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Reduction of Lift-Dependent Drag with Separated Flow

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SUMMARY

Wind tunnel tests have been done on two families of slim delta aerofoils, having 70° and 80° leading edge sweep. It is shown that by employing a certain type of transverse cross section (having spanwise camber) it is possible to reduce the lift-dependent drag below that appropriate to an aerofoil with symmetrical sections.

The present tests indicate very considerable reductions in the lift-dependent drag for the transversely cambered delta, in some cases to little more than half that of a symmetrical delta having the same planform. While it is not clear how much of this reduction is due to the favourable suction on the forward facing parts of the cambered delta and how much may be due to some of the other features inevitably incorporated into the models (such as positive fore and aft camber towards the rear), it is felt that the evidence is sufficiently strong to show that the phenomenon investigated does lead to significant reductions of drag at high lift and therefore might in some designs be exploited to advantage.

1. Introduction

An earlier note[1], described some tests carried out by Messrs. Handley Page Ltd. on the flow around delta wings with sharp leading edges. In those tests, separation occurred at the leading edge at very small angles of incidence and the aerofoil sections were symmetrical 4% biconvex circular arc profiles. Following this work, a form of conical camber was applied to the deltas to see if this would reduce the lift-dependent drag. The present note reports these tests, which showed reductions of up to nearly 50% in lift-dependent drag.

2. Basic Considerations

The idea underlying this work was to apply to the separated flow cases the same principle that is applied when designing camber for supersonic flight cases. Camber and fairing shape are adjusted so that the normals to those parts of the wing surface carrying the greatest lift are inclined as much forward as possible, thus reducing the rearward, or drag, component of the lift vector. Crudely, this means that one reduces local incidence at those parts of the wing surface where there are lift peaks.

With attached flow, there is the complication that alterations to the surface alter the pressure distribution significantly and so the problem is rather complicated to solve; however, R.A.E. work indicates that savings of between say, 10% to 30% in lift-dependent drag may be

expected/

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expected. With separated flow the problem seems easier since, to a first approximation, alterations to the surface shape would not be expected to modify appreciably the pressure distribution; this is essentially the same assumption as that in Küchemann's theory which ignores the vertical height of the vortex sheets above the wing surface.

The typical distribution of surface loading along a spanwise section of a slim delta wing with separated flow is as shown in Fig. 1. The peaks near the leading edges are due to the coiled vortex sheet and lie just beneath it. To exploit the principle outlined above, a delta wing was made which was essentially a cone having the section shown by Fig. 2, (i.e., Fig. 2 is a typical transverse section of the wing). It will be seen that the greatest outwards facing slope is on the faces ec and df; thus the lift vectors "P" are inclined outwards. Turning now to the planview shown in Fig. 3, it will be seen that the faces ec and df of Fig. 2 are also inclined forwards, being planes such as ACD and AEF; hence the vectors "P" have a forward component. With the angles shown in the figure, the forward, or anti-drag, component of a force P normal to the local surface is $P \cos \theta \sin \phi$. By this means, therefore, the resultant lift vector is inclined somewhat forwards and the drag is reduced.

Although the flow is basically conical, it is clear that the cone cannot be carried on right to the trailing edge, as this would produce a flat base to the wing at right angles to the flow direction. Therefore the rear end of the wing was faired off, starting at about 70% of the centre line chord from the apex in most cases; further details are given in Para. 3 below. By fairing the wing in this way, a considerable amount of fore and aft camber has been introduced over the rear part of the section. It has been reported that the application of flaps at the rear of a Gothic wing gave a reduction in drag due to lift and therefore this feature may have contributed towards the results obtained.

3. Model Tests

Two delta planforms were tested, one having 70° and the other 80° leading edge sweep. To provide a standard of comparison, these planforms were tested in a symmetrical form as well as with the conical camber described above. Models No. 1 and No. 2 were the symmetrical wings, while models No. 3 - No. 8 were cambered.

Model 1 - Delta with 70° L.E. sweep

Downwind section : 4% symmetrical circular arc biconvex.

No twist.

Model 2 - As model 1 except that leading edge sweep = 80°.

The remaining models are the cambered ones and are defined by the following table, in conjunction with Figs. 2 and 3.

Table/

Model No.	Λ	tan γ	λ	μ	θ	Type of Rear Fairing
3	70°	0.05	0.5	0.8	65°.4	Plane
4	70°	0.10	0.5	0.8	47°.5	Rounded
5	80°	0.05	0.5	0.8	46°.4	"
6	80°	0.10	0.5	0.8	27°.7	"
7	80°	0.10	0.3	0.8	41°.2	"
8	80°	0.10	0.3	0.5	19°.3	"

The parameter tan γ is used above to represent thickness instead of t/c ratio which is not a suitable way of describing the new forms of wing considered here. The relationship between tan γ and t/c may be seen from the fact that wings with $\tan\gamma = 0.05$ have a centre line t/c ratio of approximately 4%, while when $\tan\gamma = 0.10$, the corresponding centre line t/c ratio is about 8%.

In cases of models Nos. 4, 6, 7 and 8, ($\tan\gamma = 0.1$) and also model No. 5, the rear of the model was faired by rounding off the aft part of the wing, as indicated by the sketch in Fig. 3. The rounding covered approximately the last 30% of the centre-line chord, i.e., the first 70% of the wing was truly conical. In the case of one of the thinner models, No. 3 ($\tan\gamma = 0.05$), a simpler method of fairing was used, namely the rear of the cone was sliced off by a plane containing the trailing edge and cutting the top surface of the wing at 80% of the centre-line chord from the apex, see Fig. 3.

