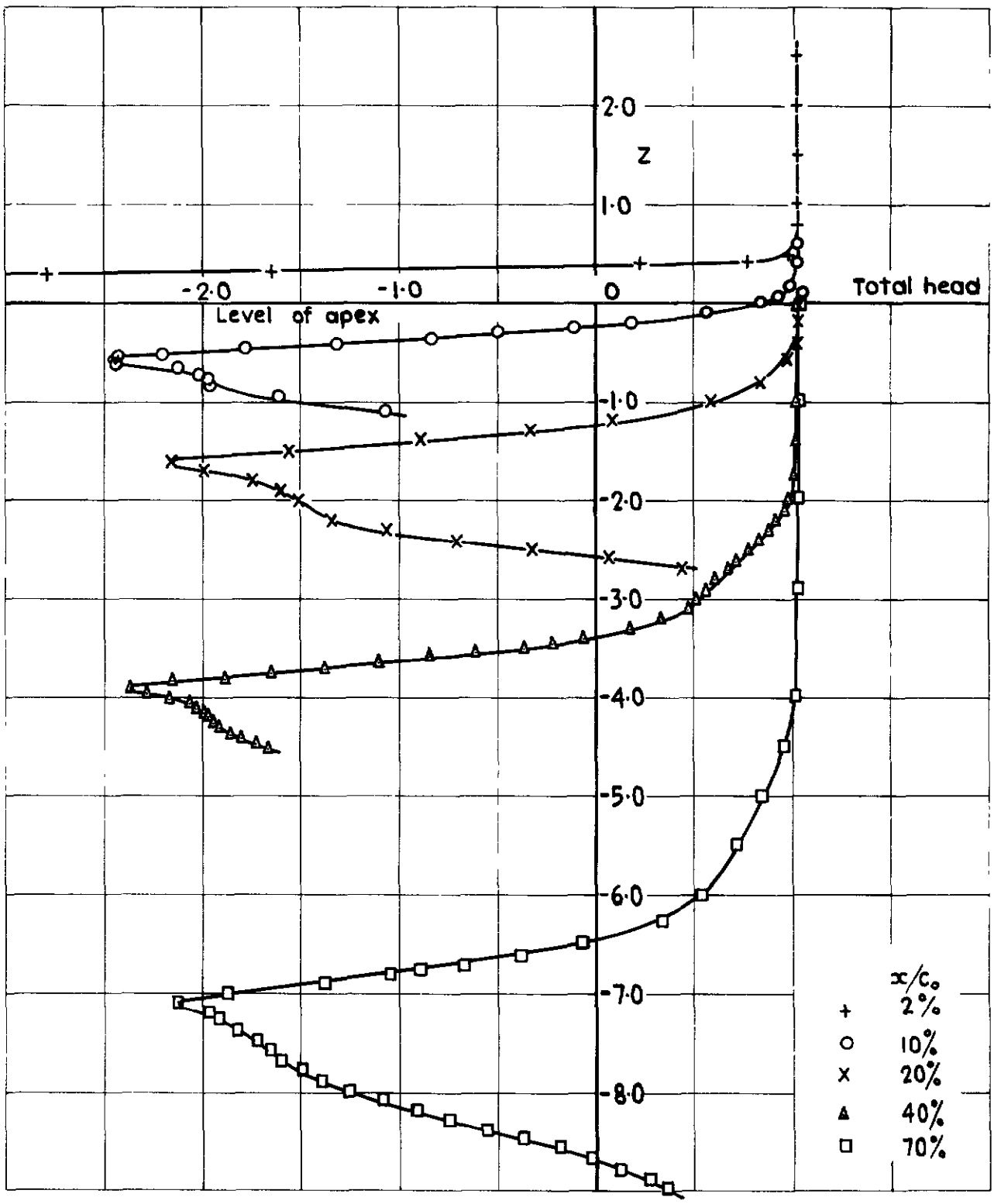


Fig.12 Total head profiles in vertical traverses through vortex centres of wing D at $\alpha = 16°$

