REPORT No. 43

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THE COLLEGE OF AERONAUTICS
CRANFIELD

MEASUREMENT OF THE PRESSURE DISTRIBUTION ON SWEPT BACK WINGS WITH TRAILING EDGE SPLIT FLAPS

by

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Measurements of the Pressure Distribution on Swept Back Wings with Trailing Edge Split Flaps

Summary of wind tunnel work at the
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- by -

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SUMMARY

This is an interim report giving measurements that have so far been made of the pressure distribution on two untapered wings swept back 45°, aspect ratios 2 and 4, fitted with both full span and part span trailing edge split flaps. The Reynolds number in these tests was about 0.5×10^{6}.

At small to moderate incidences there was a build up of lift near the tips over the rear part of the wing, which was intensified by the flaps. At higher incidences the flow separation is more gradual on a swept back wing than on an unswept wing. The increase in $C_{L\ max}$ due to flaps on a swept back wing is smaller than that on an unswept wing. With full span flaps the flow breaks down at a lower incidence. These effects are analysed in some detail and it is suggested that because the flaps increase the suction on the upper surface of the inner part of the wing they reduce the boundary layer drift towards the tips and hence cause the main part of the wing to stall at a lower incidence. A programme of tests is given for further work on the stalling properties of swept back wings.

The tests were carried out by Messrs. Caiger Carter, Eldridge, Hodges, R.S. Jones, Rossiter, Ruben, Turner and Watts.

Introduction

It is well-known that swept back wings have many adverse features at low speeds, being more liable to tip stalling and rendering trailing edge flaps far less effective than on unswept wings. Several reasons have been advanced for these effects (reference 1), among them:-

(a) the increase in local C_L near the tips due to sweepback,

(b) the negative induced camber near the tips,

(c) the outward drift of the boundary layer on the upper surface of the wing.

The present series of tests were initiated to clarify the separation and stalling properties of sweptback wings both with and without flaps.

Models tested

Spanwise and chordwise pressure distributions have been obtained for two untapered wings, swept back 45°, (i) aspect ratio 4 fitted with 20 percent chord trailing edge split flaps, and (ii) aspect ratio 2 fitted with 25 percent chord trailing edge split flaps. Pressure plots were made for incidences 0°, 6°, 12°, 18°, 24° and 30° at 7 spanwise positions. 19 chordwise positions being used with each spanwise position. The aerofoil was a symmetrical section, 12 percent thick in the line of flight. The span of both models was 30 inches, the corresponding Reynolds numbers being 0.6×10^6 for the wing of aspect ratio 2 and 0.5×10^6 for that of aspect ratio 4. The tips were square and were faired with half bodies of revolution. No corrections have been applied to the readings.

Flow characteristics

Wing of aspect ratio 4

Plain wing (Figures 1 and 4)

The flow is smooth up to an incidence of 12°. At this incidence (figure 1) there is a marked increase in lift over the rear part of the wing at the tip. At low incidence, the maximum suction at first increases then decreases as we go from the wing root to the tip, the highest velocity occurring at about the mid semi-

/span ...

span (0.5 s). With further increase in incidence the position of the peak suction moves towards the plane of symmetry. The suction peak is much lower than that for an unswept wing at the same incidence. These results should only be regarded as qualitative, there being very few pressure points in the neighbourhood of the suction peak. The suction at the centre section of the wing is lower than that at the mid semi-span, due to the three dimensional flow over the centre section at low incidence. At an incidence of 18°, the flow is partly detached at 0.5s and at the tip; this is indicated by small sub-pressures at the trailing edge. At an incidence of 24°, the flow is partly detached from 0.4s to 0.7s and completely detached outboard of this; the suction peak is completely eliminated in the latter region. At an incidence of 30°, the flow is partly detached from 0.2s to 0.5s and completely detached outboard of this.

These results are in good agreement with corresponding pressure measurements made in Germany and Sweden (references 2 and 3).

45° full span flaps (Figures 2 and 5)

The flow is smooth up to an incidence of 12°. The increase in lift at the tip is in evidence at an incidence of 6° (figure 2) and it is clearly intensified by the flap. At low incidence the spanwise distribution of maximum suction is similar to that of the plain wing, with the highest velocity at the mid semi-span. There is, however, an increase in suction as compared with the plain wing. At an incidence of 18°, the flow is partly detached from 0.6s to 0.7s and completely detached outboard of this. At an incidence of 24°, the flow is completely detached from 0.4s to the tip. Thus the flow breaks down at a lower incidence on the flapped wing.

45° inboard flaps (centre to 0.5s) (Figures 3 and 6)

At low incidences the pressures over the inboard half of the semi span are almost identical with those for full span flaps, but the flap is not quite so effective at its outboard tip. There is an increase in lift over the outboard half of the semi span as compared with that of the plain wing for incidences up to 18°. The flow is smooth up to an

/incidence ...

incidence of 12°, with an increase in lift at the tip at that incidence. The flow separation is almost the same as that for the plain wing.

45° outboard flaps (0.5s to tip)

At low incidences the pressures over the in-board half of the semi span are very similar to those for the plain wing. On the inboard part of the flap, at small incidence, there is a decrease in the suction peak on the upper surface as compared with the full span flaps, and thus a corresponding loss in effectiveness. The flow separation is almost the same as that for the plain wing.

Wing of aspect ratio 2

Plain wing (Figure 7)

At low angles of incidence the pressure distribution is very similar to that for the wing of aspect ratio 4, the contribution of lift from the outboard semi span being rather smaller at a given incidence. At an incidence of 18°, partial separation begins at the tip. At an incidence of 24°, the flow is partly detached from 0.6s outboard. At an incidence of 30°, the flow is partly detached from 0.3s to 0.5s and completely detached outboard of this. Thus for the wing of smaller aspect ratio at a given spanwise section separation is postponed to a higher incidence, but separation is rather more abrupt once it sets in. There is some evidence (reference 4) that for unswept wings the stall is more abrupt the lower the aspect ratio of the wing. The effect of aspect ratio is slightly masked by the difference in the Reynolds numbers between the two tests.

30° inboard flaps (centre to 0.5s) (Figure 8)

As with the wing of aspect ratio 4 there is an increase in lift over the outboard half of the semi span as compared with that of the plain wing, thus increasing the flap effectiveness. The flow is smooth up to an incidence of 18°. At higher angles of incidence the separation is almost the same as that for the plain wing.

No pressure distributions were measured for other flap configurations.

/Spanwise ...

Spanwise distribution of loading

Figures 9 and 10 show the spanwise variation of the normal force coefficient for various angles of incidence for the wing of aspect ratio 4 (i) without flaps (ii) with 45° full span flaps. The experimental results for the plain wing for an incidence of 6° are compared with a theoretical estimate giving the same total C_N (reference 5); it can be seen that the theoretical distribution is a fair representation of the experimental results.

From figure 9, it can be seen that for the plain wing, breakaway commences at the tip between an incidence of 12° and 18°. At the latter incidence there is also partial separation at 0.5s. With increase of incidence the region of completely detached flow spreads inboard from the tip causing the position of maximum C_N to move inboard.

Figure 10 shows that the lift peak at the tip is increased by the presence of the flap. This effect is not confined to swept wings (see reference 6) and is partly due to the square cut tip.

Similar spanwise loading distributions were obtained for the wing of aspect ratio 2.

Mean normal force coefficients

Figures 11 and 12 show that mean normal force coefficients for various flap configurations for the two wings. The results are summarised in the following table.