Note that models 1, 3 and 4 constitute the 70° delta series, the two cambered models, 3 and 4 having different thicknesses. Models 2 and 5 to 8 all have 80° L.E. sweep; models 5 and 6 differ mainly in thickness. The aim of the pair of models 7 and 8 was to obtain an idea of the influence of some of the parameters defining cross-sectional shape, in this case μ and θ; model 7 is similar to model 6, but differs in λ and θ so that it is necessary for its results to be given separately to provide the required strict comparison with the variant represented by model 8. At the same time, comparison of models 6 and 7 also shows effects due to changing geometry.

Test Conditions

The tests were carried out at a wind speed of 100 ft per second. The centre-line chord of the 70° delta was 3 ft and that of the 80° delta was 5 ft; this leads to Reynolds numbers based on mean chord of 1×10^6 and 1.5×10^6 for the 70° and 80° deltas respectively.

4. Results

The test results are plotted in Figs. 4 - 9.

It should be pointed out here that in the attempted analysis to see what drag reductions might be obtained, the comparison has been limited to the tests carried out by Handley Page Ltd. in their own wind tunnel. It is clearly possible that a somewhat different conclusion might be reached if the basic lift-dependent drag, that is, the lift-dependent drag of the uncambered delta, were different from that taken as the basis of the comparison given in this note. Nevertheless, it is felt that the comparison given at least has the merit that both sets of models were tested by the same people in the same wind tunnel, under very similar test conditions.

Figs. 4 and 5 show drag coefficient plotted against the square of the lift coefficient. These curves plot as fair approximations to the straight lines commonly obtained, especially for the cambered wings, but show a steady reduction in dC_D/dC_L^2 with increasing incidence. This reduction of slope with increasing C_L is most marked in the cases of the two datum wings with 4% biconvex sections, and is to be expected from an aerofoil that has a non-linear $C_L - \alpha$ relationship (see Figs. 6 and 7 for example); thus the reduction of dC_D/dC_L^2 with increasing C_L is a consequence of the corresponding increase in $dC_L/d\alpha$. In making the comparison between lift-dependent drags, therefore, two slopes for dC_D/dC_L^2 have been used in all cases; one slope for 0° to 10° incidence, and the other from 10° to 20° incidence, since the curves for the wings with biconvex sections have a fairly definite kink at about 10° incidence.

In the following tables comparisons are given of the various values of dC_D/dC_L^2 for the eight models tested. Actual values of dC_D/dC_L^2 are given and also ratios, quoted as percentages, of these slopes to the slope of the corresponding (same L.E. sweep) model with biconvex sections.

Deltas with 70° L.E. sweep

Model No.	Range 0° - 10°		Range 10° - 20°	
	dC_D/dC_L^2	Relative dC_D/dC_L^2	dC_D/dC_L^2	Relative dC_D/dC_L^2
1	0.52	100%	0.41	100%
3	0.36	69%	0.33	81%
4	0.28	54%	0.32	78%

Deltas with 80° L.E. sweep

Model No.	Range 0° - 10°		Range 10° - 20°	
	dC_D/dC_L^2	Relative dC_D/dC_L^2	dC_D/dC_L^2	Relative dC_D/dC_L^2
2	0.71	100%	0.58	100%
5	0.62	87%	0.54	93%
6	0.52	73%	0.52	90%
7	0.46	65%	0.49	85%
8	0.54	76%	0.52	90%

Since the value of dC_D/dC_L^2 is a measure of lift-dependent drag, it is clear that very considerable reductions in this quantity can be

obtained/

obtained by appropriately shaping the wings, especially for the lower incidences, which covers the very useful range of lift-coefficient from 0 to about 0.3 or 0.4. The fact that the greater reductions occur at the lower incidences is presumably related to the fact that under these conditions the cambered wings carry considerably more lift than do those with biconvex sections, see Figs. 6 and 7.

The less swept deltas and the thicker wing models show the greatest drag reductions.

The comparison between models (7) and (8) shows that modification to the shape of the cross section can influence lift-dependent drag and hence it is to be presumed that the figures quoted in this report are not the best that might be obtained after optimising the design of the wing. Other variations of shape should, obviously, also be considered and it seems possible that a smooth, curved, cross section for the cone might be better than the angular shape initially chosen to simplify model making.

The test evidence as to the effect of the cambered "formula" on parasite drag is slightly conflicting, since in some cases cambering apparently increases the zero lift drag while in others it does not do so. However, the zero-lift drag increments are small in any case and there is little doubt that by more careful attention to the fairing of the rear part of the wing the parasite drag increment can be made very small.

It may therefore be concluded that the shape of delta wing tested shows a considerable reduction in overall drag, compared with a simple delta wing of biconvex section, for a large range of lift coefficients. For example, comparing two 70° deltas, models No. 1 and 3, (see Fig. 4) which are of comparable thickness, leads to the following values of the ratios of the total drags:

C_L	$\dfrac{\text{Total drag of cambered delta}}{\text{Total drag of symmetrical biconvex delta}}$
0.3	0.77
0.5	0.77
0.8	0.80

Thus a drag reduction of about 20% is maintained over quite a wide range of lift coefficient.

The lift curves of Figs. 6 - 8 show that for wings of comparable thickness camber does not much affect lift curve slope, but, as would be expected, leads to a negative zero-lift angle. Increase of thickness, however, reduces lift curve slope throughout. Both cambered and uncambered deltas show the curved $C_L - \alpha$ plot, with $dC_L/d\alpha$ increasing with α, that is typical of slim deltas.

