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Pressure Distributions Illustrating Flow Reattachment behind a Forward Mounted Flap

By

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Pressure distributions illustrating flow reattachment behind a forward mounted flap

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SUMMARY

A series of pressure distributions over a NACA.0015 wing with a forward mounted 5% chord split flap are presented. The results, obtained by Clarke[2] in 1946, have not previously been published.

Two basic types of pressure distribution are identified; and these are associated with fully detached flow behind the flap, and with reattachment of the flow to the wing surface. An intermediate type - corresponding, it is suggested, to reattachment in the neighbourhood of the wing trailing edge - is also identified.

The physical nature of the flow behind a flap is considered, and some ideas on the mechanism of reattachment are suggested.

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1 Introduction

Force measurements on wings with forward mounted split flaps have shown marked non-linearities in the trim changes resulting from increasing flap deflection. This has been attributed to a reattachment of the flow over the flaps to the wing surface, at the smaller flap angles, and Holford and Leathers[1] found some confirmation of this from tuft observations.

This note presents a number of pressure distributions over wing-flap combinations which illustrate two basic types of flow, and appear to confirm that flow reattachment can occur. The results were obtained by Clarke[2] in the High Speed Tunnel in 1946, in the course of an investigation of the effects of Mach Number on the action of dive-recovery flaps. The low speed results have not previously been published.

Pressure distributions, for a Mach Number of 0.3, at mid-span of a part-span flap mounted on a NACA.0015 wing spanning the tunnel, have been extracted from Clarke's results. The tests were made at two angles of incidence, two flap angles, and three chordwise positions of the flap.

Two basic types of pressure distribution are identified - one resulting in a marked lift increment, and the other in a small lift increment. These two basic types are subsequently associated with detached and reattached flows, respectively.

The physical nature of the flow is considered, at length, in Section 5, where it is suggested that turbulent mixing behind a flap must always result in closure of the boundary streamlines, either on the wing surface, or somewhere downstream of the wing trailing edge. It is argued that continuity of mass flow can only be attained in this way.

2 Experimental details

The essential details of the model have been extracted from Ref.1, as follows:-

The wing was of 15 inch chord NACA.0015 section, mounted vertically, spanning the working section.

The flap had a chord of $\frac{3}{4}$ inch (5% wing chord), and extended over the middle 3 feet of the span.

Pressures were measured, at a section midway along the flap, at ten holes on each side of the wing. Pressures were also measured at three points on the front surface, and one on the back, of the flap.

3 Results presented

The pressure distributions presented are those obtained by Clarke at a Mach Number of 0.3, and a Reynolds Number of 1.4×10^6.

The tests covered two angles of incidence, of $\alpha = 0^\circ$ and 4° ; two flap angles, $\varphi = 20^\circ$ and 40° ; and three chordwise positions of the flap, $\frac{x_F}{c} = 0.2$, 0.3 and 0.4 .

The pressure distributions for the cases set out in Table I are plotted in Figs.1 - 11.

TABLE I

Incidence α	Flap Angle ϕ	Flap Position x_F/c
0°	0°	-
	20°	0.2
		0.4
	40°	0.2
		0.3
		0.4
4°	0°	-
	20°	0.2
		0.4
	40°	0.2
		0.4

The pressure distributions* have been integrated to determine lift coefficients, C_L, and pitching moment coefficients about the quarter chord point, $C_{M_{c/4}}$. These values are given on the appropriate figures, and are also plotted against incidence in Fig.12.

The pitching moment coefficients were also determined about an axis through the flap hinge. These are plotted as pitching moment increments, $\Delta C_{M_{x_F}}$, against flap position, $\frac{x_F}{c}$, in Fig.13. Lift increments, ΔC_L, due to the flap are also plotted against flap position in Fig.13.

4 Discussion

The pressure distributions, plotted in Figs.1 - 11, fall into two main groups:-

(I) those in which the pressure remains sensibly constant on the under surface of the wing behind the flap (see Figs.3, 4, 6, 11) and (II) those in which there is a marked pressure recovery behind the flap (see Figs.2, 5, 8, 10).

One pressure distribution - that for the 40° flap, at $\frac{x_F}{c} = 0.2$ and $\alpha = 4^\circ$, shown in Fig.9 - appears to be of an intermediate type. It shows a considerable pressure recovery, but a less pronounced one than the members of group II.

* The pressures on the flaps themselves have not been included in the pressure diagrams, but are included in the integrated lift and pitching moment coefficients.

4.1 Group I

The pressure distributions exhibited by the members of this group are of the type usually associated with flaps near the trailing edge. A large increase of pressure on the under surface is caused ahead of the flap. This is followed by a considerable drop in pressure over the flap, the pressure subsequently remaining sensibly constant. In order to adjust itself to the much reduced trailing edge pressure that results, the pressure falls over the entire upper surface.

4.2 Group II

The members of this group exhibit a quite different type of pressure distribution. Ahead of the flap it remains of the same form as for group I, but the level of pressure is reduced. Behind the flap, however, there is only a small range of relatively constant pressure, and this is followed by a rapid, and considerable, pressure recovery. The rapid recovery is then followed by a more gradual recovery of pressure to the trailing edge, this final recovery being of the same order of magnitude as that obtained on the wing without a flap.

In all cases the pressure recovered at the trailing edge is closely that obtained on the plain wing. Hence, the upper surface distribution requires little adjustment, and is generally very close to that on the plain wing.

4.3 The intermediate type

The pressure distribution shown in Fig.9 appears to be of an intermediate type. It exhibits a larger range of constant pressure behind the flap, and the subsequent pressure recovery - though marked - is less rapid than those occurring in the group II flows. The rate of pressure recovery also continues essentially unchanged up to the wing trailing edge - and the trailing edge pressure lies between those occurring in the group I and group II flows at the same incidence. Thus there is some fall of upper surface pressure compared with the plain wing.

4.4 The effect on lift and pitching moment

The lift coefficients and pitching moment coefficients for the different configurations are plotted against incidence in Fig.12. The pitching moment, in that figure, is referred to an axis through the quarter chord point.

It is clear that the two main types of pressure distribution result in widely different values of C_L. The group II flows produce lift coefficients very close to the corresponding plain wing values, whereas the group I flows show marked increases of lift. The lift slope shows little change, provided that the flow remains of the same basic type. There is a marked loss of lift slope for the 40° flap at 0.2 chord from the leading edge - corresponding to a change of flow from group I at zero incidence to intermediate at 4°.

The effect on the pitching moment is less marked. Here again, however, it appears that the slope of the curves is not much affected provided that the flow type does not change. The 40° flap at 0.2 chord appears to produce a noticeable increase of slope compared with the other cases.

The comparisons are based on mean slopes over the range 0° to 4° incidence - since they depend on only two points for each curve.

The effects of the two different types of flow are, perhaps, more clearly seen in Fig.13, where lift increment, ΔC_L , and pitching moment increment, $\Delta C_{M_{x_F}}$, are plotted against flap position. The pitching moment is here referred to an axis through the flap hinge line, so that differences in the lift distribution in the neighbourhood of the flaps might show up more clearly.

The small lift increment of the group II flows, compared with the large increment of the group I flows, is very clear.

The pitching moment increment shows the same trend in all cases, viz. an increase with backward movement of the flap. This is due to the fact that there is a build-up of lift ahead of the flap, in all cases, followed by a loss of lift behind the flap - or, at least, by a much reduced increase.

As the flap moves back along the wing, the build-up of lift ahead of the flap takes place over a greater length of chord, resulting in an increase of moment about the flap hinge line. The pressure distributions show this to be more marked in the group I flows, hence the greater rate of increase shown for the 40° flap at 0° incidence in Fig.13.

The actual level of the pitching moment increments appears to depend more on the flap angle than on the type of flow, the 40° flaps showing noticeably higher increments than are caused by the 20° flaps. It would seem, therefore, that the distribution of lift on either side of the flap is less affected by the type of flow than is the overall lift. There is some effect, however, as indicated by the fact that the pitching moment increment for the 40° flap at 0.2 chord and at 4° incidence (the intermediate flow type), is greater than for the corresponding flap at 0° incidence, whereas the reverse is true for all the other flaps showing the same flow type at each incidence.