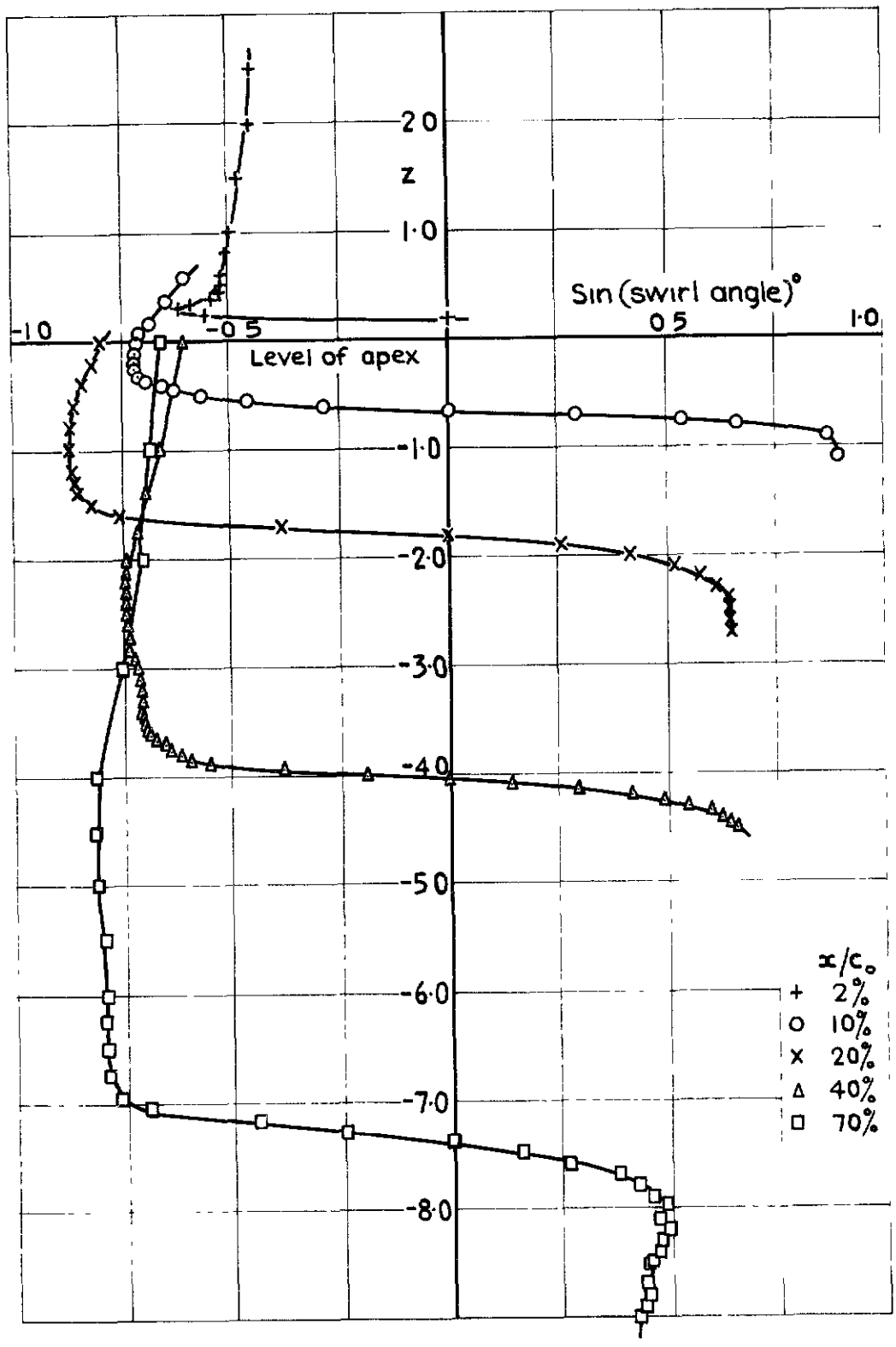


Fig.13 Swirl angle in vertical traverses through vortex centres of wing D at $\alpha = 16^{\circ}$

