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The Characteristics of a Family of Rooftop Aerofoils Designed at their Drag-Rise Condition in Viscous, Compressible Flow

Part II: Off Design Conditions

by

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THE CHARACTERISTICS OF A FAMILY OF ROOFTOP AEROFOILS DESIGNED AT THEIR DRAG-RISE CONDITION IN VISCOUS, COMPRESSIBLE FLOW
Part II: Off design conditions

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B. G. J. Thompson
S. W. Cosby**

SUMMARY

The problems of computing and of presenting off-design variations of profile drag for the new family of rooftop aerofoils described in Ref.1 are examined by considering as a typical example a 50% rooftop section designed at a Mach number (M_{des}) of 0.7 and having a thickness-chord ratio (t/c) of 0.1.

Profile drag results are presented in two ways:

(a) as a set of polar curves of C_D *vs* C_L for a range of Mach numbers, and

(b) as contours of C_D in the C_L-M plane.

Boundaries for rear separation, drag rise, and peak local Mach number equal to 1.2, are shown.

For sections of given t/c and M_{des} the present results indicate that the minimum drag anywhere along the flight locus M^2C_L = constant is obtained by choosing the particular section which has its design point on this locus.

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* Replaces RAE Technical Report 72142 - ARC 34 467.

** Aerodynamicist, Short Brothers and Harland Ltd., Belfast.

CONTENTS

1 INTRODUCTION

A new family of rooftop aerofoils designed at their drag-rise condition* was presented in Part I of this work[1,2] to replace those originally described in TDM 67010[3]. The new family was designed using the iterative scheme, first devised by Powell[4], which incorporates a more accurate compressibiliy law[5] than was used in the original work and also accounts for the principal effects of the boundary layer and wake displacement surfaces on the pressure distribution.

The new camber lines, pressure distributions and design lift coefficients are shown in Ref.2, and are discussed in Ref.1. The values of profile drag and the boundaries for separation at design $C_L \left(= C_{L_{des}}\right)$ were compared with the corresponding properties of the original sections. The new design point calculations were carried out largely under contract placed with Short Brothers and Harland Ltd., of Belfast, and provision was made also within this contract for considering the variation of profile drag in off-design conditions below drag-rise.

The results of the complete set of off-design computations are presented by Cosby in the final contract report[7]. Seven aerofoils were selected from those considered in the on-design study[1] and these permitted each of the design parameters to be varied independently as follows:

(a) The effect of varying design Mach number alone was found from sections** 102-10-40-65, 102-10-40-70 and 102-10-40-75.

(b) Sections 102-14-40-70 and 102-06-40-70, together with 102-10-40-70, allowed the effect of varying t/c to be studied.

(c) Finally, the influence of rooftop length (x_R/c) was found using the additional aerofoils 104-10-60-70 and 103-10-50-70.

The present Report considers the aims of a parametric study such as that undertaken in the Short Brothers' contract and examines the presentation and application of such information.

Following a brief consideration of the ways in which, in the light of possible project applications, a multiparameter drag function might be displayed, the results of typical computations (for section 103-10-50-70) are described

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* Defined here, as in the original work of Refs.1, 2, 3 and 6, by the condition that the local Mach number $(M_e) = 1.02$ at the aerofoil crest.

** See Notation for explanation of section designations.

and then the method of calculation is discussed. Evidence is produced to support its use in off-design conditions over a range of M, C_L, limited by onset of drag-rise, rear separation, and also probable failure of the essentially subcritical flow compressibility assumptions once extensive regions of supersonic flow are predicted near the leading edge. These limitations are discussed and finally the results, together with additional information taken from the data report[7], are used to demonstrate the comparative performance of different sections, with particular reference to their behaviour on the simple flight locus $M^2C_L = 0.288$. This locus passes through the design point of section 102-10-40-70.

2 THE PRESENTATION AND USE OF THE DRAG FUNCTION

To avoid prejudging the needs of the designer, the results of a parametric study should be presented in the most general form. Consequently, the simplest basic variables such as C_L, x_R/c should be used rather than specialised combinations such as C_L/C_D, M^2C_L, for example.

For any given t/c and combination of Reynolds number and transition positions, the profile drag depends on any two of the remaining three parameters $\left(C_{L_{des}}, M_{des} \text{ and } x_R/c\right)$ of the design point, as well as the local (off-design) values of M and C_L. That is,

$$C_D = f\left(M, C_L, t/c, R_c, [x_{tr}/c]_u, [x_{tr}/c]_\ell, C_{L_{des}}, x_R/c\right), \text{ for example.}$$

For compatibility with Ref.1 the value of $R_c = 10^7$, together with upper and lower surface transition positions at 0.05c, has been used and hence attention is now restricted to the remaining five-parameter relationship.

As the variables group naturally into design parameters, $\left(C_{L_{des}} \text{ or } M_{des}, t/c, x_R/c\right)$ specifying a section, and local coordinates M, C_L, specifying a possible operating condition, we can envisage two principal alternative presentations:

(a) Showing the variation of C_D with M and C_L for *a given aerofoil* over its permissible subcritical range, and

(b) showing the variation of C_D at *a given operating condition* (M, C_L) produced by considering all members of the family of aerofoils that are not beyond their drag-rise condition at the point M, C_L.

These two alternatives are sketched, in Figs.1a, 1b respectively, where the variation of drag is shown in contour form. So far the number of computations made is insufficient to permit a presentation of the type shown in Fig.1b and presentations only as Fig.1a are given subsequently.

In the most general terms the designer is interested in:

(i) The drag variation with M and C_L for a given section. This may be subject to certain constraints, as for instance the locus of flight at constant weight and altitude, M^2C_L = constant, or

(ii) the exchange between C_D at a given operating point (M,C_L) and the various design parameters of the sections.

For example, Pearcey[9] investigates briefly the effect of varying x_R/c at a given $t/c(= 0.12)$ and $R_c(= 2 \times 10^7)$ on the drag at (M,C_L) of sections with either $M_{des} = M$, $C_{L_{des}} > C_L$ or $C_{L_{des}} = C_L$, $M_{des} \geqslant M$. The implication is that the least drag at M,C_L is obtained by using the flat rooftop section designed at that point $\left(\text{that is, for } M_{des} = M,\ C_{L_{des}} = C_L\right)$ rather than another section below its design rooftop condition.

The flight profile for a given type of aircraft will encompass a range of M^2C_L conditions and could be drawn as a band on Fig.1a, very conveniently, if t/c were close to a chart value.

Alternatively, the behaviour of different sections, for a given t/c, at a series of values of M,C_L in the operating band could be visualised quickly from Fig.1b. Also the range of permissible sections having zero or positive margins at M,C_L is identified immediately.

The best choice of graphical presentation will vary according to application. Multiple interpolation is unavoidable including that between charts or within multiple carpets.

Past experience[10,11] in the production and use of graphical presentations of multiply-parametric relationships, has indicated that the contour plots of the kind in Fig.3, would be most convenient in practice. This has proved so far to be the case although greater detail and accuracy near to the design point is now thought to be necessary and contours for every 0.0001 in C_D are desirable.

The best way of using the off-design results would undoubtedly be to store the point values of the drag function in a small computer and to use existing visual on-line display programs to present rapidly the drag behaviour interpolated to the exact design or operating points required or worked out along suitable loci intersecting the 'five-dimensional solid'. Drag optimisation could be achieved by a trial and error conversation or a formal searching routine.

The storage requirements ($<$ 4000 points) are small and the cost should be low. The flexibility of this method would be preferable to hand calculations and the manipulation of multi-parametric functions should be of interest outside aeronautical problems.

3 OFF-DESIGN CALCULATIONS FOR A PARTICULAR SECTION

3.1 Drag-polars

The computed values of drag for 103-10-50-70 at $R_c = 10^7$ are shown as ringed points in Fig.2, to give an idea of the amount of effort needed to define the off-design behaviour of a given section. About 30 to 40 runs are required as a minimum for full coverage from $M = 0.3$ to drag rise and/or the predicted separation boundaries.

The polars are rather more curved than a simple parabolic form for each Mach number.

