

WAVE DRAG COEFFICIENT FOR AXISYMMETRIC FORECOWLS AT ZERO INCIDENCE ($M_\infty \leq 1.5$)

1. NOTATION AND DEFINITIONS

1.1 Notation

A	cross sectional area
A_{max}	maximum cross sectional area of forecowl, $= \pi D_{max}^2/4$
A_∞	cross sectional area of internal streamtube in undisturbed (<i>i.e.</i> freestream) flow
$C_{D_{tot}}$	total external force coefficient, $= C_{\phi_{pre}} + C_{\phi_{cowl}}$
C_{D_w}	wave drag coefficient based on maximum cross sectional area, $= D_w/(\frac{1}{2}\rho_\infty u_\infty^2)A_{max}$
$C_{D_{wA}}$	value of C_{D_w} at $M_\infty = 1.0$ and $mfr = 0.8$, see Section 5.1.1
C_p	pressure coefficient on forecowl surface, $= (p - p_\infty)/(\frac{1}{2}\rho_\infty u_\infty^2)$
$C_{\phi_{cowl}}$	forecowl pressure force coefficient, $= \phi_{cowl}/(\frac{1}{2}\rho_\infty u_\infty^2)A_{max}$
$C_{\phi_{pre}}$	pre-entry force coefficient, $= \phi_{pre}/(\frac{1}{2}\rho_\infty u_\infty^2)A_{max}$
CR	contraction ratio, $= A_1/A_{throat}$
D	diameter
D_{max}	maximum diameter of forecowl
D_w	wave drag (associated with external stream)
L_f	length of forecowl
M_∞	freestream Mach number
M_d	value of M_∞ at which wave drag is first identified
$\dot{m}$	mass flow
mfr	mass flow ratio, $= A_\infty/A_1$
mfr_s	value of mass flow ratio corresponding to separation, according to empirical criterion, see Section 4.2
n	exponent, see Equation (3.1)
p	pressure

R	radial coordinate with origin on forecowl axis, $= y + (D_1/2)$
SR	semi-axis ratio (refers to quarter-ellipse forming part of internal profile)
u	longitudinal component of velocity
X	normalising length for longitudinal coordinate, $= L_f$
x	longitudinal coordinate with origin at highlight, see Sketch 1.1
Y	normalising length for radial coordinate y , $= (D_{max} - D_1)/2$
y	radial coordinate with origin at highlight, see Sketch 1.1
γ	ratio of specific heat capacities, taken as 1.4
$\Delta C_{D_{wB}}$	increment in C_{D_w} at $M_\infty = 1.0$ due to decrease of mfr from 0.8 to 0.5, see Section 5.1.1
$\Delta C_{D_{wC}}$	increment in C_{D_w} at $mfr = 0.8$ due to increase in M_∞ from 1.0 to 1.3, see Section 5.1.1
$\Delta C_{D_{wD}}$	increment in C_{D_w} at $M_\infty = 1.3$ due to decrease of mfr from 0.8 to 0.5, see Section 5.1.1
ρ	density
ϕ_{cowl}	forecowl pressure force
ϕ_{pre}	pre-entry force
Suffices	
<i>int</i>	denotes internal surface
<i>max</i>	denotes maximum value
<i>st</i>	denotes conditions at stagnation point
<i>throat</i>	denotes throat
1	denotes highlight
∞	denotes freestream conditions

1.2 Definitions

1.2.1 Highlight

The highlight is the most forward location on the forecowl profile, see Sketch 1.1.

1.2.2 Crest

The crest is the location on the forecowl external profile corresponding to maximum diameter. For the forecows in this Item it is positioned at the downstream extremity of the forecowl profile, see Sketch 1.1.

1.2.3 Internal stream, external stream and pre-entry streamtube

When calculating the aerodynamic forces which act on a forecowl, it is convenient for the flow field to be considered as two separate regions, the internal stream and the external stream. The internal stream comprises the fluid which passes through the forecowl, while the external stream comprises the fluid which passes around the forecowl.

Depicting the flow in a plane through the axis of symmetry, see Sketch 1.1, the interface in the fluid between the internal and external streams is formed by rotating ab , the stagnation streamline in this plane, about the axis of symmetry. This interface is termed the pre-entry streamtube.

1.2.4 Mass flow ratio

The mass flow of fluid (*i.e.* the mass flux) of the internal stream is expressed as a non-dimensional ratio, the mass flow ratio, by dividing it by the mass flow of fluid which would pass through a streamtube of cross sectional area A_1 , if the fluid were to remain undisturbed from its freestream flow conditions. Thus

$$mfr = \dot{m}/\rho_{\infty} u_{\infty} A_1. \quad (1.1)$$

Since $\dot{m} = \rho_{\infty} u_{\infty} A_{\infty}$, (1.2)

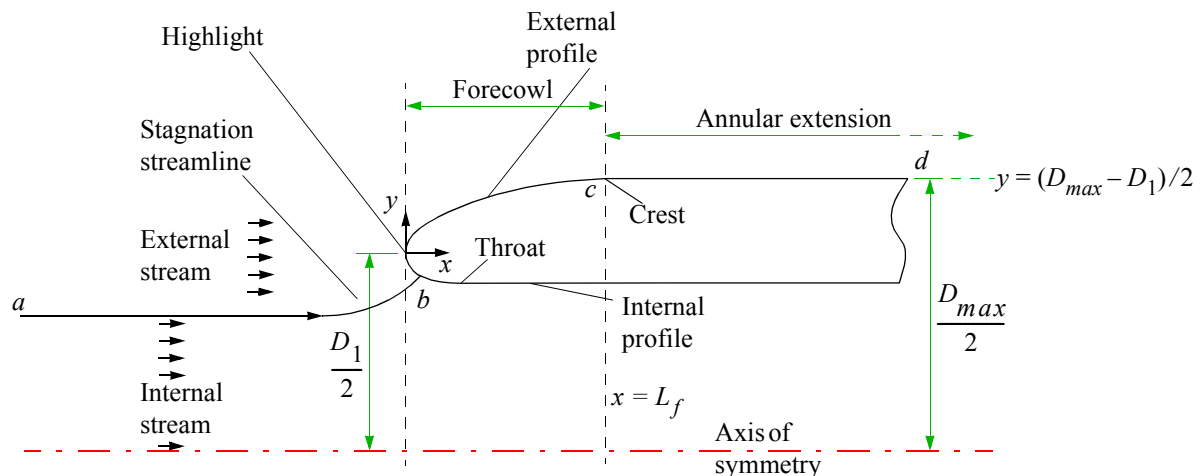
$$\text{then} \quad mfr = A_{\infty} / A_1. \quad (1.3)$$