TABLE I

Values of $\frac{d\,C_N}{d\alpha}$, $C_{N\,max}$, α_{stall}, and ΔC_N at $\alpha = 12^{\circ}$

Wing Aspect Ratio 4. Sweepback 45°
Reynolds Number 0.5×10^6

	No flaps	Flaps at 45° over		
		Full span	Inboard semispan	Outboard semispan
$dC_N/d\alpha$	2.5	2.6	2.6	2.6
$C_{N\,max}$	1.00	1.35	1.23	1.18
α_{stall}	30°	22°	24°	27°
ΔC_N at $\alpha=12^{\circ}$		0.54	0.40	0.21

Wing Aspect Ratio 2. Sweepback 45° Reynolds Number 0.6×10^6			
	No flaps	Flaps at 30° over	
		Full span	Inboard semispan
$dC_N/d\alpha$	2.2	2.1	2.1
C_N max	1.06	1.19	1.12
α_{stall}	30°	26°	27°
ΔC_N at $\alpha=12^\circ$		0.23	0.14

These results are in agreement with those of earlier tests in showing that at the stall, flaps on a swept back wing are less effective than on an unswept wing. The stalling incidence is lower with flaps, and the stall is more sudden than with the plain wing. Thus for the wing of aspect ratio 4 the lift curve slope for the plain wing begins to decrease at an incidence of 18°, whereas the wing does not reach its stalling incidence before 30°. For the wing of aspect ratio 2 there is an increase in $dC_N/d\alpha$ at an incidence of 21° ($C_N = 0.8$). This has been noticed in previous tests and has been attributed to the additional lift from the tips.

Discussion of results

Loading distribution at low angles of incidence (Figures 9 and 10)

From figure 9 we see that at low angles of incidence the experimental determination of the spanwise normal force distribution for the wing of aspect ratio 4 without flaps is in fair agreement with theoretical results (reference 5), showing that the local C_N near the tip is higher than for an unswept wing.

At low angles of incidence up to 12°, the lift effectiveness of trailing edge split flaps is almost as great as for the corresponding flaps on an unswept wing. As with the unswept wing, inboard flaps are more effective than outboard ones. With

/the ...

the inboard flap there is also an increase in lift over the outboard half of the semi-span as compared with that of the plain wing, thus increasing the flap effectiveness.

Tip effects

The marked increase in lift at the tip over the rear part of the wing at an incidence of 12° (figures 1, 2, 3, 7 and 8) has been similarly noted in some tests on unswept wings (see references 6 and 7), and appears to be associated in part with the square cut tip. In German work on wings of small aspect ratio (references 8 and 9), this tip effect is attributed to the end plate effect of a vortex sheet running up the edge of the wing, the height of the vortex sheet varying with incidence. Another possible explanation is that the increase in lift at the tip is associated with a laminar separation followed by a reattachment of the flow in the turbulent condition. This would give the tip section an apparent increase in camber. The size and position of such a transition bubble would depend on the nature of the adverse pressure gradient; such reattachment would normally occur within the first 30 % c of the aerofoil. The increase in local C_L at the tip is not however the dominant effect in producing a tip stall; German tests (reference 10) have shown that devices intended to decrease the lift at the tips, such as wash out and counter flaps, are only partly successful.

Lifting surface theory would suggest that some negative induced camber effect should be present at the tip. The effect of negative induced camber is to increase the local peak suction at the tip and reduce the local $C_{L\,max}$. Thus, if for a given local value of C_N the outer part of the span is compared with the equivalent straight wing, the swept wing pressure distribution should show the greater peak suction. It is difficult to observe this effect in these tests; at an incidence of 18° there is a definite peak near the leading edge at the tips both with the plain wing and with the inboard flaps. At higher incidences, however, there is separation at the tips which tends to smother any induced camber effect which may be present.

To investigate these effects more fully it would be necessary to take a more detailed set of pressure measurements near the tips, supplemented by visual flow observations using tufts.

/Separation ...

Separation effects and boundary layer drift
(Figures 1-6)

It is well known that with sweepback there is a tendency for the boundary layer to drift out along the wing span. We shall analyse this effect more closely. It has been demonstrated in reference 10 that the transverse or spanwise distribution of velocity in the boundary layer of a yawed wing is relatively unaffected by the chordwise distribution and is reasonably close to the distribution of velocity in the boundary layer on a flat plate at zero yaw; the magnitude of the spanwise velocity in the boundary layer will depend on the magnitude of the component of the main stream velocity in the spanwise direction. The chordwise velocity distribution in the boundary layer will depend on the chordwise pressure distribution; if the pressure gradient is adverse, the chordwise velocity component near the surface will be reduced as compared with regions in which the pressure gradient is favourable. Further, the magnitude of the chordwise velocity component in the boundary layer will depend on the magnitude of the chordwise component outside the boundary layer. Thus in regions of large adverse pressure gradient and low velocity the transverse component of velocity near the surface may become large compared with the chordwise component. In such cases, drift of the boundary layer from the inner part of the wing will become evident. Thus it appears that the high angle of incidence at which a swept wing stalls as a whole is due to the fact that the inner parts of the wing are cleared of tired air in the boundary layer and hence stall later than if the wings were not swept. The tips clearly stall earlier, but the net effect is a gain in overall stalling incidence.

The effect of flaps is to speed up the chordwise flow particularly over the rear part of the wing, and hence to suppress to some extent the tendency for the boundary layer to drift out towards the tips. Thus the stalling incidence over the main part of the wing is reduced to a more normal value. With full span or inboard flaps the mid semi-span section stalls at 18° incidence, whereas on the plain wing or with outboard flaps this section stalls at 25°. Similarly, there is evidence that the centre section stalls at a lower

/incidence ...

incidence with inboard flaps.

We can see from figures 11 and 12 that separation is more abrupt when full span or inboard flaps are down, due to the earlier stalling of the mid semispan sections of the wing with the resulting loss in $C_{L\ max}$. For the full span flap on the wing of aspect ratio 4 the flow is completely detached from 0.4 s to the tip at an incidence of 24^{o}. This is in agreement with the German tests (references 11, 12 and 13); $\Delta C_{L\ max}$ is only about 60 percent ΔC_L at an incidence of 12^{o}. However, the above explanation of the relative loss in the maximum lift coefficient measurement of a flap with sweepback can only be regarded at present as tentative; more investigation is clearly needed before it can be accepted.

Influence of aspect ratio

Separation was postponed to a slightly higher incidence on the wing of smaller aspect ratio but was slightly more abrupt once it set in. Reference 14 has shown that if the aspect ratio can be reduced to unity, there is an improvement in stalling characteristics, the wing stalling at the root.

Influence of Reynolds Number

These tests have been carried out at low Reynolds numbers. At higher Reynolds numbers we might expect the effect of separation to be delayed to higher angles of incidence, giving higher maximum lift coefficients both for the plain wing and for the wing with flaps (see references 11, 12, 13 and 15). The tests of reference 11 carried out at a Reynolds number of 1.4×10^6 bear out our general conclusions. If the increase in lift at the tips is due to laminar separation and reattachment it may disappear at higher Reynolds numbers.

Ways of increasing the effectiveness of trailing edge flaps

From the above remarks it is seen that any decrease in the adverse pressure gradient over the mid semispan of the wing should be beneficial in delaying the stall with flaps - and hence in increasing the maximum lift coefficient attainable. Kruger has shown (reference 11) that nose flaps or nose slots are

/effective ...

effective in increasing $C_{L\ max}$. Nose flaps reduce the severity of the suction peak at the leading edge and thus delay stalling. German tests (references 11, 12 and 13) have shown that the maximum lift coefficient can be greatly increased by using a full span nose flap together with either full span or part span trailing edge flaps.

Programme of future tunnel tests

To verify the above conclusions and to provide fundamental data on the stalling properties of swept back wings it is proposed to conduct further tests on both these wings to investigate

(i) nose flaps
(ii) nose slots
(iii) Fowler flaps, and doubled slotted flaps
(iv) chordwise fences
(v) visual flow observations of the boundary layer flow.

Further extensions could include the effect of taper, aerofoil section and fuselage.

Acknowledgement

The author wishes to acknowledge the advice and criticism given him by Professor A. D. Young.