The pitching moment curves given on Fig. 9 indicate that the primary effect of camber is to give a negative zero-lift pitching moment, as one would expect. Otherwise, the $C_M - C_L$ curves for cambered and uncambered deltas are reasonably parallel, though the thicker wings show some irregularity at the smaller lift coefficients. This is probably due to imperfections on the rear fairing leading to local breakaway; at the higher incidences, the well developed leading edge vortices suppress the local separation and impose the characteristic high C_L slim delta flow pattern on the model.

Oil flow observations were made during the tests and the resulting patterns indicated that the type of flow was exactly what had been expected, i.e., the cambering of the aerofoils did not appear to have changed the flow significantly from that observed on symmetrical aerofoils.

Reference

No.	Author	Title, etc.
1	G. H. Lee	Note on the flow around delta wings with sharp leading edges. A.R.C. R. & M.3070. September, 1955.

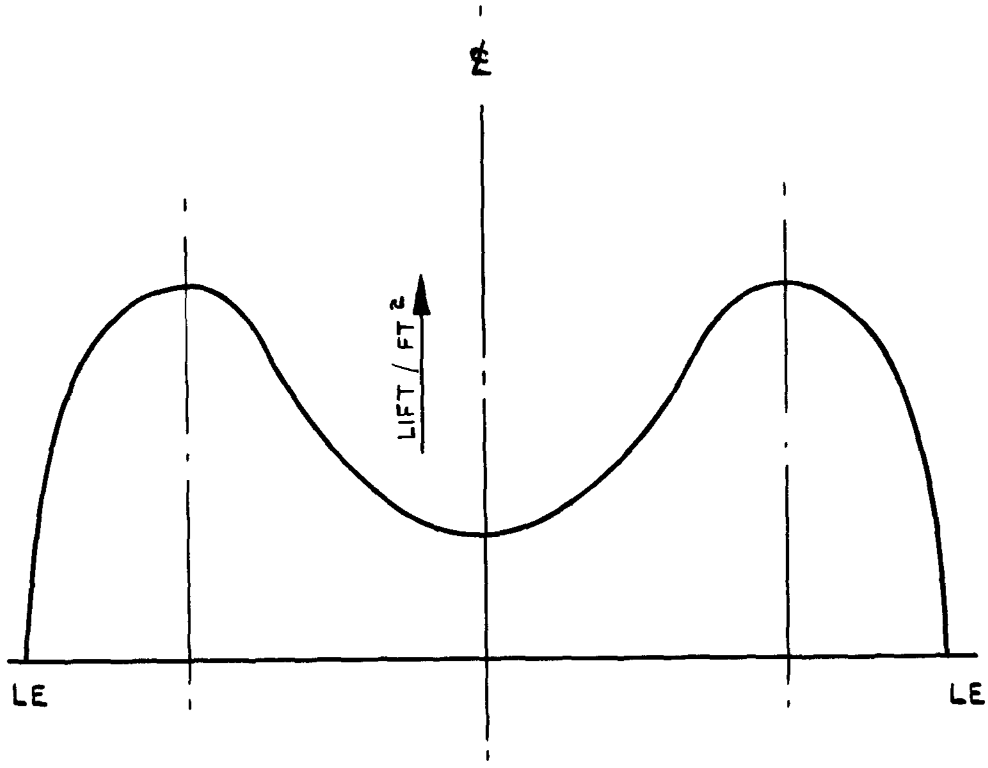


FIG. 1. TRANSVERSE SECTION THROUGH SURFACE LOAD DISTRIBUTION.