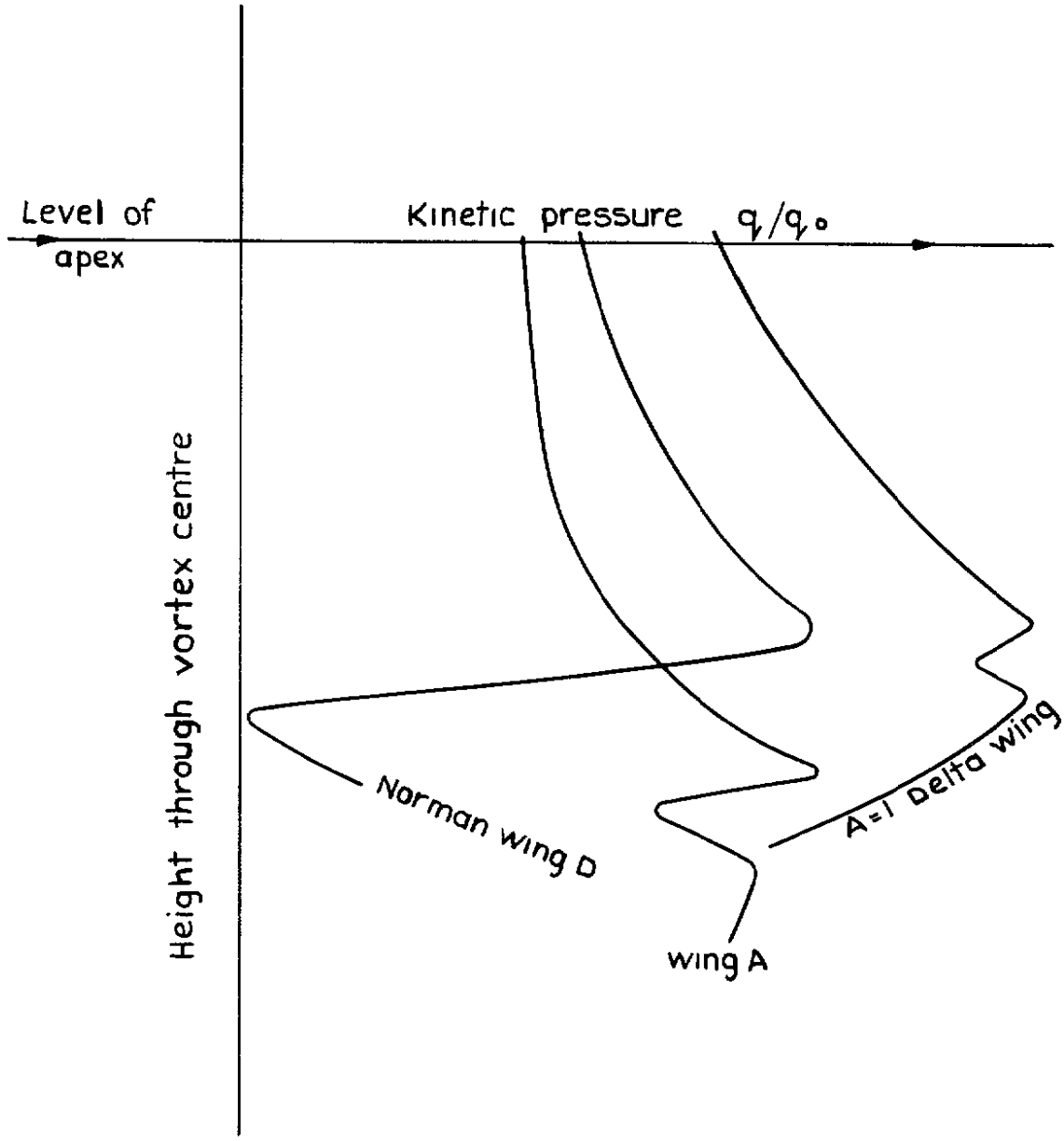


Fig 14 Sketch showing form of kinetic profiles of vortices