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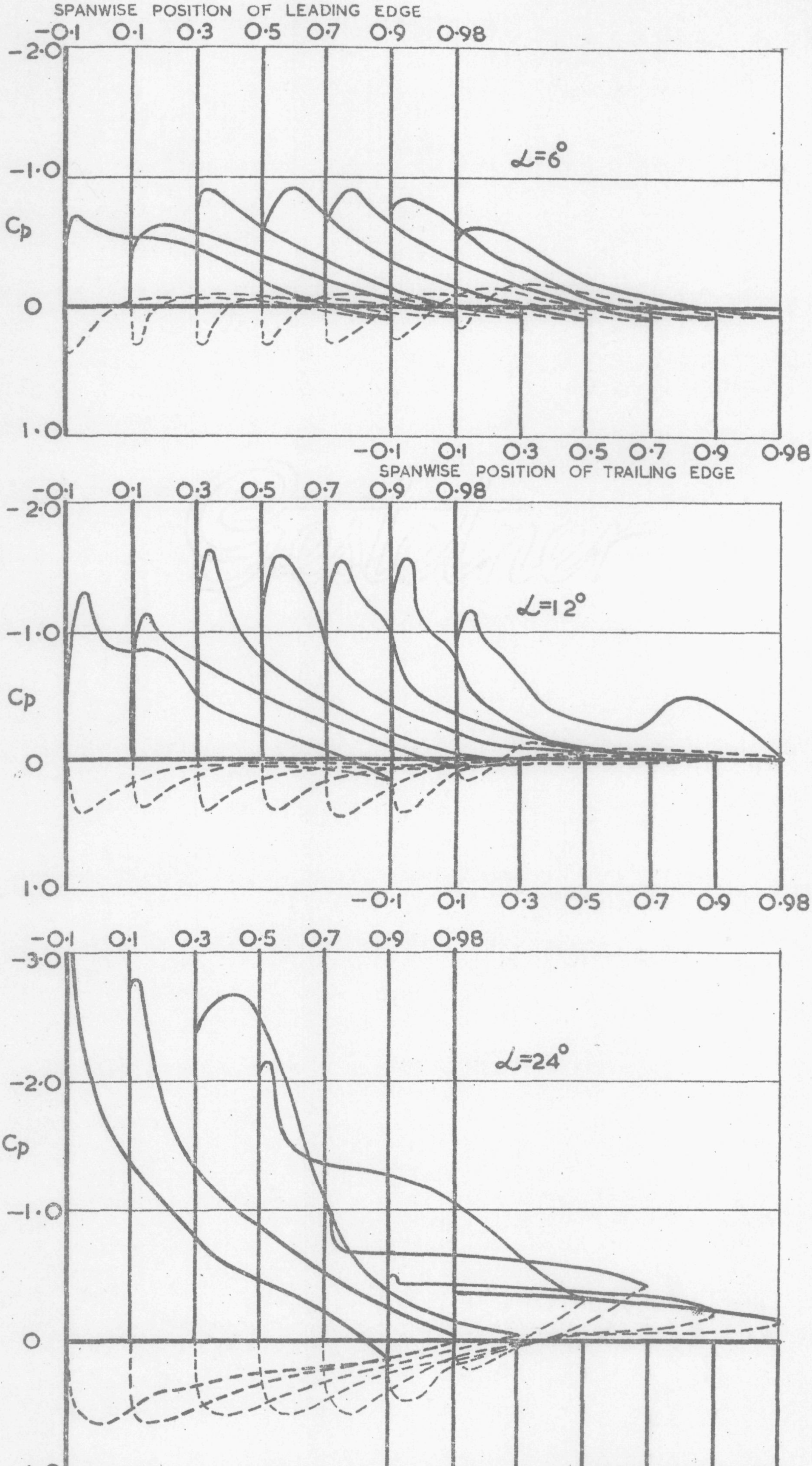
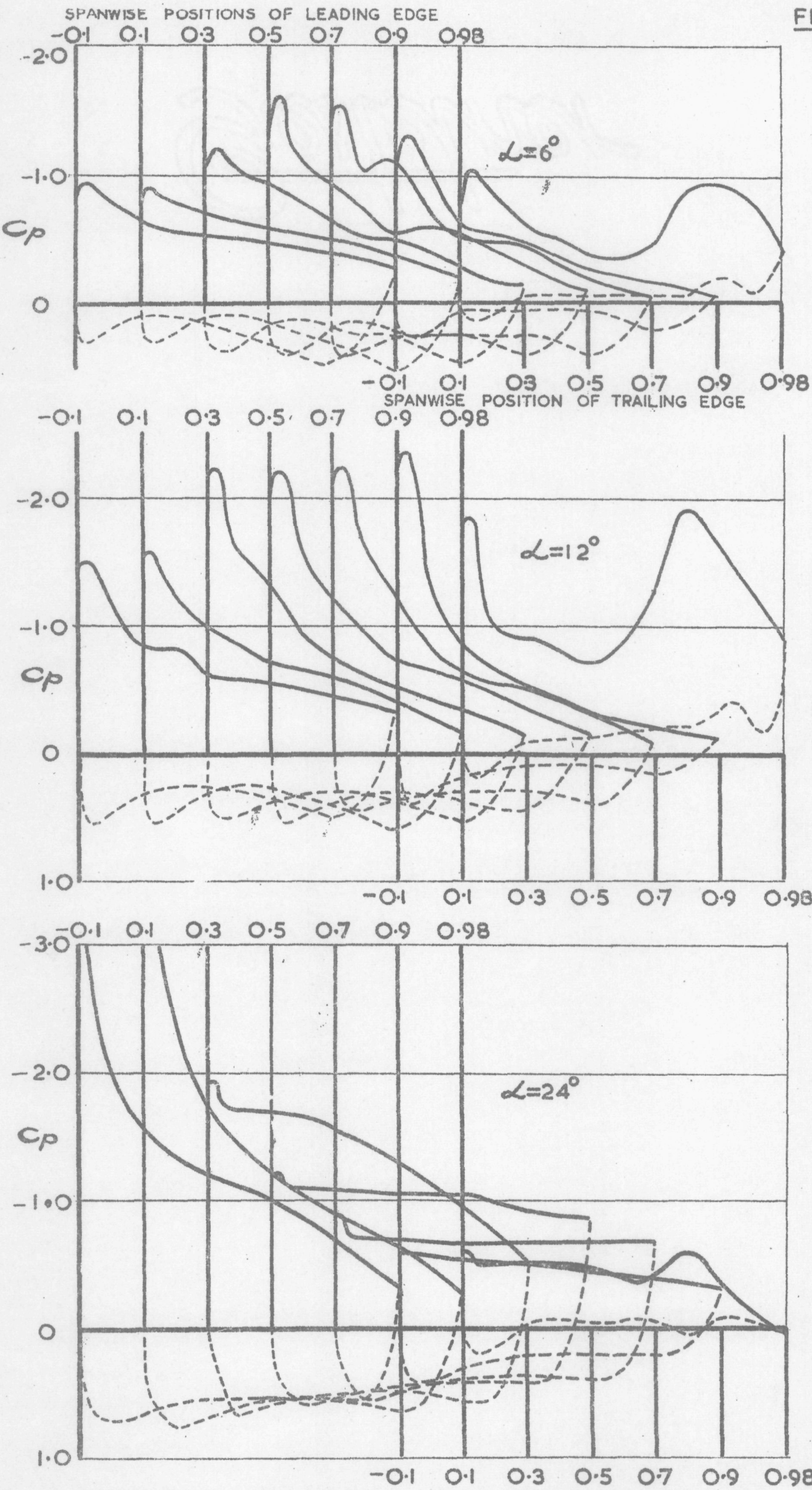
FIG 1



