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An Analysis of Aerodynamic Data on Blowing Over Trailing Edge Flaps for Increasing Lift

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An Analysis of Aerodynamic Data on Blowing Over Trailing Edge Flaps for Increasing Lift

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September, 1954

SUMMARY

Available results on blowing over T.E. flaps are discussed and the force measurements from wind-tunnel tests are correlated in terms of the blowing moment coefficient. Simple methods are tentatively suggested for the practical prediction of the lift increment (at constant incidence) attainable on finite wings, and the associated increase in pitching moment. Theoretical curves, relating to compressible isentropic flow through the blowing slot, are presented for the determination of the various blowing coefficients in terms of the blowing pressure ratio.

For sweptback wings in particular, more experiments are needed to establish a satisfactory method of prediction and to determine the optimum blowing configuration. The change in wing stalling angle due to blowing over T.E. flaps also warrants further investigation, since the available results are somewhat conflicting and were mostly obtained at low Reynolds numbers.

1. Introduction

It is now well established that the effectiveness of T.E. flaps, in producing increased lift at constant incidence (and increased $C_{L\ max}$)*, can be considerably improved by boundary-layer control over the upper surface of the flap nose. With the adoption of the gas turbine for aircraft propulsion, and hence the provision of a built-in supply of compressed air, renewed interest has been shown in blowing over simple T.E. flaps as an alternative to the use of conventional flaps of increased mechanical complexity. In this report available wind tunnel results on blowing over flaps are examined, as a preliminary to further tunnel tests. The lift, drag and pitching moment data are analyzed and correlated in terms of the blowing momentum coefficient C_μ, and an attempt is made to deduce a simple approximate method for the estimation of blowing requirements on finite wings.

Some two-dimensional tests were made at the R.A.E.[1,2] before the last war, and further tests in this country have since been completed at Westlands Ltd. on both two-dimensional[3,4] and sweptback wings[4,5]. The Germans made extensive two-dimensional investigations during the war on a wide range of section shapes and flap configurations[7-12], and a few tests on a sweptback wing[13]. Some flight experiments were also in hand on an Arado 232 light aircraft, a Dornier DO-24 flying boat and a Messerschmidt 109 fighter, but these were never completed. Subsequent

wind-tunnel/

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*This method of increasing $C_{L\ max}$, which often leads to a reduction in stalling incidence, may be contrasted with boundary-layer control over the wing nose to extend the linear part of the lift incidence curve to higher incidences and thereby increase $C_{L\ max}$.

wind-tunnel work carried out in France[14] culminated in full-scale tunnel tests on a sweptback wing with combined suction and blowing over double T.E. flaps[15,16], and tests on a complete model of a straight-wing aircraft with blowing both over the T.E. flaps and ailerons[17]. More recently, in America, investigations on blowing over flaps have been sponsored both by the Bureau of Aeronautics (U.S. Navy)[18-20] and Wright Air Development Center (U.S. Air Force); some flight tests have also been made[20].

The symbols used in this paper are fully defined in Appendix I. Formulae relating the blowing quantity and momentum coefficients to the blowing pressure ratio are derived in Appendix II for the case of compressible slot flows, and some curves and tabulated values are included.

2. Basic Parameters

With T.E. flap angles greater than 20°, the lift increment achieved without boundary layer control falls considerably short of the value expected from theoretical (potential flow) considerations, since boundary layer separation takes place over the upper surface of the flap due to the severe adverse velocity gradients there (see Fig. 1a). The primary action of blowing over the nose of the flap is to induce flow against these adverse gradients. The plane jet emerging at high velocity in the streamwise direction, from the nozzle slit ahead of the flap, adheres to the curved upper surface of the flap nose (Coanda effect) and entrains the slowly moving air in the separated flow region. As the rate of blowing is increased, the extent of the separated region is steadily reduced and ΔC_L increases until the flow is completely attached over the flap, when the theoretical ΔC_L is sensibly achieved (see Fig. 1). With even higher rates of blowing ΔC_L continues to increase but more slowly (see Fig. 7). This latter improvement may be regarded as arising from an effective jet extension of the flap chord; in addition, at large wing incidences, the flow separation on the wing ahead of the flap will be reduced by induction effects from the high velocity jet, and the vertical component of the jet reaction also becomes more significant.

From the results of tests in which slot width was varied[5,11,14] it appears that the value of the quantity coefficient C_Q required for a given ΔC_L increases considerably as the slot is widened, indicating that the blowing velocity v_b is also important. Moreover, blowing gives little or no improvement until the blowing velocity is greater than the free-stream velocity U_o. In fact, the blowing momentum coefficient C_μ proves to be a far more satisfactory unique parameter than C_Q, as might well be inferred from injector and mixing considerations. For low-speed blowing, i.e., virtually incompressible slot flows, it is easily shown that since

$$v_b/U_o = C_Q/(w_t/c),$$

$$C_\mu = 2C_Q^2/(w_t/c), \quad \text{i.e.,} \quad C_Q = \sqrt{\tfrac{1}{2}C_\mu \cdot (w_t/c)};$$

the blowing pressure coefficient ...(2.1)

$$C_{pD} \simeq (v_b/U_o)^2 = \tfrac{1}{2}C_\mu/(w_t/c).$$

The/

The power coefficient

$$C_Q C_{pD} \simeq \sqrt{C_\mu^3/8(w_t/c)}.$$

Moreover $C_\mu/C_Q \simeq 2\sqrt{C_{pD}}$, i.e., is approximately independent of slot width.

For compressible slot flows, relations between the blowing coefficients can be derived by simple Laval nozzle theory. Table I and Fig. 3 give $C_\mu(U_o/a_o)^2/(w_t/c)$ and $C_Q(T_D/T_o)^{\frac{1}{2}}(U_o/a_o)/(w_t/c)$ in terms of the pressure ratio p_D/p_o, where the suffices D and o denote conditions in the blowing duct and free-stream respectively (see Appendix II). For slot flows with the duct to free-stream pressure ratio greater than the critical value for a choked convergent nozzle, the momentum coefficient has been based on the mass flow rate through the slot, and on the jet velocity beyond the slot throat assuming isentropic expansion to free-stream pressure.

The lift improvements attainable with a specific C_μ-value may be expected to be sensitive to flap location, as well as to flap angle, in particular to the alignment of the upper surface of the flap nose relative to the line of the blowing slot (see Fig. 2). Differences also may arise according as to whether the flap is of the 'plain' or 'slotted' type*. In the analysis of the results from the various tests, the lift increment ΔC_L at small constant incidence - above the C_L for the unflapped aerofoil at the same incidence - and the corresponding value of $\Delta C_M/\Delta C_L$ have been plotted against C_μ. In most cases curves of $\Delta C_{L\,max}$ or stalling angle have also been included. For the general assessment and correlation of the lift results, ΔC_L has been chosen rather than $\Delta C_{L\,max}$ since the variation in stalling angle and $C_{L\,max}$ can depend markedly on test Reynolds number and free-stream turbulence as well as on wing section shape.

As a datum for comparing the sectional lift increments obtained with the various flap configurations, the lift increment ΔC_{Lt} given by thin aerofoil theory for the appropriate flap angle η and flap-chord ratio c_f/c has been used. This provides a measure of the lift increment due to the flap when flow separation is precluded. The amount of blowing needed to realize ΔC_{Lt} (i.e., to prevent separation) can thus be deduced from the experimental $\Delta C_L - C_\mu$ curves, and compared for the various flap configurations. Interpreting the effect of flap deflection as a change in the no-lift angle of the section, we may write

$$\Delta C_{Lt} = a_1 \cdot \lambda_1 (c_f/c) \cdot \eta, \qquad \ldots(2.2)$$

where a_1 is the sectional lift-curve slope and η is the flap angle. For our purposes the value of a_1 has been taken as the mean experimental lift-curve slope for the unflapped aerofoil (without blowing), well below the stall, when there is no separation over the rear of the aerofoil. The function $\lambda_1(c_f/c)$ has been given values derived by Glauert's mean-line theory[21], as plotted in Fig. 4; typical values are 0.55, 0.61 and 0.66 for c_f/c values of 0.20, 0.25 and 0.30 respectively**.

The/

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*Note that the optimum gap (between wing and flap) for a slotted flap without blowing may not be the same as that for the slotted flap with blowing.

**If there is substantial rearward movement of the flap as it deflects, then the ratio c_f/c' should be taken instead of c_f/c, where c' is the effective (extended) wing chord.

The experimental values of $-\Delta C_M/\Delta C_L$ due to the flap may also be compared with those given by mean-line theory (see Fig. 4); for example 0.185, 0.17 and 0.155, when c_f/c is 0.20, 0.25 and 0.30 respectively.

3. Analysis of Two-Dimensional Wind Tunnel Results

The model details of each test discussed below are included along with the corresponding $\Delta C_L - C_\mu$ curves, for completeness.

R.A.E. Experiments

These early tests[1,2] were made on an 18% thick section with various types of plain flaps and a constant blowing slot width, $w_t/c = 0.0083$. As the flap was deflected, the effective wing chord c' was considerably increased by flap rearward movement, and the flap nose was slightly lowered. Fig. 5 shows that for the smaller flap chord ($c_f/c' = 0.18$, $\eta = 60°$) the variation of lift increment ΔC_L with C_μ is almost linear*, which at first sight would appear to conflict with our remarks in §2. However, it should be noted that the values of C_μ employed in the R.A.E. experiments were about 0.1, 0.25 and 0.4 and that only the first of these is within the present practical range.

Westland Experiments

These tests[3,4] on a 12% thick section were intended merely as a preliminary to swept-wing tests (see §4), and were made with a 30% chord plain flap at angles only up to 35°; the upper surface of the flap nose was roughly in line with the blowing slot (cf., Fig. 2), and the value of w_t/c was 0.0083. The general shape of the $\Delta C_L - C_\mu$ curves shown in Fig. 6 is as outlined in §2, and the much lower rate of increase of ΔC_L with C_μ after the initial sharp rise is clearly evident. As a further point of interest curves of $\Delta C_{L\,max}$ have also been included in Fig. 6, and it is seen that although the $\Delta C_{L\,max}$ for zero C_μ is considerably less than the corresponding ΔC_L, the further improvements due to blowing are much the same. This occurs, despite the substantial reduction in the stalling angle (up to 5°) of this thin-nosed section when the flap is deflected, because there is little further reduction in stalling angle with blowing. The lift curve slope a_1 also tended to decrease with flap deflection, but to increase with blowing.

German Experiments

A wide range of tests, chiefly on the wing section shapes NACA 0009, 23012 and 23015 were made at A.V.A. Göttingen. A previous German analysis[22] of the results is somewhat misleading since variations in the flap configuration and blowing slot width were not taken into account.

The investigations on NACA 0009[10] were carried out with a slotted T.E. flap ($c_f/c = 0.25$) with $\eta = 0$ to 60° and $w_t/c = 0.005$; the effect of adding a wing L.E. flap was also determined. Better results were obtained with the nose of the T.E. flap 'in-line' - as already described - rather than lowered; Fig. 7 shows the analysis of lift results for the former flap configuration.

In/

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*Except for Fig. 5, the curves of ΔC_L and ΔC_M include the increment due to flap deflection as well as blowing.

In subsequent experiments on the NACA 23012 section[11], with 25% chord T.E. flaps, both plain and slotted types were tested and again various flap nose positions. It was shown that better results could be obtained by raising the flap nose slightly above the line of the basic section shape and blowing slot. In the case of the plain flap, two different slot widths were tried for the same flap position; the correlation of results on a C_μ basis is far from satisfactory but is nevertheless considerably superior to correlation in terms of C_Q. Fig. 8a gives the lift increments obtained with two of the best plain and slotted flap configurations. At an assigned C_μ, the ΔC_L achieved with the plain flap is greater than that from the slotted flap. The corresponding results for $\Delta C_{L\ max}$ (see Fig. 8b) indicate that, if anything, the converse holds.

In the final experiments, on the NACA 23015 section[12] with 20% chord T.E. flaps, both plain and slotted types were again examined and improvements in ΔC_L obtained by careful attention to flap nose location (see Figs. 2 and 9a). As before, the plain flap, with blowing was slightly better than the slotted flap with blowing, as regards ΔC_L (see Fig. 9a), but the plain flap was somewhat inferior for $\Delta C_{L\ max}$ by an amount almost independent of C_μ (see Fig. 9b).