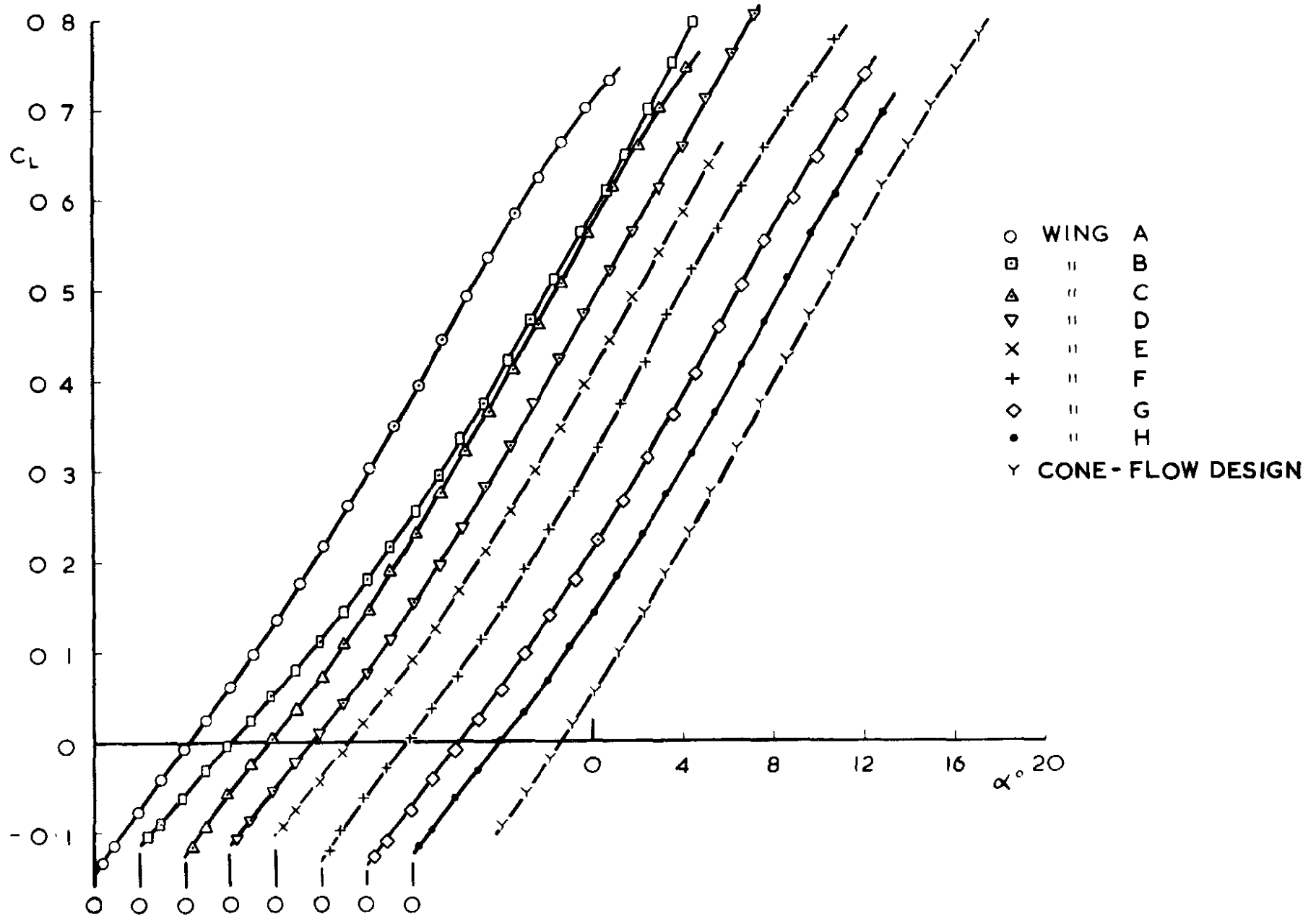


FIG.15 LIFT CURVES OF WAVE-RIDER WINGS

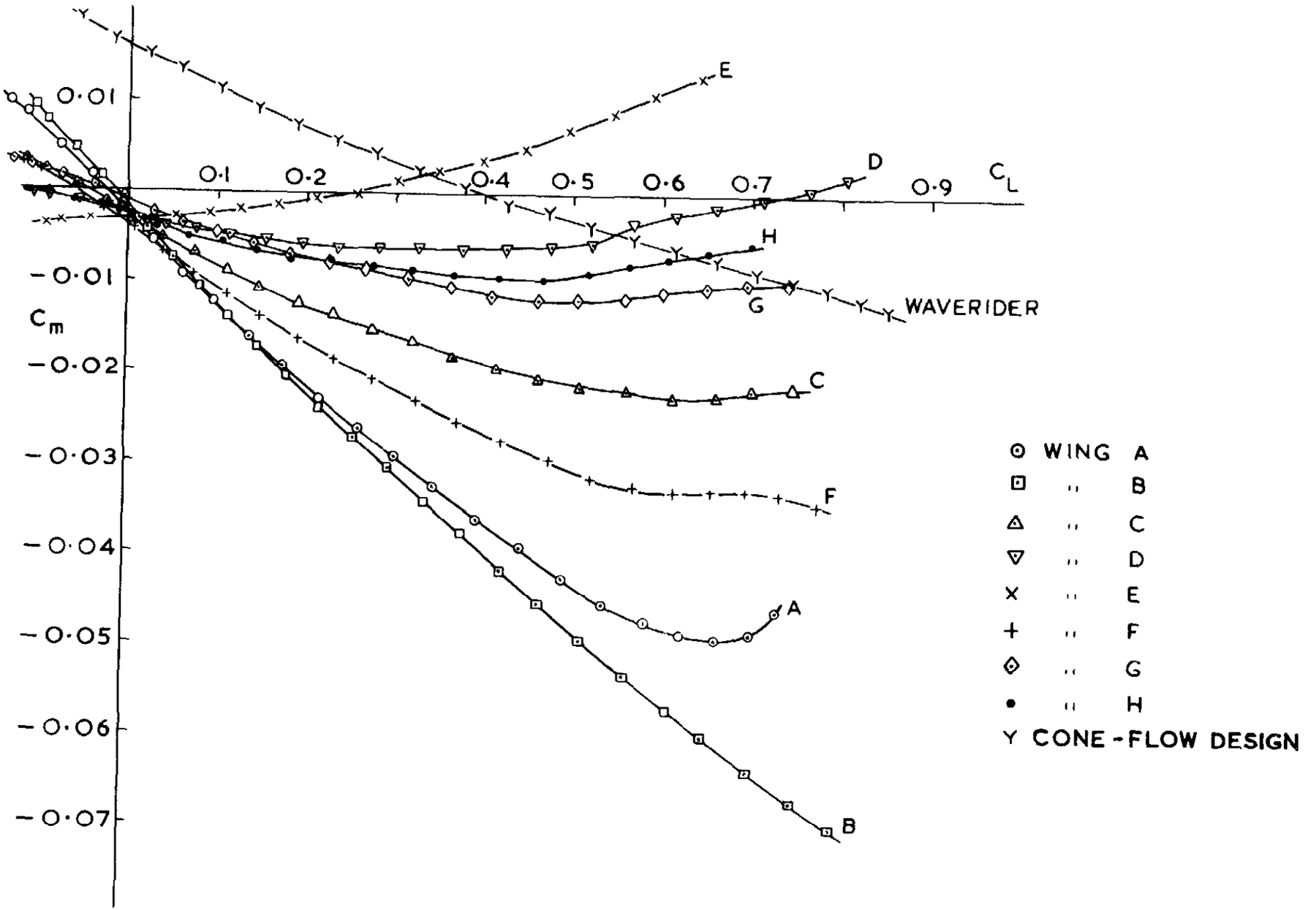