1.2.5 Forecowl pressure force coefficient

The forecowl pressure force, ϕ_{cowl} , is the aerodynamic force due to pressures acting on the part of the forecowl surface ‘wetted’ by the external stream, bcd in Sketch 1.1. By symmetry, the forecowl pressure force is aligned with the x -axis. It is taken as positive in the direction of increasing x . No net contribution to ϕ_{cowl} is produced by pressures acting on the cowl aft of the crest (c in Sketch 1.1). The forecowl pressure force coefficient is given by

$$C_{\phi_{cowl}} = \frac{2\pi}{A_{max}} \int_{R_{st}}^{R_{max}} C_p R \, dR, \quad (1.4)$$

where the integral is taken along the forecowl profile from the stagnation point to the crest.



Sketch 1.1 Forecowl and flow nomenclature

1.2.6 Pre-entry force

The pre-entry force is the aerodynamic force due to pressures acting on the pre-entry streamtube exerted by the external stream. By symmetry it is aligned here with the x -axis, and is taken positive in the direction of increasing x . It is a 'conceptual force' only, since the pressures considered act within the fluid, rather than on a physical surface. It is of use in thrust and drag accounting, in which the overall gasdynamic forces are split into contributions from the internal stream (thrust) and the external stream (drag), see Reference 1.

The pre-entry force coefficient is given by

$$C_{\phi_{pre}} = \frac{2\pi}{A_{max}} \int_{R_{\infty}}^{R_{st}} C_p R \, dR, \quad (1.5)$$

where the integral is taken along the stagnation streamline from the freestream condition to the stagnation point.

1.2.7 Total external force and wave drag

The total external force is the aerodynamic force exerted by the external stream on a surface comprised of the pre-entry streamtube and the part of the forecowl surface 'wetted' by the external stream. If viscous forces are neglected (*i.e.* the flow is assumed inviscid, as in this Item) the total external force is equal to the sum of the pre-entry force and the forecowl pressure force. The total external force coefficient is then given by

$$C_{D_{tot}} = C_{\phi_{pre}} + C_{\phi_{cowl}}. \quad (1.6)$$

Here the use of the suffix D in $C_{D_{tot}}$ refers to a drag force, and conforms to the convention of Reference 1, which reserves the word 'drag' for a force which is non-zero only where it corresponds to a loss of fluid momentum at downstream infinity. If the external stream is not only inviscid but also free of shock waves it is 'loss-free', and then

$$C_{D_{tot}} = 0. \quad (1.7)$$

Where one or more shock waves affect the external stream (either by forming within it, or penetrating into it), the momentum losses in the external stream correspond to a wave drag, D_w^* . In such a case

$$C_{D_w} = C_{D_{tot}} > 0. \quad (1.8)$$

* By definition, the shock losses of the internal stream are not included in C_{D_w} .

2. INTRODUCTION

This Item presents charts of computed wave drag coefficient for twenty axisymmetric forecows at zero incidence. The computations have been carried out using a computer code which generates solutions of the Euler equations in finite difference form for inviscid compressible axisymmetric flow. Computed shock waves are 'smeared' over a few mesh cells but, in principle, should result in correctly calculated shock pressure jumps and wave drag. The value taken for the ratio of specific heat capacities, γ , in the flow is 1.4. Data are presented for ranges of values of mass flow ratio and freestream Mach number. The maximum freestream Mach number for which data are presented is 1.5.

Sixteen of the forecows have the NACA 1-Series external profile, with differing combinations of the diameter ratio, D_1/D_{max} , and fineness ratio, L_f/D_{max} , see Sketch 9.1. The remaining four shapes each have $D_1/D_{max} = 0.8$ and $L_f/D_{max} = 1.0$, but have different external profile forms. All forecowl properties are summarised in Table 9.1.

In addition to charts of wave drag coefficient, charts of computed forecowl pressure force coefficient and pre-entry force coefficient are presented for each forecowl at those flow conditions of freestream Mach number and mass flow ratio at which a non-zero wave drag is calculated.

Corresponding surface pressure distributions are presented in Reference 12.

The data in the charts may be applied to a cowl having one of the given forecowl shapes followed by a mid-cowl and further geometrical and flow features, such as a nozzle and exhaust jet, provided the flow downstream of the forecowl produces negligible upstream interference effects.

The data are applicable to real (*i.e.* viscous) flows provided the boundary layer produces only small changes to the surface pressure distributions. In practice, viscous effects are likely to influence C_{D_w} , $C_{\phi_{cowl}}$ and $C_{\phi_{pre}}$ significantly only when boundary-layer separation occurs. Data for certain combinations of forecows and flow parameters, where separation would probably occur, have been omitted from the Item for this reason – see Section 4.2. However a few cases are included which correspond to flows in which shock waves emanating from the forecowl external profile have upstream Mach numbers in excess of 1.3. Such strong shock waves may induce boundary-layer separation, particularly at relatively low Reynolds numbers. The occurrence of such shock waves in the flows about the three forecows with $L_f/D_{max} = 0.2$ may be determined from the computed pressure distributions presented in Reference 12, Figures 1, 4 and 8.

Results of calculations demonstrating the influence of the internal geometry on calculated force coefficients are presented in Appendix A.

3. FORECOWLS CONSIDERED

Table 9.1 lists the overall geometric parameters of the forecows for which data are presented.