Some rough values of $-\Delta C_M/\Delta C_L$ at zero incidence, calculated from the German results, are also shown in Figs. 7, 8a, 9a. At practical flap angles ($30^\circ \leqslant \eta \leqslant 60^\circ$), it is seen that $-\Delta C_M/\Delta C_L$ varies only slightly with C_μ in most cases, and is little different from the value without blowing. For the NACA 0009 and 23012 sections with 25% chord flaps experimental values of $-\Delta C_M/\Delta C_L$ between 0.20 and 0.25 were obtained compared with the theoretical value of 0.17 given by mean-line theory. But for NACA 23015 with a 20% chord flap, the experimental values were less than 0.2, and surprisingly close to the theoretical value 0.18.

The stalling angle in these German tests decreased steadily with increased T.E. flap angle and blowing coefficient, so that $\Delta C_{L\ max} < \Delta C_L$, irrespective of whether or not nose devices were used. The variations in the lift curve slope a_1 for incidences well below the stall are not entirely consistent.

American Experiments

Some blowing experiments along the lines of the German work described above have been carried out at the University of Wichita[18,19]. These were directed towards the incorporation of an Arado-type system on a Cessna 170 light aircraft[20]. Tests on blowing have also been made by the David Taylor Model Basin (U.S. Navy) and the N.A.C.A.

Comparison of Lift Increments

In an attempt to compare and correlate the results from the various experiments, the value of C_μ at which the relevant ΔC_{Lt} (see Eqn. (2.2)) were achieved have been plotted against flap angle in Fig. 10. Each point is designated with the relevant percentage flap chord ratio ($100\ c_f/c$) since the C_μ required ought to increase with this ratio. The plot shows considerable scatter due to the different flap chord ratios and flap configurations, and possibly due to difficulty in selecting the value of a_1. Nevertheless, the results show the general trend in the values of C_μ required to give ΔC_{Lt}, and hence to prevent flow separation over the flap, as η and c_f/c are varied. The plain flaps appear slightly superior to the slotted flaps, at least for subsonic blowing. The full-line curve has been included to indicate the values of C_μ which should *certainly* be adequate in practice for 25% chord T.E. flaps.

4./

4. Effect of Finite Aspect Ratio and Sweepback

In correlating results from two-dimensional and three-dimensional tests, it is useful to define the boundary-layer control coefficients for the finite wing in terms of a wing area S' corresponding to the spanwise extent of boundary-layer control. The C_Q and C_μ values for the finite wing then become identical with the sectional values when the latter are constant along the span.

For unswept wings of finite aspect ratio, extension of two-dimensional simple flap theory on the basis of lifting line concepts leads to a convenient datum lift increment.

$$\Delta C_{Lt} = a_1 \cdot \lambda_1 (c_f/c) \cdot \lambda_3 (b_f/b) \cdot \eta \qquad \ldots(4.1)$$

where a_1 here denotes the lift-incidence curve slope of the wing, and $\lambda_3 (b_f/b)$ is a correction factor to allow for flap span including body cut-out. The values of $\lambda_3 (b_f/b)$ in common use for conventional flaps[23,24] could be employed, or for an untapered wing $\lambda_3 (b_f/b)$ could be taken as roughly equal to the ratio of flap span to wing span. The C_μ-value required to give this theoretical lift increment for unswept wings may reasonably be expected to be much the same as the values deduced for two-dimensional tests with the same flap configuration (see §3). More generally it might also be inferred that, as a rough working rule, the lift increment due to T.E. flaps with blowing on unswept finite wings at any prescribed C_μ could be determined from two-dimensional results with the same C_μ and flap configuration, by the simple relation

$$\Delta C_L \text{ (3-diml.)} = \frac{a_1 \text{ (3-diml.)}}{a_1 \text{ (2-diml.)}} \cdot \Delta C_L \text{ (2-diml.)} \cdot \lambda_3 (b_f/b). \qquad \ldots(4.2)$$

For moderately swept wings, further simple considerations suggest that the same formulae might apply equally well, provided η were measured in the plane along-wind. However, in the following discussion of the few sweptback wing results available, this is found to be rather optimistic and modified formulae are tentatively suggested (see Eqns. (4.1a) and(4.2a)).

German 45° Sweptback Wing

Investigations were carried out[13] on an untapered wing (without body) of aspect ratio 3.8, and wing section NACA 23012 normal to the L.E.; 20% chord plain T.E. flaps were fitted across the whole span. Results were obtained with blowing normal to the hinge line and $w_t/c_n = 0.0035$, for flap angles η_n ranging between 0 and 60°*. Fig. 11 shows some curves of ΔC_L and $\Delta C_{L\,max}$ against C_μ. The improvements in ΔC_L obtained by blowing were small; limiting ΔC_L values of 0.60 and 0.85, for η_n of 45° and 60° respectively, were reached with $C_\mu \simeq 0.05$. The stalling angle decreased from about 25° to 20° due to flap deflection ($C_\mu = 0$), but there was little further reduction due to blowing. Although $\Delta C_{L\,max} < \Delta C_L$ for $C_\mu = 0$, $\Delta C_{L\,max}$ increased steadily with C_μ up to the highest value tested.

Westland/

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*The suffix n is added to signify measurements made in the plane normal to the flap hinge line; $\eta \simeq \eta_n \cos \Lambda_f$ where Λ_f denotes the sweep of the flap hinge line. Also, since the direction of blowing was normal to the hinge line instead of along wind, $C_\mu = 2C_Q^2/(w_t/c_n)$.

Westland 40° Sweptback Wing

An extensive series of experiments were carried out on an untapered wing (with a large body) of aspect ratio 5, having a 12% thick section along wind; both full-span and part-span plain T.E. flaps of 30% chord were tested with blowing along wind. The first series of tests[4] were made with full-span flaps and $w_t/c = 0.0069$ only. Nose flaps were added in an attempt to maintain stalling incidence. Even so, severe root stalling occurred and in subsequent tests[5] the wing root-body junction was improved so that the nose flaps could be fitted closer to the body. Without nose flaps, there was a substantial reduction in stalling angle as η and C_μ were increased; but with full-span nose flaps the loss was much smaller, being less than 5° in most cases.

Curves of ΔC_L against C_μ are shown in Figs. 12a and 12b for the old body with full-span T.E. flaps and the improved body with part-span flaps, respectively*. In the latter tests the effect of varying slot width was investigated. The correlation of the results on a C_μ basis is not too good (see Fig. 12b); but the blowing quantities and power increased as the slot was widened, and the blowing pressure decreased, in general agreement with the conclusions from such a correlation (see Eqn. (2.1)). Results obtained by varying the flap span indicated that ΔC_L was approximately proportional to flap span. The optimum T.E. flap angle was found to be 65°; at larger angles and the same C_μ, the wing drag merely increased without any further improvement in lift.

Although pitching moments were measured, it has been found difficult to interpret the results satisfactorily; moreover the stalling characteristics of the wing were not representative of those encountered on full-scale wings with this sweepback.

French 31° Sweptback Wing

Experiments were carried out in the large wind-tunnel at Chalais-Meudon, on a full-scale model of a 10% thick sweptback wing (with body), of aspect ratio 3.3 and taper ratio 0.49, with double T.E. flaps and a drooped nose. Suction was applied at the L.E. of the first flap and the sucked air was ejected downstream through a slot over the nose of the second flap, the combined flow being induced by using compressed air from the jet engine on an injector pump principle. Lift, drag, pitching moment, and hinge moment** were measured for a range of blowing momentum coefficient C_μ and flap angles, and a study of injector design was made. Unfortunately, the results are lacking in some important details. A few additional comments and results are given in Ref. 16.

For completeness, the detailed wing configuration is included in Fig. 13, together with some $\Delta C_{L\,max} - C_\mu$ curves which it was possible to derive approximately[16]. Since, however, suction as well as blowing played an important part in this set up, correlation with the blowing experiments already considered has not been attempted.

Comparison/

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*It should be noted that the boundary layer control coefficients C_Q and C_μ quoted in the original Westland reports are based on gross wing area S instead of boundary layer control area S' as here.

**It should be noted that the force coefficients quoted in Ref. 15 are based on nett wing area rather than gross wing area (1.25 x nett).

Comparison of Lift Increments on Sweptback Wings

In both the German and Westland tests the values of ΔC_{Lt} given by (4.1) were reached only at abnormally high C_μ-values, if at all, so that for sweptback wings this relation appears to be far too optimistic. If a further sweepback factor is introduced in (4.1), to provide a modified datum

$$\Delta C_{Lt}\ (\text{mod.}) = a_1 \cdot \lambda_1 (c_f/c) \cdot \lambda_3 (b_f/b) \cdot \eta \cdot \cos \Lambda_f \qquad \ldots(4.1a)$$

the C_μ-values required in the Westland swept wing tests tie up reasonably well with the Westland two-dimensional results (see Fig. 10), and also with the other two-dimensional results when due allowance is made for the large flap chord and poor flap location. On this basis, a more reasonable formula to replace (4.2), might be

$$\Delta C_L\ (\text{3-diml.}) = \frac{a_1\ (\text{3-diml.})}{a_1\ (\text{2-diml.})} \Delta C_L\ (\text{2-diml.}) \cdot \lambda_3 (b_f/b) \cdot \cos \Lambda_f \,. \qquad \ldots(4.2a)$$

However, it must be stressed that further tests are needed before the formulae (4.1) and (4.2), the formulae (4.1a) and (4.2a), or any others*, can be used with confidence for sweptback wings.

5. General Conclusions

The blowing momentum coefficient C_μ rather than the quantity coefficient C_Q is a more satisfactory parameter for determing the lift increment with a specific flap configuration but arbitrary slot width. Some compromise between the blowing pressures and quantities is possible therefore in practice through the choice of slot width. The pressures necessary for small slot widths are high, but the quantities required are correspondingly lower; both factors are conducive to smaller ducts. For economical blowing requirements, a large flap angle (up to 65°) is advantageous, at least for flap-chord ratios of 20% to 30%, so that the blowing is primarily preventing flow separation over the flap. In addition the flap nose is best located with its upper surface slightly raised above the line of the blowing slot (see Fig. 2) for blowing pressure ratios much less than the critical value. There seems little point in using flaps of the 'slotted' type instead of the simple plain flaps.

The values of C_μ needed in practice on two-dimensional and finite wings, to provide a 'datum' lift increment corresponding nominally to unseparated flow over the flap, can be roughly estimated from Fig. 10 (see §4). The more general formulae also put forward in §4 may be used for the prediction of lift increments on finite wings at any C_μ-value from available two-dimensional blowing data on a similar flap configuration. Further experimental results are essential to provide adequate data for project work, and to justify in particular the formulae tentatively suggested for sweptback wings. It is hoped that additional information of this character will become available from the American and British work now in progress.

The/

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*An alternative approach based on a 'flap effectiveness factor' was used in Ref. 6.

The changes of stalling angle obtained with blowing in the various tests are not altogether consistent. The available evidence and other considerations suggest that, while for many sections the stalling angle will decrease as both η and C_μ are increased, for thin- or sharp-nosed sections and for sweptback wings the reduction in stalling angle due to blowing (η constant) may be small* even though the decrease due to flap deflection (C_μ zero) is appreciable. In this connection it is worth recalling that blowing or suction at the wing nose could be employed to maintain the stalling incidence or to increase the maximum usable C_L by delaying L.E. separation.

The value of $-\Delta C_M/\Delta C_L$ for unswept wings appears to vary little with blowing for practical flap angles, and roughly takes the same value as for an unblown flap. In the absence of sufficient data on sweptback wings, pitching moment calculations on a strip-theory basis (using two-dimensional data) may suffice as an interim measure. It should be noted that the values of the wing pitching moment obtained with blowing over simple flaps are in general no greater than those from conventional mechanical flaps providing the same ΔC_L, and may even be less if the latter have substantial rearward movement. Moreover, for a complete aircraft, the downwash over the tail will tend to trim out such nose-down pitching moments by an amount depending on tail volume and tail location. The possibility of tail stalling will then require consideration and the loss in aircraft lift on trimming out the wing pitching moment (by a combination of downwash effect and elevator angle) will have to be taken into account, particularly if the tail arm is short. To keep the nose-down pitching moments on sweptback wings within practical bounds, it is probably essential to restrict the T.E. flaps to the inboard half or two-thirds wing span.