3.2 Contour plots

The results have been cross-plotted to give the drag contours in the $C_L - M$ plane (Fig.3). The drag-rise boundaries are shown for both surfaces. The design point loci are shown for the new 10% thick sections having 50% rooftops. The design point loci lie *below* the drag-rise boundary for a range of values of C_L larger than the design value at D of the section, as Ref.9 suggests. Fig.4 shows this more clearly and includes curves for 102-10-40-70 as well as 103-10-50-70.

The hatched areas on Fig.3 are rough indications from the Powell program* of where the leading edge laminar separation is about to occur at or ahead of the assumed transition position 0.05c.

The boundary for possible rear separation is assumed to occur when $H_{TE} = 2.8$ and this provides a less severe restriction on the performance of this particular section.

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* RAE (Teddington) program JWDOBP506 in KDF9 ALGOL.

3.3 Mach number distributions and crest location

Typical upper surface distributions of local Mach number are plotted, in Fig.5, for different conditions B to F (see also Fig.3) along the drag-rise boundary. The maximum peak value of M_e is about 2.3 for B.

Condition A, at the low Mach number end (M = 0.3) of the separation boundary has a high peak of $C_p = -4.7$ but is subcritical everywhere.

4 DISCUSSION

4.1 The method of calculation

Before assessing the present results in practical terms, it is important to establish that the simple method[4] used here is a satisfactory means of predicting pressure distributions and profile drag in off-design conditions.

In subcritical flow there is ample experimental justification for the present method as a means of predicting pressure distributions (see Powell[4], Lock, Wilby and Powell[5], for example) provided comparisons are made at the same lift coefficient. The present approach and the more recent one produced by Firmin[8] both employ the same compressibility law devised by Lock[5]. They differ, however, in their treatment of the turbulent boundary layer and wake. It is encouraging to notice, therefore, in Fig.6 the good agreement for both pressures and drag values between these methods for a situation which is well away from the section design point $\left(C_{L_{des}} = 0.68,\ M_{des} = 0.7\right)$ and has not only a large upper surface velocity peak followed by a concave form of pressure recovery, that is very different from the design condition, but also exhibits a moderate amount of rear loading. The quite reasonable agreement between the two methods, as far as displacement thickness is concerned, is demonstrated in Fig.7.

Fig.8, shows the good agreement between profile drag values obtained from the two methods over a wide range of off-design Mach numbers for the same aerofoil (103-10-50-70) and for one with a 40% rooftop. This comparison is made for the locus $M^2 C_L = 0.288$. The agreement between the two methods is everywhere within $2\frac{1}{4}$%, but of even greater importance is the fact that the *relative* behaviour of the two sections is nearly the same whichever method of prediction is chosen.

The range of conditions of Mach number and C_L for which the predictions are valid is limited by,

(a) the appearance of shock waves of sufficient strength to affect the profile drag noticeably - this is the 'drag-rise' condition.

(b) The failure of the present compressibility assumptions in the pressure prediction method once supercritical flow occurs to any appreciable extent, and thirdly,

(c) separation of the boundary layer.

These limitations are discussed below.

4.1.1 Drag-rise boundary

The criterion used here for the probable onset of drag-rise is the same in principle as that first adopted for the original rooftop family. This criterion is supported experimentally, as shown in Ref.6, for older types of section and argues that wave-drag will not become noticeable until shocks reach the crest of the aerofoil; further that this will occur when the local Mach number at the crest is 1.02, as predicted by using subcritical methods in conditions beyond their strict physical limits. It is also required that the suction loops generated at the leading edge in incompressible flow, at a related incidence, showed exhibit a hollow form to avoid premature drag 'creep'.

For the present type of section, at least near design point, these conditions are satisfied and in general we may expect that most of the present drag-rise boundaries will be pessimistic rather than optimistic. This contention is supported in Fig.9, where the theoretical drag-rise boundary is compared with measurements of the conditions for the occurrence of the initial steep drag rise for a 35% rooftop section similar* to a member of the present aerofoil family.

The accuracy of prediction of the condition for which the crest $M_e = 1.02$ depends on three factors:-

(1) Comparison with experiment suggests that, at a given C_L, the Powell method predicts an incidence lower than tunnel measurements by 0^o to 0.3^o, depending on Mach number. The effect of this on the crest position could represent an error equivalent to up to 0.003 in M_e or 0.01 in C_L on the drag-rise locus.

(2) Simple graphical or numerical differentiation using only the 16 Weber ordinates could be equivalent to a crest uncertainty of ±0.007c (Fig.10). This leads to about half the uncertainty due to (1).

(3) Interpolation to find C_p or local Mach number at a given x/c is usually very accurate except for crest positions near the end of the rooftop. Thus at incidences well below design (F in Fig.5, for example) there is a further error equivalent in magnitude to (1).

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* But with rather more rear loading.

The overall accuracy of the boundary is therefore roughly ±0.015 in C_L and ±0.005 in M_e. The cross-over of the design point and drag-rise curves is thus confirmed for 102-10-40-70 (Fig.4) but the result for 103-10-50-70 is less certain.

4.1.2 Pressure and profile drag prediction with supercritical flow present

Assuming the drag-rise criterion to be satisfactory and that there is negligible wave drag at this condition, it is still not certain that the pressures in the supercritical region ahead of the crest are predicted accurately enough to provide satisfactory values of profile drag. This will probably depend on the magnitude of the predicted peak Mach number. In Fig.5, condition C is probably acceptable, but condition B is certainly not.

Nieuwland's exact solutions[12] for shock-free transonic flow around aerofoils of a special type might possibly be useful as a test of the present compressibility laws in supercritical flow, although direct measurements of the behaviour of sections of the present type are also desirable.

For the present purposes, a boundary is marked on the figures showing where the predicted peak local Mach number on the aerofoil upper surface reaches 1.2.

4.1.3 Separation

The problem of choosing a criterion of 'significant trailing edge separation' was discussed briefly in Ref.1. It was shown (Fig.7 of Ref.1) how the predictions for trailing-edge properties (such as H, C_f, etc.) of the turbulent boundary layer vary quite slowly with C_L at a given off-design Mach number. Hence there was a large uncertainty in any attempt to predict a value of C_L at separation for a given section. The difficulty is not resolved by changing to another method of boundary-layer prediction as it is essentially an interaction problem.

If a more detailed pressure prediction is obtained near the leading edge, a method of predicting the possible growth and bursting of short laminar bubbles (see Ref.13) could be incorporated and this should clarify the nature of the separation behaviour at least at low Mach numbers. For values of $C_L > 1.1$, approximately, the 103-10-50-70 section has a value of H at the trailing edge that is larger than 2.8 so rear separation is likely anyway[3].

4.2 Transition

The present choice of a transition position at 0.05c is a reasonable approximation to conditions at moderate flight Reynolds numbers and can be regarded as a representative 'leading-edge' value suitable as a basis for applying sweep factors.

At values of C_L, near to the separation boundary, a sharp leading edge velocity peak (see, for example in Fig.6) forms on the upper surface. This peak will induce transition ahead of the position assumed in the present calculations. The latter may therefore underestimate systematically the true drag increase with rising C_L. The forward movement of transition in real flows will also increase the likelihood of rear separation.

4.3 Application of the present results

For section 103-10-50-70, the variations of C_D along the drag-rise boundary and along a possible constant-altitude flight locus $M^2C_L = M^2_{des}C_{L_{des}} = 0.33$ are shown in Fig.11, using the results presented in Fig.3. The slight decrease of C_D for Mach numbers lower than the design value along M^2C_L = constant is easily seen. C_D falls with falling C_L along the drag-rise boundary until it reaches a minimum at $M = 0.74$ at about half the design C_L value. The boundary terminates at about $M = 0.76$ after a slight rise in drag, when the flow on both surfaces becomes critical.

The magnitude of the range parameter MC_L/C_D rises continuously (see Fig.12) from the design value at D as the Mach number falls along the flight locus.

The importance of a parametric study lies not in the prediction of individual aerofoil behaviour but in the possibility of showing comparative behaviour between different sections. As mentioned in the Introduction sufficient computations have been made to allow exchange rates to be evaluated for the separate effects of t/c, M_{des} and x_R/c. The reader is referred to Ref.7 for the full presentation. Two comparisons only are presented here, namely:

(a) The effect of rooftop length on the drag variation along the locus $M^2C_L = 0.288$ (see Fig.13), and

(b) the effect of rooftop length on the flow boundaries for aerofoil upper surfaces in the M,C_L plane (see Fig.14) and hence upon the M^2C_L margins to possible onset of shock-wave drag or rear separation.