CHORDWISE PRESSURE DISTRIBUTION WING ASPECT

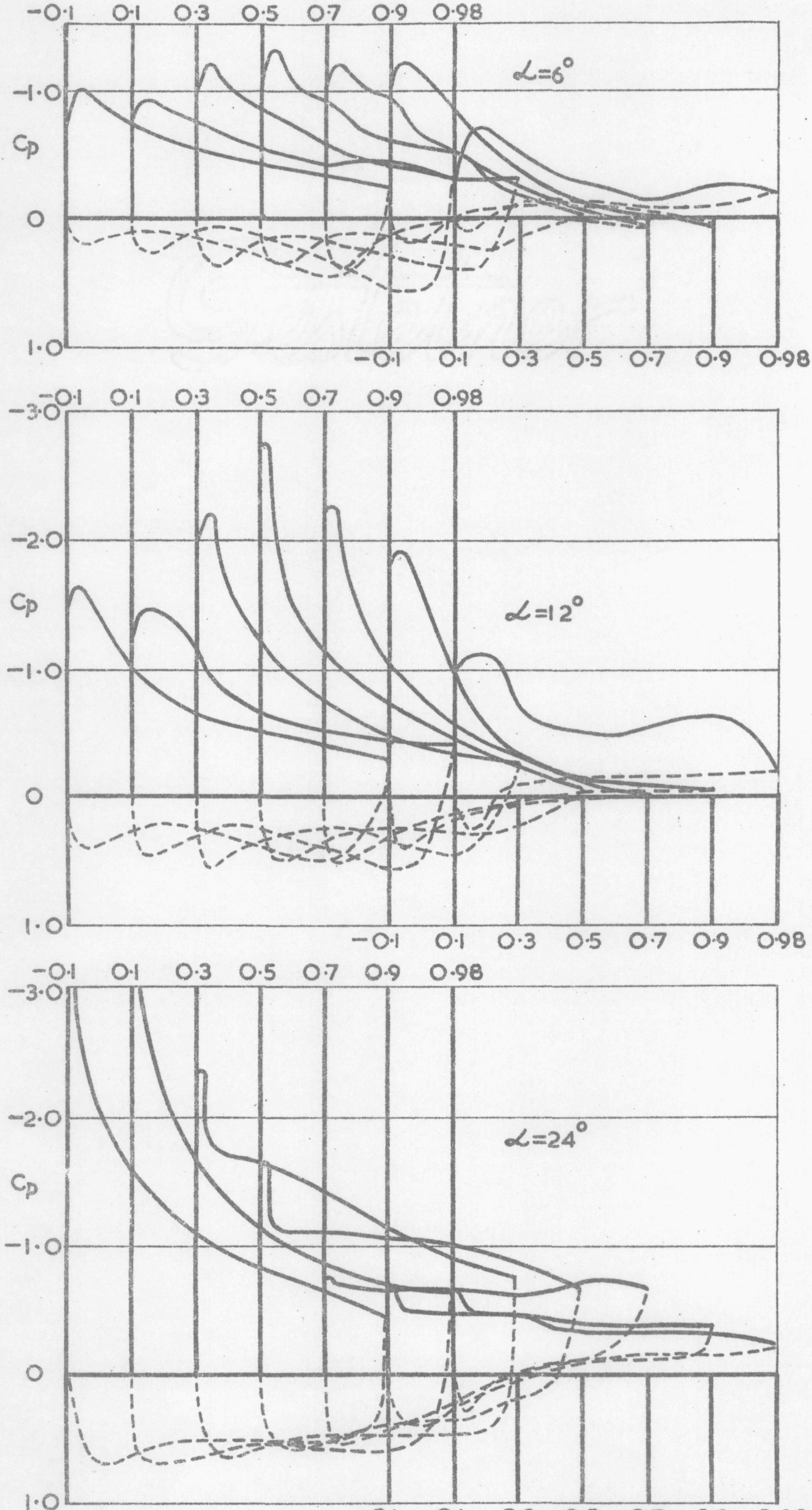
RATIO 4: NO FLAPS

FIG 2



CHORDWISE PRESSURE DISTRIBUTION WING ASPECT RATIO 4:45° FULL SPAN FLAPS

FIG 3



CHORDWISE PRESSURE DISTRIBUTION WING ASPECT RATIO 4: 45° INBOARD FLAPS

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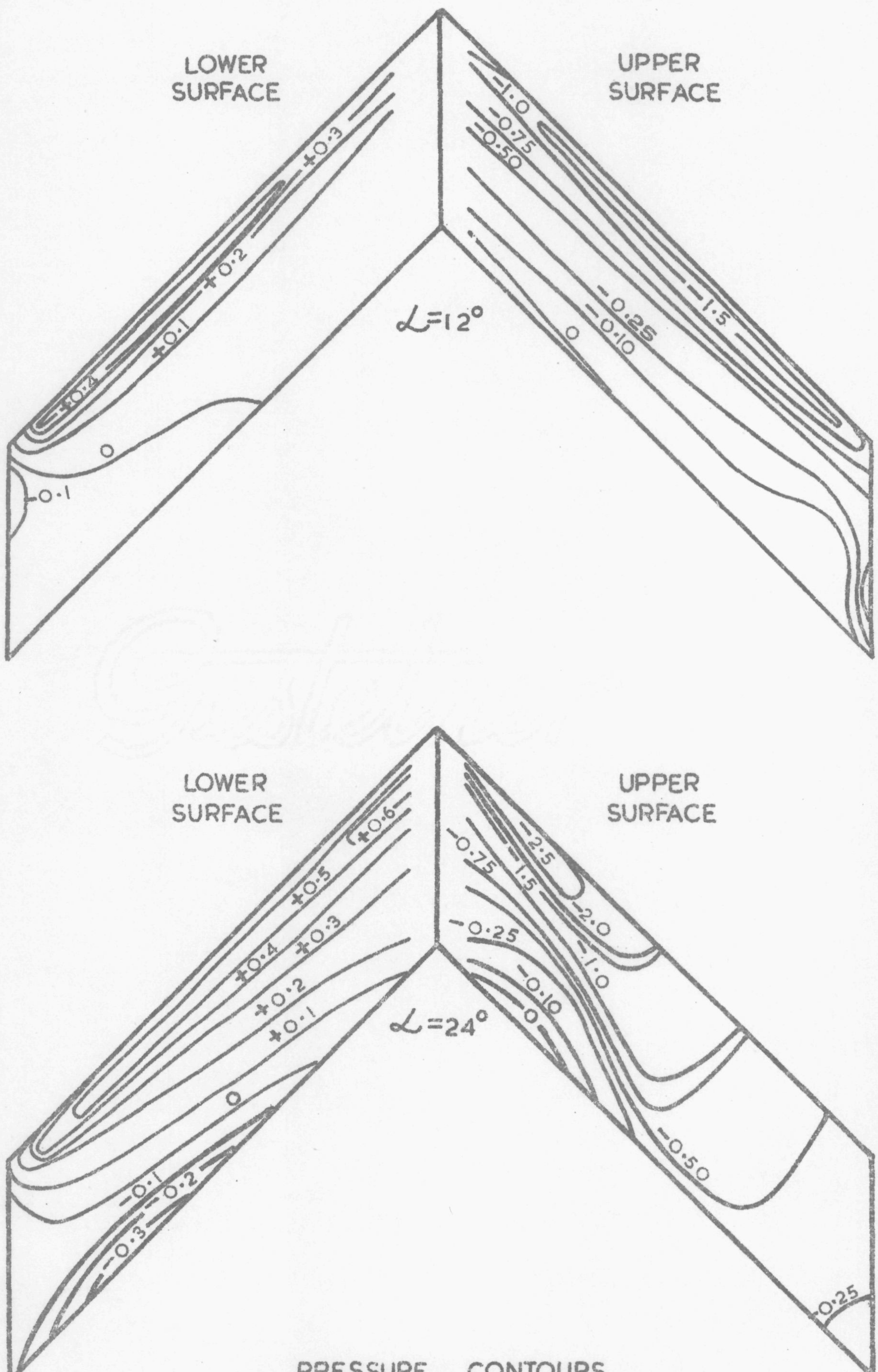
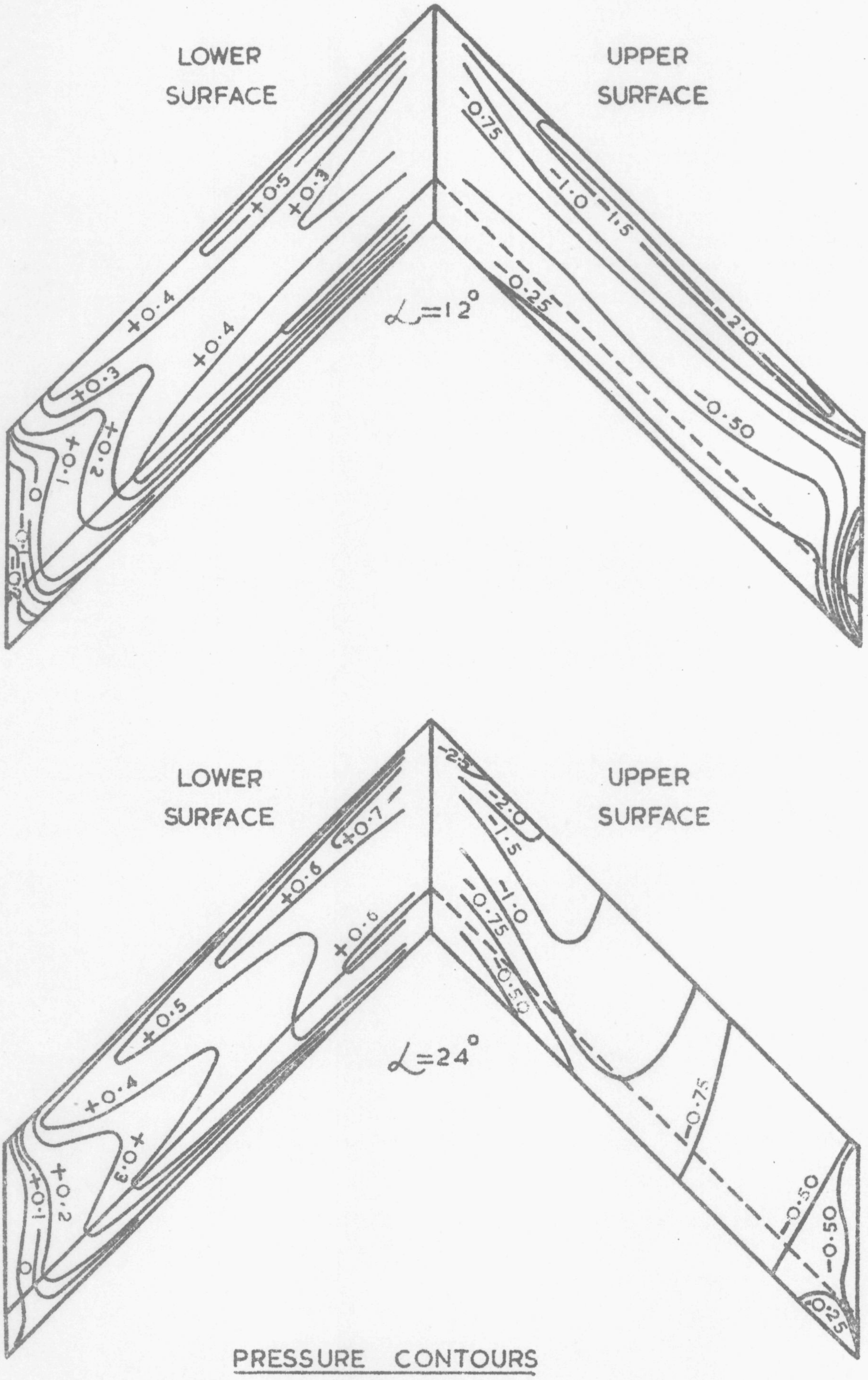
FIG 4