The few drag measurements available with blowing over T.E. flaps, indicate that there is a substantial reduction in section profile (wake) drag due to blowing, which at small wing incidences is of the order of the C_μ-value[14,17]. With finite span wings there will of course be greater induced drag associated with the increased lift.

There is clearly need for further high-lift tests with blowing over T.E. flaps, particularly on thin straight and sweptback wings, and at high Reynolds numbers. The effect of varying the blowing direction, both in the plane of the wing sections and of the wing planform, could also profitably be investigated.

APPENDIX I/

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*Possibly because the induction effect of the blowing can reduce flow separation just ahead of the flap and boundary-layer migration towards the wing tip.

APPENDIX I

List of Symbols

a speed of sound

a_1 lift-incidence curve slope $dC_L/d\alpha$

b wing span

b_f flap span

c local wing chord (along wind)

c' effective (extended) local wing chord

c_m mean wing chord (along wind) = S/span

c_f local flap chord (along wind)

c_{fn} " " " (normal to hinge line)

C_L, C_D, C_M Lift, drag, and pitching moment coefficients (about $\frac{1}{4}$-chord); based on gross wing area S for wing with body

ΔC_{Lt} Datum lift increment defined by Eqn. (2.2), and Eqn. (4.1) or (4.1a).

C_Q Blowing quantity coefficient $= \int m \, ds/\rho_o U_o S'$ - finite wing,

$= m/\rho_o U_o c$ - two-dimensional.

C_μ Blowing momentum coefficient $= \int m \, v_b d_s/\frac{1}{2}\rho_o U_o^2 S'$ - finite wing,

$= m \, v_b/\frac{1}{2}\rho_o U_o^2 c$ - two-dimensional.

C_{pD} Blowing pressure coefficient $= (p_D - p_o)/\frac{1}{2}\rho_o U_o^2$

m mass rate of blowing per unit span

p_o, ρ_o, T_o free-stream static pressure, density and temperature

p_D, ρ_D, T_D blowing duct stagnation pressure, density and temperature

R free-stream Reynolds number $= U_o \, c_m/\nu$

s spanwise distance

S gross wing area

S' wing area corresponding to spanwise extent of boundary layer control (for boundary-layer control over whole wing span, S' = nett wing area)

U/

U velocity on aerofoil surface

U_o free-stream velocity

w_t slot throat width

v_b blowing velocity

α wing incidence

η T.E. flap angle (along wind)

η_n " " " (normal to hinge line)

$\lambda_1 (c_f/c)$ function giving change in sectional no-lift angle due to flap deflection, see Eqn. (2.2)

$\lambda_3 (b_f/b)$ correction factor for flap span in estimation of change of no-lift angle due to flap deflection, see eqn. (4.1)

Λ sweepback of wing $\frac{1}{4}$-chord line

Λ_f sweepback of flap hinge line.

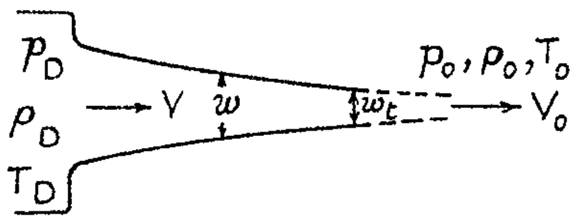
APPENDIX II/

APPENDIX II

Blowing Coefficients for Compressible Slot Flows

By definition, for two-dimensional slot flows,

$$C_\mu = \frac{m v_b}{\frac{1}{2}\rho_o U_o^2 c}$$



where

m is the mass rate of flow through the blowing slot per unit span,

v_b is the jet velocity assuming isentropic flow to free-stream pressure p_o.

The symbols w, v, and a are used here to represent to local slot width, the local slot velocity, and the local speed of sound; as usual p, ρ and T represent pressure, density and absolute temperature. The suffices o, D, t, s and b signify values appropriate to the free stream, the blowing duct (stagnation), the slot throat, sonic flow and in the jet at free-stream pressure.

From simple Laval nozzle considerations, we may write

$$C_\mu = \frac{\rho_s a_s w_s \cdot v_b}{\frac{1}{2}\rho_o U_o^2 c}$$

$$= \frac{2}{U_o^2}\,\frac{w_t}{c}\,\frac{w_s}{w_t}\,\frac{\rho_s}{\rho_D}\,\frac{a_s^2\rho_D}{\rho_o}\,\frac{v_b}{a_s}.$$

For isentropic flow of a perfect gas

$$\frac{a_s^2\rho_D}{\rho_o} = \frac{2}{\gamma+1}\,\frac{a_D^2\rho_D}{\rho_o} = \frac{2}{\gamma+1}\,a_o^2\,\frac{p_D}{p_o}\,,\quad \frac{\rho_s}{\rho_D} = \left(\frac{2}{\gamma+1}\right)^{1/(\gamma-1)}.$$

If/

If the pressure ratio p_D/p_o equals or exceeds the critical value $\{2/\gamma + 1\}^{\gamma/(\gamma-1)}$ then the symbols t and s are synonymous and $w_t = w_s$. For pressure ratios less than the critical the symbols b and t are synonymous, and the ratio w_t/w_s becomes a function of p_D/p_o only following from the two parametric relations in $M(= v_b/a_b)$

$$\frac{p_D}{p_o} = \left\{1 + \frac{\gamma - 1}{2} M^2\right\}^{\gamma/(\gamma-1)}, \quad \frac{w_t}{w_s} = M^{-1}\left\{\frac{2}{\gamma + 1}\left(1 + \frac{\gamma - 1}{2} M^2\right)\right\}^{(\gamma+1)/2(\gamma-1)}$$

Moreover, the ratio v_b/a_s is also a function of (p_D/p_o) only, for both choked and subsonic flows, and is given by the foregoing expression for p_D/p_o together with the further parametric relation

$$\frac{v_b}{a_s} = M\left\{\frac{2}{\gamma + 1}\left(1 + \frac{\gamma - 1}{2} M^2\right)\right\}^{-\frac{1}{2}}$$

Thus, with γ assigned $(= 1.4)$,

$$\frac{U_o^2}{a_o^2}\frac{1}{(w_t/c)} C_\mu \text{ becomes a function of } p_D/p_o \text{ only,}$$

and has been tabulated and plotted in Table I and Fig. 3 by means of the tables of Ref. 25 for the parametric relations.

Likewise, we have that

$$C_Q = \frac{m}{\rho_o U_o c} = \frac{\rho_s a_s w_s}{\rho_o U_o c}$$

$$= \frac{1}{U_o}\frac{w_t}{c}\frac{w_s}{w_t}\frac{\rho_s}{\rho_D}\frac{a_s \rho_D}{\rho_o} .$$

The ratios w_s/w_t and ρ_s/ρ_D are determined as above, and

$$\frac{a_s \rho_D}{\rho_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{2}}\frac{a_D \rho_D}{\rho_o} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{2}}\frac{a_o p_D}{p_o}\left(\frac{T_o}{T_D}\right)^{\frac{1}{2}} .$$

Thus, with γ assigned,

$$\frac{U_o}{a_o}\frac{1}{(w_t/c)}\left(\frac{T_D}{T_o}\right)^{\frac{1}{2}} C_Q \text{ becomes a function of } p_D/p_o \text{ only;}$$

this has also been tabulated and plotted in Table I and Fig. 3.

Acknowledgement/

Acknowledgement

The writer is indebted to Miss L. M. Esson and Miss A. K. Kernaghan for their assistance with the preparation of the diagrams.

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TABLE I/

TABLE I

Standard Table for Blowing Parameters

$\frac{p_D}{p_o}$	$C_\mu f_\mu$*	$C_Q f_Q \frac{T_D^{1/2}}{T_o^{1/2}}$*	$\frac{T_b}{T_D}$	$\frac{\rho_b}{\rho_D}$	M $=v_b/a_b$
1.000	0	0	1.000	1.000	0
1.064	0.0090	0.00135	0.982	0.956	0.30
1.186	0.0250	0.00229	0.952	0.885	0.50
1.276	0.0359	0.00278	0.933	0.840	0.60
1.387	0.0489	0.00328	0.911	0.792	0.70
1.524	0.0639	0.00380	0.887	0.740	0.80
1.604	0.0721	0.00406	0.874	0.714	0.85
1.691	0.0808	0.00433	0.861	0.687	0.90
1.787	0.0901	0.00461	0.847	0.660	0.95
1.893	0.0998	0.00489	0.833	0.634	1.00
2.009	0.1103	0.00519	0.819	0.608	1.05
2.135	0.1217	0.00552	0.805	0.582	1.10
2.274	0.1343	0.00588	0.791	0.556	1.15
2.425	0.1481	0.00627	0.776	0.531	1.20
2.590	0.1632	0.00670	0.762	0.507	1.25
2.771	0.1799	0.00716	0.747	0.483	1.30
2.968	0.1981	0.00767	0.733	0.460	1.35
3.182	0.2181	0.00823	0.718	0.437	1.40
3.416	0.2401	0.00883	0.704	0.416	1.45
3.671	0.2642	0.00949	0.690	0.395	1.50
3.949	0.2905	0.01021	0.675	0.375	1.55
4.250	0.3195	0.01099	0.661	0.356	1.60
4.936	0.3859	0.01276	0.634	0.320	1.70
5.746	0.4654	0.01486	0.607	0.287	1.80
6.701	0.5604	0.01733	0.581	0.257	1.90
7.825	0.6738	0.02023	0.556	0.230	2.00

$$^*f_\mu = 0.04991 \frac{U_o^2}{a_o^2} \frac{1}{(w_t/c)}, \quad f_Q = 0.004468 \frac{U_c}{a_o} \frac{1}{(w_t/c)}$$

where unit values of f_μ and f_Q correspond to the representative conditions

$$U_o = 100 \text{ ft/sec}, \quad a_o = 1117 \text{ ft/sec}, \quad w_t/c = 4 \times 10^{-4}.$$

FIG. 1.