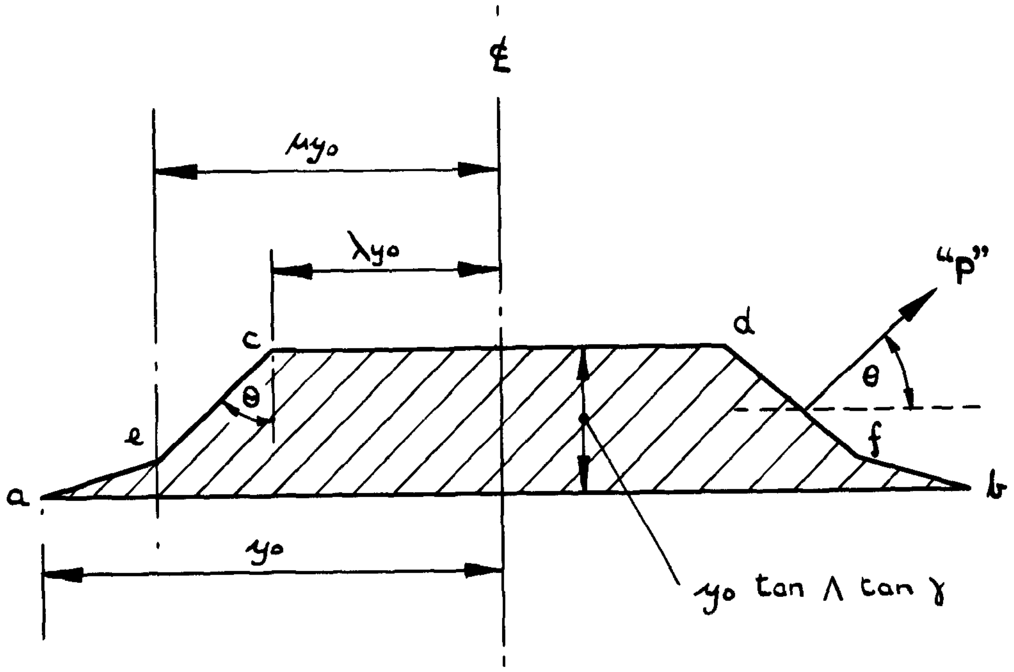
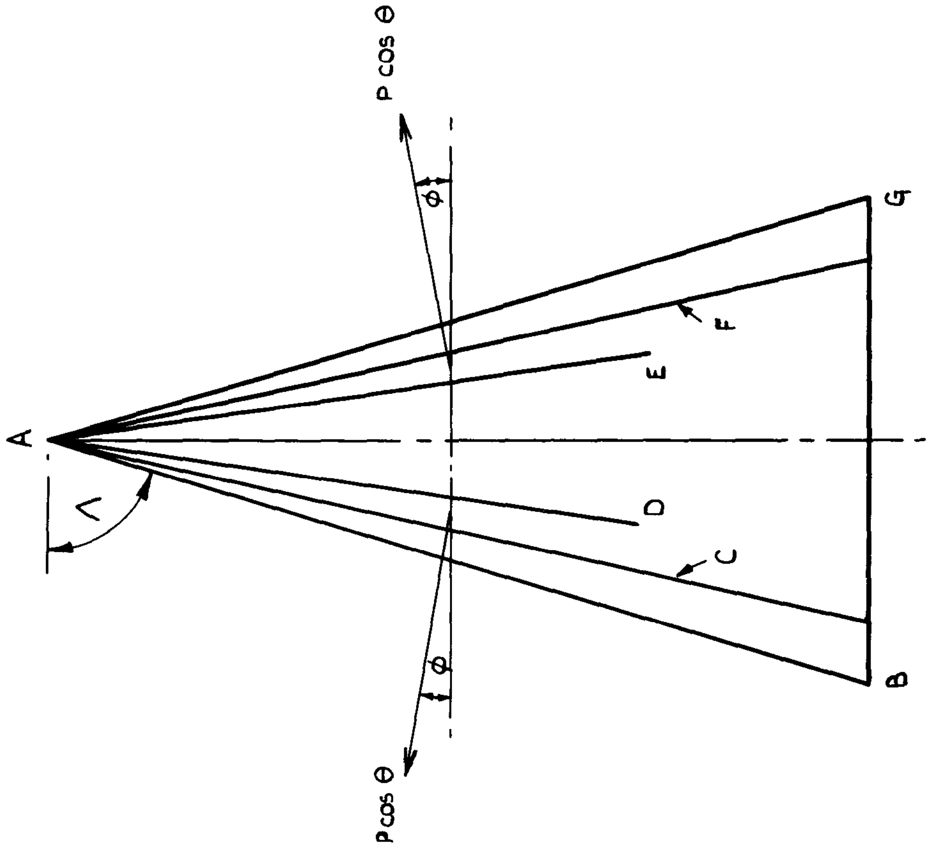
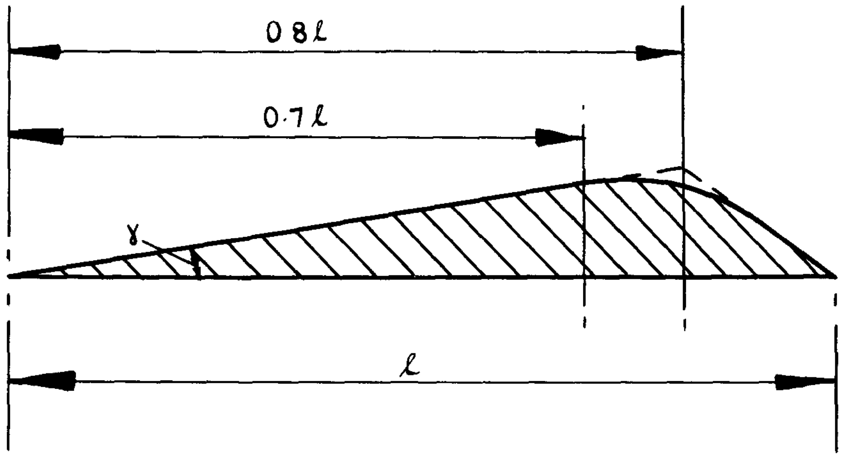


FIG. 2. TYPICAL TRANSVERSE CROSS - SECTION SHOWING DEFINITION OF GEOMETRICAL PARAMETERS.



PLAN VIEW.