PRESSURE CONTOURS

WING ASPECT RATIO 4 : NO FLAPS

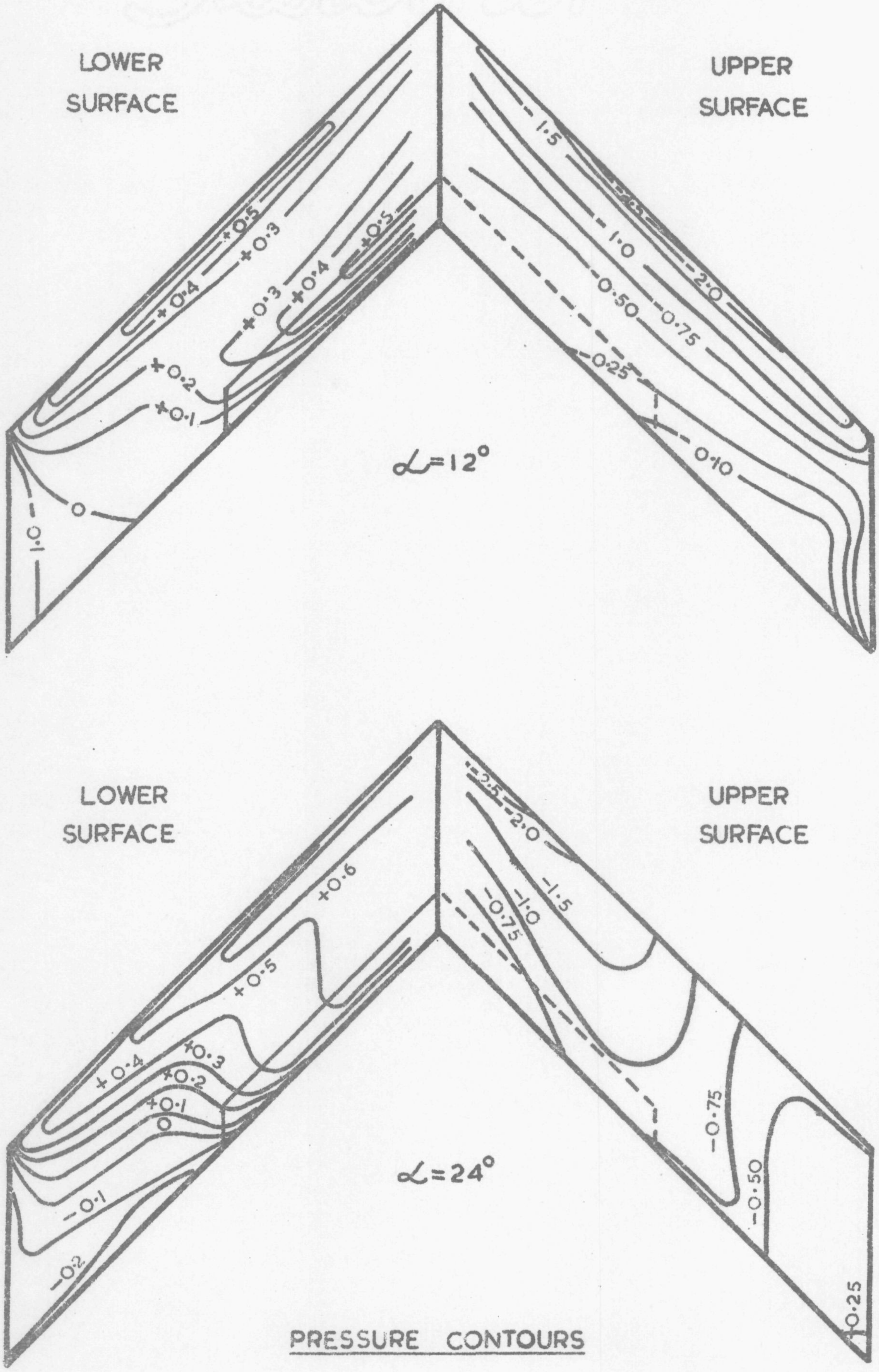
FIG 5



PRESSURE CONTOURS

WING ASPECT RATIO 4: 45° FULL SPAN FLAPS

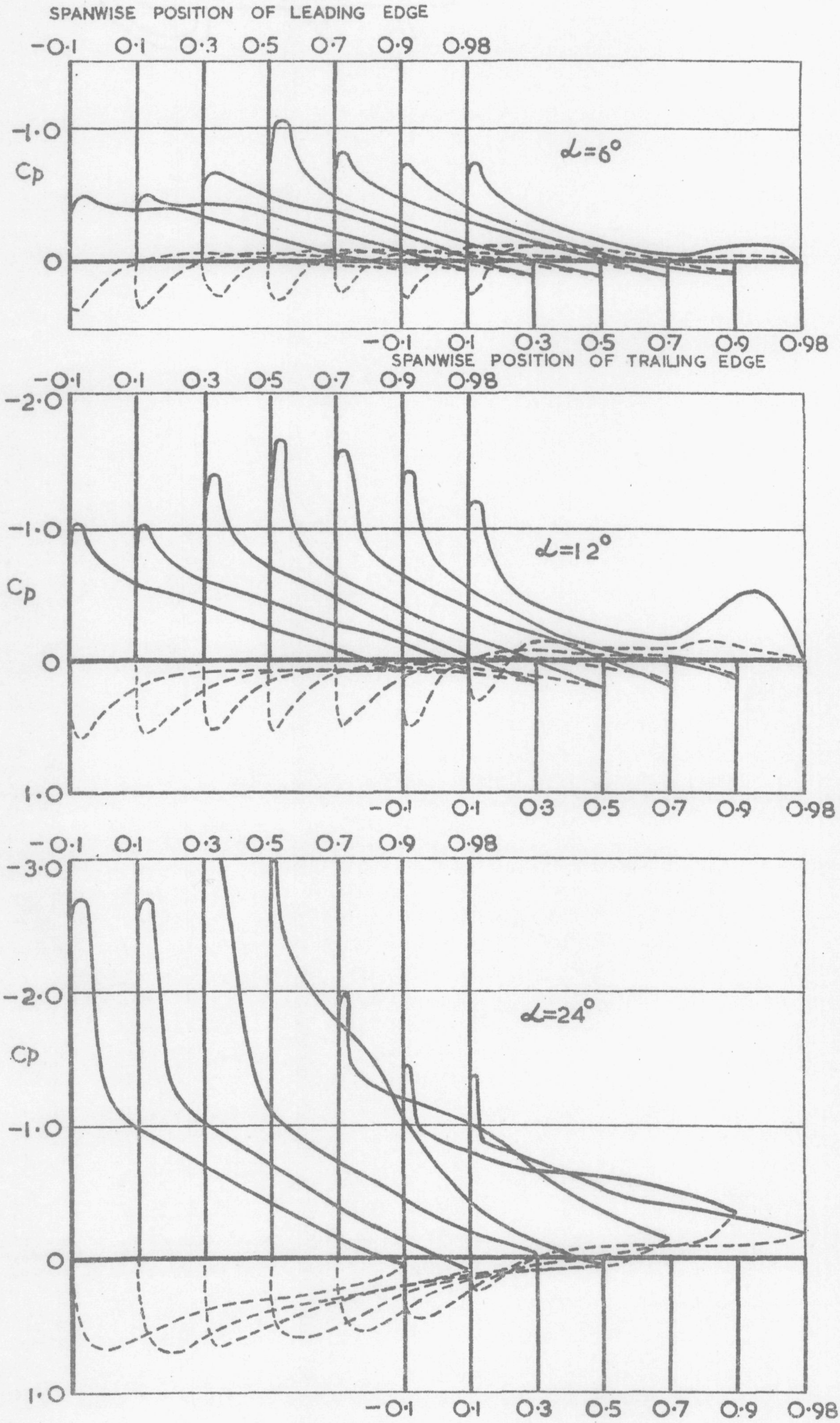
FIG 6



PRESSURE CONTOURS