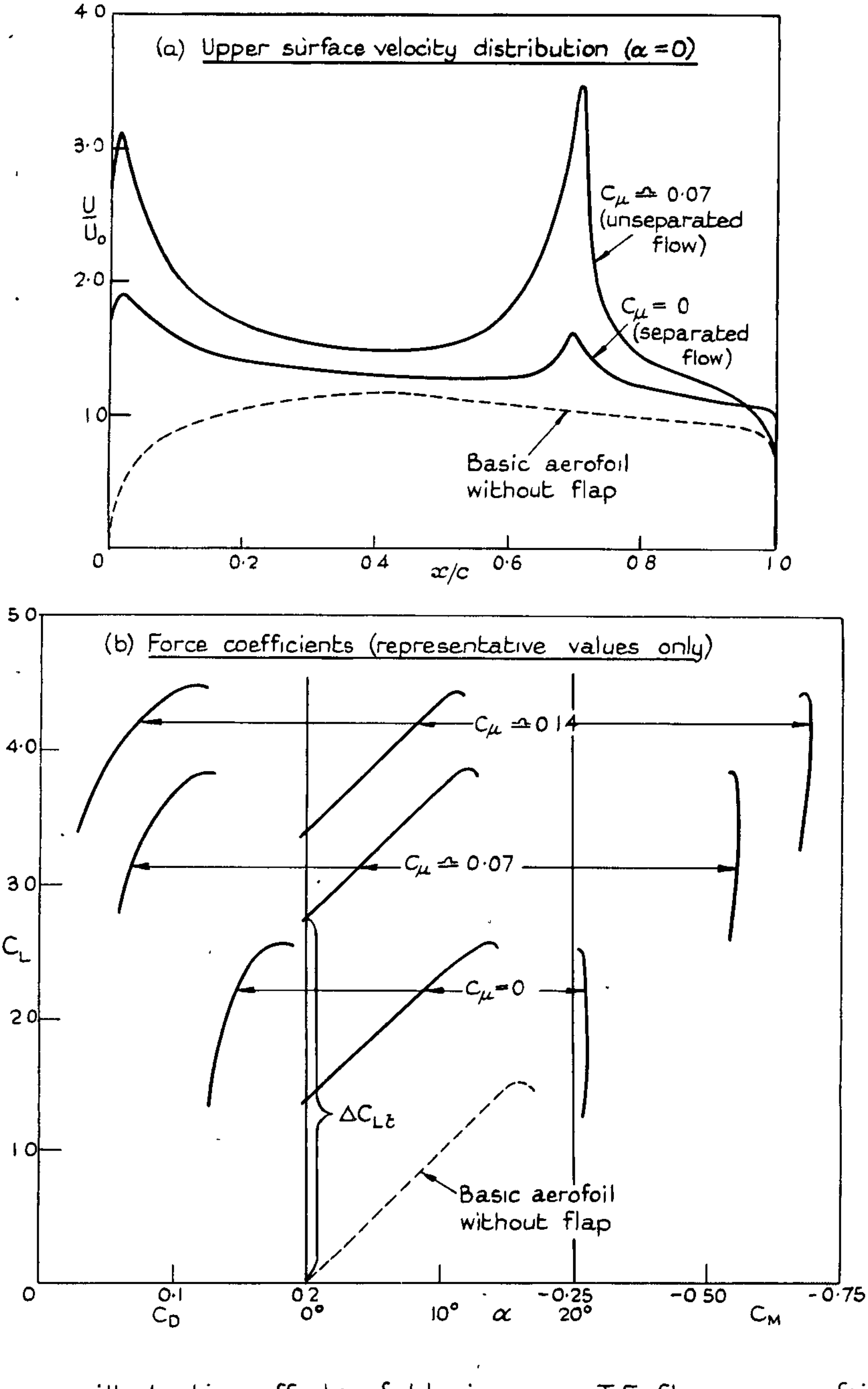
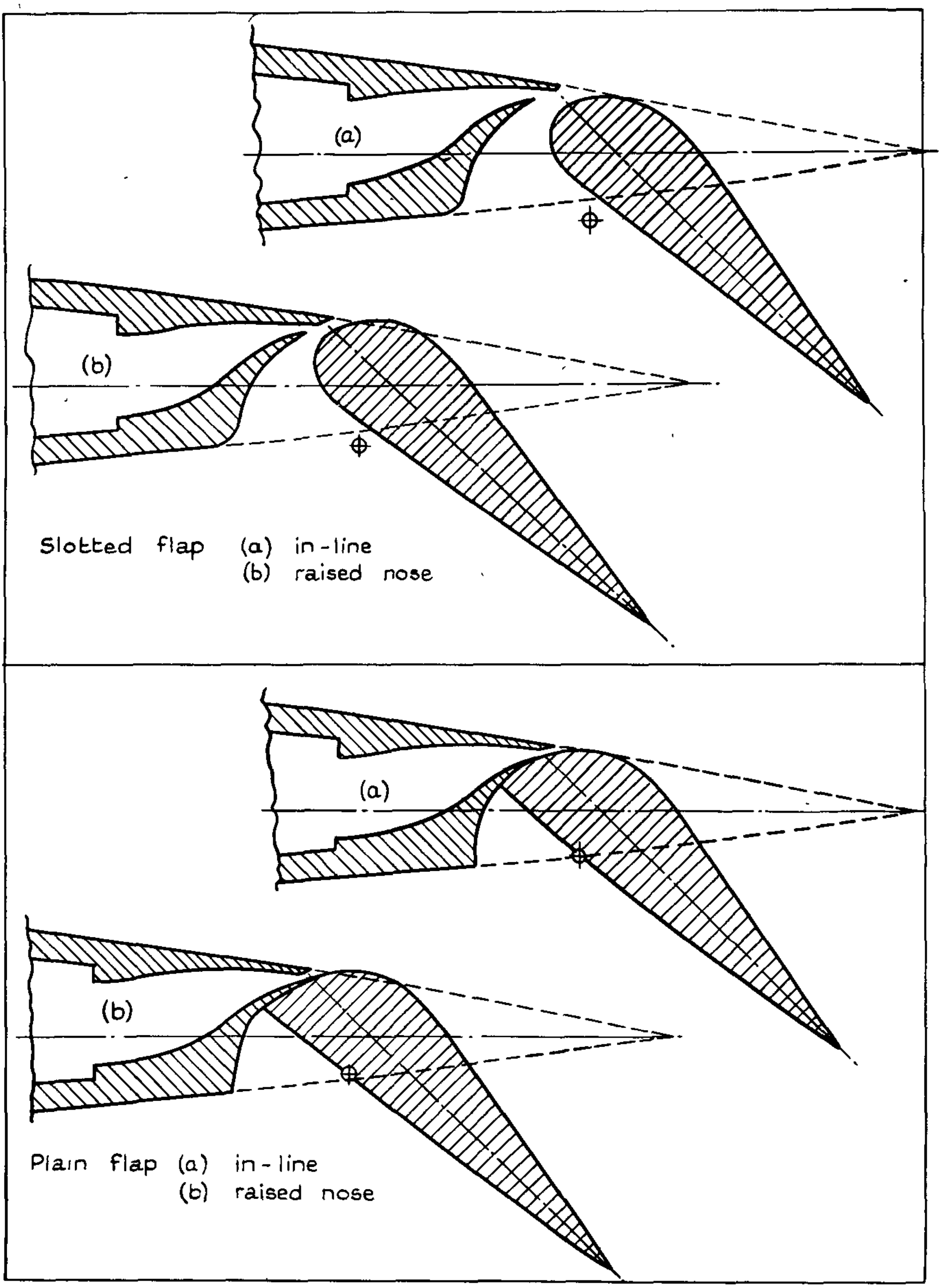


Diagram illustrating effects of blowing over T.E. flap on aerofoil velocity distribution and force coefficients

FIG. 2.



German two-dimensional tests on NACA 23015 with 20% plain and slotted T.E. flaps.

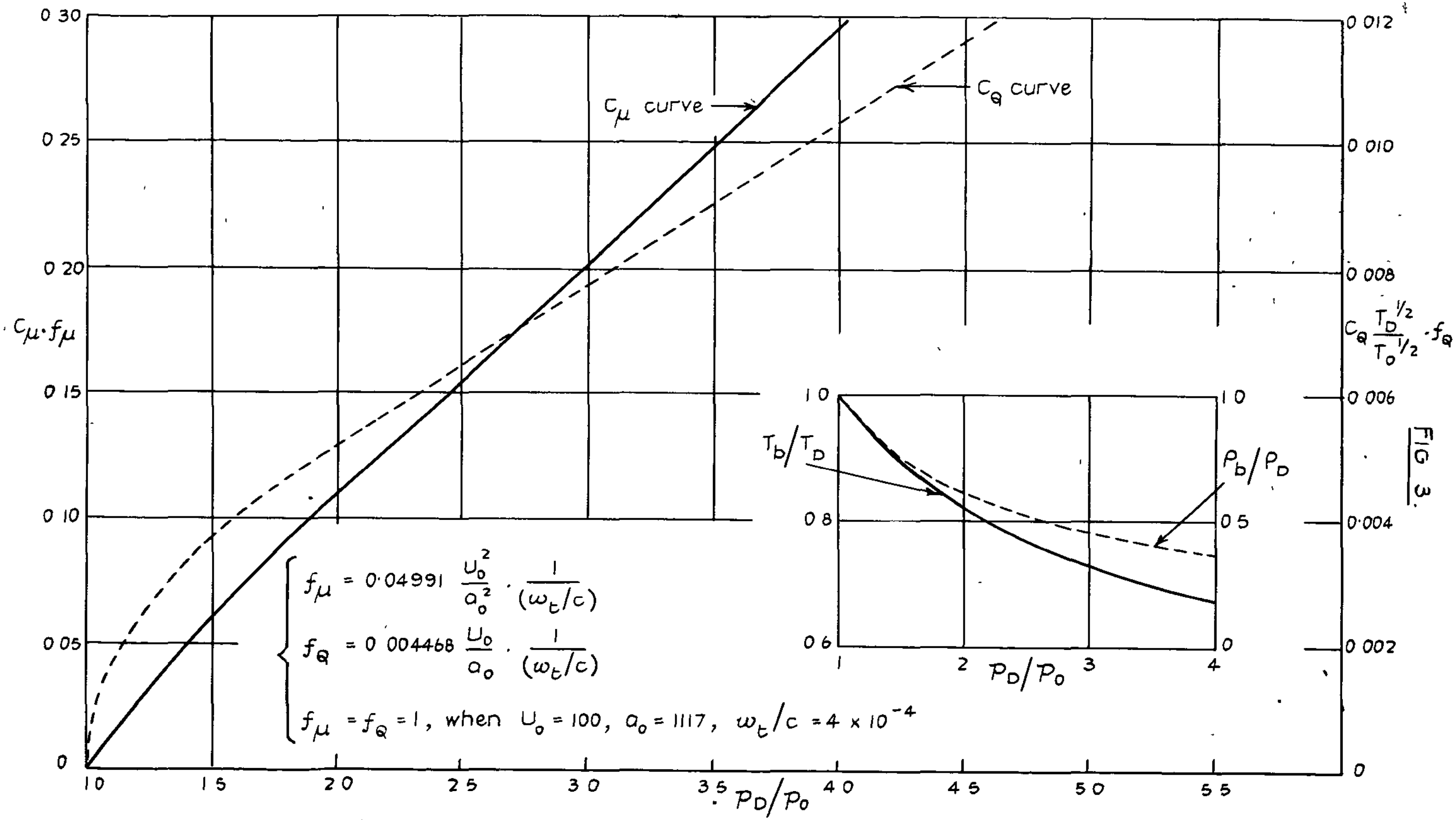
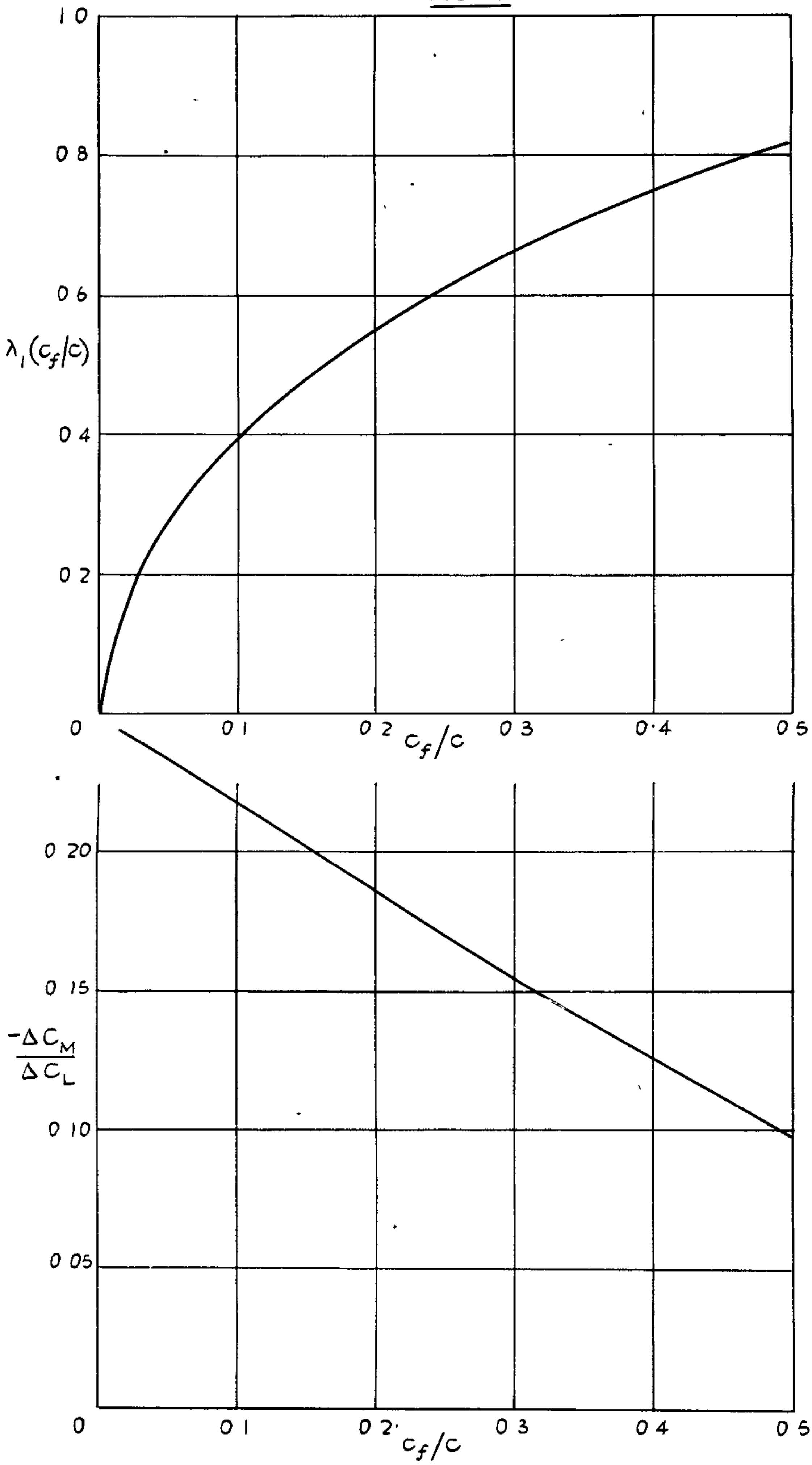


FIG 3.