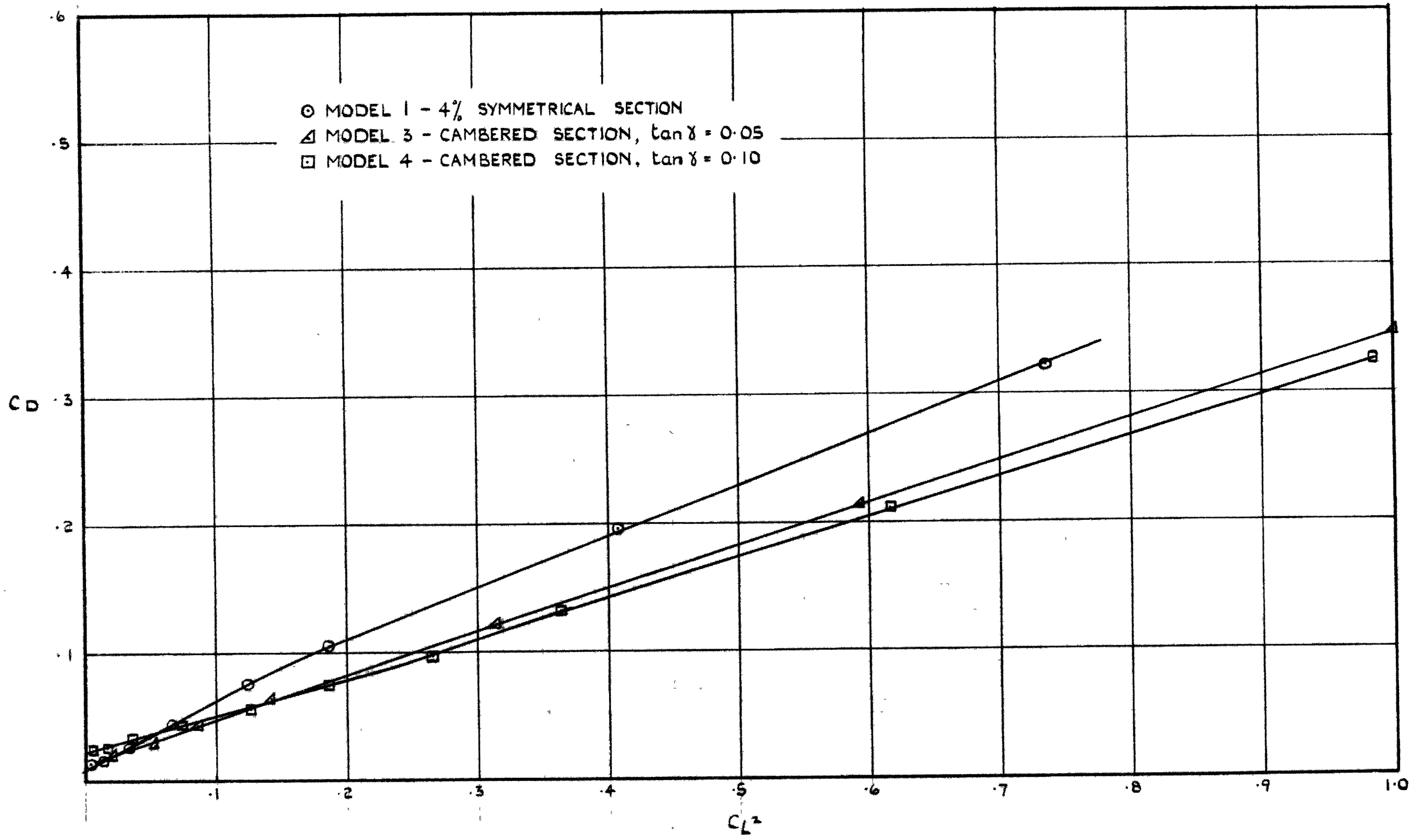


CENTRE-LINE CROSS-SECTION.

FULL LINE : MODELS No 4-8.
DOTTED LINE : MODEL No. 3.