If, however, the pitching moment be referred to some other axis in the wing, the pitching moment increment curves will change their form. For the group II flows, because of the small lift increment, this change of form will be small. The group I flows, however, will show a marked change of form of the ΔC_M curves, because of the large values of ΔC_L - the position of the flap relative to the pitching moment axis being the controlling factor.

5 A physical model of the flow

It is suggested that pressure recoveries of the order observed in the group II flows can only be associated with a reattachment of the flow to the wing surface at some point behind the flap. It is clear that, if reattachment occurs, there must be a local expansion of the main stream just before reattachment, and a pressure recovery must occur. That the observed pressure recovery is relatively large implies that the expansion is rapid.

The boundary layer separates from the trailing edge of the flap and becomes a free layer of vorticity. The air contained between this free vorticity layer and the wing surface must, for continuity of mass flow, be stationary relative to the wing. It need, however, only be stationary in the mean - it may have a highly disturbed motion about this mean, but no net downstream mass flow. Vorticity will spread towards the wing surface, by the process of turbulent diffusion, entraining air in the 'stationary' region and imparting downstream momentum to it. Air nearer the surface will have to acquire upstream momentum, therefore, in order to maintain the state of no net flow downstream within the 'stationary' region. As more and more air in the 'stationary' region becomes re-energised by the turbulent diffusion, the return flow nearer the surface must also increase, and we might expect a forced vortex to be formed between the separated flow and the wing surface, and the separated boundary streamline to return to the surface.

With this model of the flow there is, of course, no reason why reattachment should occur on the wing surface. If it does not, the process of turbulent diffusion will continue, downstream of the wing trailing edge, from the vorticity layers discharged from both wing surfaces. Again, however, because of the inward transport of downstream momentum, the 'stationary' region must close in order that the continuity condition be satisfied.

It should be emphasised that these considerations apply to the mean motion. The true flow might be highly unsteady about this mean, and a considerable interchange of air between the main flow and the 'stationary' region might take place. It is suggested, however, that the mean effect on the potential flow outside of the boundary layer and wake must correspond to the existence of a 'stationary' bubble of air which closes either on the wing surface or somewhere downstream of the trailing edge. In other words, there must be a marked reduction in wake thickness somewhere behind the flap.

It would seem that the wake behind any bluff body must always close - in the sense that the separation streamlines must come together again at some point - otherwise the inward transport of momentum would give rise to an increase of mass flow behind the body, and the continuity condition would be violated. Thus the wake behind a bluff body can be considered as composed of two parts:- (a) a volume of air which remains 'stationary' relative to the body, and (b) that part of the wake which flows away downstream. The boundary between the two regions of the wake would not be well defined because of turbulent mixing, which also ensures that the 'stationary' part must close. The high degree of mixing close behind the body might also be expected to cause much more mainstream air to be entrained into that part of the wake which flows away downstream than would occur on a streamline body.

The classical conception of Helmholtz flows - free streamlines bounding a dead-air region extending to infinity - would seem to be physically unrealistic. A free streamline treatment which allows the streamlines to close - e.g. Woods[3] - might, however, be expected to give more realistic results, especially if the pressure recovery before reattachment can be inserted.

The different kinds of pressure distribution observed can best be explained, perhaps, in terms of the constraint applied by the wing surface behind the flap on the main stream. Immediately behind the flap trailing edge it seems clear that the wing surface can have little or no effect on the main flow so that, in this region, we might expect the pressure to remain relatively constant. The presence of a pressure gradient on the wing surface must imply, presumably, that the wing is again controlling the flow. Thus we might expect the presence of the wing to cause a marked pressure change before reattachment, and subsequently to constrain the flow in much the same way as it does without a flap.

If reattachment occurs well aft of the trailing edge the wing can hardly control the flow very much - hence the relatively constant pressure in detached flows - but if it occurs only a short distance behind the trailing edge, the effect of the wing will again be apparent. This would account for the pressure recovery observed in the so-called intermediate flow - and also for the fact that there is no marked change of pressure gradient before the trailing edge is reached.

The above model assumes a steady two-dimensional mean flow. In the real case, however, we might expect the motion to be highly unsteady and essentially three-dimensional. The unsteadiness can, perhaps, be regarded as an oscillation of the 'bubble' size and shape. It seems, therefore, that the steady model might give a simple physical picture of the nature of the motion.

Nor does it seem that three-dimensional effects need necessarily alter the suggested mechanism of reattachment. We might expect, anyway, that the motion in the region of intense mixing behind the flap will always be essentially three-dimensional - giving rise to a complicated vortex pattern far different from the simple forced vortex suggested. The effect, however, will still be the same. With a three-dimensional flap the inward spread of turbulence from the ends might be expected to reinforce the above process, and so to cause reattachment closer to the flap. Reattachment will also occur closer to the flap the nearer to its ends.

6 Conclusions

Pressure distributions over a wing with a forward mounted flap are of two main types, identified by:-

Group I, a relatively constant pressure on the under surface of the wing, behind the flap, and a marked increase in overall lift,

and Group II, a rapid pressure recovery behind the flap, and very little increase in lift.

A transitional type is also possible.

It is argued that turbulent mixing behind a flap, and the consequent inward transport of downstream momentum, must, from considerations of continuity, result in closure of the boundary streamlines. The group I flows are associated with closure well aft of the wing trailing edge; the group II flows with closure on the wing surface; and the transitional flows with closure in the neighbourhood of the trailing edge.

LIST OF SYMBOLS

x_F : distance of flap hinge from leading edge (measured parallel to chord)

c : chord of wing

ϕ : flap angle (measured from tangent to wing at hinge line)

ΔC_L : increment of lift coefficient due to flap at constant incidence

$C_{M_{c/4}}$: pitching moment coefficient, referred to an axis through the quarter chord point

$\Delta C_{M_{x_F}}$: increment of pitching moment coefficient, referred to an axis through the flap hinge line, due to the flap at constant incidence

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2	D.A. Clarke	High Speed Tunnel Tests of a 5 per cent Chord Dive Recovery Flap on a NACA.0015 Aerofoil. R. & M. 2689. June, 1948.
3	Sqn.Ldr. L.C. Woods	Theory of Aerofoils on which occur Bubbles of Stationary Air. A.R.C. No. 16,277. November, 1953.

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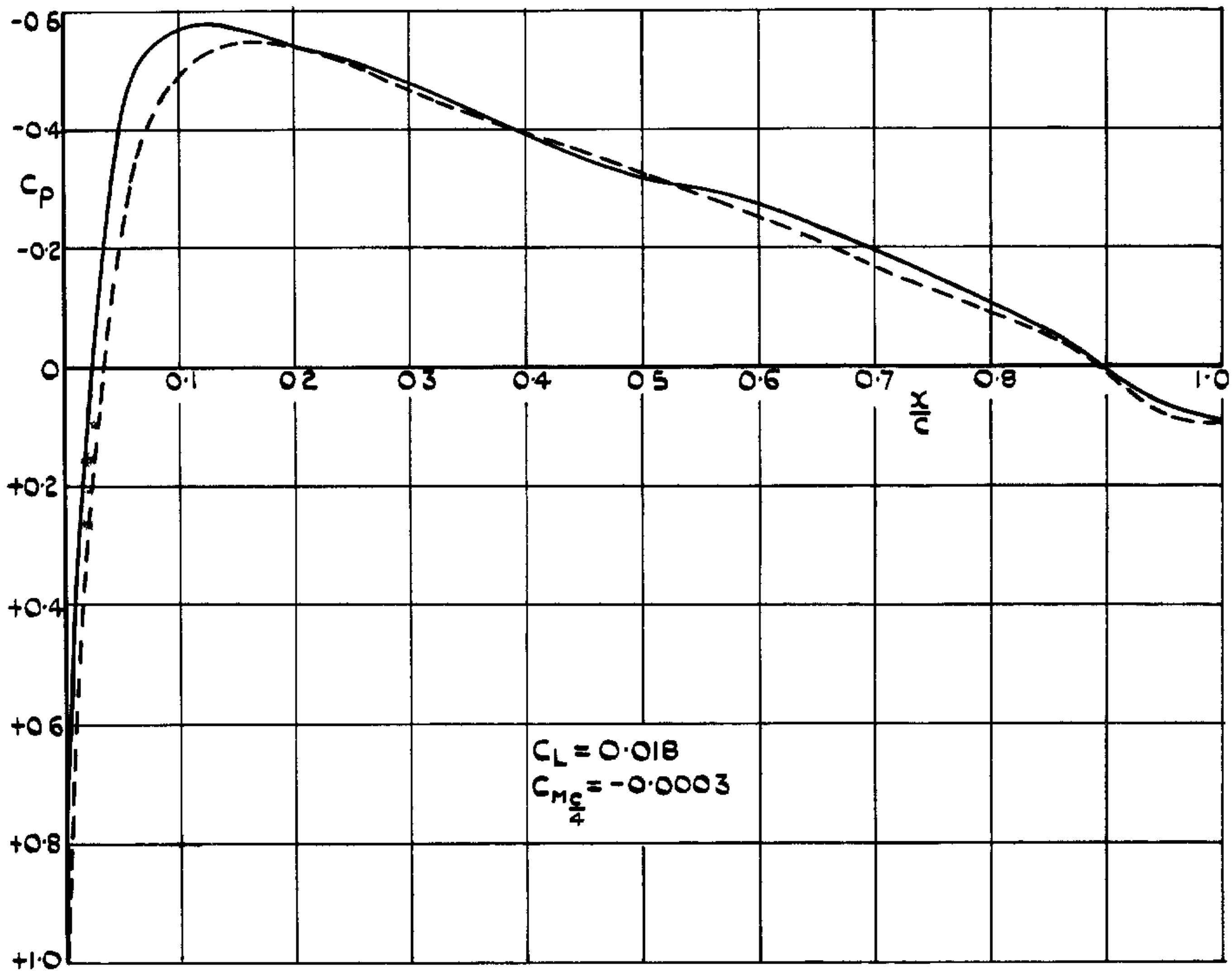