FIG.16 PITCHING MOMENT CURVES OF WAVE-RIDER WINGS

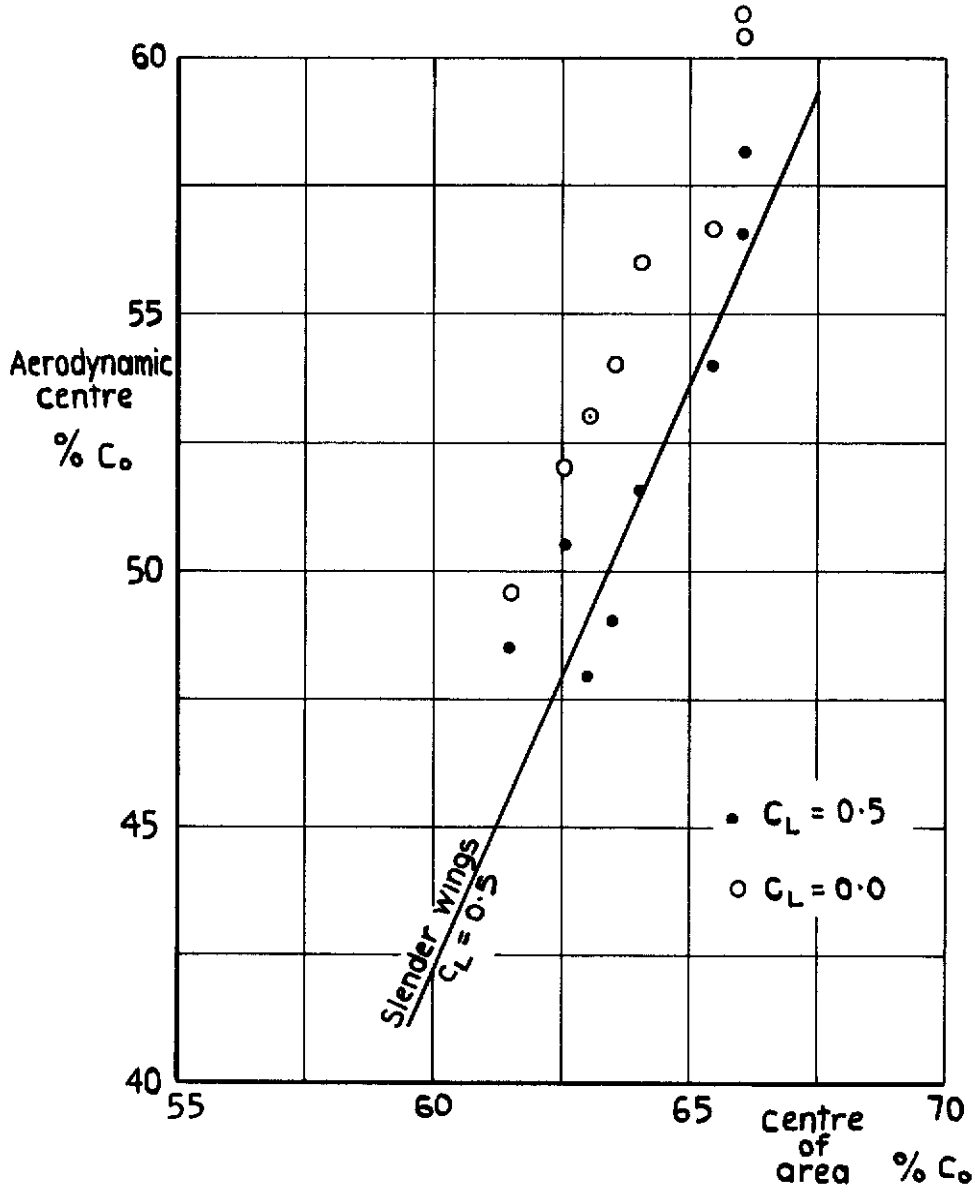


Fig.17 Position of aerodynamic centres