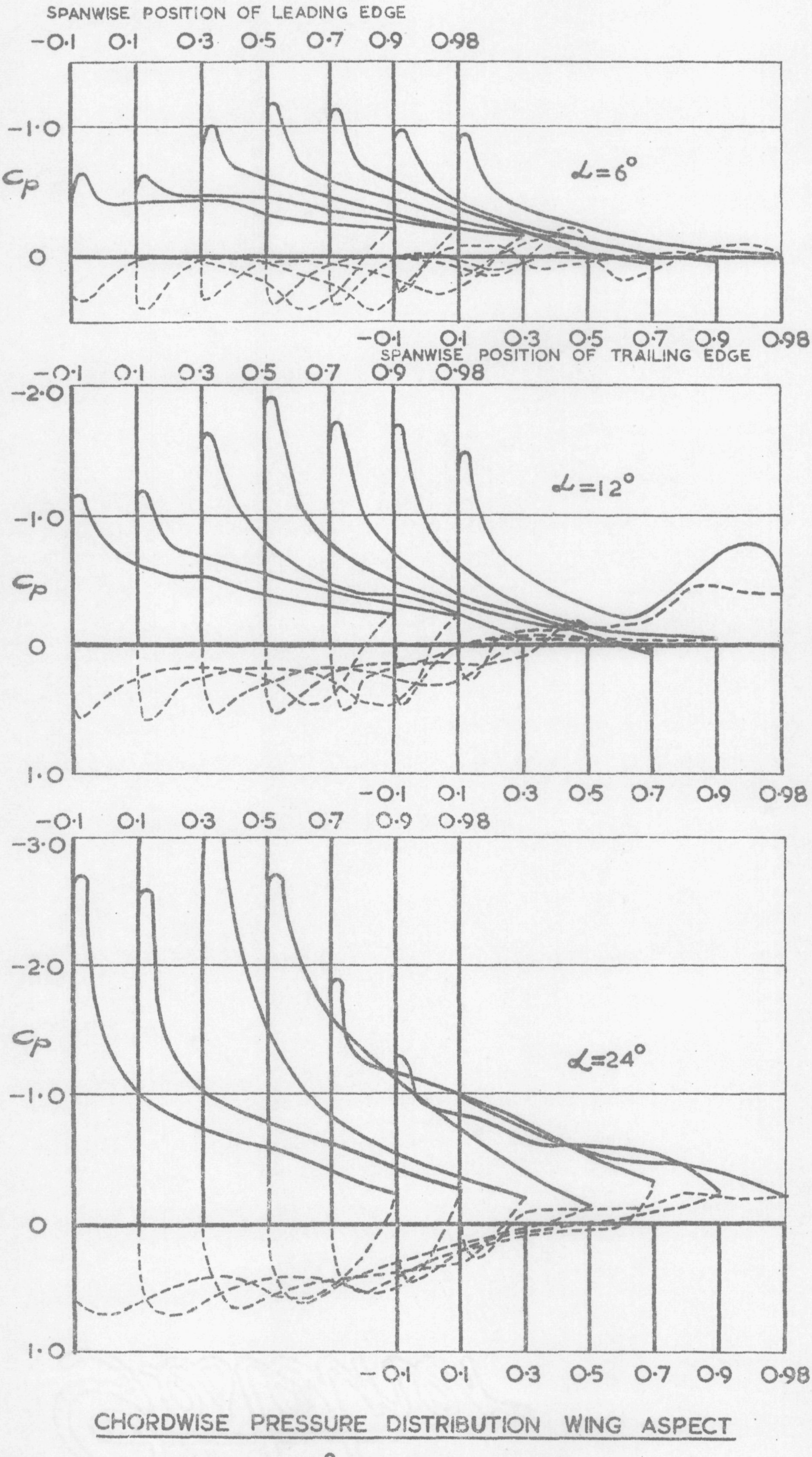
WING ASPECT RATIO 4: 45° INBOARD FLAPS

FIG 7



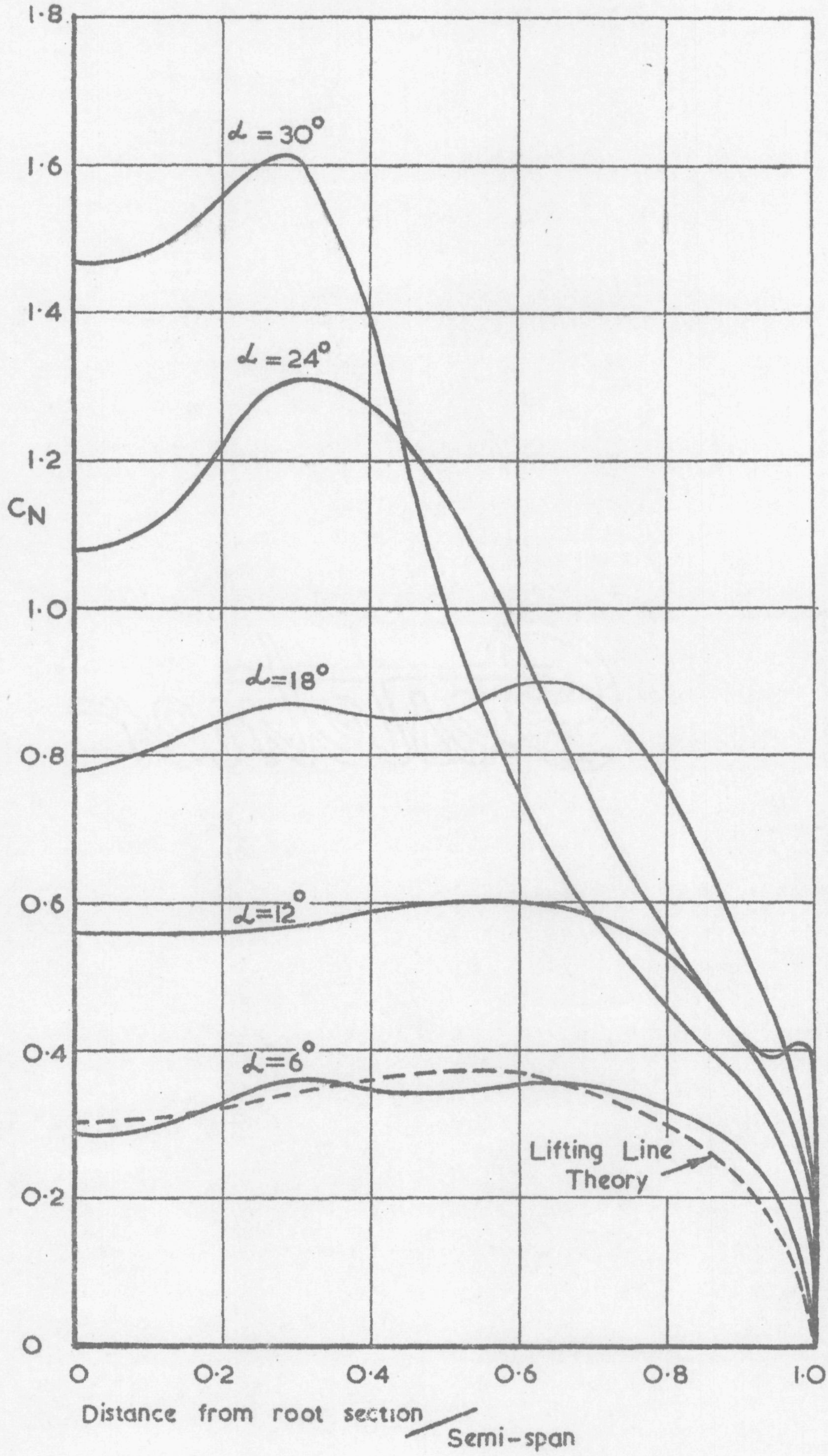
CHORDWISE PRESSURE DISTRIBUTION WING ASPECT RATIO 2: NO FLAPS

FIG 8



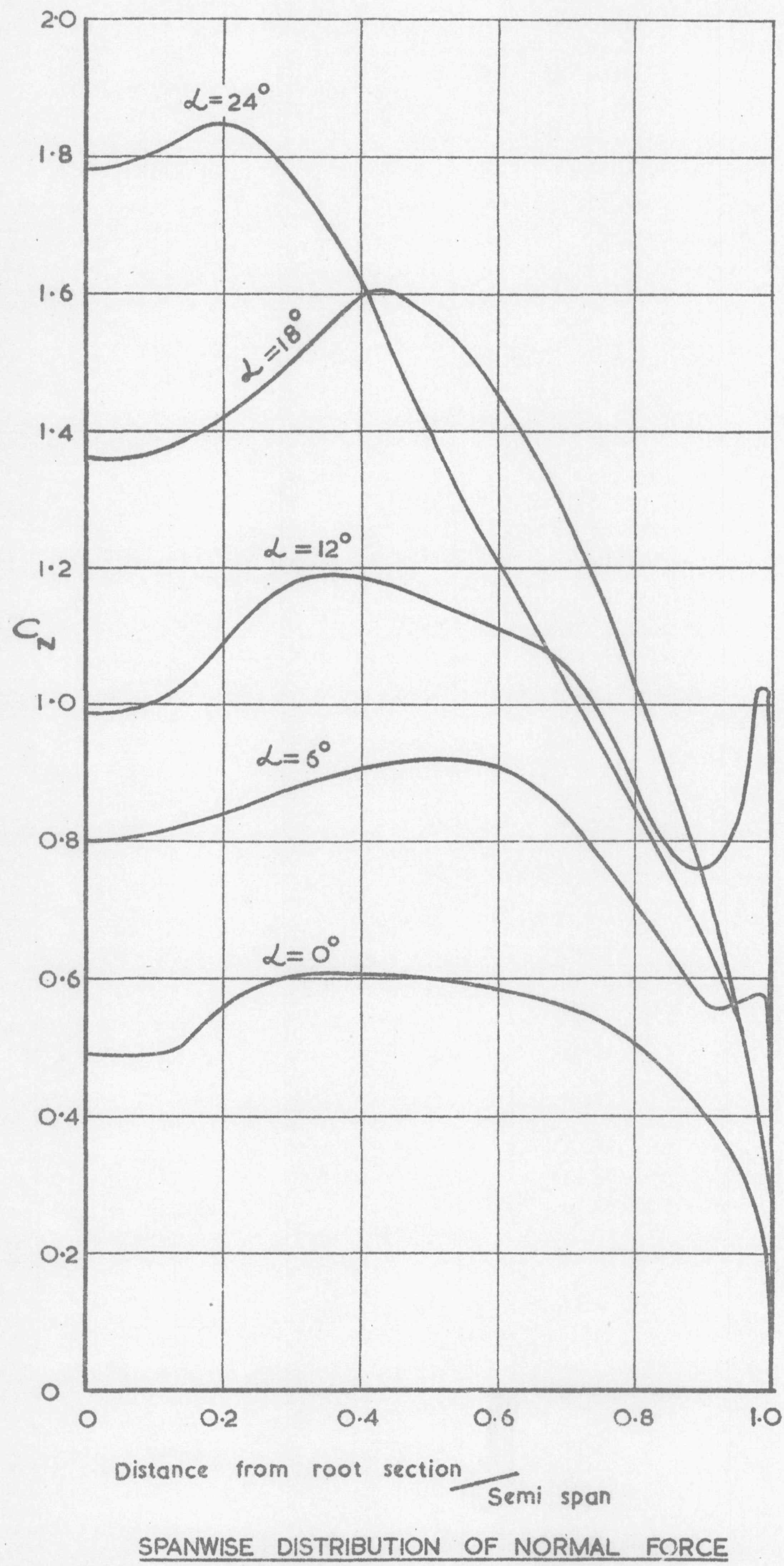