FIG. 1. PRESSURE DISTRIBUTION NO FLAP.
$\alpha = 0^\circ$

FIG. 2.

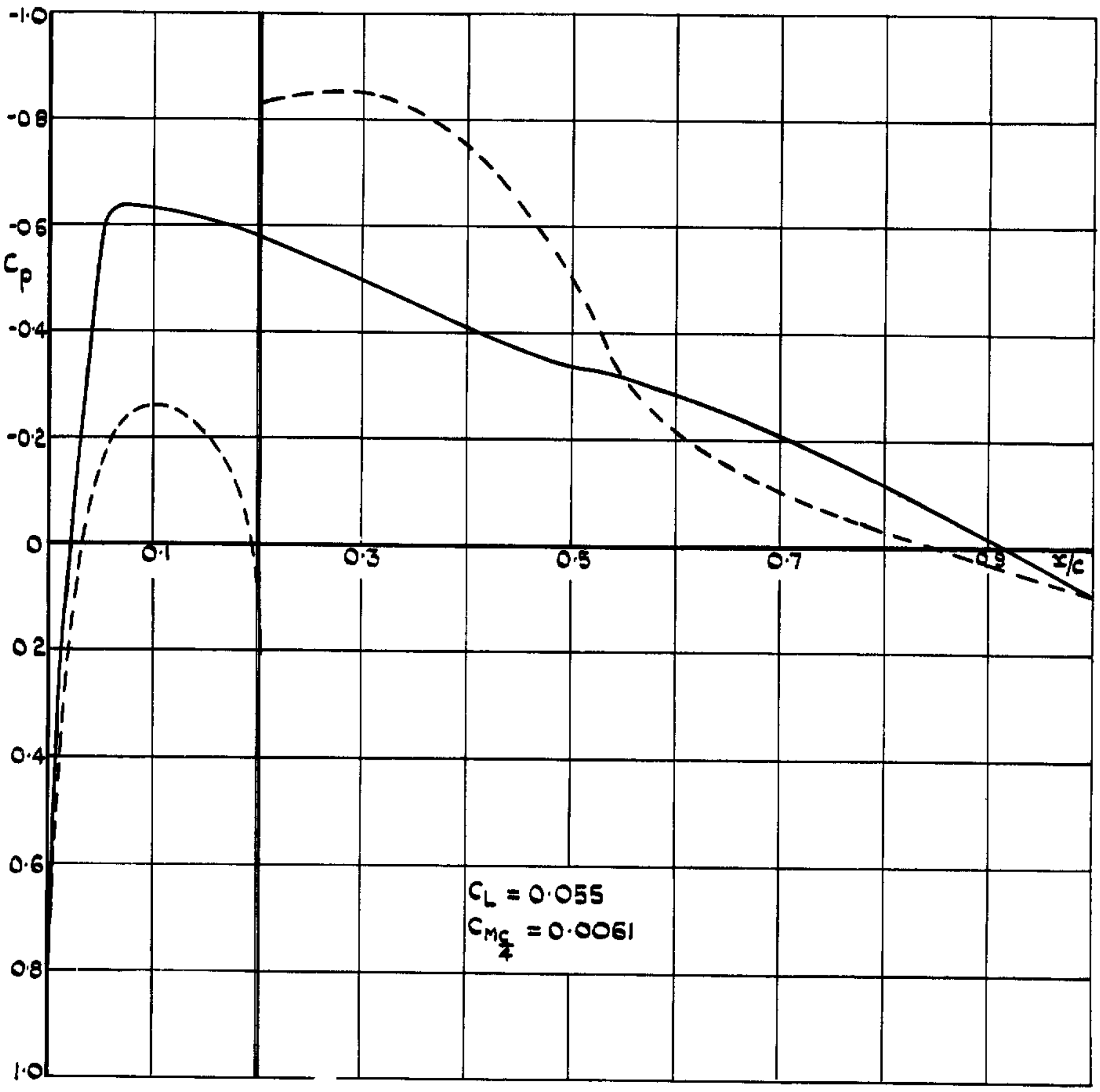

FIG. 2. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 0°, \quad \phi = 20°, \quad \frac{x_F}{c} = 0·2.$