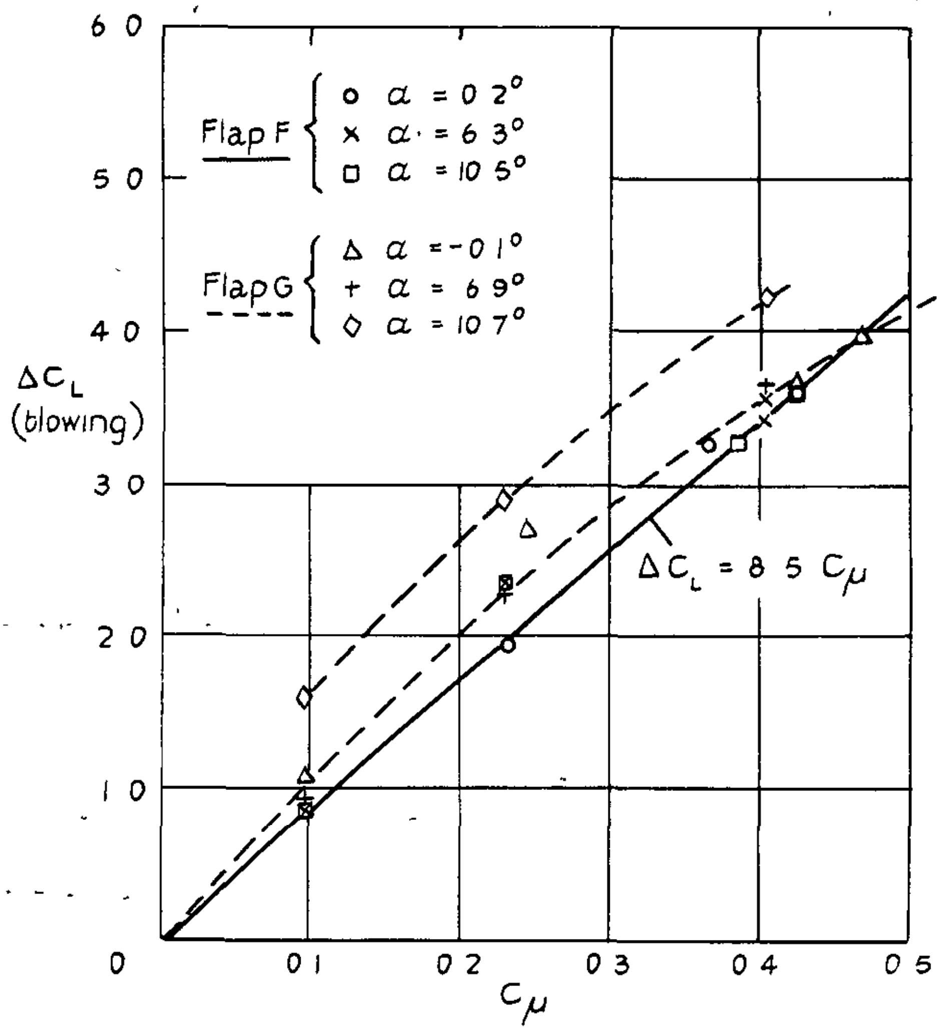
Standard curves for blowing parameters in terms of blowing pressure ratio.

FIG 4



Functions for determination of lift and pitching increments due to flap deflection

FIG 5.



Model data

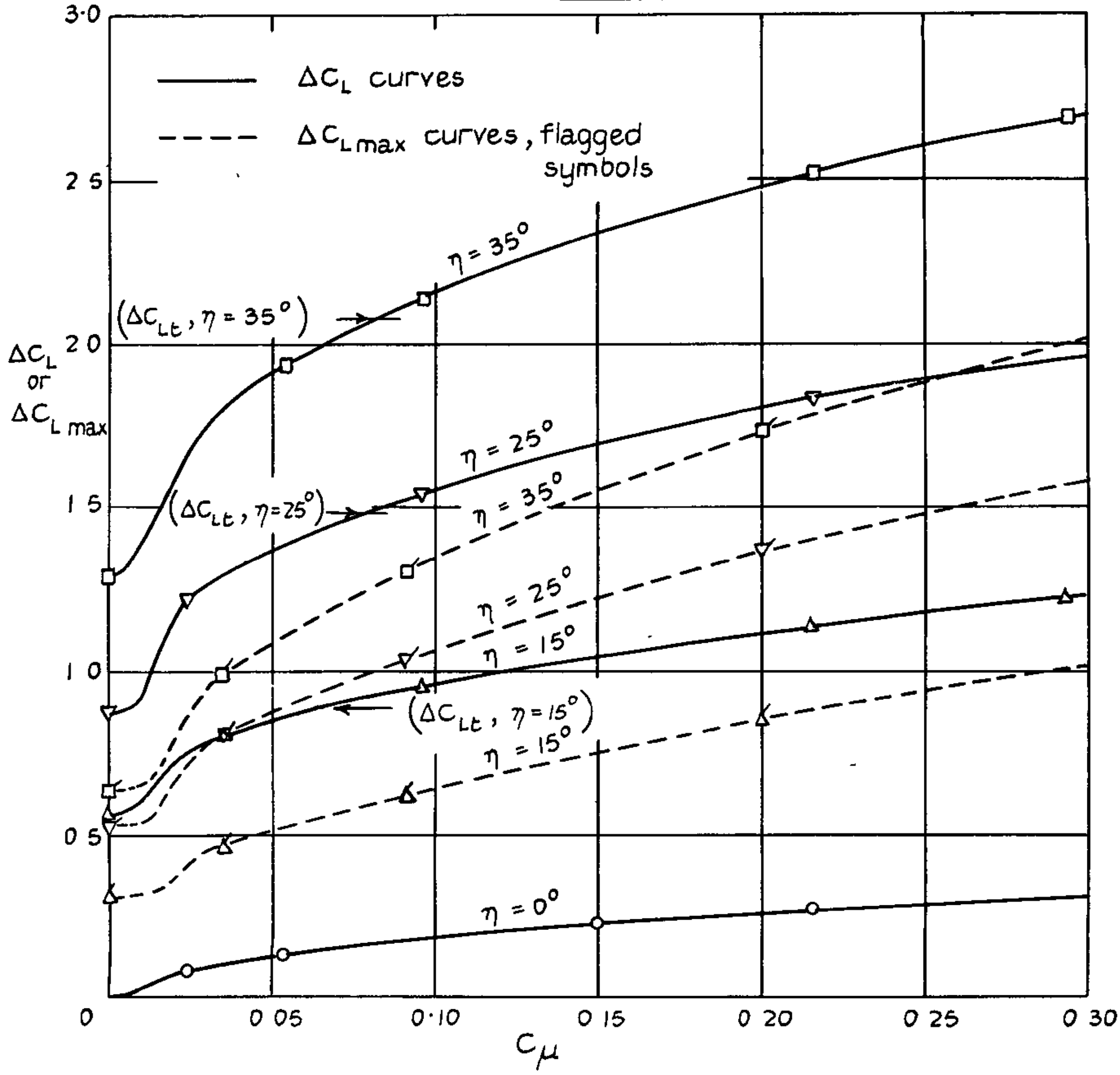
Wing section NACA 2218, $R \simeq 0\ 75 \times 10^6$

Plain T E flaps (a) $c_f/c = 0\ 20$, $c_f/c' = 0\ 185$, $\eta = 60°$ (Flap F)
(extending chord)
(b) $c_f/c = 0\ 50$, $c_f/c' = 0\ 42$, $\eta = 53°$ (Flap G)

$w_t/c = 0\ 0083$

R.A.E. two-dimensional tests on NACA 2218 with plain T E flaps

FIG. 6.



Model data

Wing section ~ NACA 65-012, $t/c = 0\ 12$, $R \doteq 0{\cdot}7 \times 10^6$

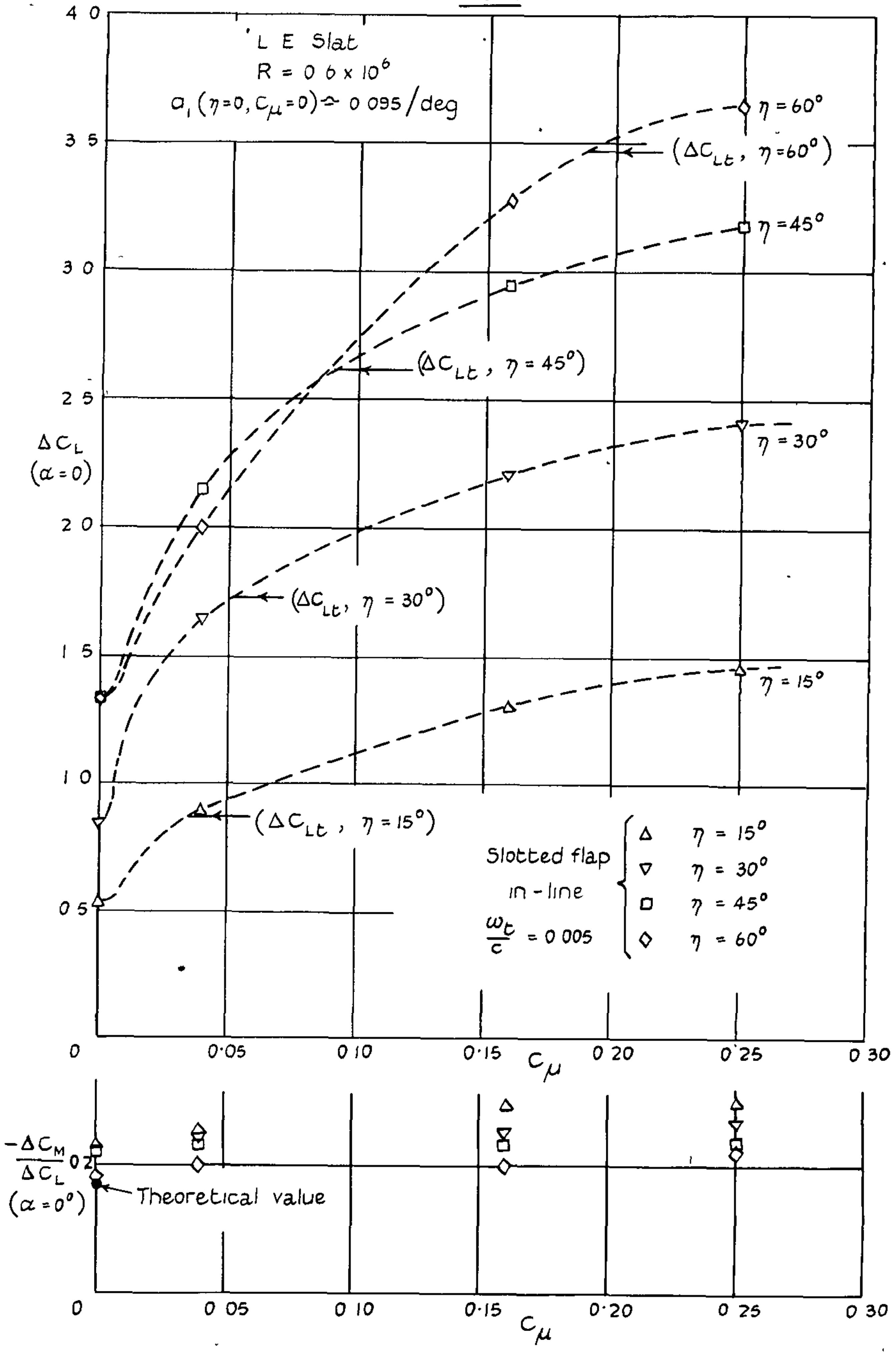
$c_f/c \doteq 0\ 30$, plain flap in-line

$w_t/c = 0{\cdot}0083$

$C_{L\ max}\ (\eta = 0,\ C_\mu = 0) = 0{\cdot}95$, $a_1\ (\eta = 0,\ C_\mu = 0) \doteq 0\ 09$/deg