of wave-rider wings

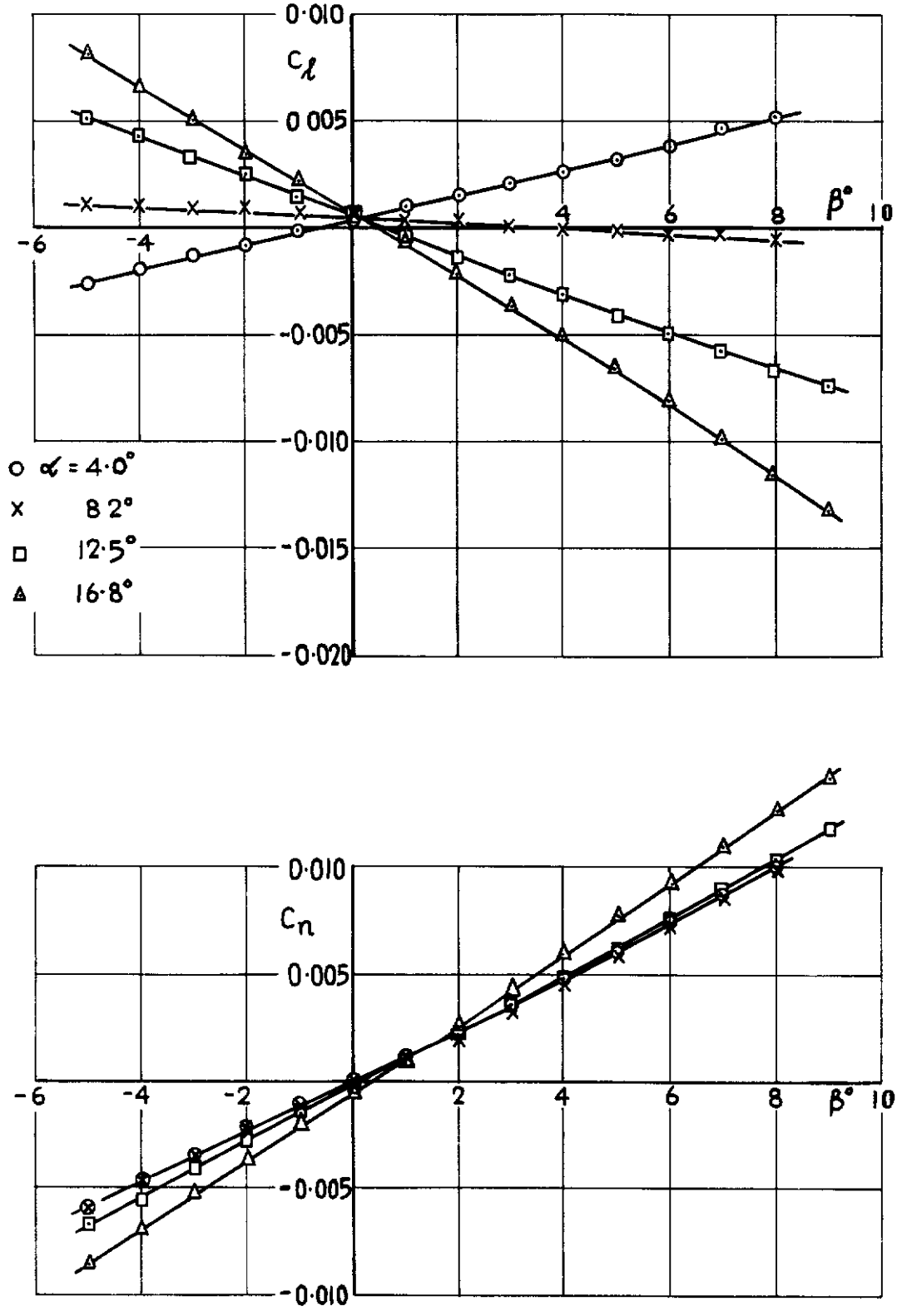


Fig.18 Lateral characteristics of wing D with fin