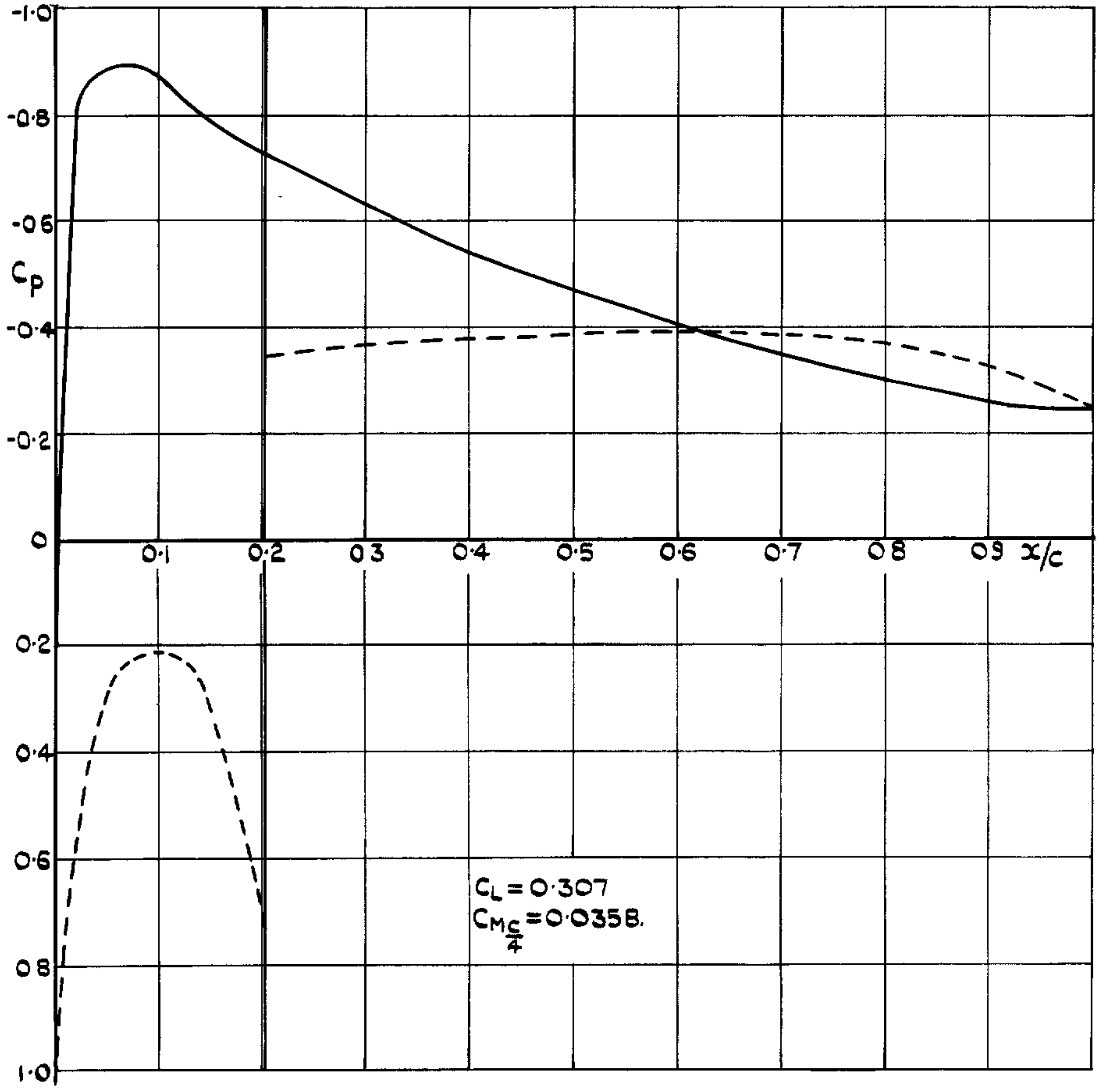

FIG. 3. PRESSURE DISTRIBUTION. 5% CHORD FLAP

$\alpha = 0°, \quad \phi = 40°, \quad \frac{x_F}{c} = 0·2.$

FIG.4.

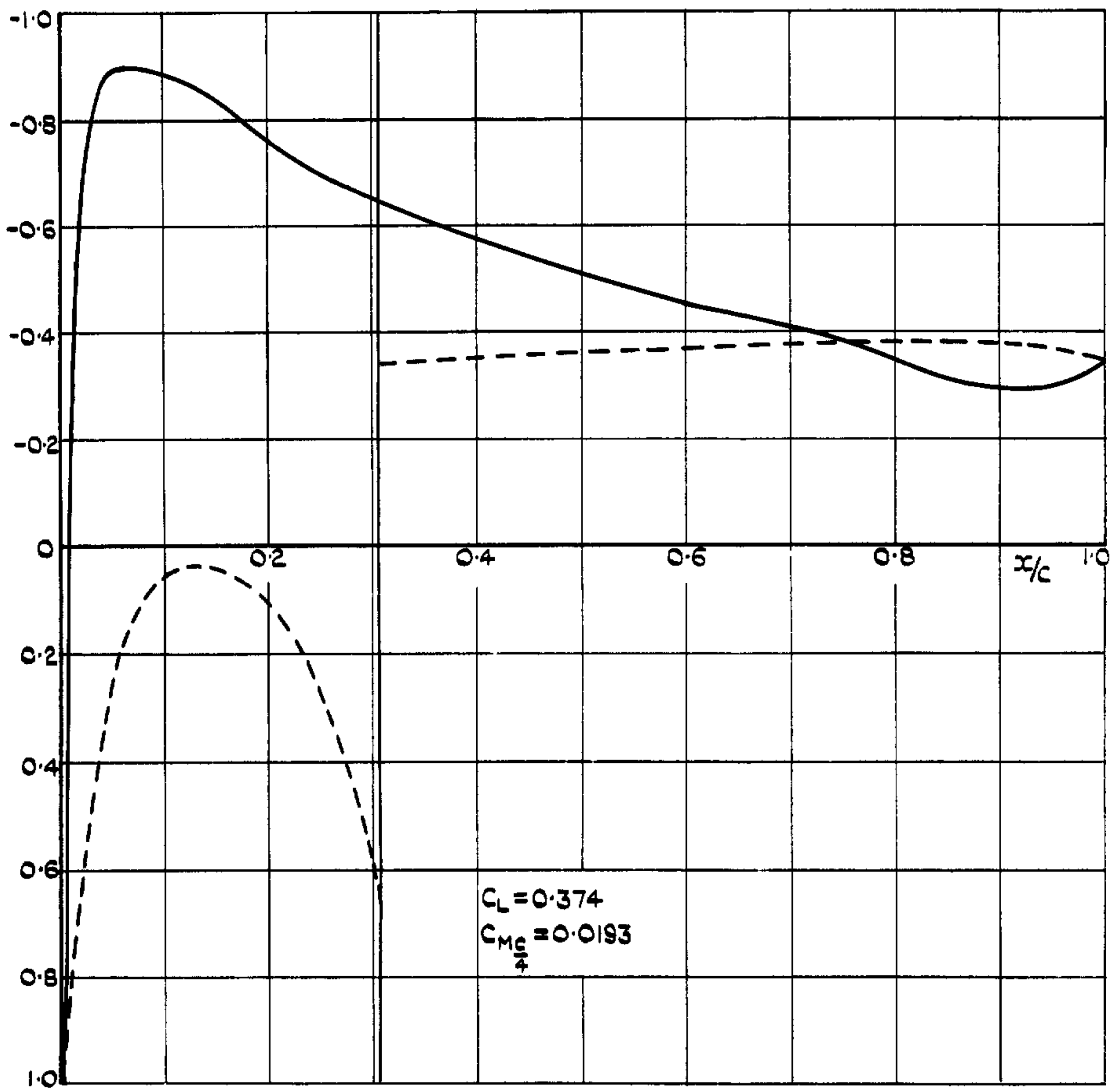

FIG. 4. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 0°, \ \phi = 40°, \ \frac{x_F}{c} = 0{\cdot}3$.