Combination of information from Figs.13 and 14 then permits a rapid evaluation of the exchange between available g-margins (say) and drag level at cruise.

Fig.13 shows clearly that, as suspected by Pearcey[9], there is no advantage in running longer rooftops below their design condition and that the least drag on a given M^2C_L = constant locus is obtained by using the aerofoil section designed on this locus $\left(\text{i.e. with } M^2_{des}\ C_{L_{des}} = M^2C_L\right)$. This comparison refers to sections with given t/c and design Mach number.

It may be objected that any discussion of boundaries, such as mentioned in connection with Figs.13 and 14, would be of limited practical value in view of the shortcomings of present aerofoil prediction methods (see sections 5.1.1 to 5.1.3, above). However, unless a parametric study is made, no ideas can be ascertained of the relative importance of different bounding criteria. Indeed, it is already useful to notice, for example, from Fig.14, that the predictions are often limited less severely by possible rear separation than by a possible breakdown in the model of the potential flow (Mach number at peak becomes greater than 1.2).

5 CONCLUSIONS

(i) For off-design conditions, the drag predictions used here are adequately supported by good agreement with results from Firmin's more recent method.

(ii) The compressibility assumptions due to Lock need testing in supercritical flow. Nieuwland's exact solutions for transonic shockfree aerofoils might be used, although measurements of the behaviour of the present type of section are also required.

(iii) Further investigation is urgently needed to enable predictions of drag to be made when moderate rear separations are present. Criteria of significant separation effects are required for design purposes.

(iv) A further analysis along the lines indicated in this paper of the calculations presented in Ref.7 would be helpful in providing a guide for the choice of aerofoils in project applications.

(v) For aerofoils of a given t/c and M_{des}, application of the present results suggests that the least drag can be obtained, for a given flight locus M^2C_L = constant, if the section chosen is that which has its design point on that locus.

(vi) The drag-rise boundary in C_L for a given aerofoil at $C_L > C_{L_{des}}$ is higher than for an aerofoil of the present rooftop family designed at that C_L and with the same t/c.

Acknowledgments

The authors thank Mr. H.H. Pearcey, Dr. R.C. Lock and other members of the Transonics Committee of the Royal Aeronautical Society for helpful discussion especially concerning the forms of presentation.

NOTATION

c	aerofoil chord length
C_L	lift coefficient
C_D	drag coefficient
C_f	coefficient of local skin friction
C_p	pressure coefficient
H,G	conventional boundary layer profile shape factors
M_e	local Mach number
M	freestream Mach number
R_c	chord Reynolds number of aerofoil
u	local velocity inside boundary layer
U_e	local external freestream velocity
x	coordinate distance along chord
x_R	value of x at end of rooftop
t	thickness of aerofoil
TDM	Transonic Data Memorandum
α	angle of incidence
δ^*	local boundary layer displacement thickness $\left(= \int_0^\infty \left(1 - \frac{\rho u}{\rho_e U_e}\right) dy\right)$
θ	local boundary layer momentum thickness $\left(= \int_0^\infty \frac{\rho U}{\rho U_e} \left(1 - \frac{u}{U_e}\right) dy\right)$
π	equilibrium pressure gradient parameter $\left(= \frac{\delta^*}{\tau_0} \frac{dp}{dx}\right)$
τ_0	local wall shear stress

Subscripts:

u,ℓ	upper, lower surface respectively
tr	value at transition
D	value at drag-rise condition, for example, C_{L_D}
des	design condition

Aerofoil specification for TDM sections:

Member of RAE 100 series of thickness forms used - t/c - length of rooftop (x_R/c) - design Mach number (M_{des}), e.g. 103-10-50-70 has an RAE 103 thickness form of 10% thickness-chord ratio, a 50% rooftop length and its design Mach number is 0.70.

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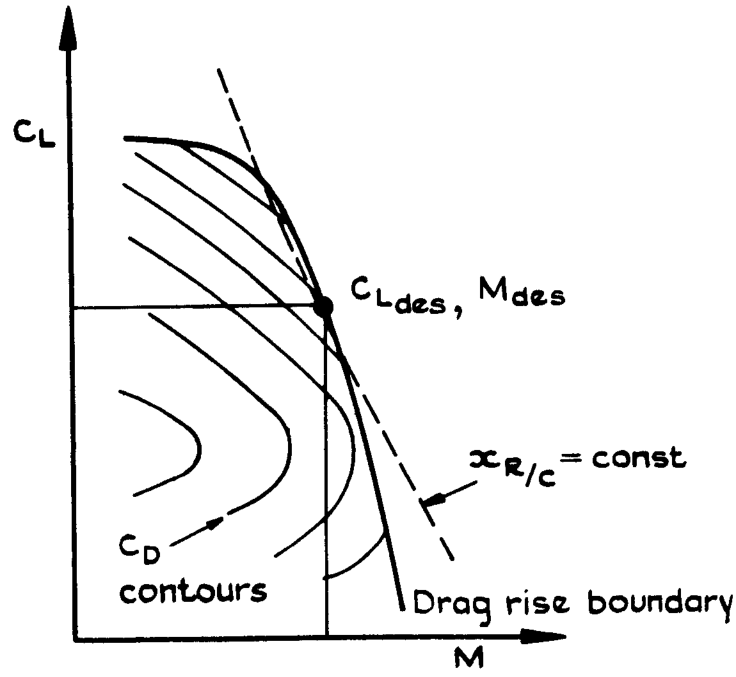
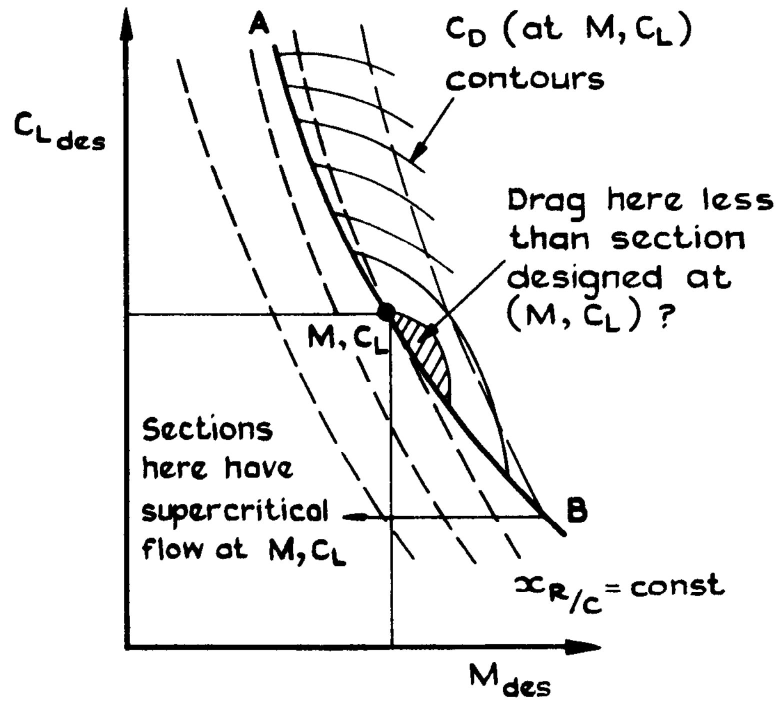
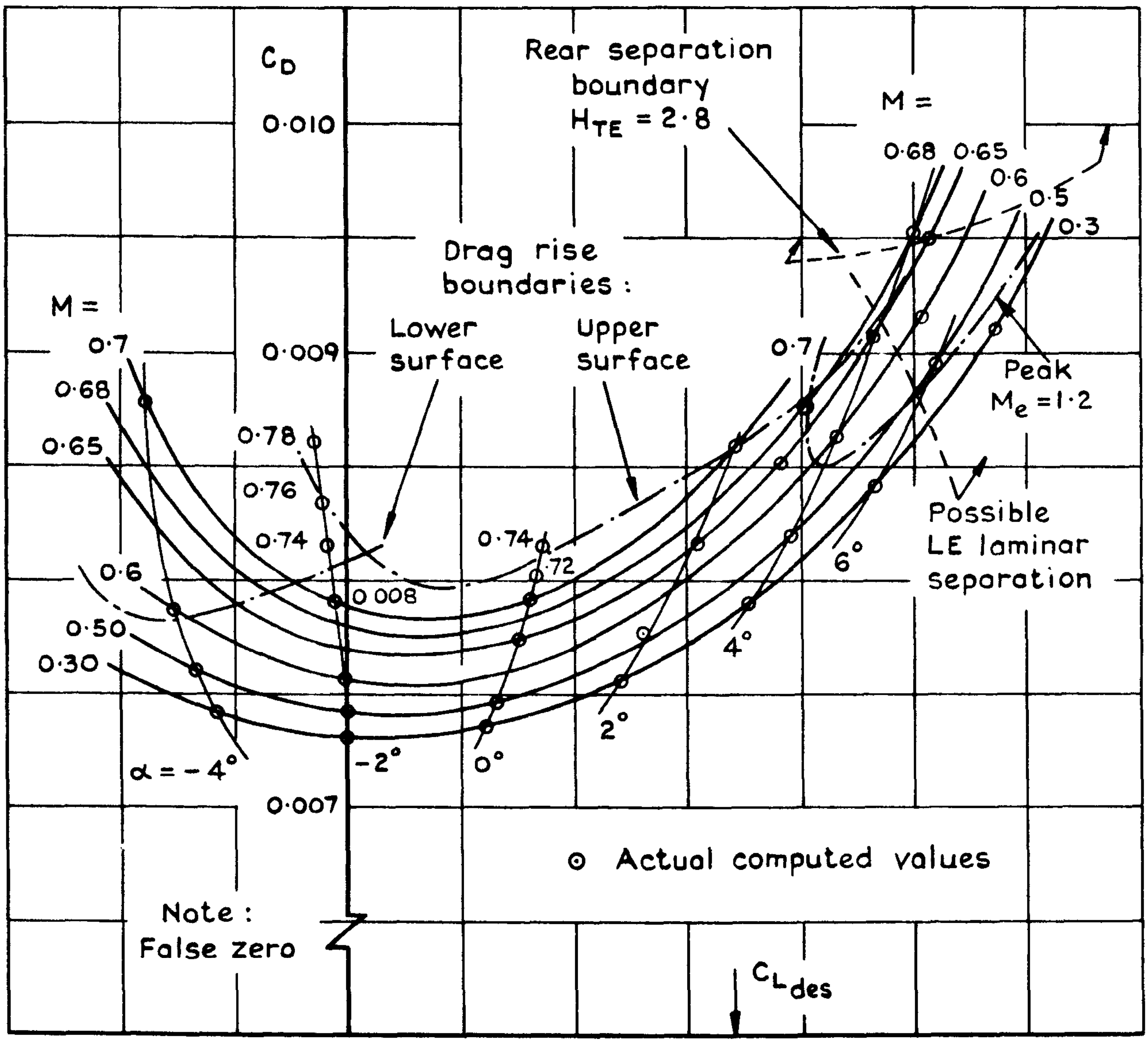