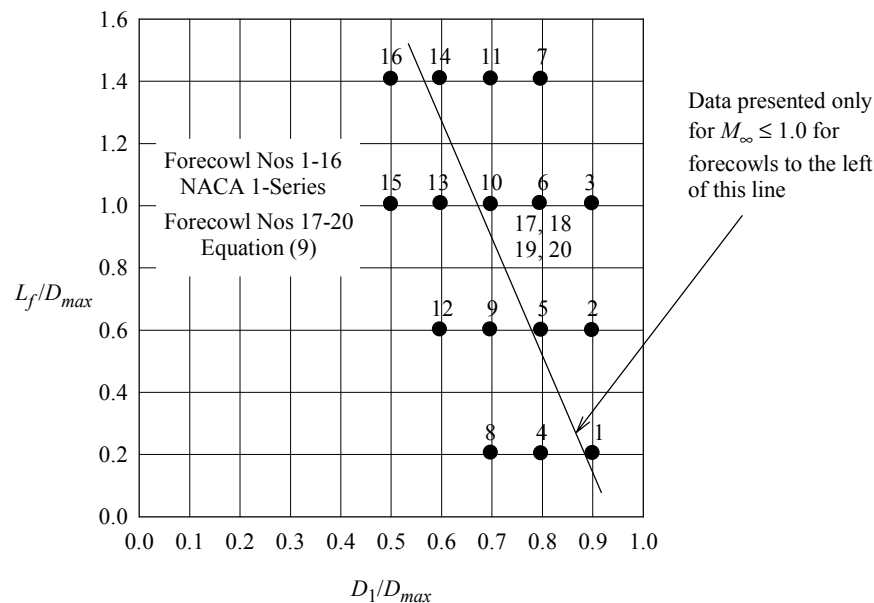
The choice of values of D_1/D_{max} , and L_f/D_{max} was made on the basis of a survey of a wide range of actual and projected powerplant forecows, Reference 16. The survey indicated that fineness ratios in the range 0.2 to 1.4 are of main interest, and that emphasis should be placed on forecows with a diameter ratio of 0.7 and above. The values of D_1/D_{max} and L_f/D_{max} selected are shown in Sketch 3.1 together with the corresponding designated forecowl numbers used in this Item. Forecows defined by points to the left of the straight line in Sketch 3.1 are relatively 'thick', with $(D_{max} - D_1)$ up to $0.6L_f$, and would almost certainly yield wave drag values too high for them to be considered for supersonic flight. For this reason data presented for these forecows are restricted to $M_\infty \leq 1.0$.

For the purpose of computation, each forecowl was considered to be extended indefinitely downstream by an external surface of diameter D_{max} extending from the crest, and an internal surface of diameter D_{throat} extending from the throat. For most of the forecows the throat is well forward of the crest, but for one, Forecowl 3, the throat is aft of the crest. The size of the computed flow field region, relative to the length of the forecowl, was selected so that at each flow condition there was a considerable length of the extension to the forecowl along which the computed values of the various flow parameters were closely uniform in both the external and internal streams. A typical computational grid, (indicating the extent of the computed region of flow), is shown in Sketch 6.1.

The data relating to forecows having a NACA 1-Series external profile utilised coordinates derived from the analytic expression given by Equation (4.1) in Reference 2*. As explained in Reference 2, these coordinates correspond closely to those of the original NACA 1-Series definition but have smoother curvature variations. They have the advantage that calculated pressure distributions, when accurately determined, are also smooth (apart from any shock regions), and calculated variations of aerodynamic coefficients are regular.

To enable some assessment to be made of the wave drag of forecows having an external profile different from the NACA 1-Series, a limited number of results are presented for other forms. The forms selected correspond to four different values of the exponent n in the expression

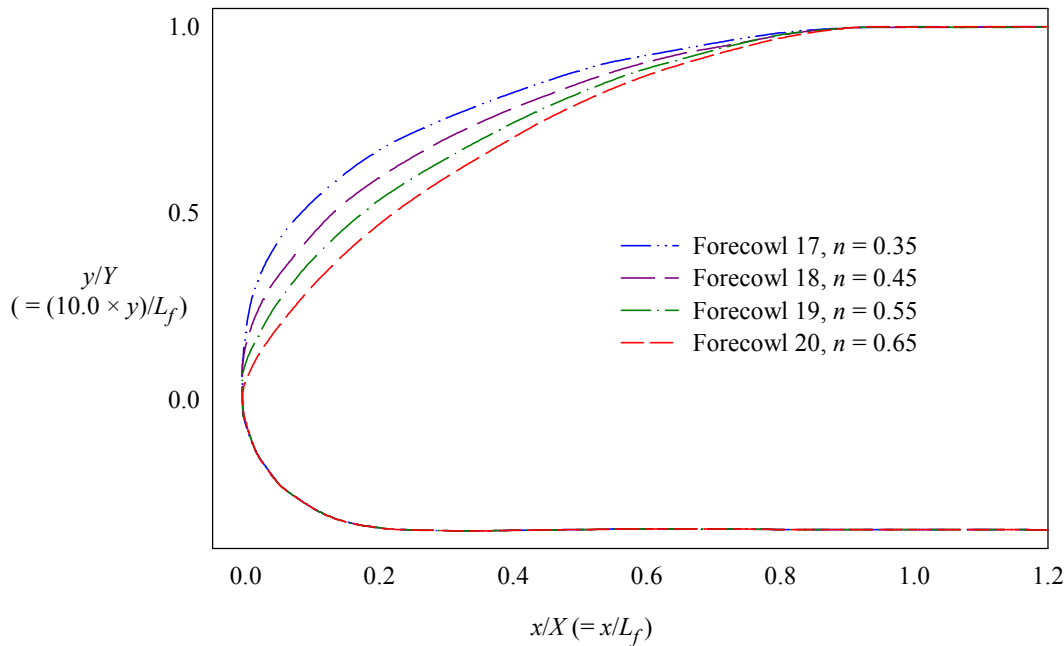
$$\left(\frac{y}{Y}\right) = \left[\sin\left(\frac{\pi}{2}\left(\frac{x}{X}\right)\right)\right]^n \quad (3.1)$$



Sketch 3.1 Overall geometric parameters of forecows considered

The values of n selected and the corresponding designated forecowl numbers are given in Table 9.1. Each of these forecows has $D_1/D_{max} = 0.80$, and $L_f/D_{max} = 1.0$. Sketch 3.2 indicates the form of the four forecowl profiles. With $n = 0.55$, the values of y differ by less than $0.006Y$ from those of the corresponding NACA 1-Series profile, and generally values of wave drag coefficient calculated for the forecowl with $n = 0.55$ (Forecowl 19) are within 0.01 of the values for the NACA 1-Series forecowl (Forecowl 6). With $n > 0.55$ a less blunted forecowl profile than the NACA 1-Series is generated, whilst with $n < 0.55$ the profile form is blunter than the NACA 1-Series.

* This Equation is also given in Appendix B, here, for convenience.