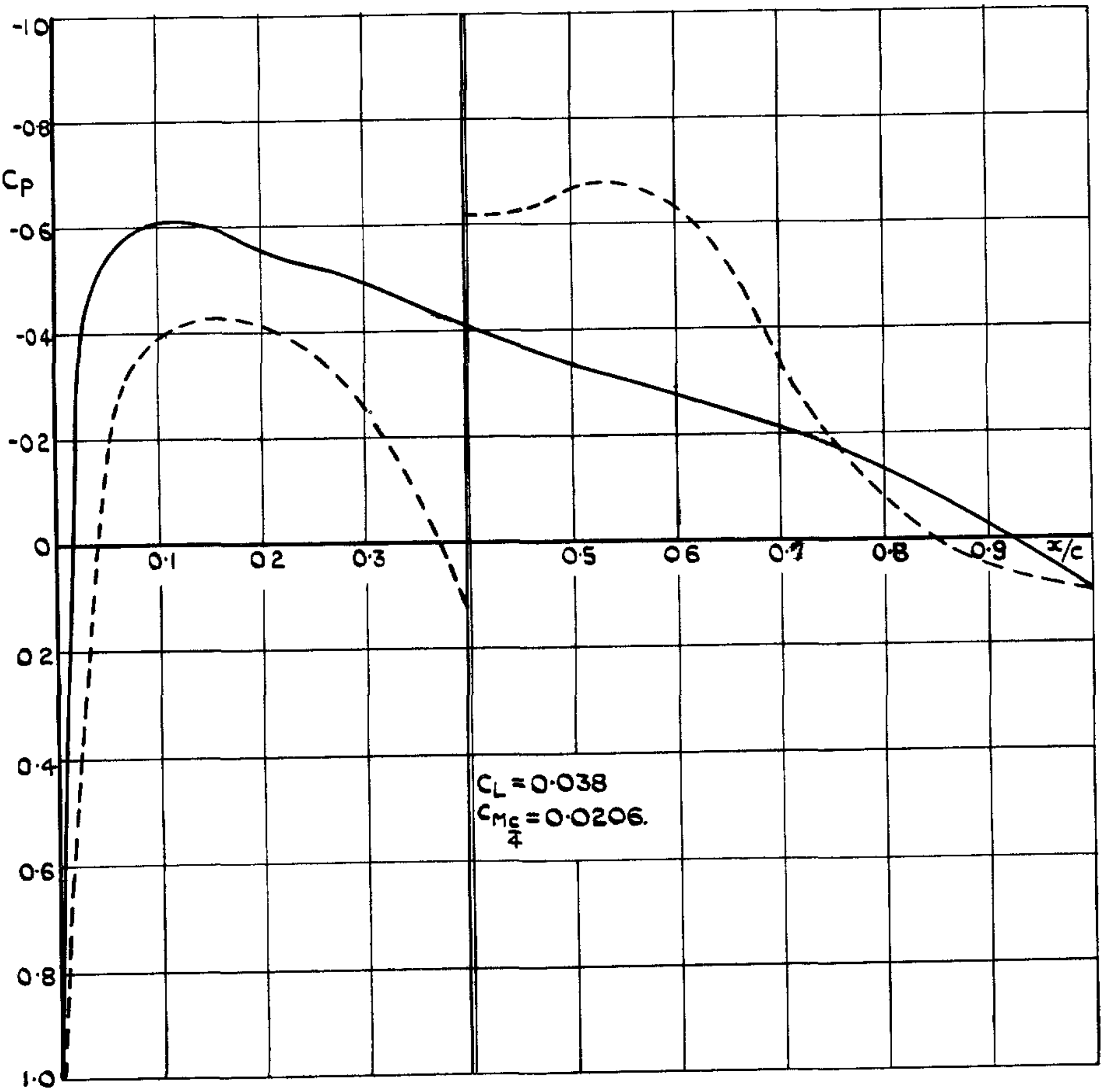

FIG. 5. PRESSURE DISTRIBUTION. 5 % CHORD FLAP.
$\alpha = 0^\circ$, $\phi = 20^\circ$, $\frac{x_F}{c} = 0·4$.

FIG. 6.

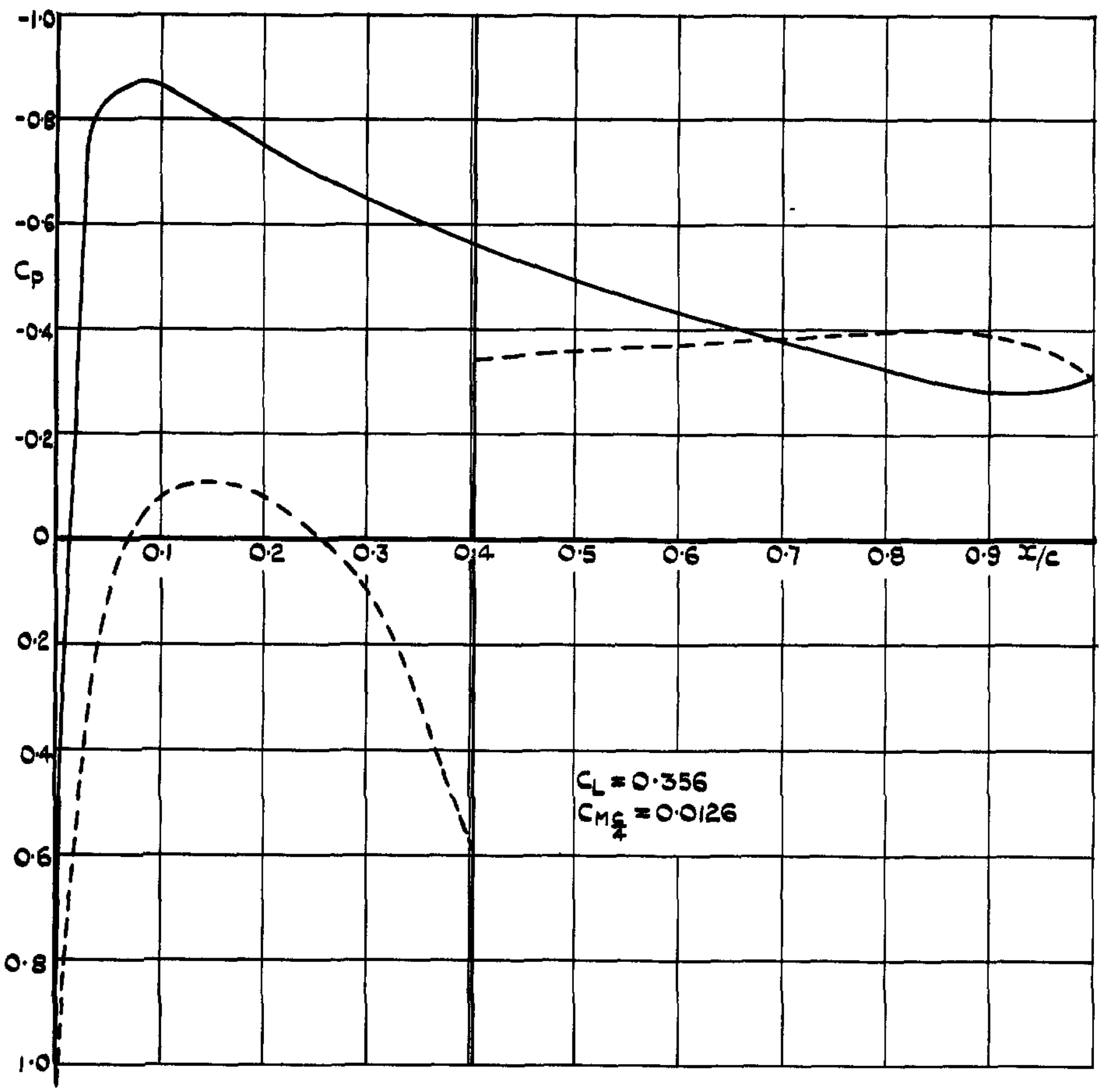

FIG. 6. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 0°, \ \phi = 40°, \ \frac{x_F}{c} = 0·4.$

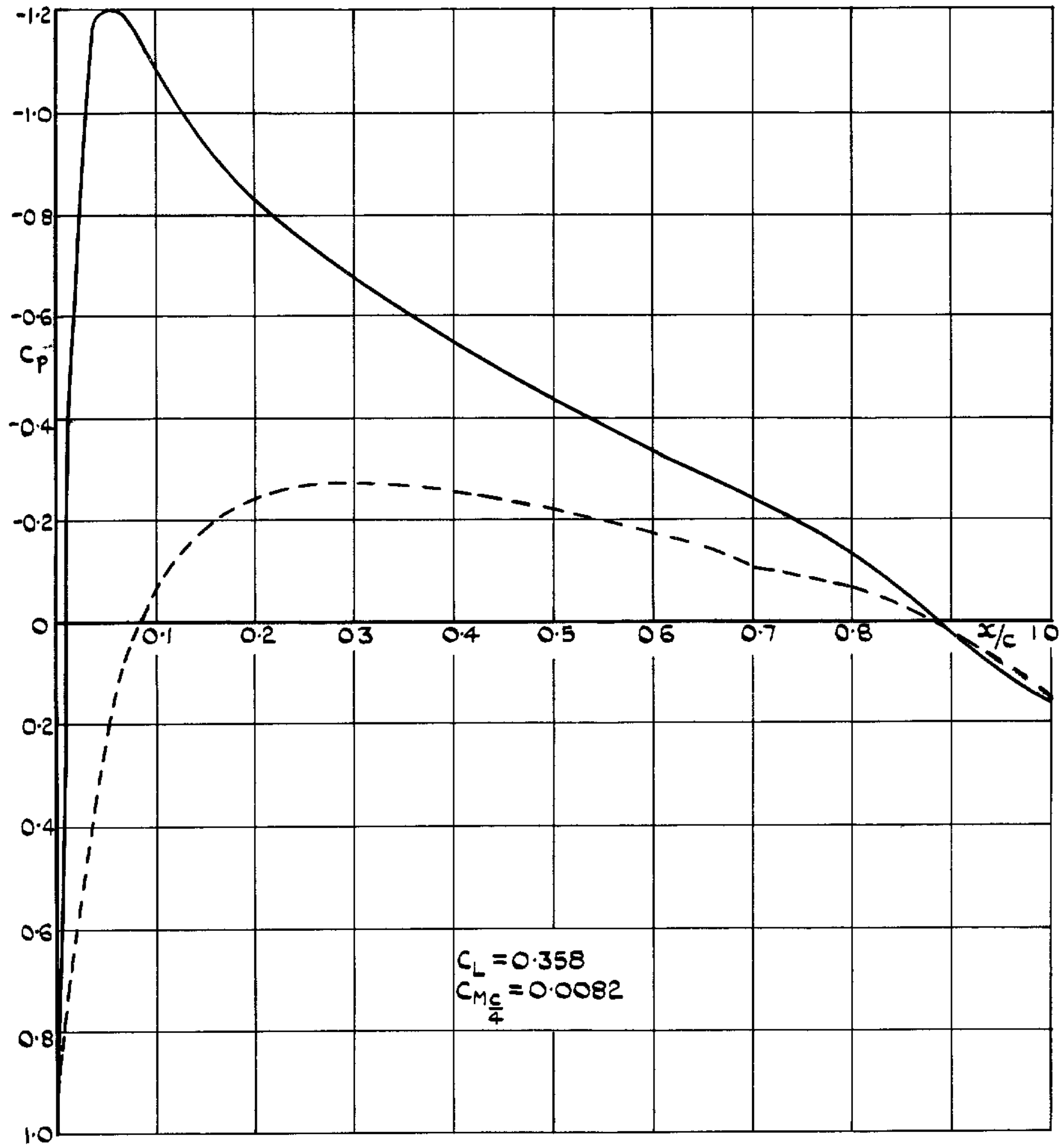

FIG. 7. PRESSURE DISTRIBUTION. NO FLAP.
$\alpha = 4°$

FIG. 8.