a Drag variation of a given section whose design point is $(M_{des}, C_{L_{des}})$



b Variation of drag at a given operating point (M, C_L) for all permissible TDM sections whose design points lie to the right of boundary A–B

Fig. 1a&b Alternative contour plots of profile drag for a given t/c



Section : 103 - 10 - 50 - 70
$R_c = 10^7$: $x_{tr/c} = 0·05$

Fig. 2 Drag polars for different Mach numbers

$R_c = 10^7$; $x_{tr/c} = 0.05$

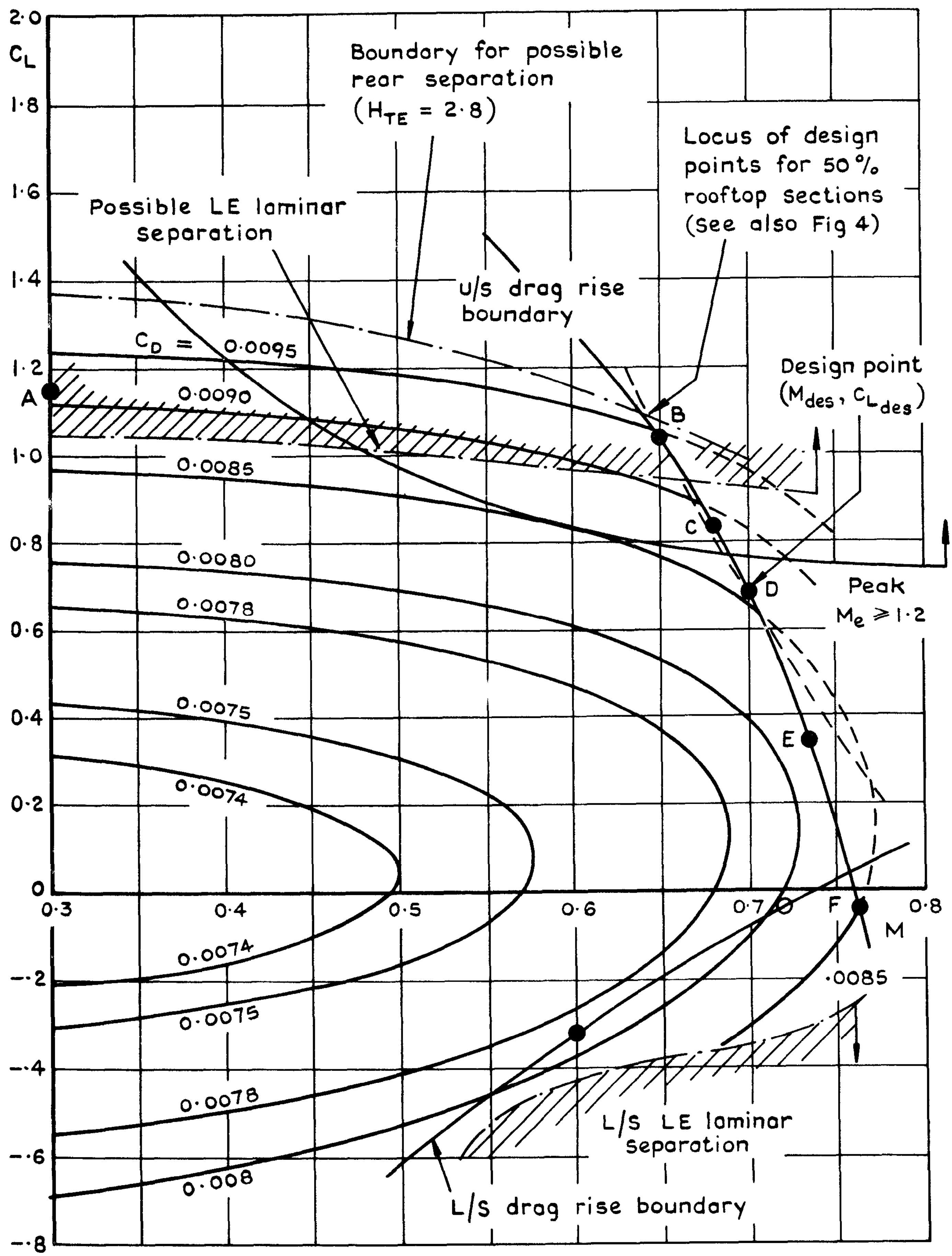


Fig. 3 Profile drag variation at constant Reynolds number and transition position for 103-10-50-70