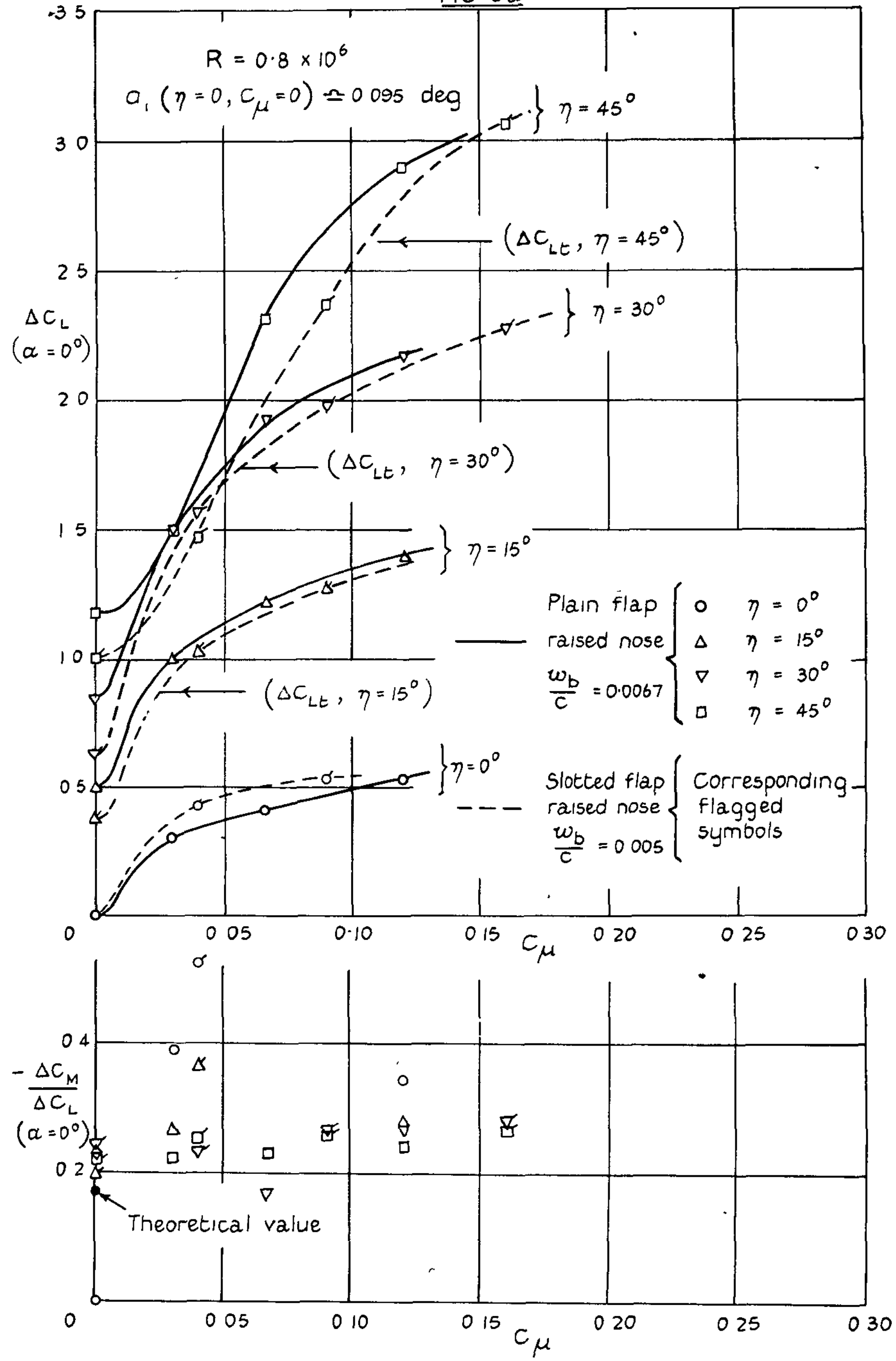
Westland two-dimensional tests on wing with 30% plain T E flap.

FIG 7



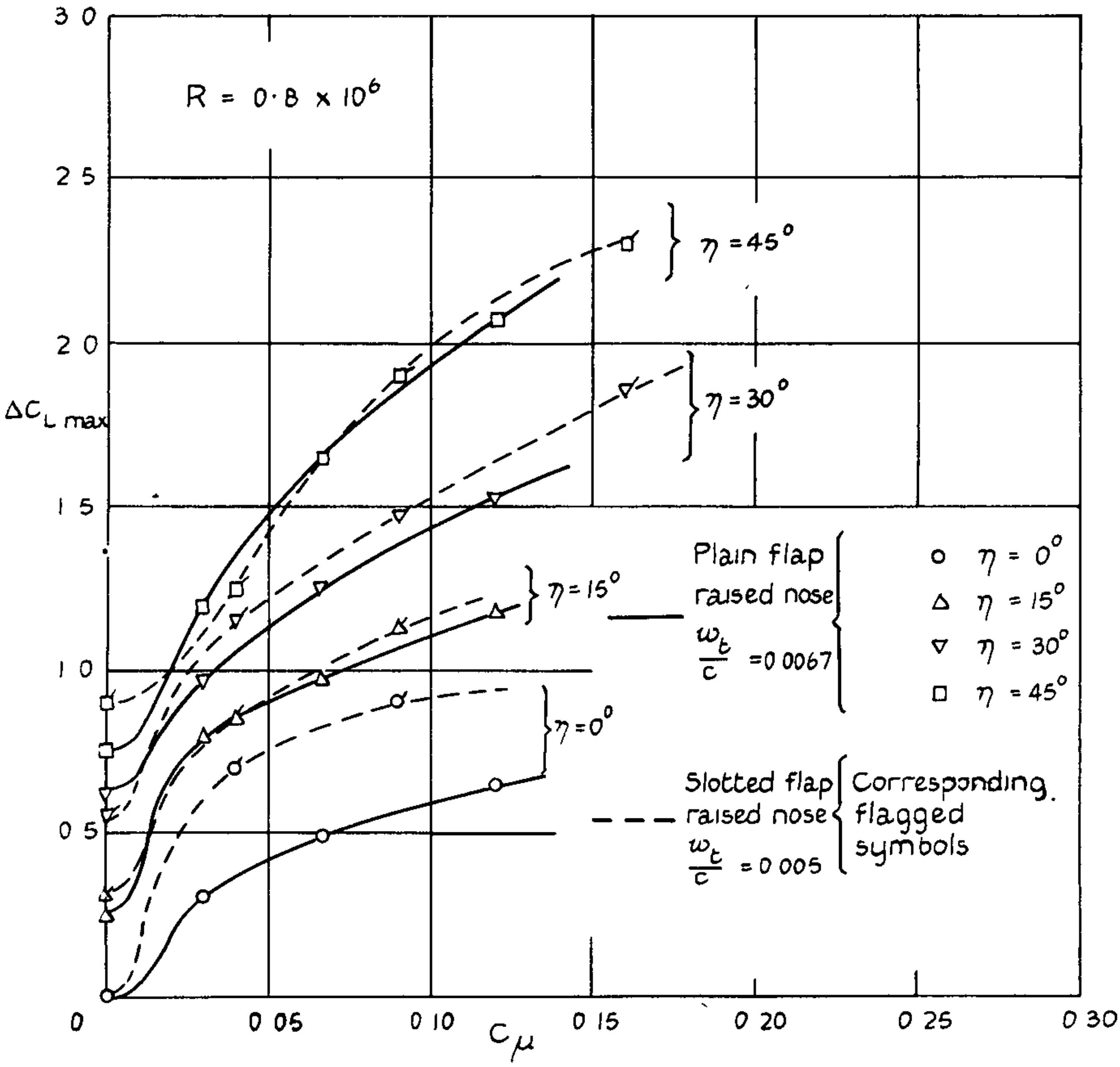
German two-dimensional tests on NACA 0009 with 25% slotted T E flap

FIG 8a



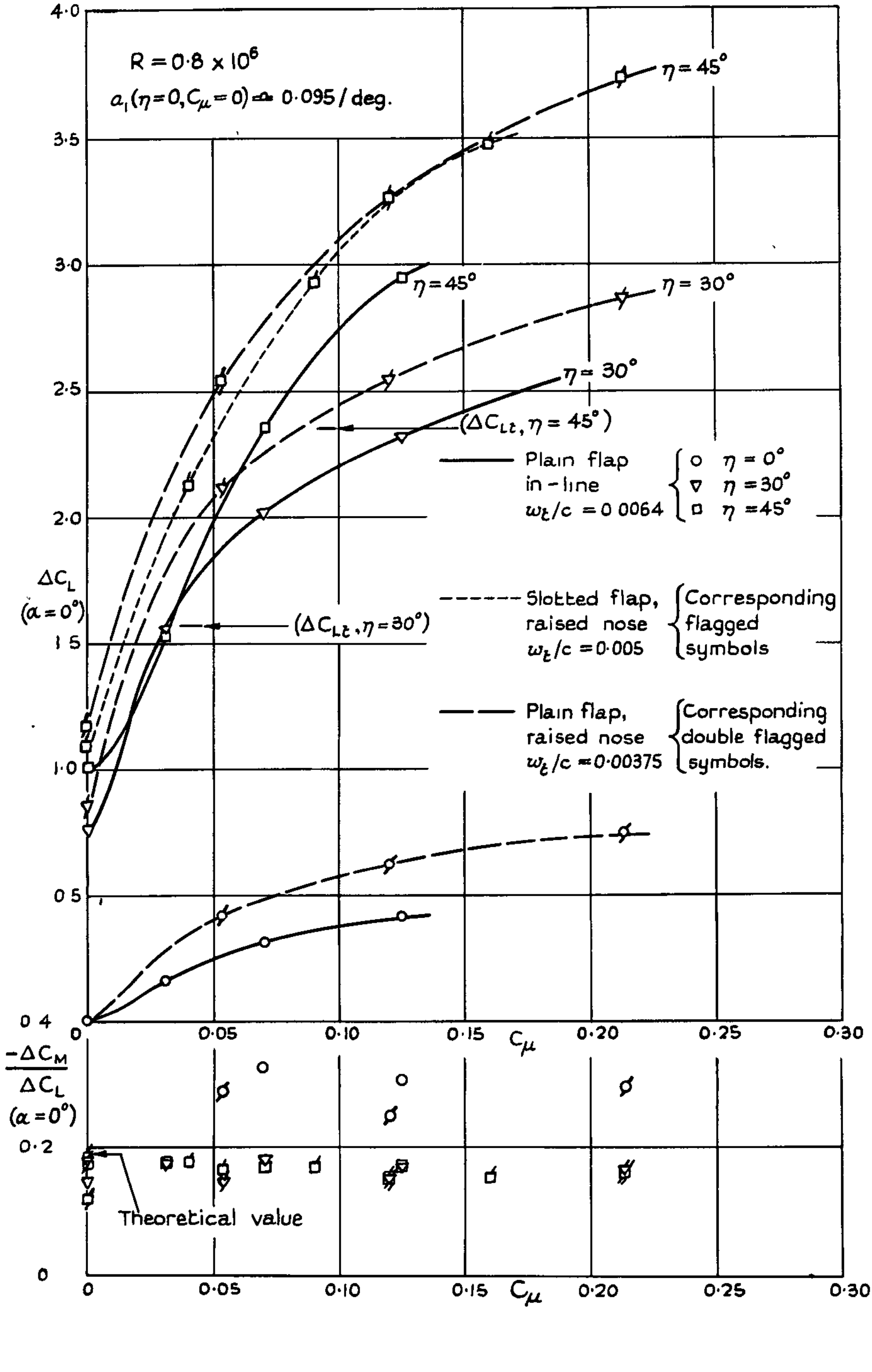
German two-dimensional tests on NACA 23012 with 25% plain and slotted T E flaps