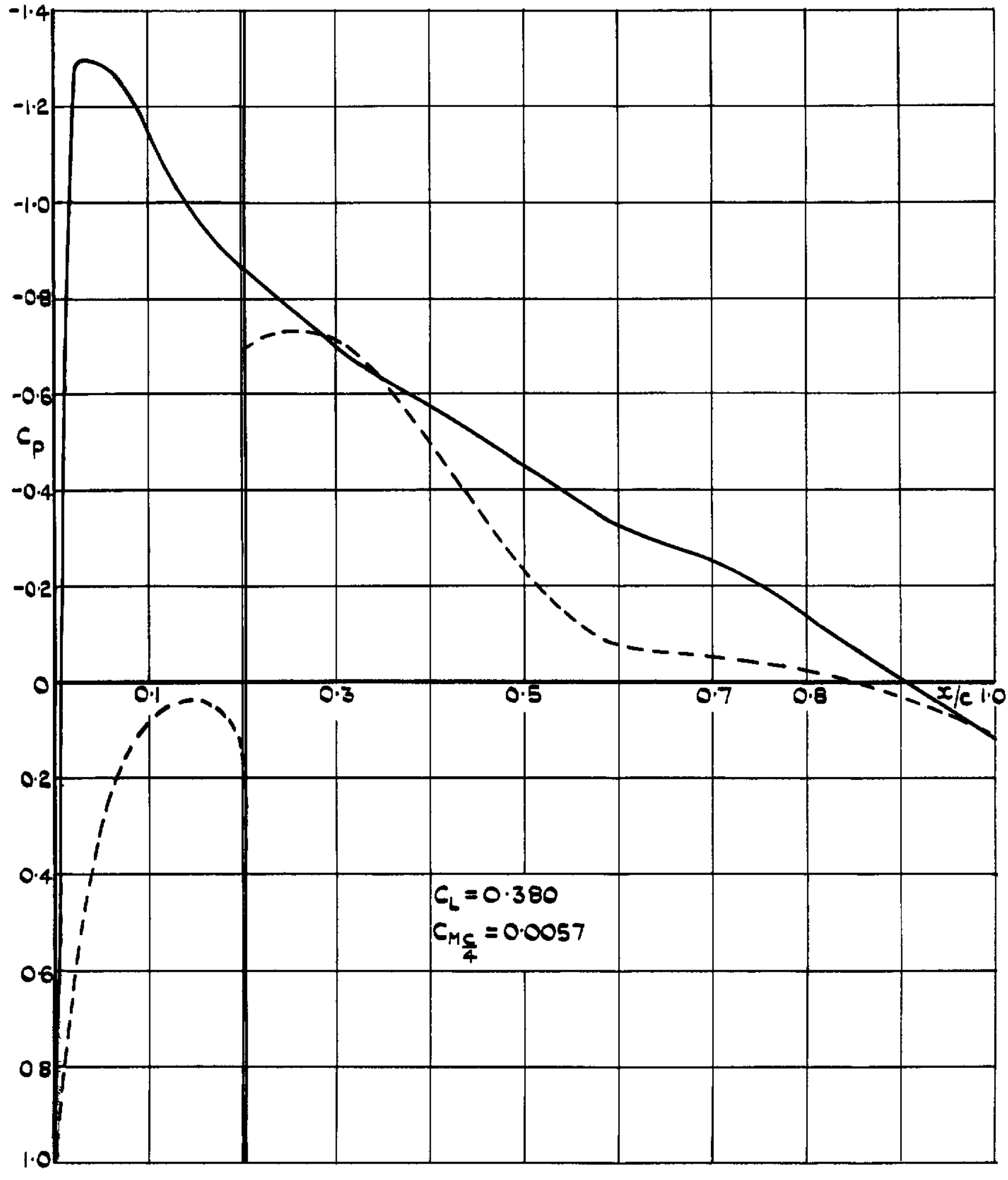

FIG. 8. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 4°, \ \phi = 20°, \ \frac{x_F}{c} = 0·2.$

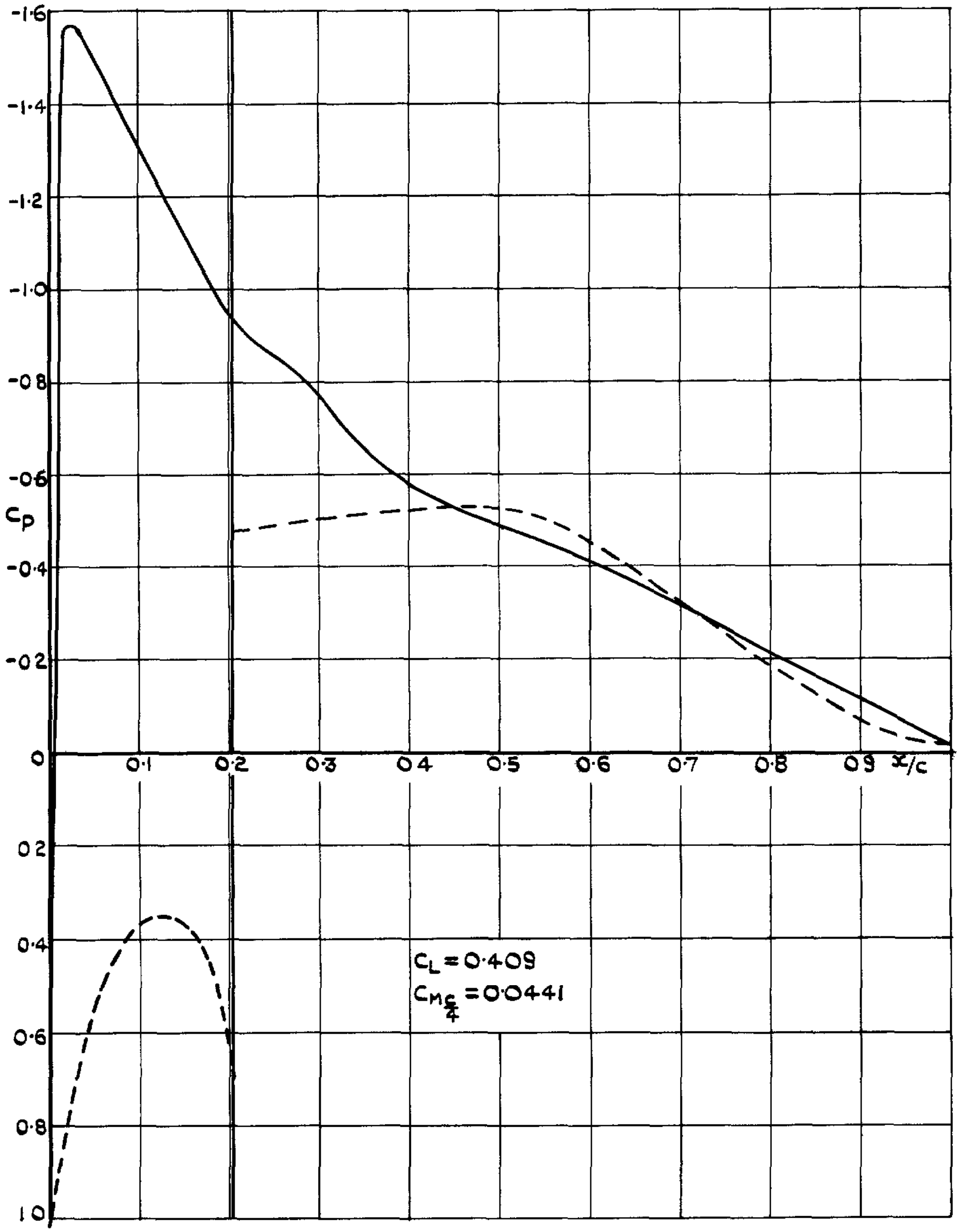

FIG. 9. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 4^\circ$, $\phi = 40^\circ$, $\frac{x_F}{c} = 0·2$.