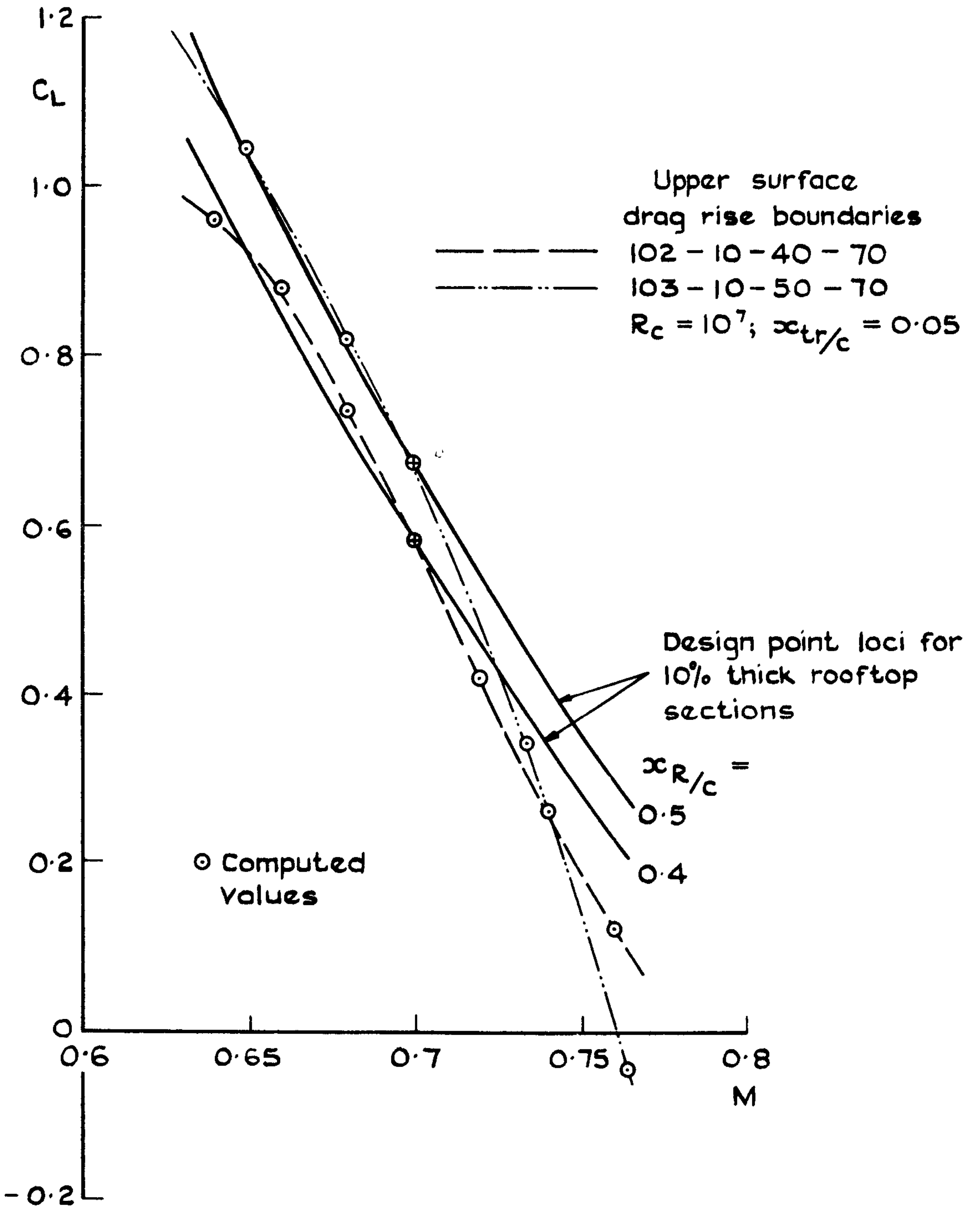


Fig. 4 Comparison of drag rise boundaries with design point loci for 10% thick sections

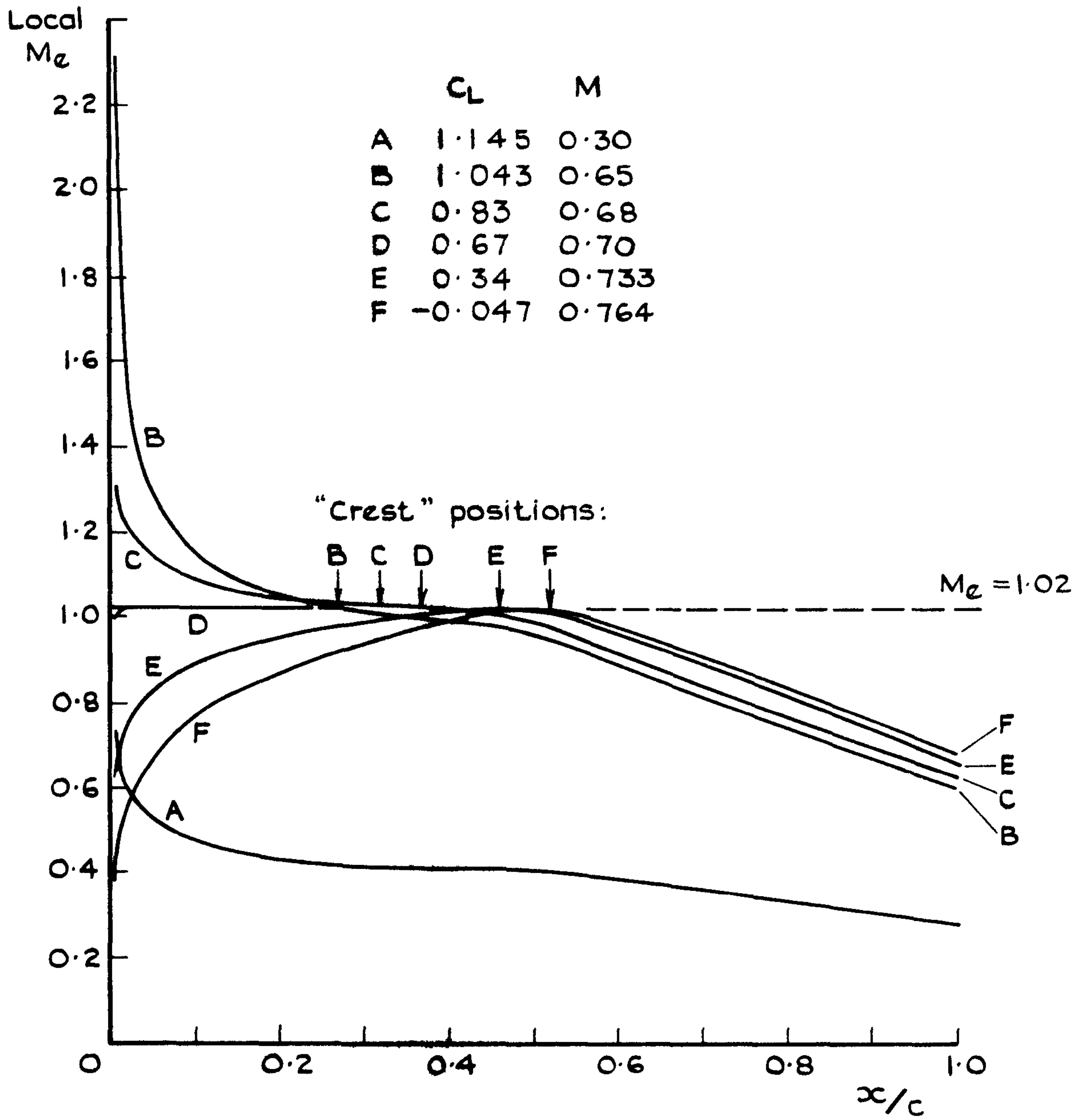


Fig. 5 Upper surface Mach number distributions for 103-10-50-70 $R_c = 10^7$; $x_{tr/c} = 0{\cdot}05$