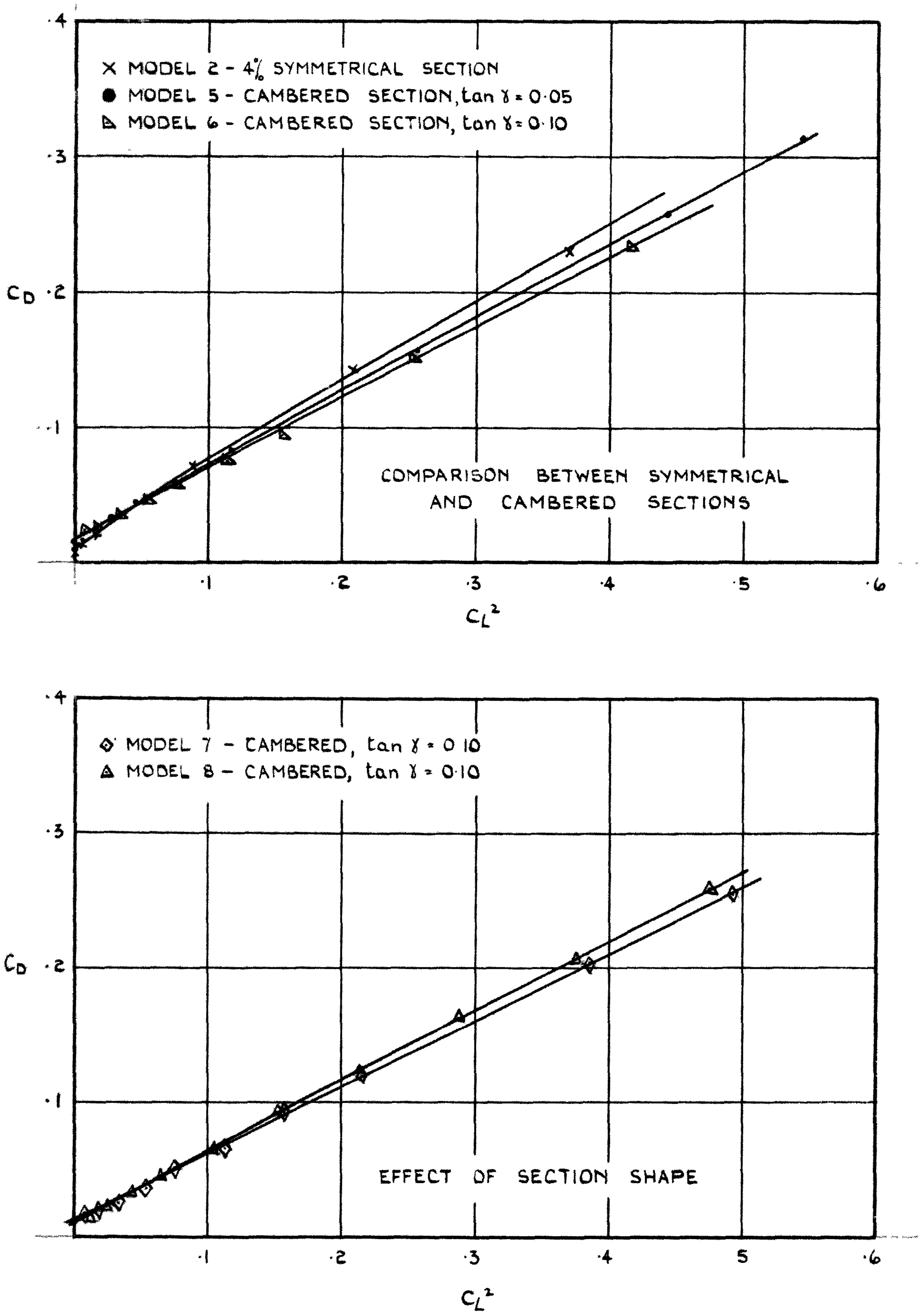
PLAN AND SIDE VIEW OF
CAMBERED MODELS

FIG. 3



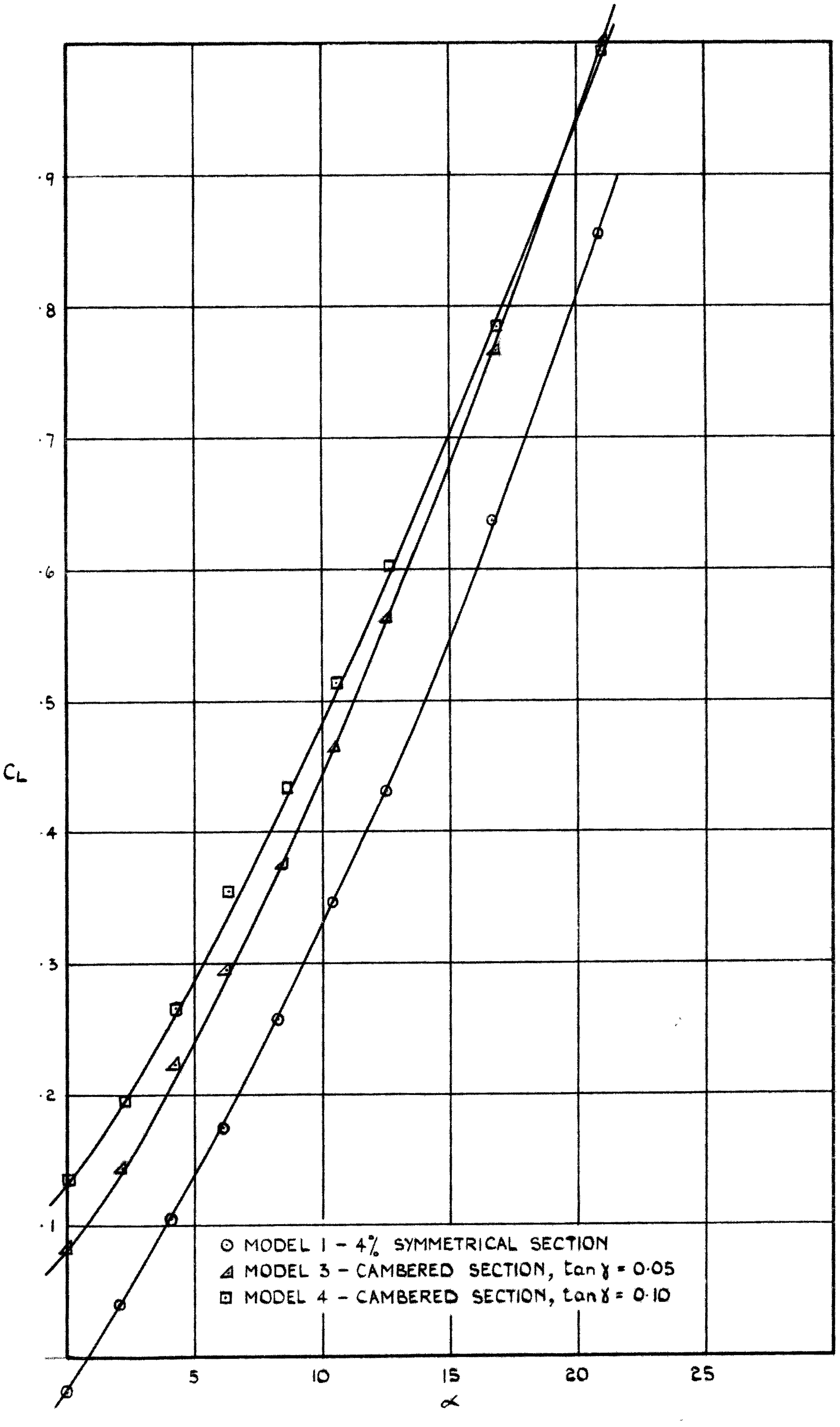
C_D vs C_L^2
70° DELTAS.