FIG. 10.

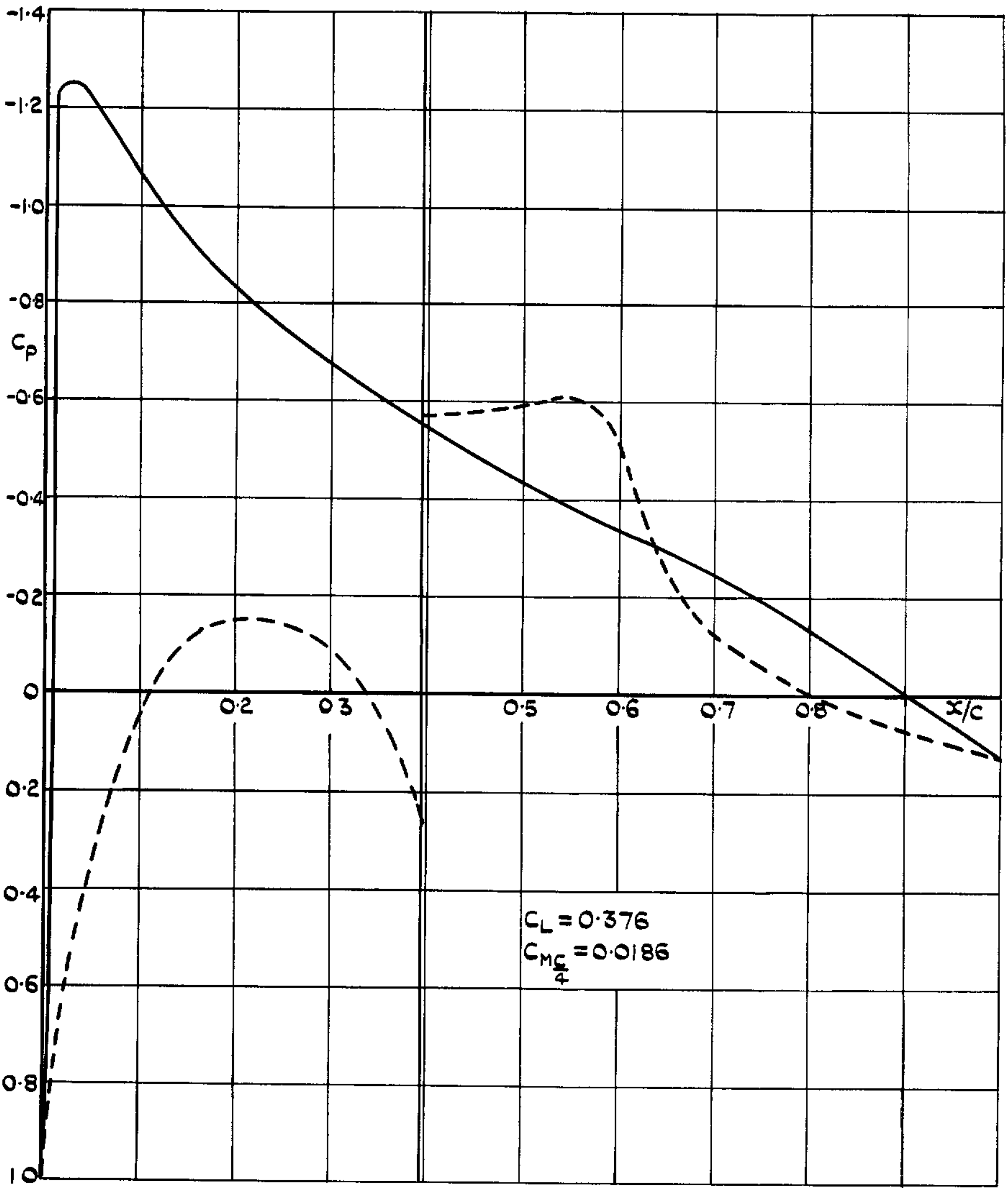

FIG. 10 PRESSURE DISTRIBUTION. 5% CHORD FLAP.

$\alpha = 4°, \ \phi = 20°, \ \frac{x_F}{c} = 0·4.$

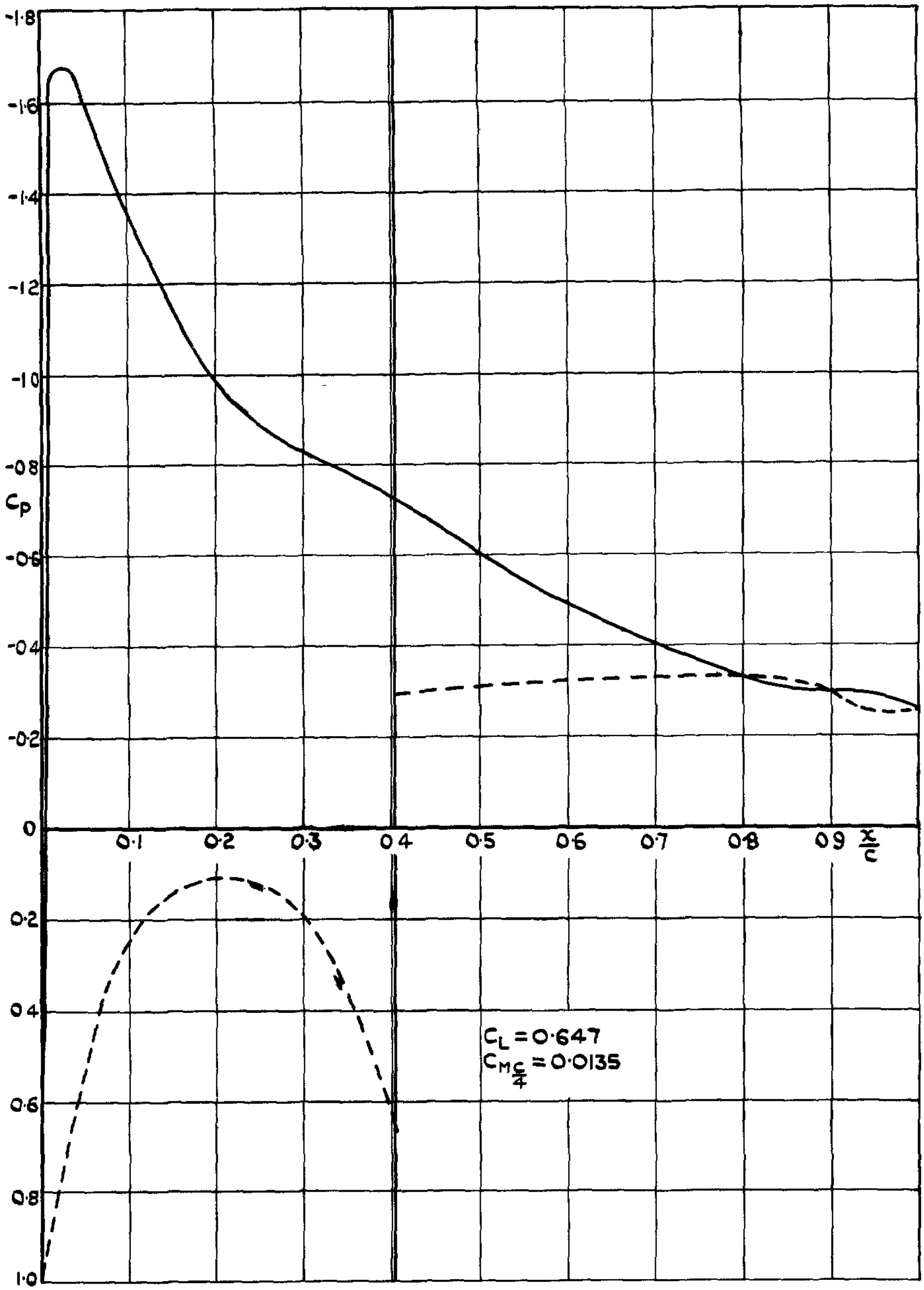

FIG. 11. PRESSURE DISTRIBUTION. 5% CHORD FLAP.
$\alpha = 4^\circ,\ \phi = 40^\circ,\ \frac{x_F}{c} = 0·4.$

FIG.12.