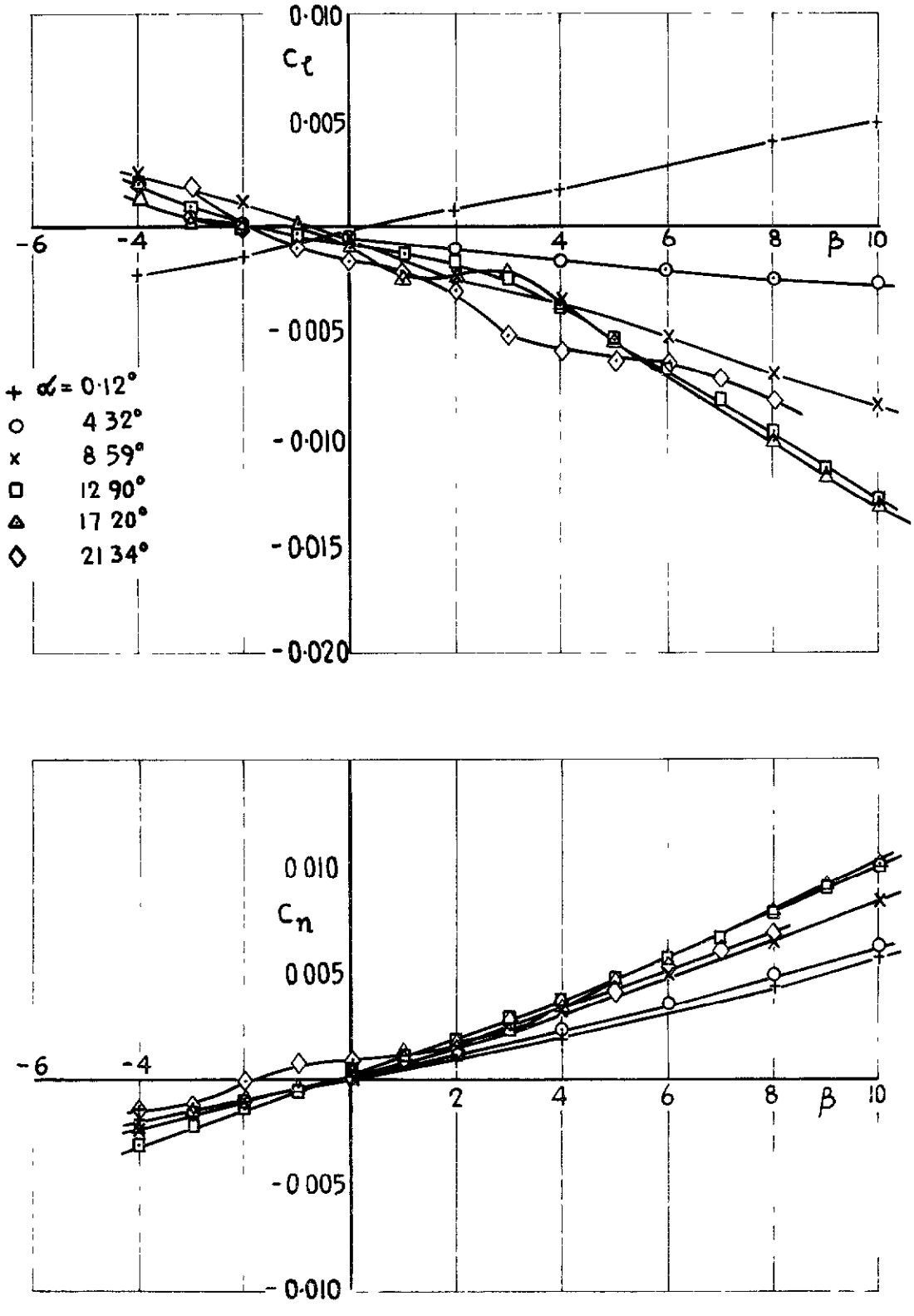
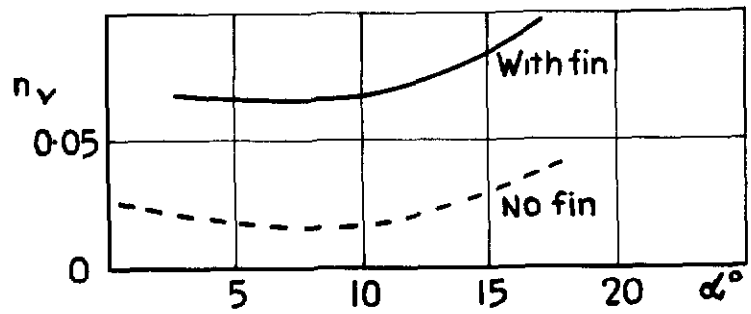
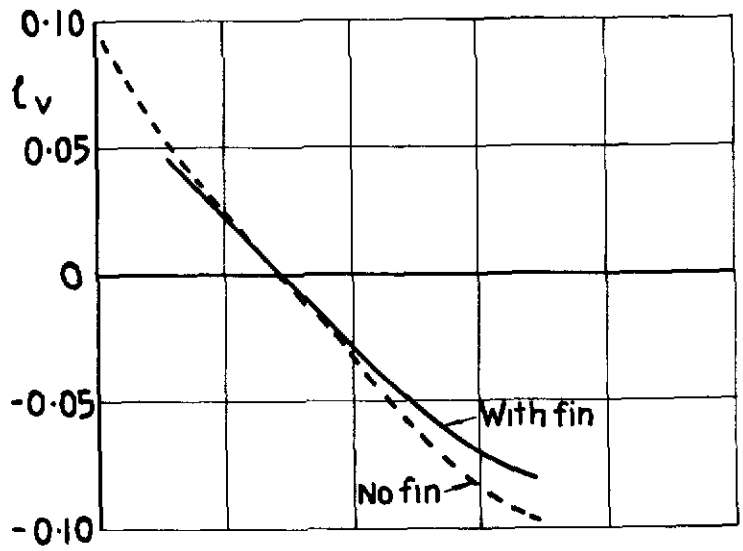