FIG. 4



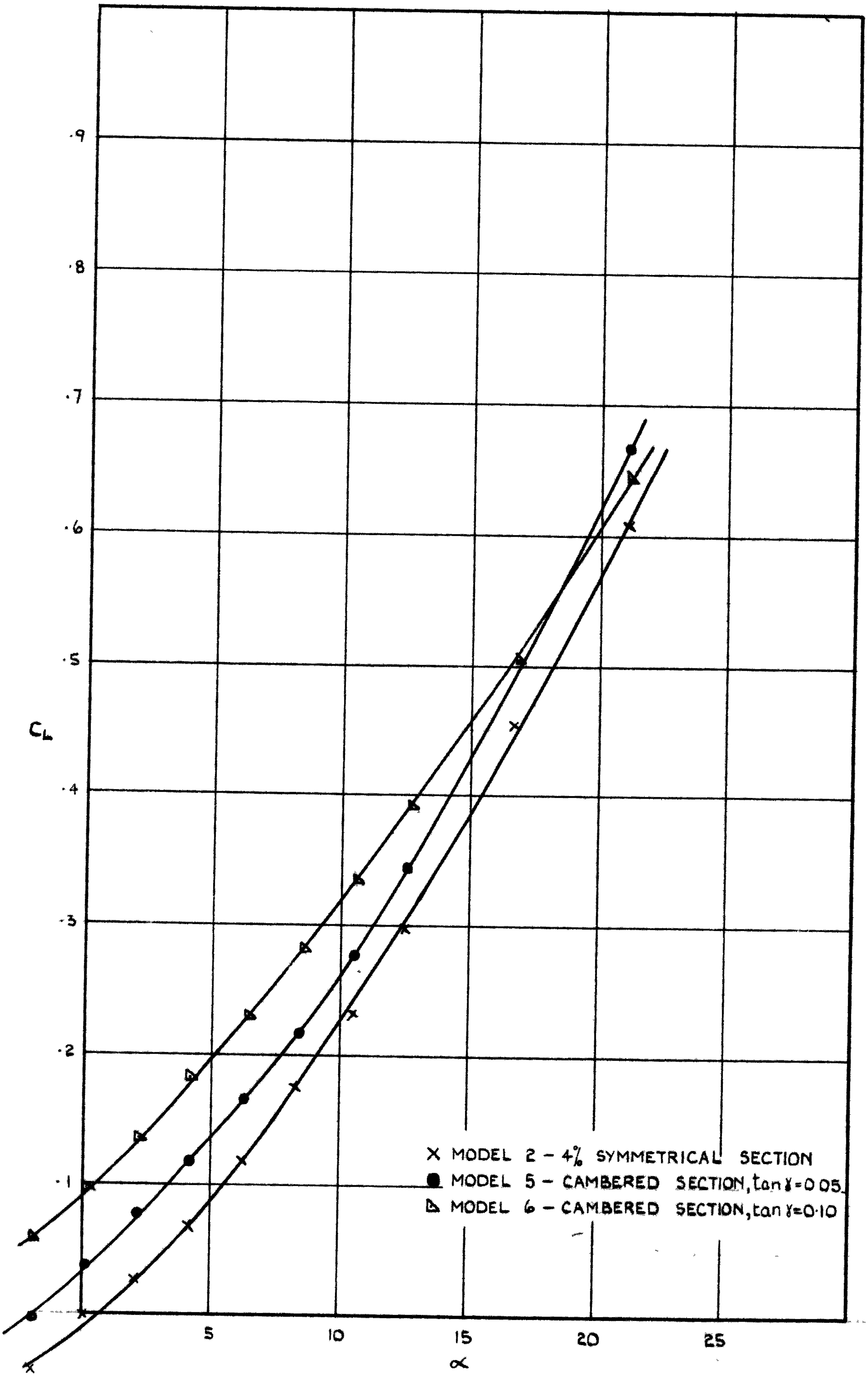
C_D vs C_L^2
80° DELTAS.

FIG. 5.