FIG. 8 b



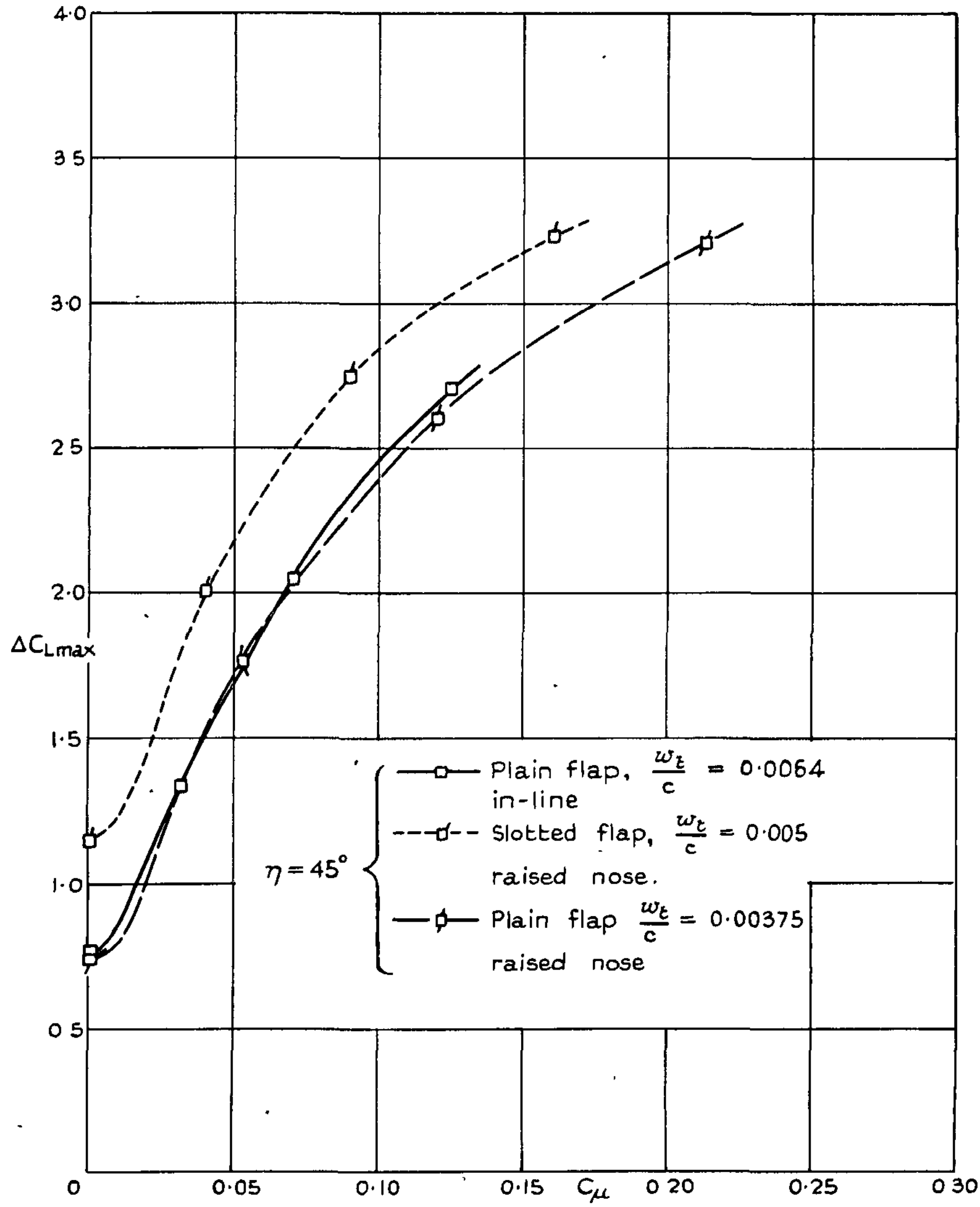
German two-dimensional tests on NACA 23012 with 25% plain and slotted T E flaps

FIG. 9 a.



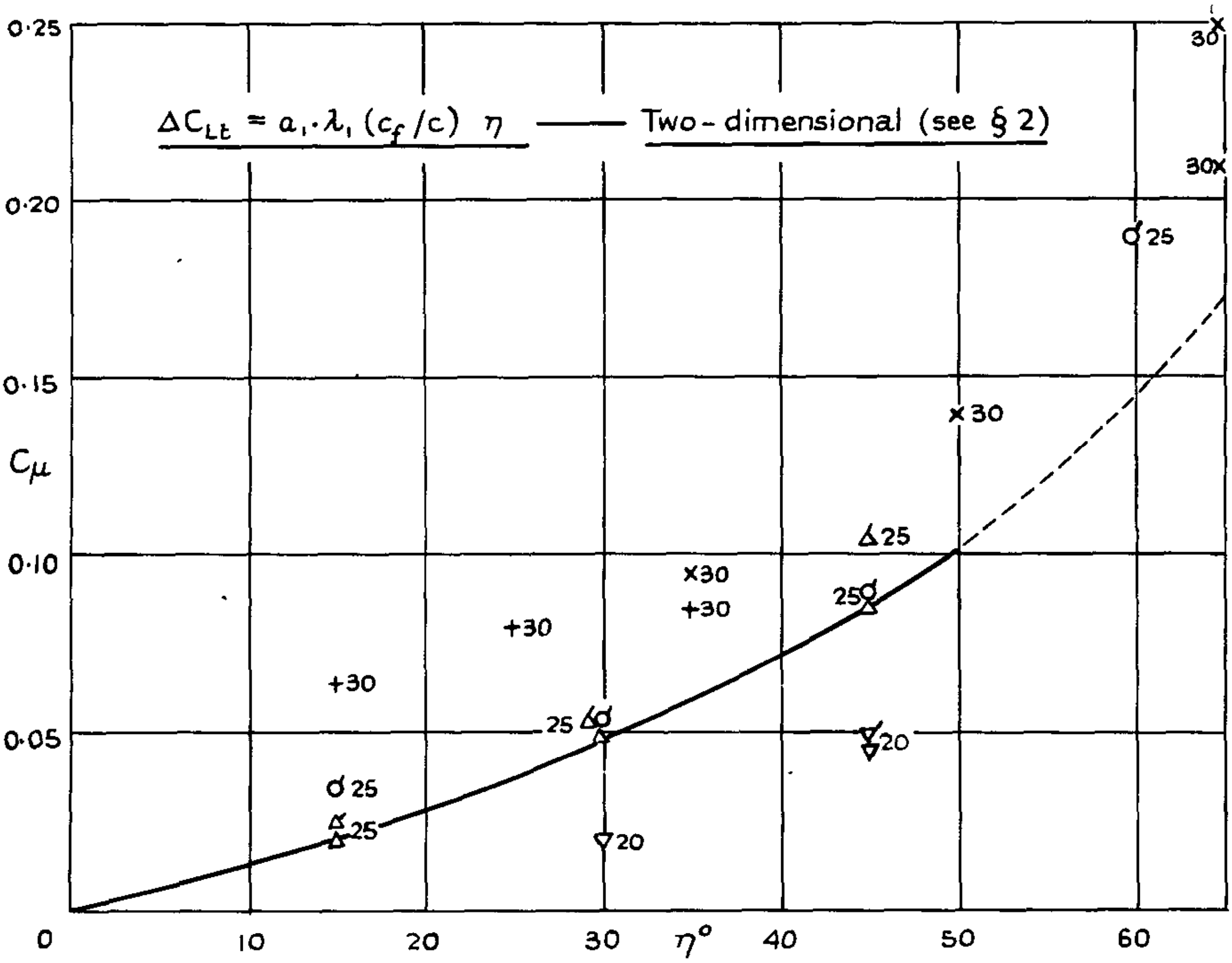
German two-dimensional tests on NACA 23015 with 20% plain and slotted T.E. flaps.

FIG. 9 (b)



German two-dimensional tests on NACA 23015 with 20% plain and slotted T.E. flaps

FIG. 10.



Symbol	Wing	c_f/c	Flap config.	w_t/c	Origin
+	NACA 65-012	0·30	plain, in-line	0·0083	Westland[3]
σ	NACA 0009	0·25	slotted, in-line	0·005	German[10]
△	NACA 23012	0·25	plain, raised	0·0067	German[11]
⍋	NACA 23012	0·25	slotted, raised	0·005	German[11]
▽	NACA 23015	0 20	plain, raised	0·00375	German[12]
⍒	NACA 23015	0·20	slotted, raised	0·005	German[12]
×	Sweptback (with body)	0·30	plain, in-line	0·0069	Westland[4,5]
	$\Delta C_{Lt}(\mathrm{mod}) = a_1 \cdot \lambda_1 (c_f/c) \cdot \lambda_3 (b_f/b) \cdot \eta \cos \Lambda_f$. (see § 4)				

Experimental C_μ - values required to attain datum lift increment.

Model data

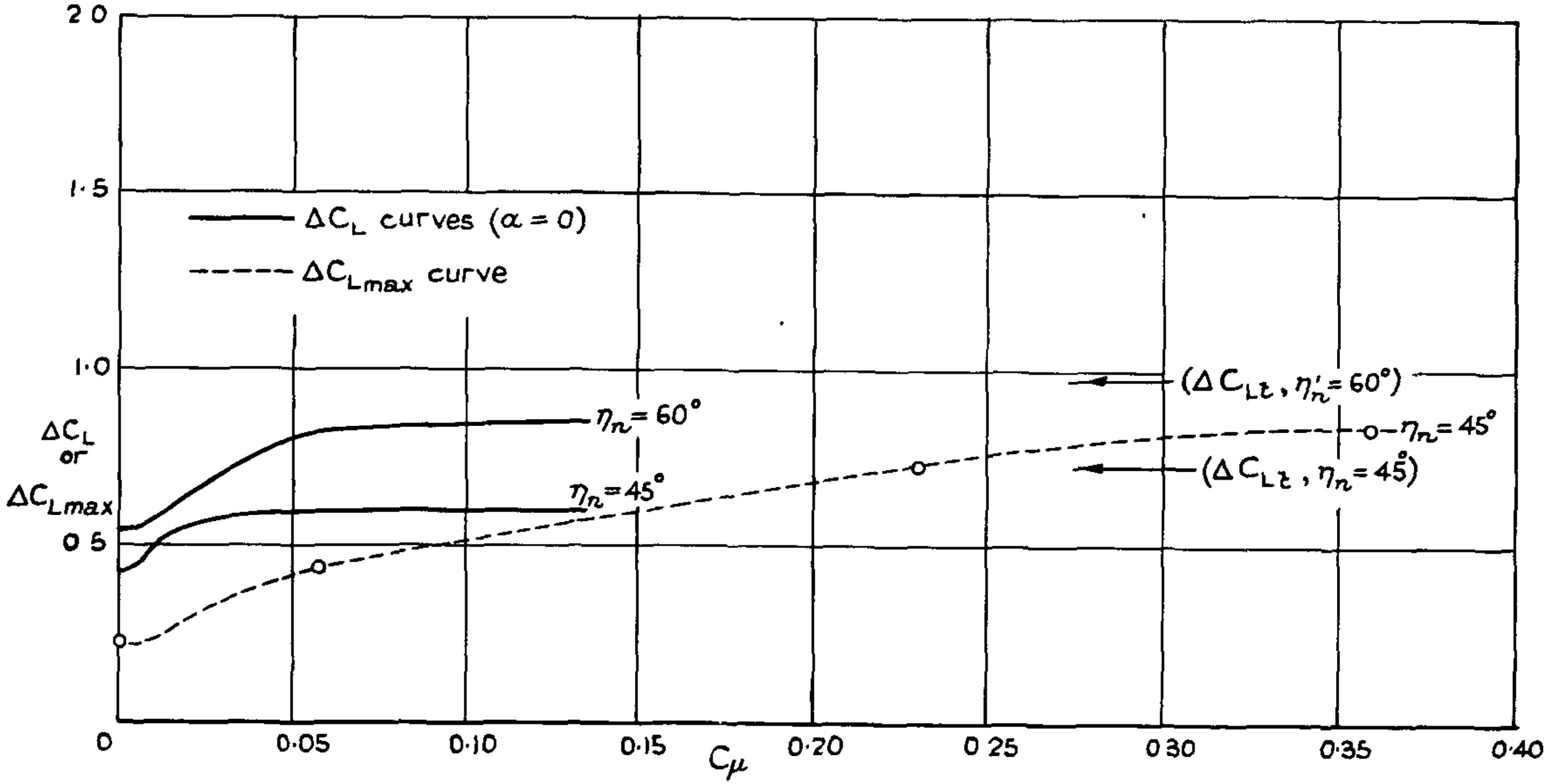
Wing section NACA 23012 normal to L E $R \doteq 1.5 \times 10^6$

Plain flap in-line, $c_f/c = 0.20$, full span. (η_n measured in plane $\perp^r$ flap hinge)