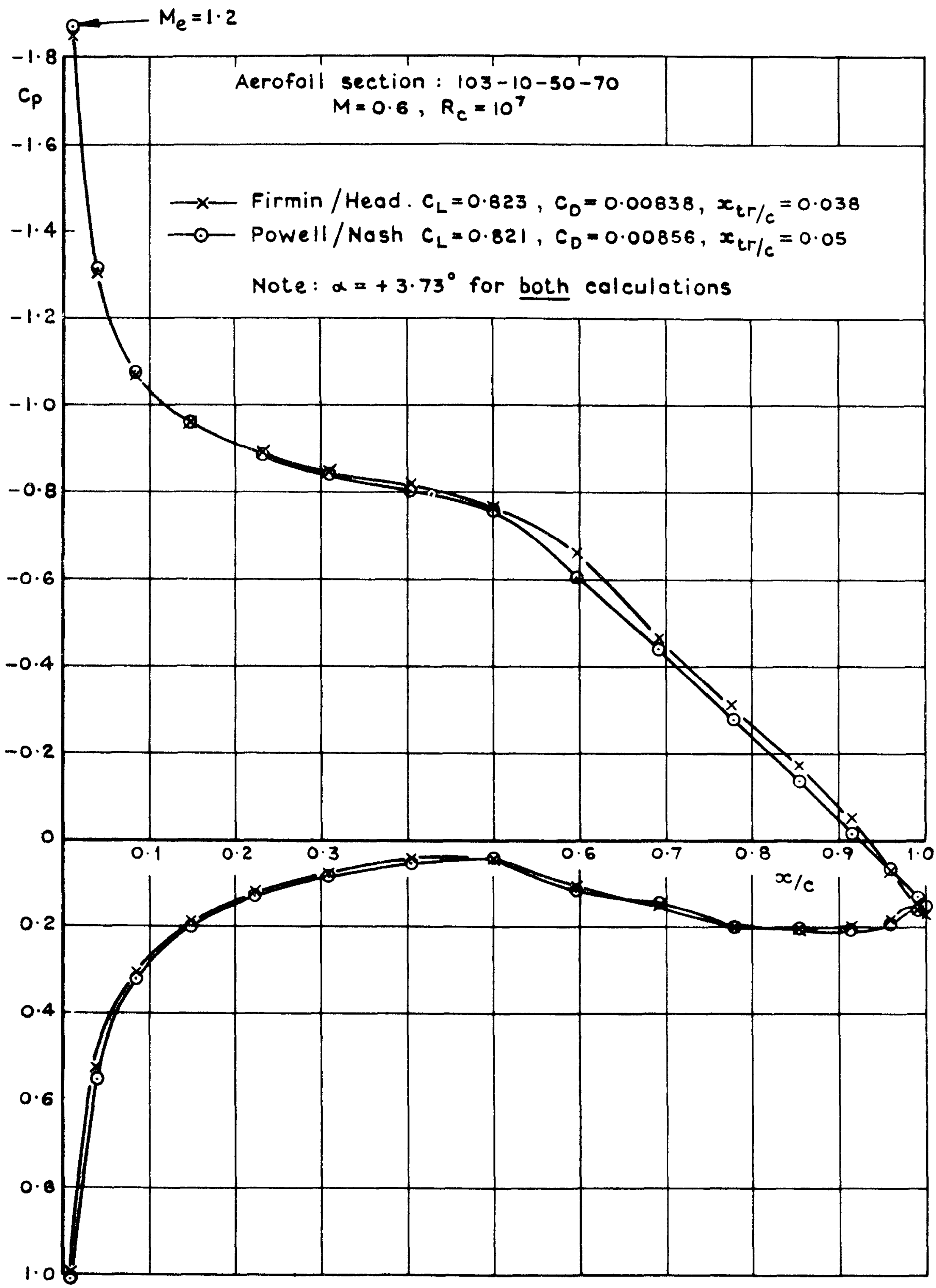


Fig.6 Comparison of pressure distributions, as predicted by two different methods, for an off-design condition