Sketch 3.2 Profiles of Forecows 17 to 20

With a value of n greater than about 0.65, the form of profile obtained has a low radius of curvature at and near the highlight, and as a result is unrepresentative of a forecowl that would be used in practice. For this reason, forms produced by values of n larger than 0.65 have not been investigated, even though, judging by trends of C_{D_w} with n , they would appear to yield low values of wave drag. It has been suggested that a profile form which is somewhat blunter than the NACA 1-Series near the highlight and somewhat less 'full' further aft might have wave drag and boundary layer separation characteristics which are comparable to, or rather better than, those of the NACA 1-Series at subsonic freestream speeds. However, no such forms have been considered in the present Item. The design or selection process to obtain an optimum forecowl is likely to involve consideration of several factors, including some not related to aerodynamic characteristics. Thus, although the results presented for the forms differing from the NACA 1-Series provide an indication of the changes in wave drag that would be found by adopting these alternative forms, or ones similar to them, they are not sufficient to indicate which profiles would be preferred in practice.

3.1 Internal Geometry

For each of the forecows the internal profile between the highlight and the throat is a quarter ellipse giving a contraction ratio of 1.2. For Forecows 1 to 16 the semi-axis ratio of the internal profile quarter ellipse was chosen, where feasible, so that the radius of curvature of the internal and external profile curves was continuous at their junction, *i.e.* at the highlight. For about half of these forecows, however, this choice led to the throat being located much further forward than appeared realistic for a practical forecowl, and it then often led to the appearance of shock waves in the internal streamtube of the computed flows and a consequent unreliability in the computed pre-entry force (and thus also in the computed wave drag). To avoid this problem, for a number of forecows the internal profile was chosen to be a quarter ellipse with semi-axis ratio 5:1. These forecows are indicated in Table 9.1. Relaxing the condition of continuity of curvature at the highlight for these forecows did not appear to give rise to any undesirable feature in the computed pressure distributions or in the computed wave drag and force coefficients.

For Forecows 17 to 20 a common internal profile was selected, this being the same as that of Forecowl 6.

The selected contraction ratio of 1.2 may be compared with values typical of military forecows, *i.e.* 1.05

to 1.10, and those typically used in civil applications, *i.e.* 1.25 to 1.35. In practice, as demonstrated in Appendix A, the choice of internal forecowl profile significantly affects the values of computed pre-entry and forecowl pressure force coefficients, but hardly influences the computed wave drag coefficient, which is the sum of these coefficients.

4. FLOW CONDITIONS CONSIDERED

4.1 Freestream Mach Number

Calculations for a particular forecowl were generally made for each value of mass flow ratio as a sequence with M_∞ decreasing. Each sequence commenced with $M_\infty = 1.5$ (or 1.01 for the forecows on the left of the line in Sketch 3.1), and continued (with intervals of 0.05, 0.1, or 0.2 in M_∞) until the computed surface flow parameters revealed no region where the speed was locally supersonic. Throughout, calculations were carried out with $M_\infty = 1.01$ rather than $M_\infty = 1.00$, since the convergence of the results produced by the computer code was then very much improved, see Section 6. Data are presented for all supersonic freestream cases and also for those subsonic freestream cases where both a non-zero value of wave drag coefficient was computed and the local surface Mach number somewhere equalled or exceeded 1.02. This procedure removes from presentation some few results where a small spurious wave drag coefficient was calculated (*i.e.* $C_{D_w} < 0.005$), as a result of errors due to finite difference approximations, see Section 6.1.

4.2 Mass Flow Ratio

In general, calculations were carried out, for each forecowl and value of M_∞ , at values of mass flow ratios covering the range likely to be of interest in practice. An upper limit on the mass flow entering a particular forecowl at a given Mach number is imposed by choking, namely the condition where a sonic surface (*i.e.* an imaginary surface at every point of which the flow speed is sonic) just extends over the whole of the internal streamtube. Although the choking mass flow ratio may be estimated using one-dimensional flow theory, it can only be found accurately by a procedure which correctly solves the three-dimensional flow equations, such as the finite difference solution procedure employed in this Data Item. However, determining the value of the choking mass flow ratio accurately in this way is a time-consuming process, because properly converged results may only be obtained at mass flow ratios below (or equal to) the (unknown) choking value. Consequently a suitable strategy for selecting a sequence of values of mass flow ratio would have to be devised, so that the choking value could be found to the desired accuracy. In the data presented no attempt has been made to determine the values of choking mass flow ratio; results are simply presented up to a maximum value for mass flow ratio of 0.8. In no case was it found that the choking mass flow ratio was lower than 0.8.

There is no lower limit (other than zero) on the mass flow that may enter a forecowl. However, below some finite value of mass flow ratio (which depends on the forecowl shape, freestream Mach number and Reynolds number), boundary layer separation occurs in the flow around the external surface of the cowl, leading to significant viscous drag. It is clearly inappropriate to present calculated wave drag data, which are only relevant to attached flows with thin boundary layers, at conditions where significant flow separation would be likely to occur. As a result, an empirically based method (Reference 3) has been used to estimate, for each forecowl, the mass flow ratio below which significant boundary layer separation is likely to occur in a real viscous flow. For simplicity, the method has been used to estimate the appropriate value of mass flow ratio only for a freestream Mach number of 0.6 and these values, denoted by mfr_s , are given in Table 9.1. For each forecowl, no data for $M_\infty < 1.0$ are presented for mass flow ratios more than 0.1 below mfr_s . For $M_\infty > 1.0$, results are presented generally for values of mfr in the range 0.5 to 0.8. For two forecows (numbers 10 and 14) the range is 0.4 to 0.8.

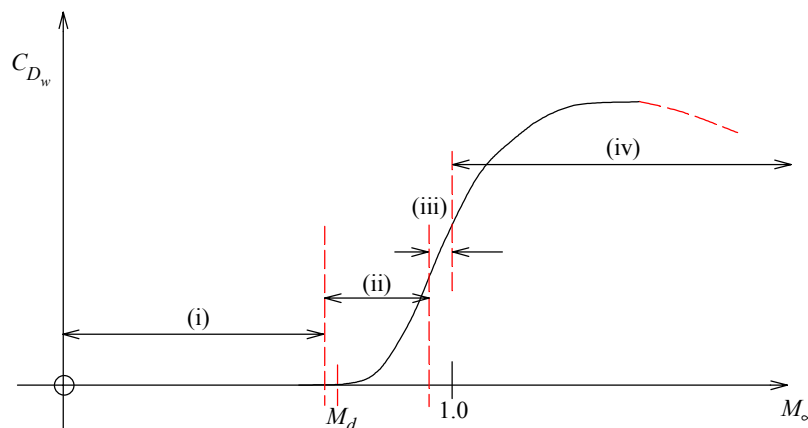
5. PRESENTATION OF RESULTS

5.1 Wave Drag Coefficient

Charts of wave drag coefficient, as a function of M_∞ and mfr , are presented in Figures 1a to 20a, see Table 9.1. The values of C_{D_w} have been obtained from calculations utilising the finite difference solution method described in Section 6.