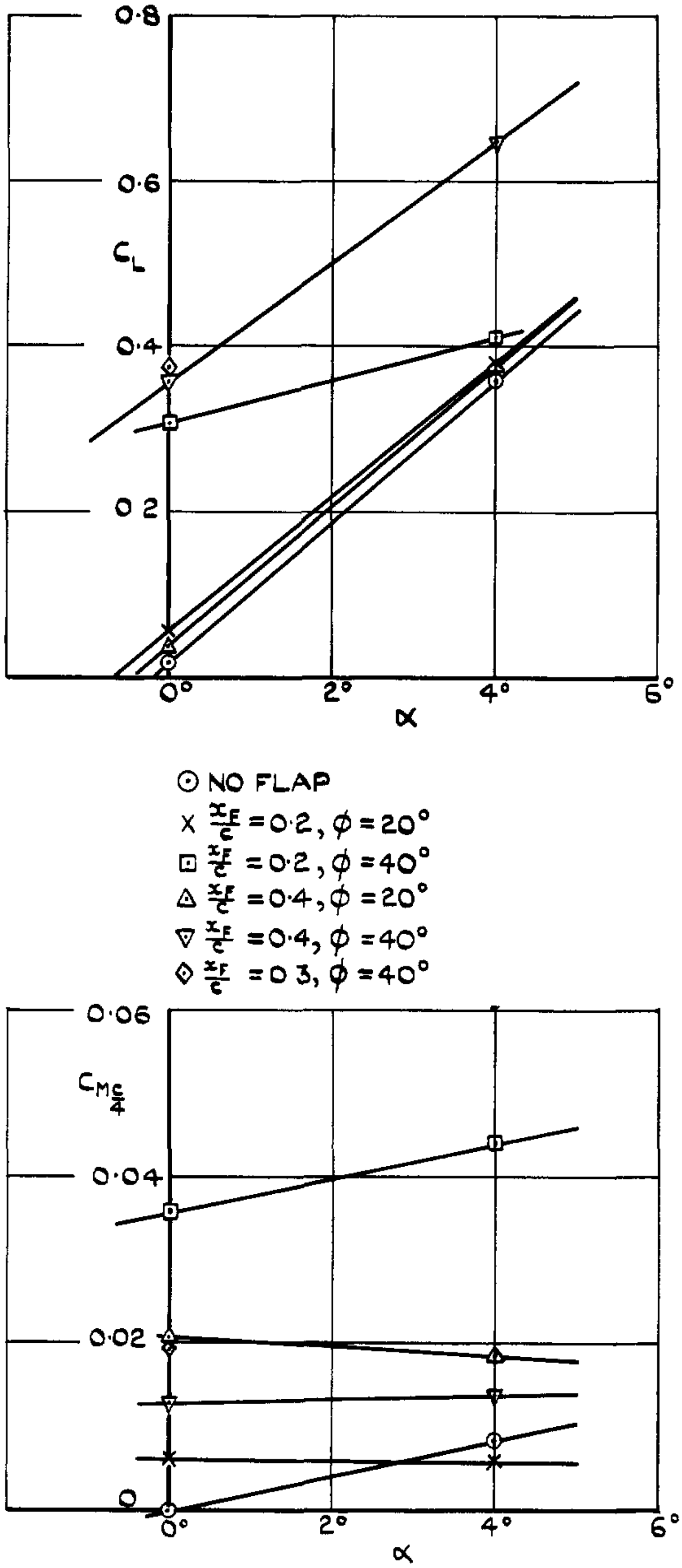

FIG. 12. LIFT AND PITCHING MOMENT (ABOUT THE QUARTER CHORD POINT) OF WING AND FORWARD MOUNTED FLAP.

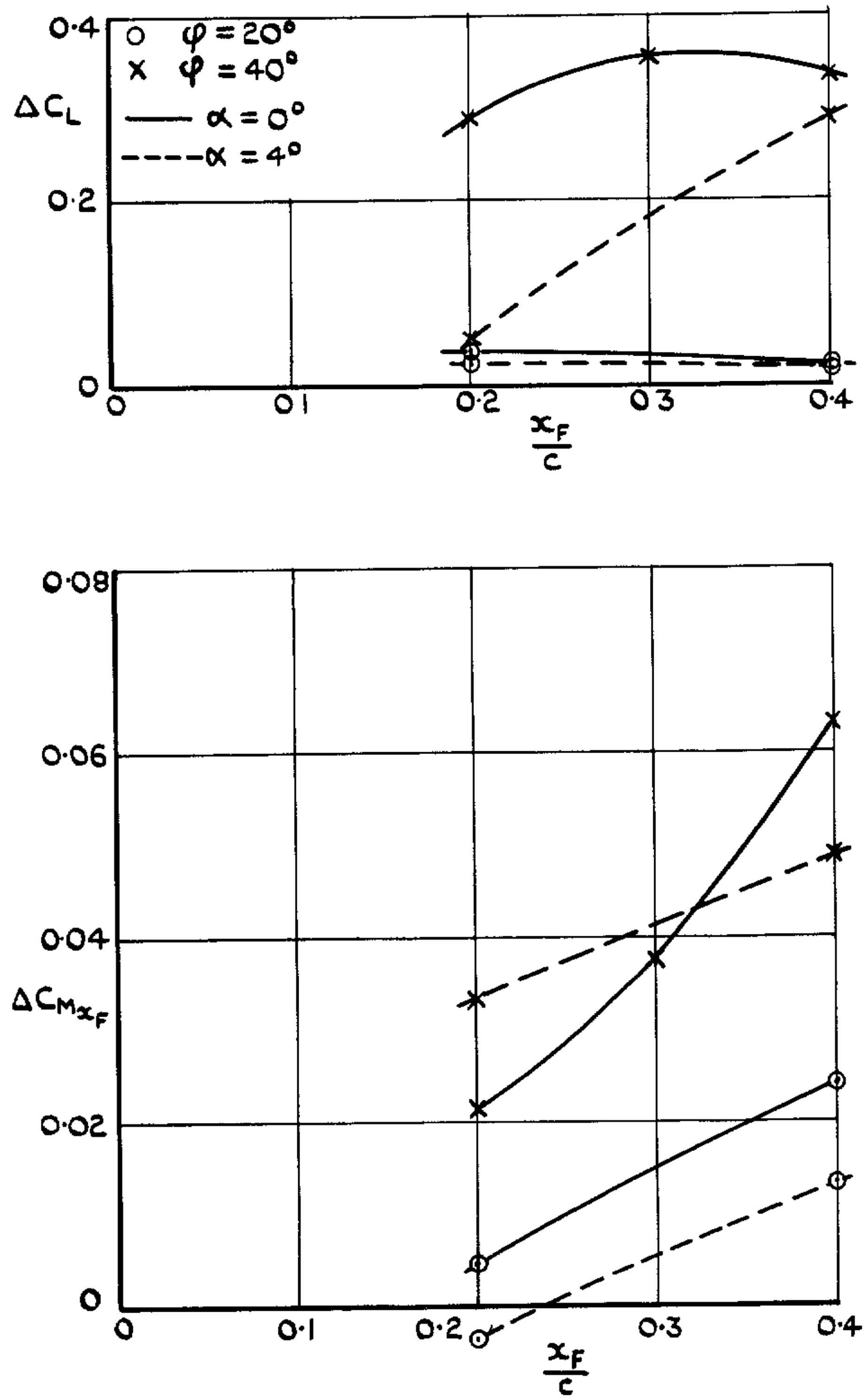

FIG. 13. INCREMENTS OF LIFT AND PITCHING MOMENT (ABOUT THE FLAP HINGE LINE) DUE TO THE FLAPS.

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