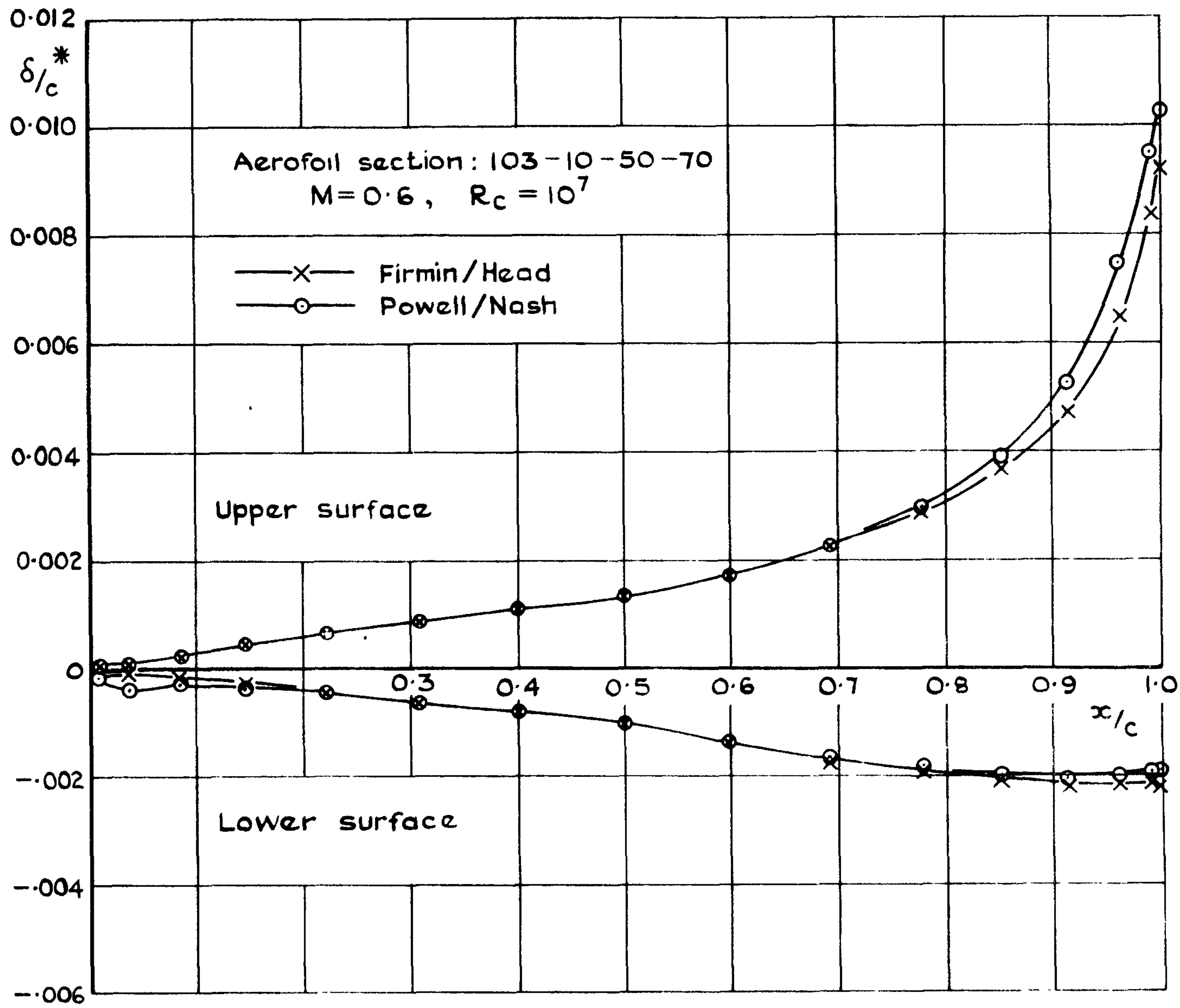


Fig.7 Comparison of displacement thicknesses for conditions of Fig. 6

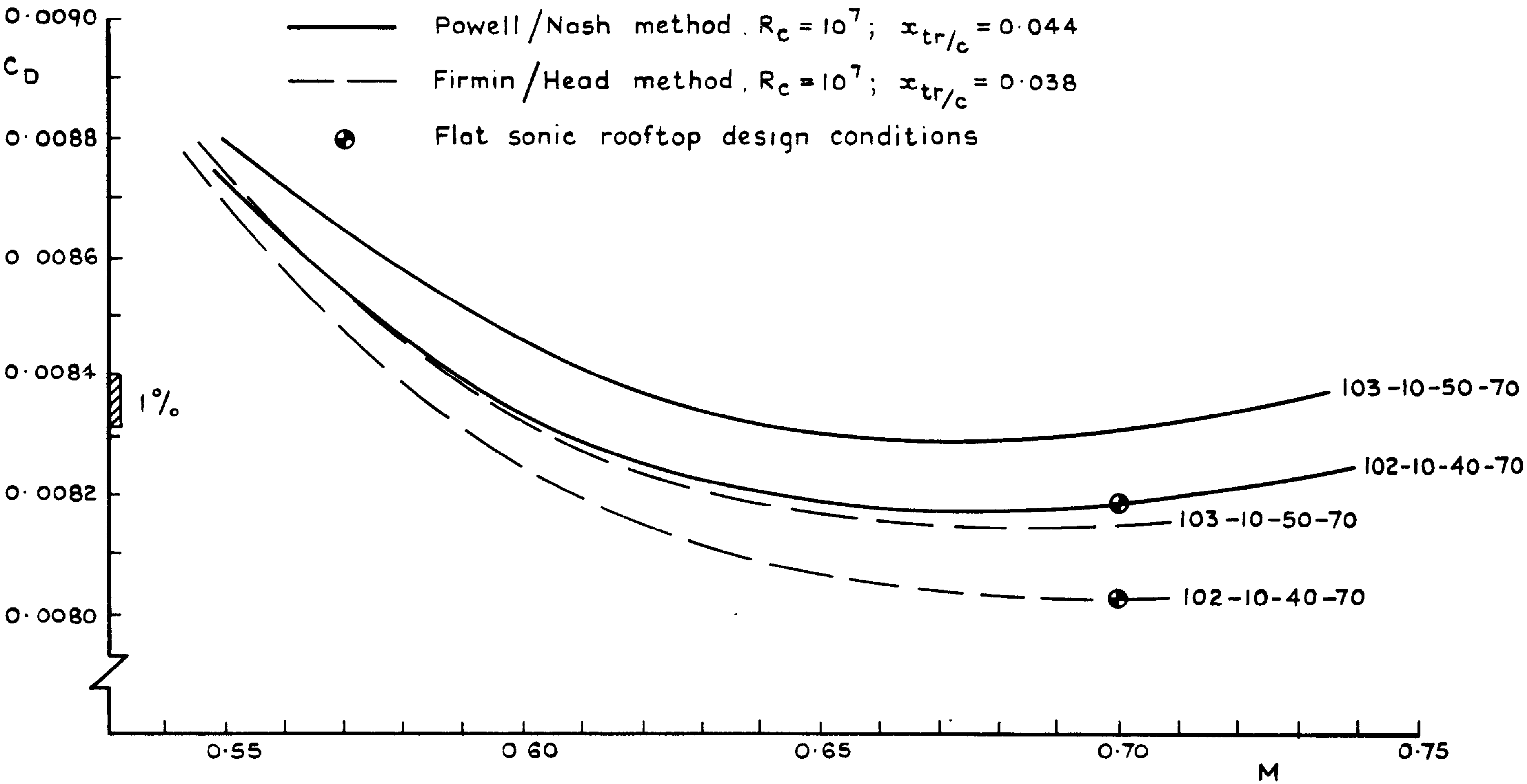


Fig.8 Comparison of predictions for profile drag in off-design conditions, with $M^2 C_L = 0{\cdot}288$

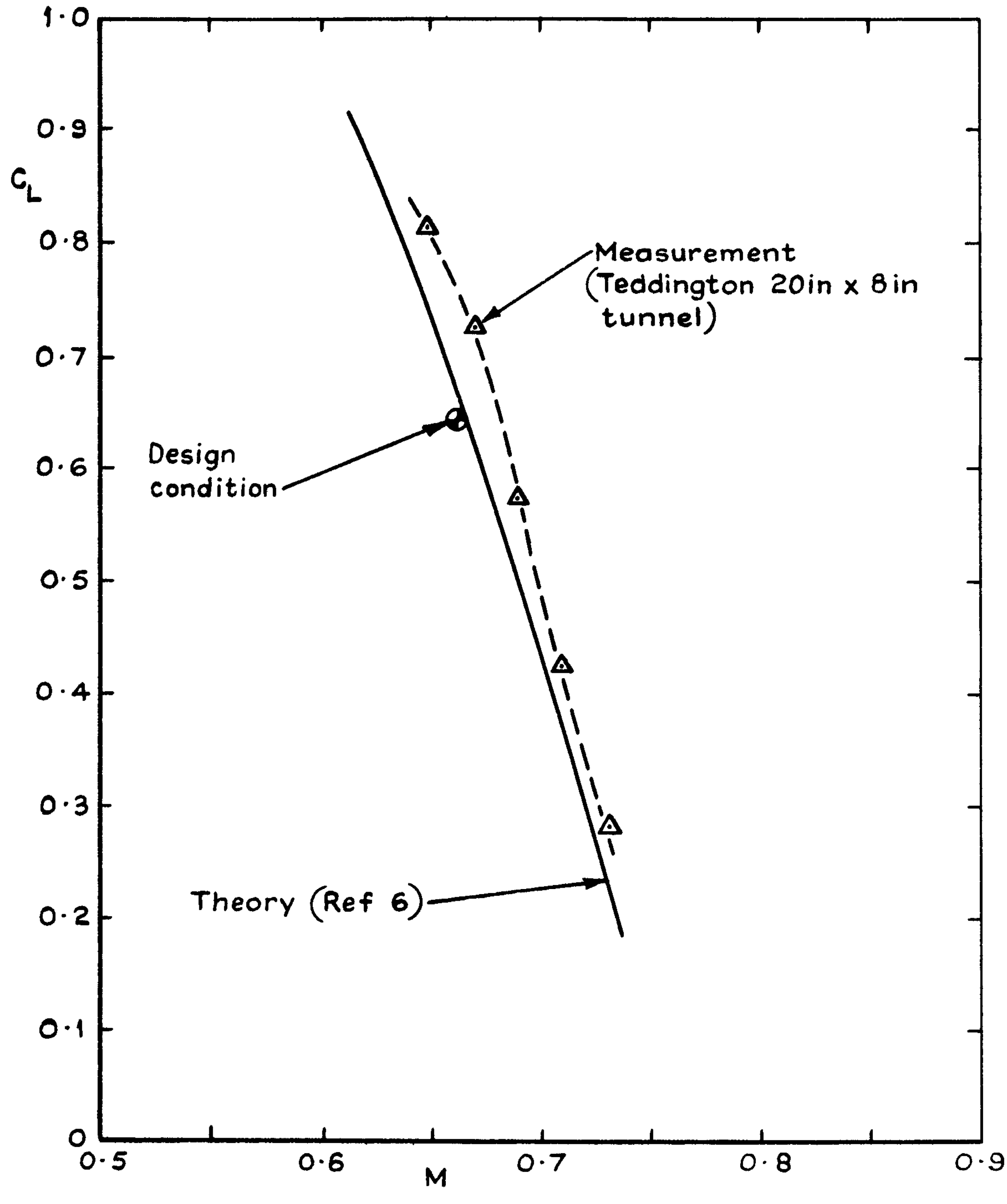


Fig.9 Comparison between theoretical and experimental drag-rise boundaries for a 35% flat roof top section (RAE (NPL) 3111)