For each forecowl, the variation of wave drag coefficient with freestream Mach number, at fixed mass flow ratio, may be generalised by considering a graph of C_{D_w} against M_∞ to be comprised of a number of more or less well-defined segments, see Sketch 5.1.

In Segment (i) the wave drag is zero because the flow field is subsonic throughout. As the freestream Mach number is increased, the external stream becomes locally supersonic and one or more shock waves form*. The drag associated with these shock waves then increases rapidly with increasing freestream Mach number (typically like $(M_\infty - M_d)^3$, where M_d is the value of the freestream Mach number at which wave drag is first identified). This comprises Segment (ii). As M_∞ approaches 1.0, the shock wave(s) move downstream aft of $x = L_f$, and the rate of increase of wave drag with increasing M_∞ decreases. This constitutes Segment (iii). C_{D_w} continues to increase with M_∞ when the freestream speed becomes supersonic and a bow shock wave forms – Segment (iv). With increasing supersonic freestream speed the outer parts of the bow shock become increasingly swept back and at sufficiently high speeds the wave drag decreases with increasing M_∞ . However, conditions presented in this Item do not extend to sufficiently high Mach numbers for such decreases to appear.



Sketch 5.1 Schematic form of wave drag variation

At fixed M_∞ the influence of mfr on C_{D_w} is such that C_{D_w} increases as mfr decreases. This may be explained in terms of the greater disturbances produced in the external stream as mfr decreases, arising from progressively larger changes in cross sectional area of the pre-entry streamtube between a and b in Sketch 1.1.

5.1.1 NACA 1-Series forecows

To present the broad effects on wave drag of changes in the geometric variables D_1/D_{max} and L_f/D_{max} for the NACA 1-Series forecows in a simple way, four 'key' wave drag parameters, reflecting different aspects of the forecowl wave drag characteristics, are selected for consideration. These are:

* A supersonic flow region may occur without shock wave formation. However, such flows, which involve isentropic re-compression to subsonic speed, usually only occur as a result of careful design, and relate to specific isolated (or 'singular') conditions.

- $C_{D_{wA}}$: value of C_{D_w} at $M_\infty = 1.0$, $mfr = 0.8$,
 $\Delta C_{D_{wB}}$: increment in C_{D_w} at $M_\infty = 1.0$ due to decrease of mfr from 0.8 to 0.5,
 $\Delta C_{D_{wC}}$: increment in C_{D_w} at $mfr = 0.8$ due to increase in M_∞ from 1.0 to 1.3,
 $\Delta C_{D_{wD}}$: increment in C_{D_w} at $M_\infty = 1.3$ due to decrease of mfr from 0.8 to 0.5.

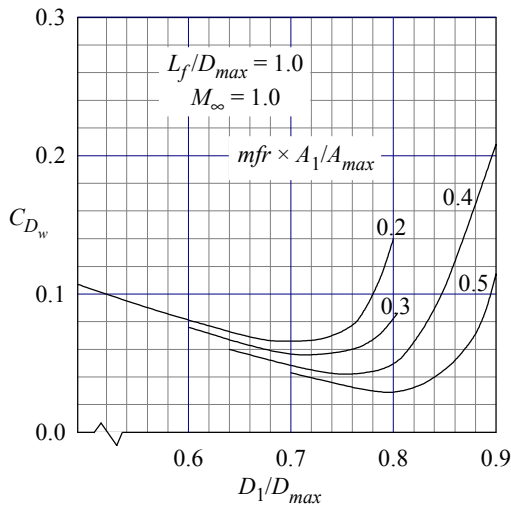
Charts of $C_{D_{wA}}$, $\Delta C_{D_{wB}}$, $\Delta C_{D_{wC}}$, $\Delta C_{D_{wD}}$ are presented in Figures 21 to 24.

In Figure 21 the high values of wave drag at $M_\infty = 1.0$ and $mfr = 0.8$ associated with the large flow disturbances produced with the lower values of D_1/D_{max} and L_f/D_{max} are apparent. Differences in $C_{D_{wA}}$ between Forecowls 2, 3, 6, 7, and 11 are slight, and each of these forecowls produces a value close to the minimum.

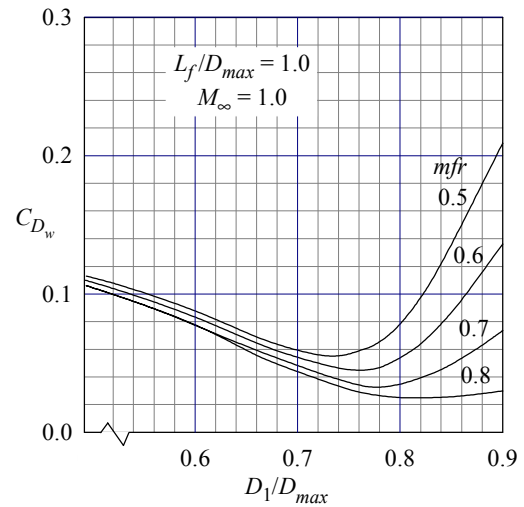
In Figure 22, large wave drag increments produced by a decrease in mfr at $M_\infty = 1.0$ are seen for the forecowls with $D_1/D_{max} = 0.9$. These increments progressively decrease with decreasing D_1/D_{max} (for L_f/D_{max} fixed), and this is due to the fact that, at low values of mfr , lower values of D_1/D_{max} result in lower maximum local Mach numbers and to weaker shock waves. (The opposite effect occurs at high values of mfr , particularly at low values of L_f/D_{max} .)