CHORDWISE PRESSURE DISTRIBUTION WING ASPECT RATIO 2: 30° INBOARD FLAPS

FIG 9



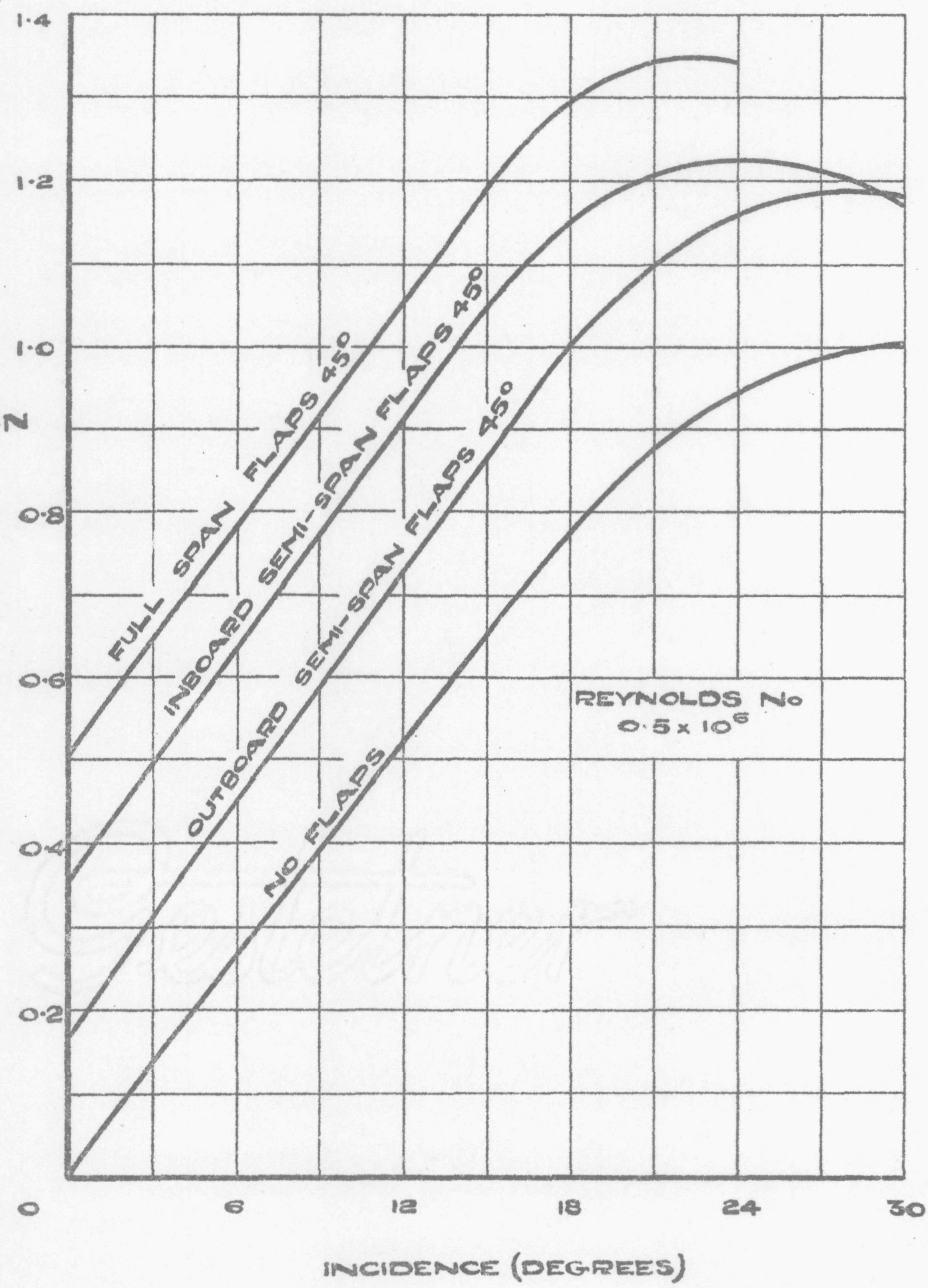
SPANWISE DISTRIBUTION OF NORMAL FORCE COEFFICIENT WING ASPECT RATIO 4: NO FLAPS

FIG 10



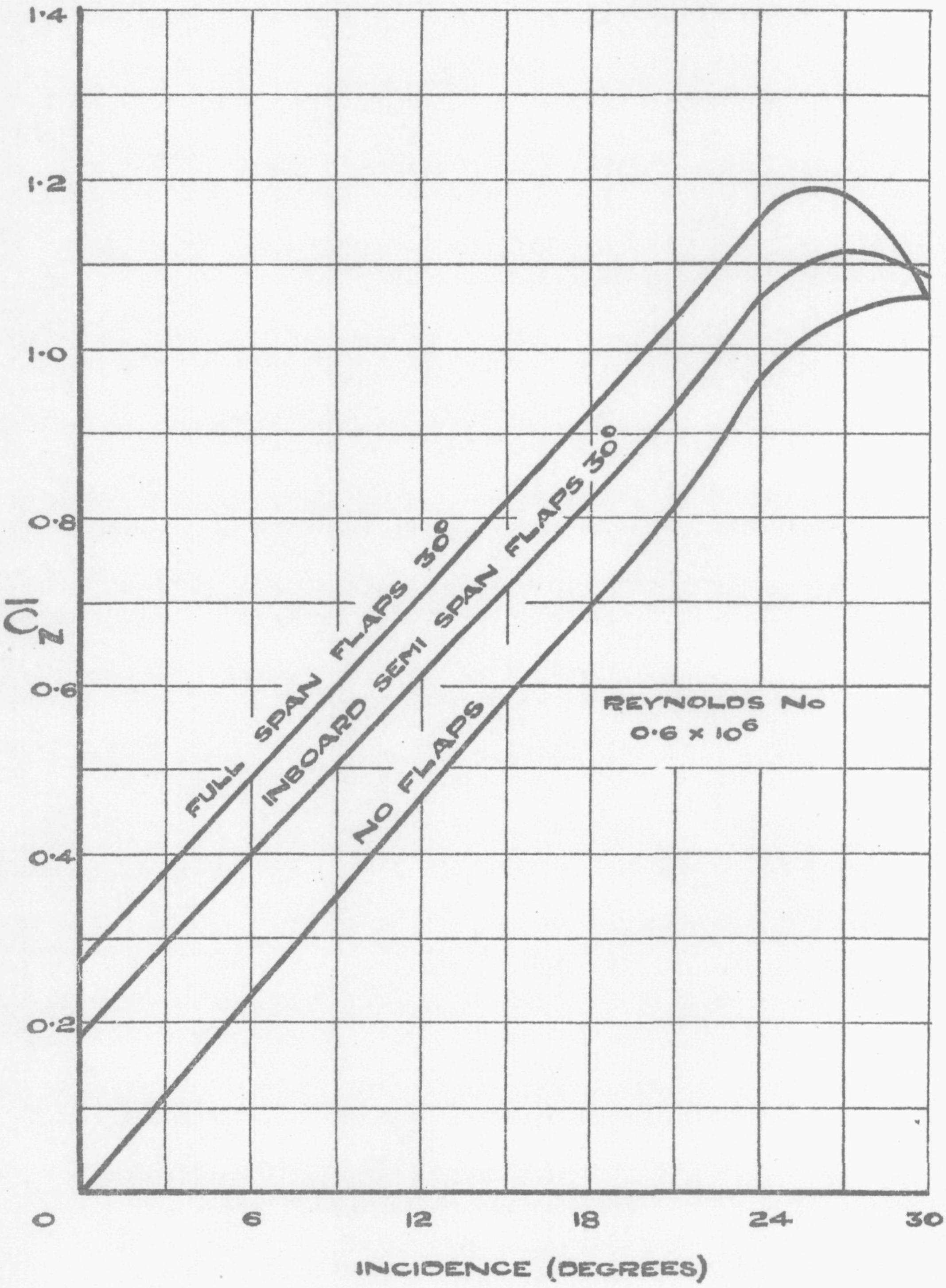
SPANWISE DISTRIBUTION OF NORMAL FORCE COEFFICIENT WING ASPECT RATIO 4: 45° FULL SPAN FLAPS

FIG 11



MEAN NORMAL FORCE COEFFICIENT
FOR ALL FLAP CONFIGURATIONS
WING ASPECT RATIO 4

FIG 12



MEAN NORMAL FORCE COEFFICIENTS
FOR ALL FLAP CONFIGURATIONS
WING ASPECT RATIO 2