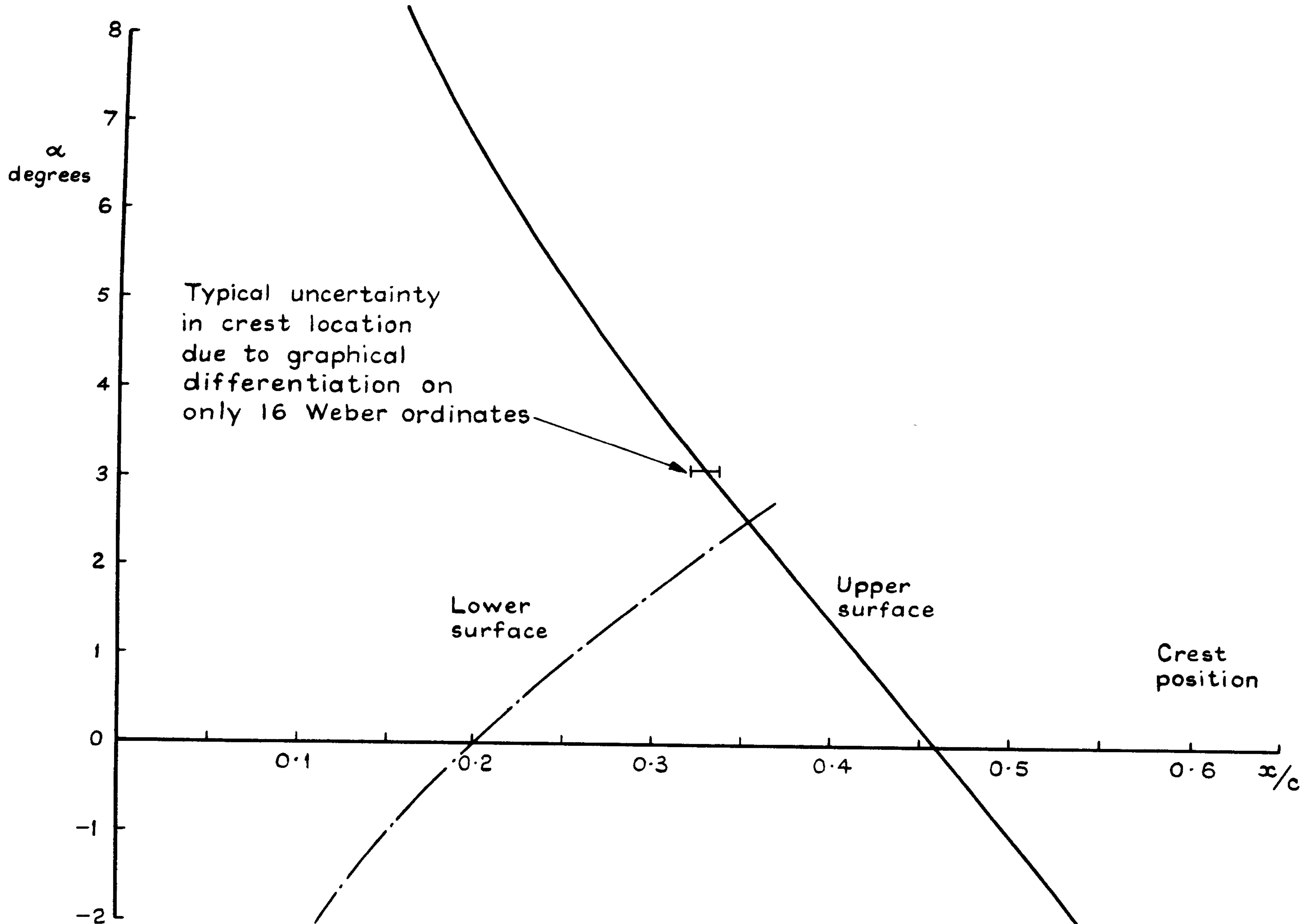


Fig. 10 Movement of crests with incidence for section 103-10-50-70

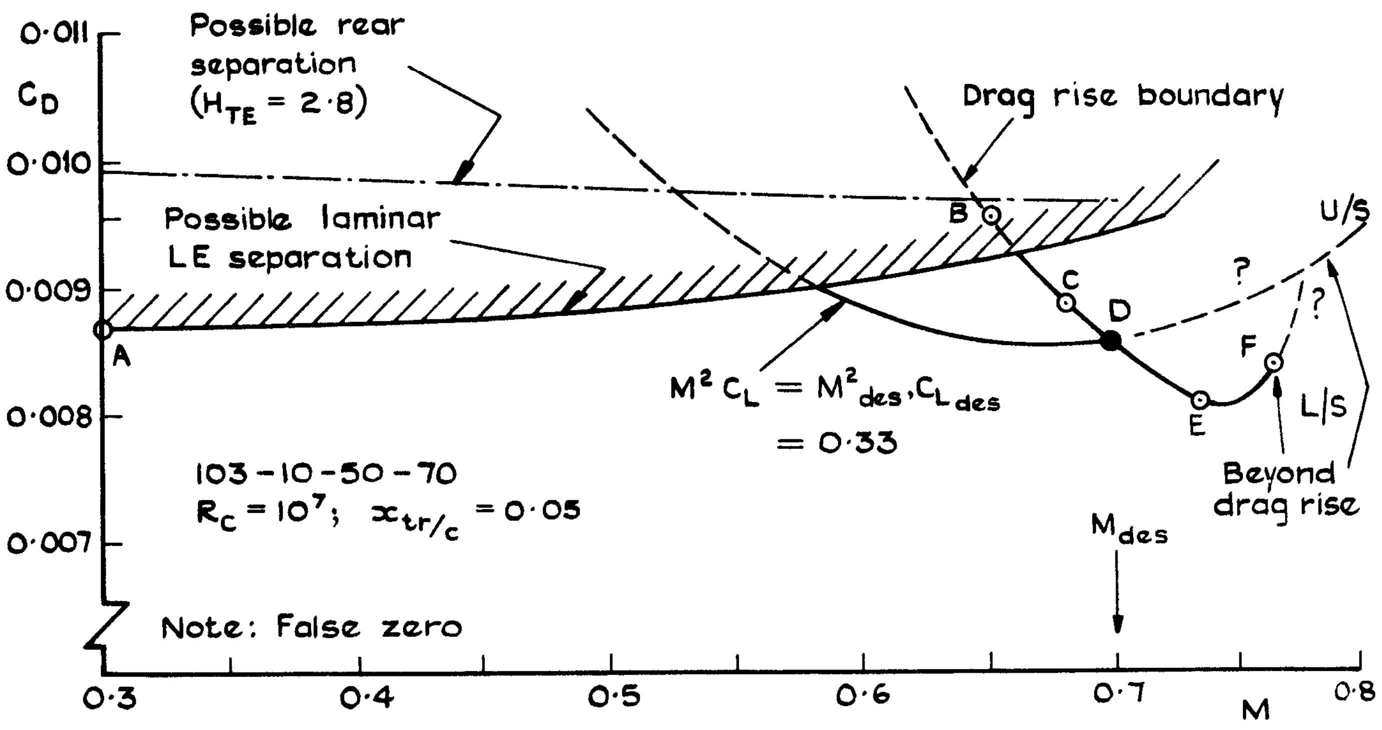


Fig. 11 Variation of profile drag along different loci in the $M-C_L$ plane

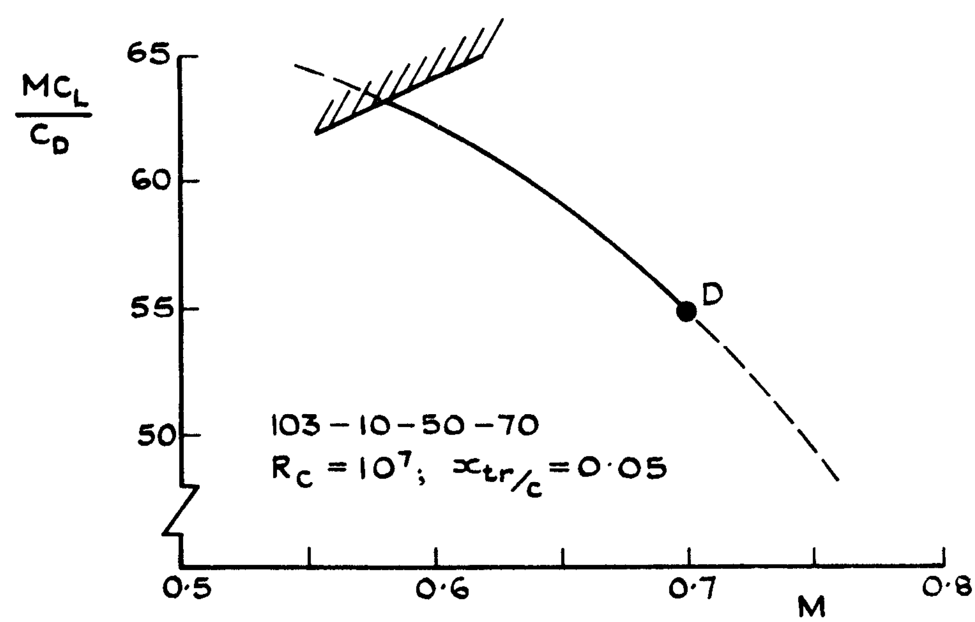


Fig. 12 Variation of range parameter along flight locus $M^2 C_L = 0{\cdot}33$

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Profile drag results are presented in two ways·

(a) as a set of polar curves of C_D *vs.* C_L for a range of Mach numbers, and

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For sections of given t/c and M_{des} the present results indicate that the minimum drag anywhere along the flight locus M^2C_L = constant is obtained by choosing the particular section which has its design point on this locus.

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