In Figure 23 the increase in wave drag coefficient at $mfr = 0.8$ resulting from an increase in M_∞ from 1.0 to 1.3 is seen to be within ± 0.020 of 0.120 for the nine forecowls considered, which suggests that the increase is dominated by the value of mfr rather than by the geometric parameters D_1/D_{max} and L_f/D_{max} . A similar observation that can be made (by referring to Figures 1a to 16a) is that the corresponding increases in wave drag coefficient at $mfr = 0.5$ as M_∞ increases from 1.0 to 1.3 are within ± 0.023 of 0.194. This reinforces the suggestion that such increases are related more to the value of mfr than to the parameters D_1/D_{max} and L_f/D_{max} , and indicates that such increases in wave drag are influenced more by the disturbances to the external flow produced by the pre-entry streamtube cross sectional area variation than by the details of the forecowl profile. In Figure 24, the values of $\Delta C_{D_{wD}}$ are seen to vary with D_1/D_{max} and L_f/D_{max} in a way similar to those of $\Delta C_{D_{wB}}$ (Figure 22), where such comparison is possible, although, as would be expected, the increments corresponding to the higher value of M_∞ are considerably larger, by up to 0.08, with this amount depending mainly on D_1/D_{max} .

Plots, such as one of the curves in Figure 21, which reveal a variation of C_{D_w} with D_1/D_{max} at fixed values of L_f/D_{max} , M_∞ and mfr , sometimes indicate that C_{D_w} has a minimum value at a value of D_1/D_{max} within the range of values considered. In Figure 21 such a minimum value is indicated approximately (by an arrow) for the curve corresponding to $L_f/D_{max} = 1.0$. Such a minimum yields the optimum value of D_1/D_{max} in respect of C_{D_w} for forecowls having a NACA 1-Series profile, at the relevant conditions of L_f/D_{max} , M_∞ and mfr . This optimum may be misleading, however, since it relates to a fixed value of mass flow ratio based on A_1 rather than on A_{max} , which would probably be a more practical constraint to adopt. To determine an optimum at a fixed value of mfr based on A_{max} it is necessary to examine values of C_{D_w} at constant values of $mfr \times (A_1/A_{max})$. The result of doing this for forecowls with $L_f/D_{max} = 1.0$ (at $M_\infty = 1.0$) is shown in Sketch 5.2. This sketch may be compared with the corresponding plots of C_{D_w} against D_1/D_{max} at constant values of mfr shown in Sketch 5.3. The values of D_1/D_{max} yielding the minimum values of C_{D_w} range from 0.73 to 0.80 in Sketch 5.2 and from 0.73 to 0.84 (approximately) in Sketch 5.3. Probably more important considerations than obtaining a value of D_1/D_{max} yielding a near-minimum C_{D_w} value, however, are (a) the requirement to operate with a sufficiently high value of $mfr \times (A_1/A_{max})$, which places a lower limit on the acceptable D_1/D_{max} value (by virtue of choking), (b) the need to avoid high values of D_1/D_{max} should low wave drag be required for low values of mfr , and (c) the sensitivity of C_{D_w} to variations of mfr at the higher values of D_1/D_{max} .



Sketch 5.2 Wave drag variations at constant values of $mfr \times (A_1/A_{max})$



Sketch 5.3 Wave drag variations at constant values of mfr

5.1.2 Forecows defined by Equation (3.1)

As noted in Section 3, the shape of Forecowl 19 (derived from Equation (3.1) with $n = 0.55$) differs only slightly from that of Forecowl 6, and values of C_{D_w} for these two forecows at corresponding conditions of M_∞ and mfr are generally within 0.01. Comparing the wave drag characteristics of Forecows 17, 18, 19 and 20, it is seen that, at given M_∞ and mfr , the fuller profiles yield the higher values of C_{D_w} , with the more significant differences being observed between $n = 0.35$ and $n = 0.55$, i.e. between Forecows 17 and 19. Between $n = 0.55$ and $n = 0.65$ (Forecows 19 and 20) the corresponding changes in C_{D_w} are relatively slight, being less than 0.02 at all the conditions considered.

5.2 Pre-entry Force Coefficient and Forecowl Pressure Force Coefficient

Charts of pre-entry force coefficient* are presented in Figures 1b to 20b and forecowl pressure force coefficient charts are presented in Figures 1c to 20c for the same ranges of flow conditions for which the corresponding data for C_{D_w} are presented.

Relative to wave drag, values of pre-entry force and forecowl pressure force are of less interest. Variations of these component forces, particularly with mfr and at $M_\infty < 1.0$, may appear to be significant, but since they may be roughly equal in magnitude and opposite in sign the net consequence for wave drag is often small. Thus, for Forecowl 1 at $M_\infty = 0.8$, reducing mfr from 0.8 to 0.5 results in a change of about 0.05 in C_{D_w} , whilst the corresponding changes in $C_{\phi_{pre}}$, and $C_{\phi_{cowl}}$ are 0.18 and -0.13 . This reflects the fact that as mfr is decreased the positive values of C_p 'act' on a pre-entry streamtube with an increased area change between a and b (Sketch 1.1) and contribute a (positive) increase in $C_{\phi_{pre}}$, whilst the lower C_p values generated by the flow in the region near the highlight provide a negative contribution to $C_{\phi_{cowl}}$.

The variation of pre-entry force coefficient with freestream Mach number, at constant mass flow ratio, is relatively small, with pre-entry force coefficient increasing with increasing freestream Mach number.

* Note that here pre-entry force is based upon the maximum cross sectional area of the forecowl. For comparison with the one-dimensional theory (References 11 and 13) the pre-entry force coefficient should be adjusted so that it is based on A_1 (i.e. $C_{\phi_{pre}} \times (A_{max}/A_1)$).

The variation of forecowl pressure force coefficient with mass flow ratio, at constant freestream Mach number, is almost linear, with forecowl pressure force coefficient increasing with increasing mass flow ratio.

Note that, for any given forecowl at given conditions of M_∞ and mfr , the values of C_{D_w} , $C_{\phi_{pre}}$ and $C_{\phi_{cowl}}$ derived from the charts in this Data Item should be such that $C_{D_w} = C_{\phi_{pre}} + C_{\phi_{cowl}}$. Any difference obtained between C_{D_w} and $C_{\phi_{pre}} + C_{\phi_{cowl}}$ should be negligible.