Aspect ratio (no body) 3·8, taper ratio 1, $\Lambda = 45°$

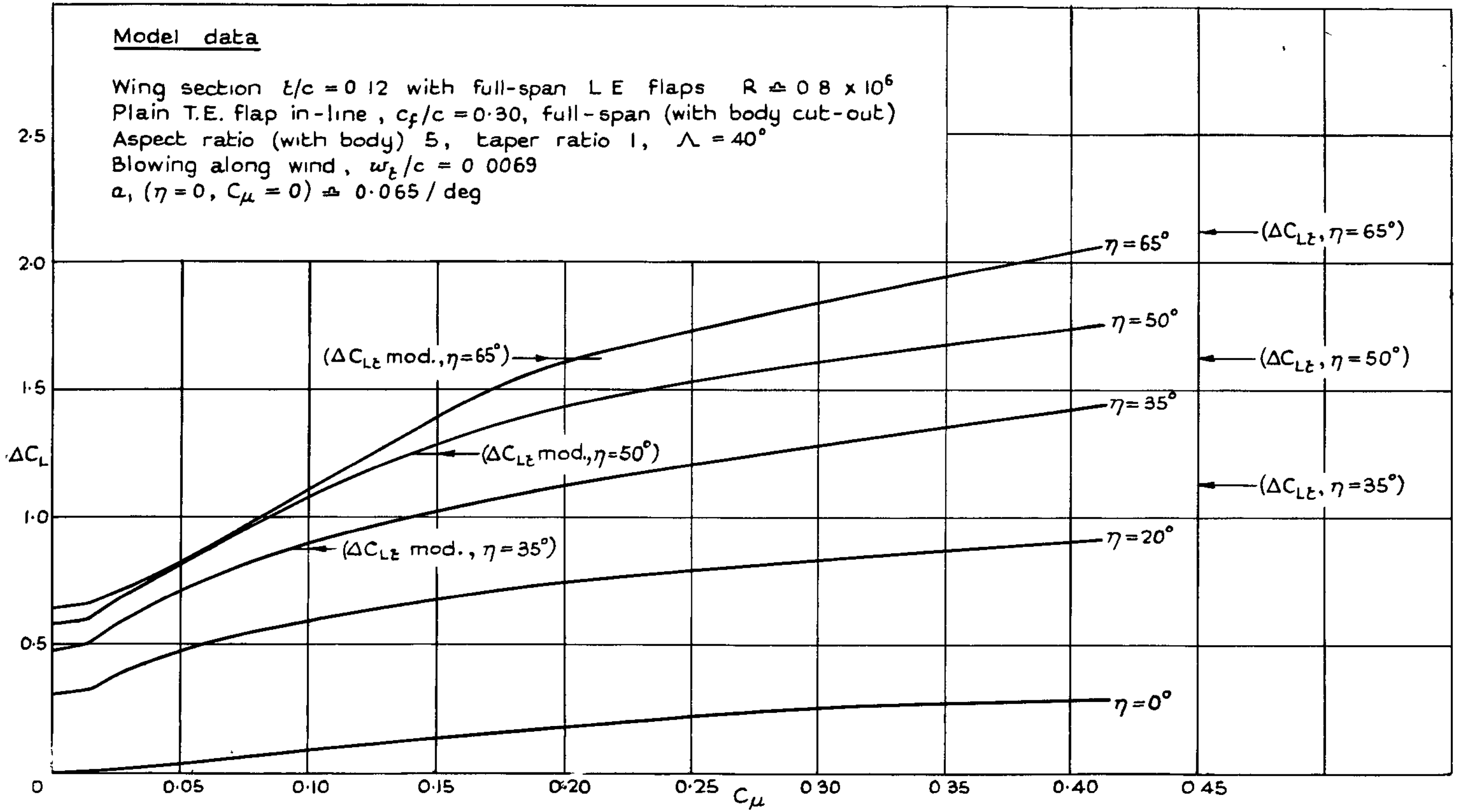
Blowing normal to flap hinge $w_t/c_n = 0.0035$

$a_1 \doteq 0.042$/deg $C_{L\,max}$ ($\eta = 0$, $C_\mu = 0$) $\doteq 1.0$



German sweptback wing tests with 20% plain flap.

FIG. 11.

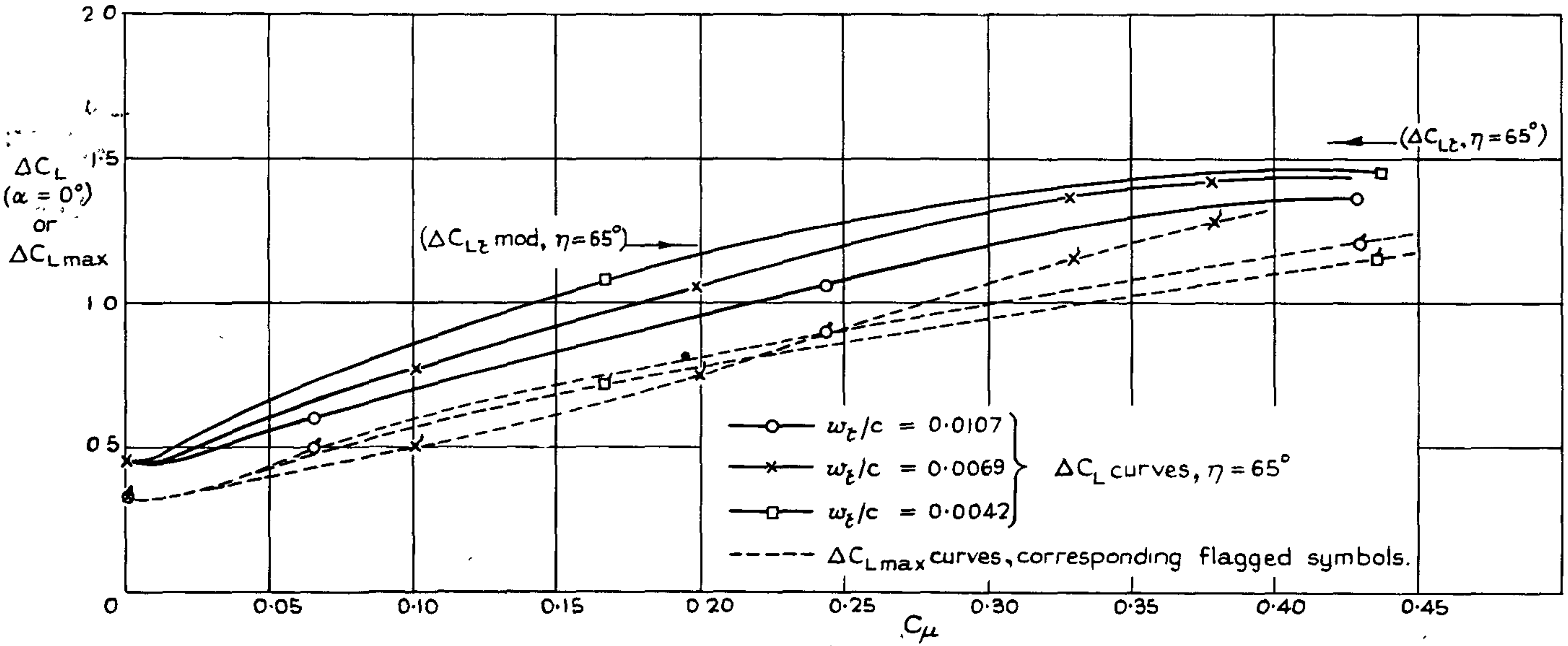


Westland sweptback wing tests with 30% plain T. E. flap. (Old body)

FIG. 12a.

Model data

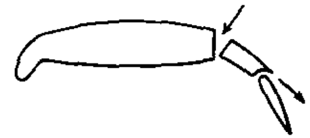
As in FIG 13a except
Improved body with full-span L.E. flaps, part span T.E. flaps, w_t/c varied
a_1 ($\eta = 0$, $C_\mu = 0$) = 0.065/deg. $C_{L max}$ ($\eta = 0$, $C_\mu = 0$) = 1·43

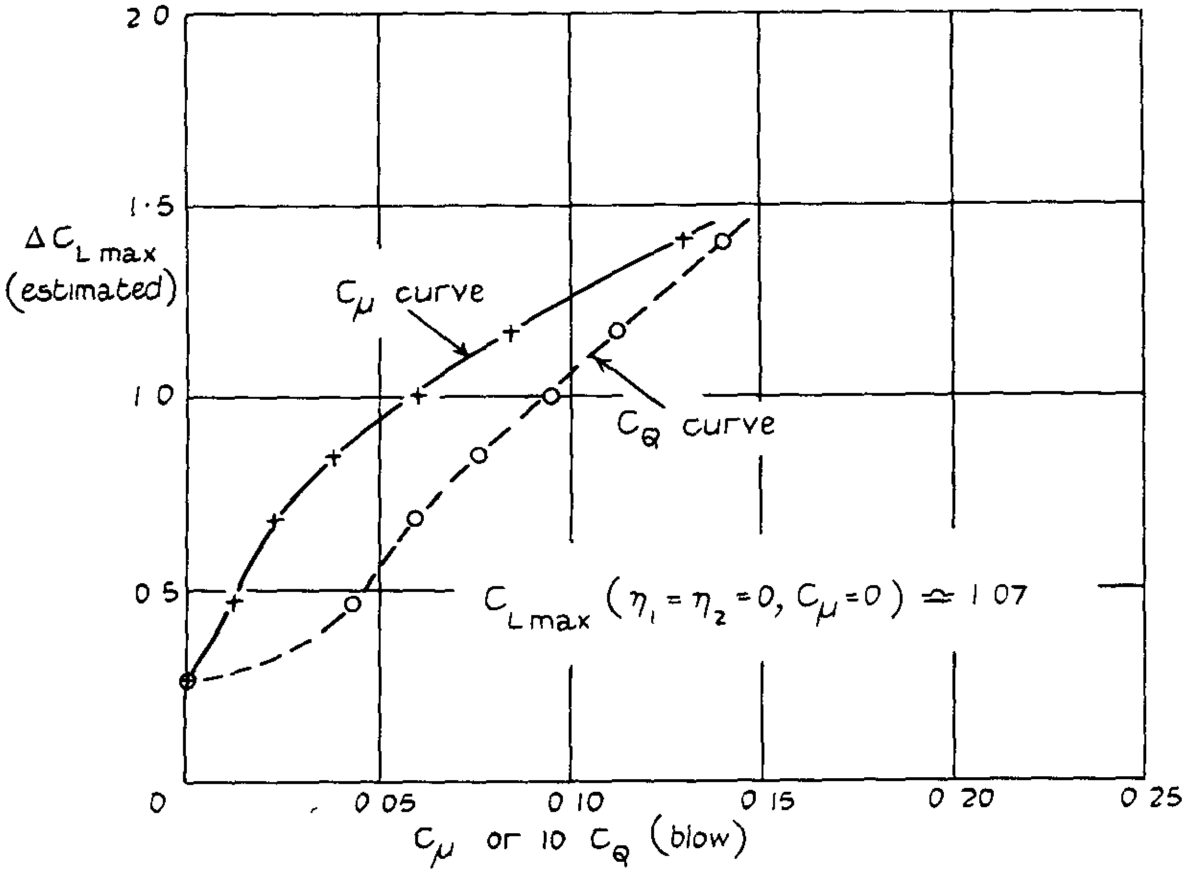


Westland sweptback wing tests with 30% plain T.E. flap. (Improved body)

FIG. 12 b.

Wing section, $t/c = 0{\cdot}10$, $\rho_L/c = 0{\cdot}0057$; with full-span drooped nose, chord $0{\cdot}12c$ at 30° $R \simeq 5 \times 10^6$
Double T.E. flap, $c_{f_1}/c = 0{\cdot}20$, $c_{f_2}/c = 0{\cdot}20$, $\eta_1 = 25^\circ$, $\eta_2 = 45^\circ$, full-span (with body cut-out)
Aspect ratio (with body) = 3.3 , taper ratio 0.49 , $\Lambda = 31^\circ$ at $^1/_4$-chord
Suction at hinge of first flap, $w_t/c = 0{\cdot}044$
Blowing along wing over second flap, $w_t/c = 0{\cdot}003$.





French sweptback wing tests with combined suction and blowing at hinges of full-span double T.E. flap

FIG. 13.

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