Fig.19 Lateral characteristics of cone-flow wave rider





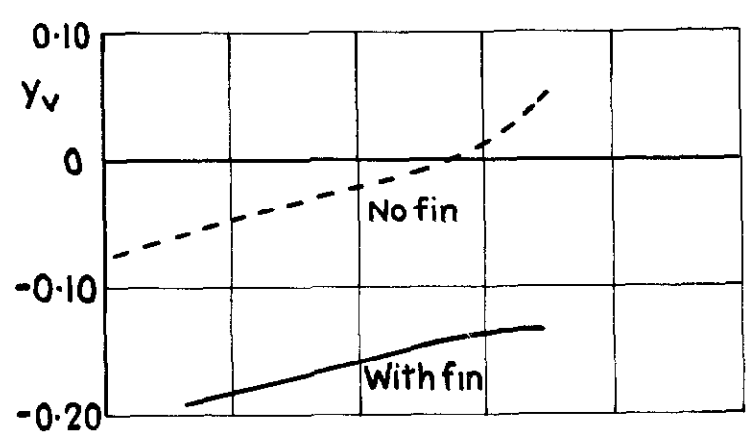


Fig.20 Lateral derivatives of wing D

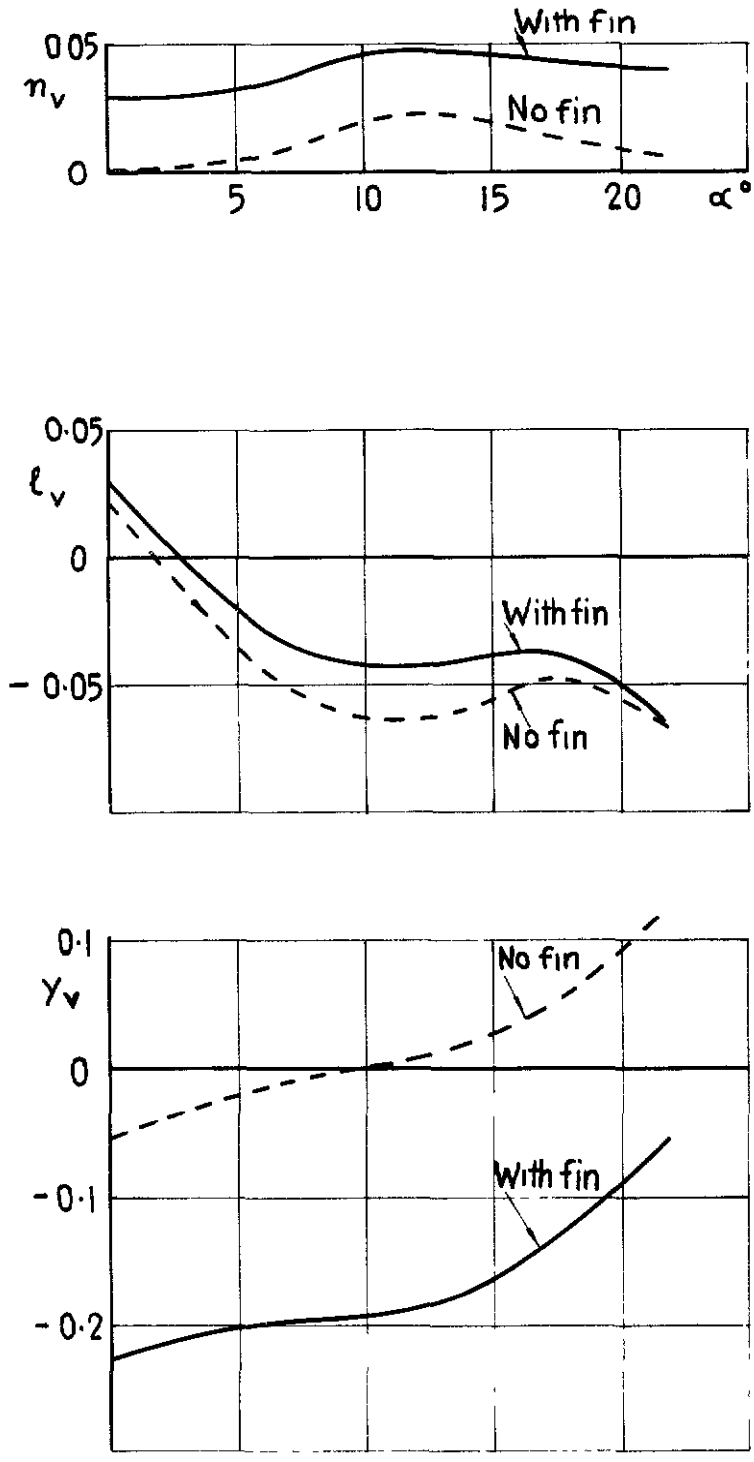


Fig.21 Lateral derivatives of cone-flow wave-rider

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