6. DERIVATION OF RESULTS

6.1 Calculation of Flow Fields

The flow fields were calculated using the computer program EJ50 (Reference 4), which was developed by British Aerospace. This program provides solutions of the Euler equations for inviscid flow about ducted bodies. The Euler equations are solved by means of a finite-volume technique due to Jameson *et al*, see Reference 5, which uses a four-stage Runge Kutta time-marching scheme at subsonic freestream speeds and a three-stage Runge Kutta time-marching scheme at supersonic freestream speeds. Local time-stepping (*i.e.* advancing the solution by time steps that vary through the field) is employed to improve the rate of convergence to the steady state solution.

The Euler equations are solved utilising points on an orthogonal grid onto which the physical domain has been mapped. The mapping is achieved using a conformal mapping technique (due to Jameson and Caughey, see Reference 6) in which the cowl profile is unwrapped about a singular point close to the highlight.

Changing the values of a number of parameters allows the user to control the extent and local density of the computational grid. The grids used contained 149×49 points* and extended to a distance of about $10D_1$ from the highlight. Sketch 6.1 shows the computational grid used for Forecowl 6, which is typical. The computed results were found to be relatively insensitive to moderate variations in the distribution of points within the grid, although adequate definition of the forecowl, especially in the region around the highlight, was found to be important.

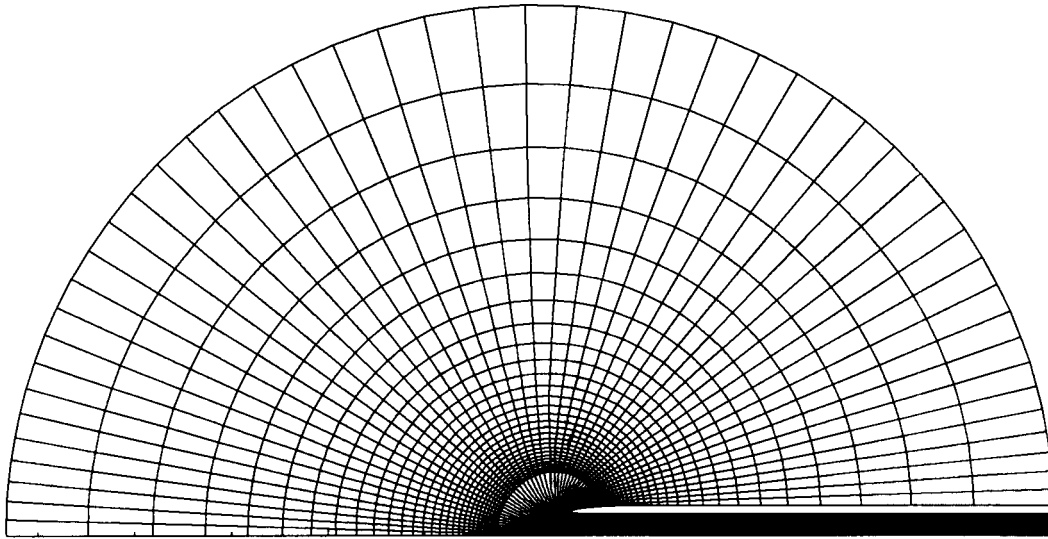
Convergence of a computed flow field to the steady state solution was generally found to occur before 15 000 successive time steps had been completed. The solution was judged to be converged when the average rate of change of density and the average excess enthalpy† took suitably small values. Values of 5×10^{-4} for the average rate of change in density and average excess enthalpy were found to be adequate for $M_\infty < 1.0$, but for $M_\infty > 1.0$ it was found that the values should be no more than 5×10^{-4} and 1×10^{-6} respectively.

A number of checks on the accuracy of the computed data have been applied. One of the most searching is a check on the values of C_{D_w} calculated for shock-free flows, which should be zero. It was generally found that the values calculated for C_{D_w} for such flows were small and positive. In no case did the magnitude of C_{D_w} calculated for a shock-free flow exceed 0.005. Judging by this and by the 'smooth' nature of the variations of calculated C_{D_w} (with M_∞ , mfr , D_1/D_{max} etc.), it seems likely that errors in calculated C_{D_w} are within 0.005.

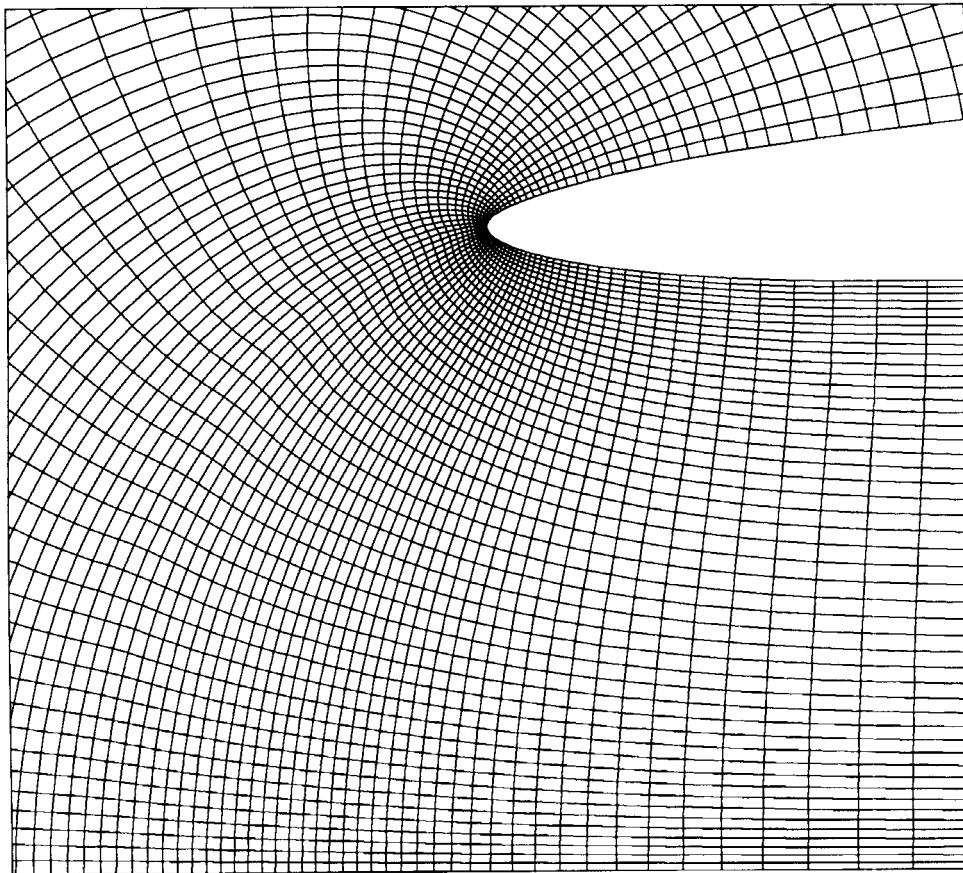
With the number of grid points used, it was found that EJ50 required about 200 minutes of computing time on a DEC 5000 workstation to perform 15 000 time steps.