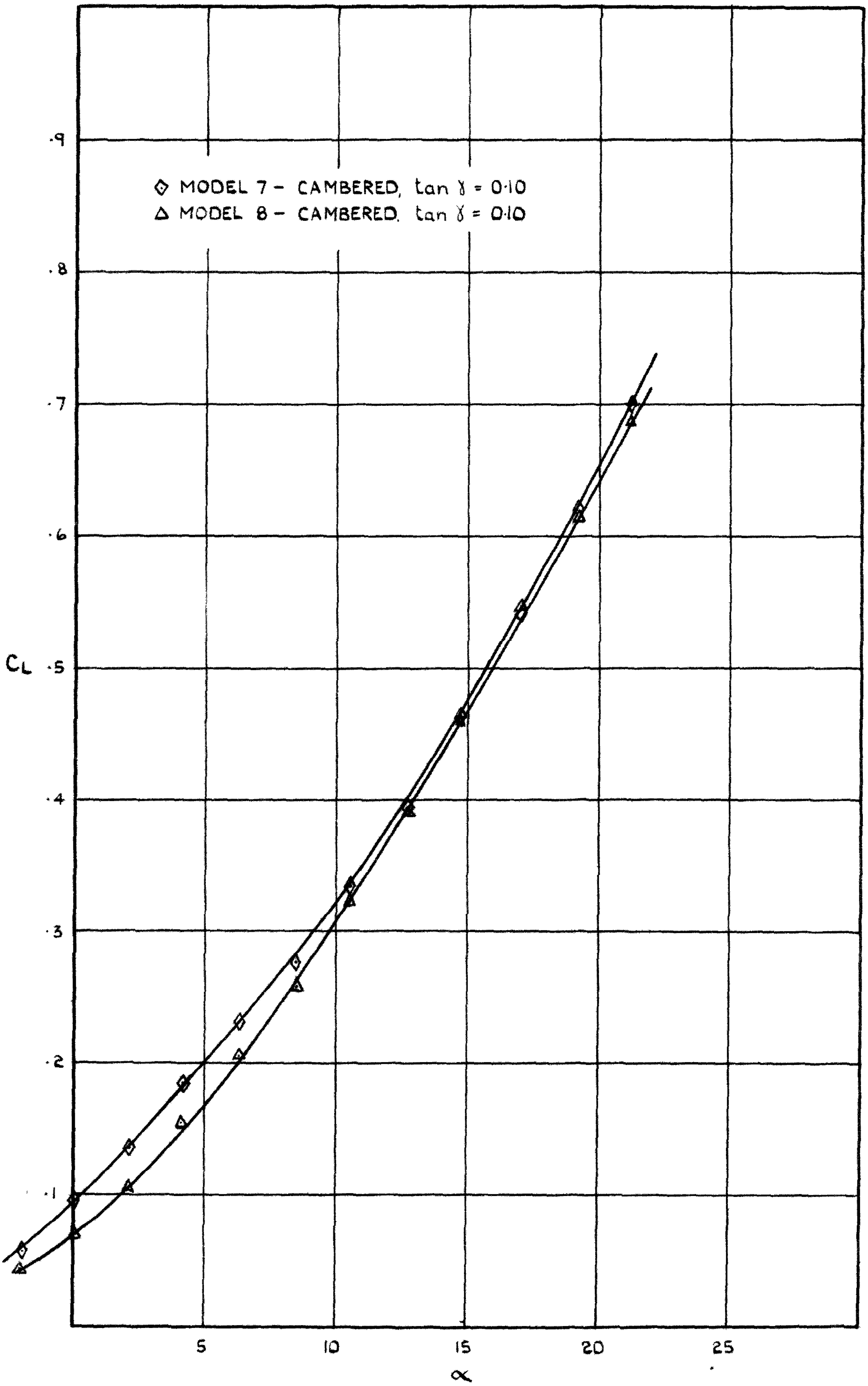
CL vs α
70° DELTAS

FIG. 6.



C_L vs α
80° DELTAS

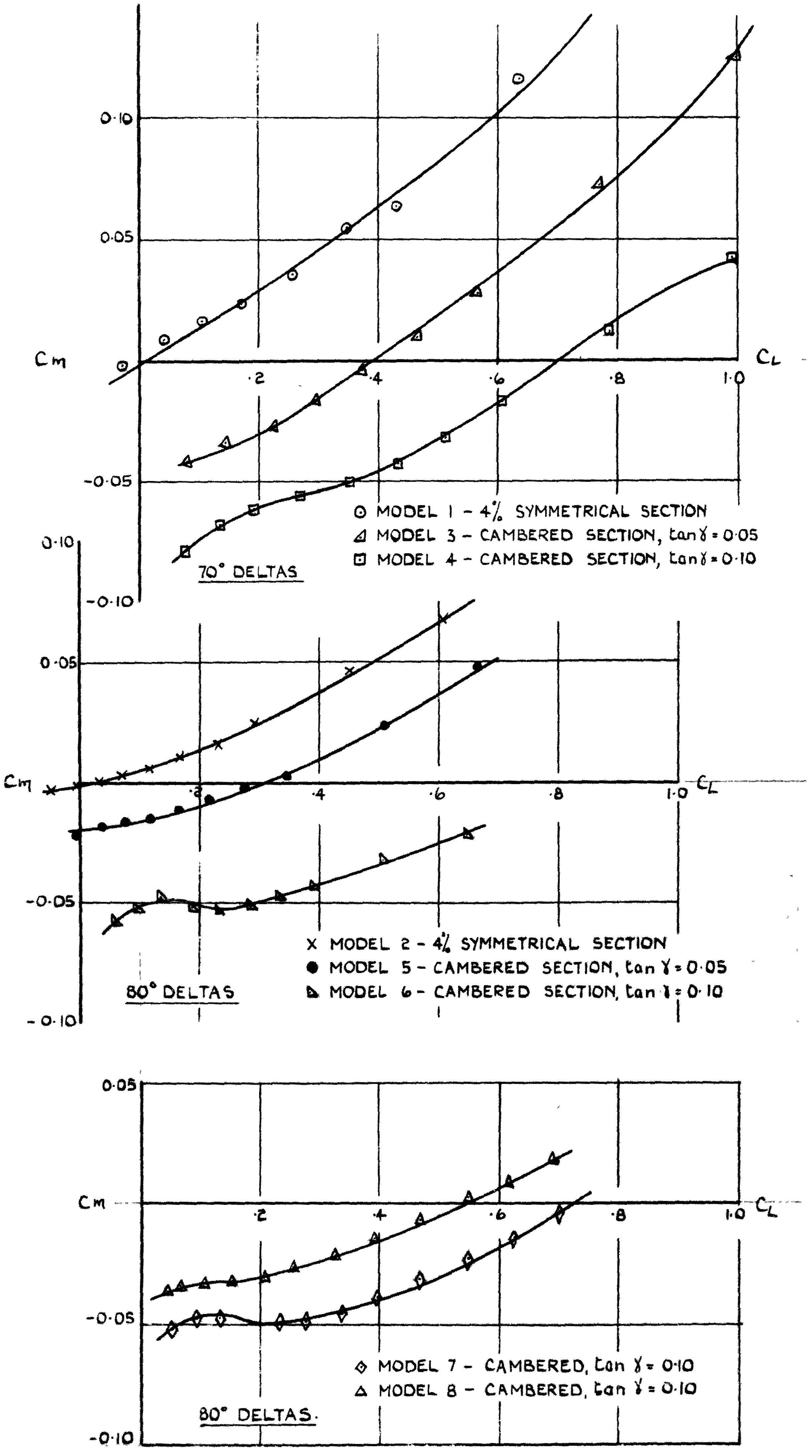
FIG. 7



C_L vs α

80° DELTAS.

FIG. 8.



Cm vs CL

FIG. 9.

DS 65355/1/Wt.58 K.4 7/62 CL

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REDUCTION OF LIFT DEPENDENT DRAG WITH SEPARATED FLOW

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