* The larger number refers to the number of grid points around the profile (comprising both internal and external parts).

† The excess enthalpy is the value by which the enthalpy exceeds that of the freestream flow.



(a) Full extent of grid (some grid lines near highlight omitted)



(b) Detail of grid near highlight

Sketch 6.1 Computational grid for Forecowl 6

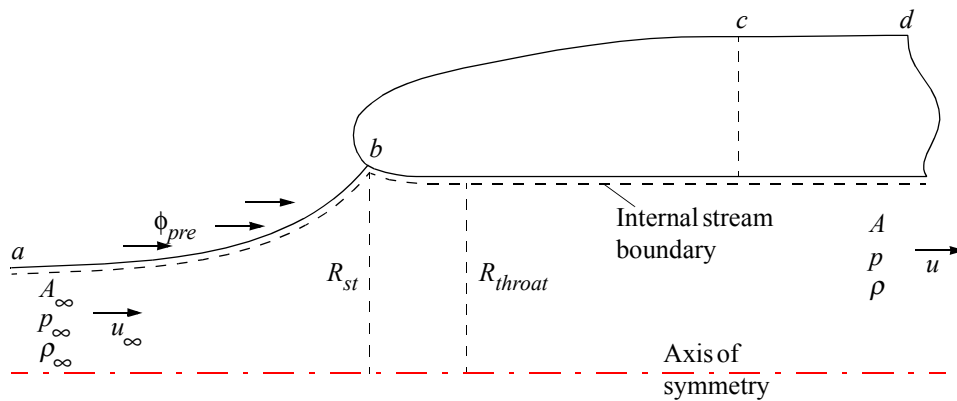
6.2 Calculation of Force Coefficients

At the conclusion of each flow field calculation, pressure distributions over the body surface were calculated, and from these the coefficients of pre-entry force and forecowl pressure force were determined by numerical integration. The sum of these forces yielded the wave drag.

Difficulty in accurately determining the location of the stagnation streamline, from the calculated flow field, means that it is preferable not to use Equation (1.5) directly to evaluate pre-entry force coefficient. The pre-entry force coefficient was evaluated in EJ50 and hence here by use of the following Equation, which is obtained by application of the momentum theorem to the internal stream (see, for example, References 13 and 14).

$$C_{\phi pre} + \frac{2\pi}{A_{max}} \int_{R_{st}}^{R_{throat}} C_p R dR = \frac{(p - p_{\infty})A_{throat} + \dot{m}(u - u_{\infty})}{\frac{1}{2}\rho_{\infty}u_{\infty}^2 A_{max}}. \quad (6.1)$$

The integral is taken along the forecowl (internal) profile, and p and u take their values 'far downstream' in the internal stream – see Sketch 6.2.



Sketch 6.2 Nomenclature for momentum theorem applied to internal stream

7. COMPARISON OF CALCULATED AND EXPERIMENTAL DATA

7.1 Pressure Distribution

Good agreement between calculated and measured force coefficients can only be expected if the corresponding surface pressure distributions are in good agreement. A number of calculations further to those presented in Figures 1 to 20 have been made to provide comparisons with the wind tunnel test data of References 7 to 10 which relate to a range of axisymmetric forecowl geometries. In general there is reasonable agreement between experiment and computation for surface pressure distributions. This is illustrated in Figure 25 where a comparison is presented for a NACA 1-Series forecowl with $D_1/D_{max} = 0.85$ and $L_f/D_{max} = 1.0$ for $M_\infty = 1.2$ and $mfr = 0.70$. The errors near the peak suction may be due to the fact that pressures in this region are very sensitive to the value of mfr , which is difficult to determine very accurately from measured data. Another possible source of error near the peak suction is the sensitivity of the computed pressures in this region to the surface geometry representation, as illustrated in Reference 2, Figure 3. It appears likely that use of the smoothed NACA 1-Series geometry representation somewhat decreases the levels of the computed suction peaks. The other discrepancies between measured and calculated pressure coefficient values for $x/L_f > 1.0$ seen in Figure 25 are largely the result of viscous effects.

Further examples of comparisons between computed and experimental forecowl pressure distributions are given in Reference 12.

7.2 Wave Drag Coefficient

Calculated wave drag coefficients have been compared with measured total external force coefficients* presented in Reference 10. Reasonable agreement is found between measured values and those obtained by computation for flows in which there was little or no boundary-layer separation. This is illustrated in Figure 26 where measured and calculated data are compared for a NACA 1-Series forecowl with $D_1/D_{max} = 0.89$ and $L_f/D_{max} = 1.0$.

7.3 Pre-entry Force and Forecowl Pressure Force Coefficients

Calculated pre-entry force and forecowl pressure force coefficients have been compared with the experimental data of Reference 10 for a range of flow conditions. It is found that, in general, for flows in which there is no boundary-layer separation, agreement between calculation and measurement is good. As the effects of separation become significant, the agreement between experiment and computation deteriorates.

Comparisons of pre-entry force and forecowl pressure force coefficients are illustrated for a NACA 1-Series forecowl with $D_1/D_{max} = 0.85$ and $L_f/D_{max} = 1.0$ in Figures 27 and 28 respectively. The onset of separation can be seen in Figure 28 as the point at which computations and experiment begin to diverge. The effects of separation are particularly noticeable for the data corresponding to $M_\infty = 0.4$.

* In Reference 10, measured values of $C_{D_{tot}}$ are determined as the sum of pre-entry and forecowl pressure forces as deduced from pressure measurements and thus exclude direct viscous contributions. They should therefore be very nearly equal to corresponding values of C_{D_W} , unless viscous effects significantly influence the surface pressures (as occurs with boundary layer separation).

8. REFERENCES

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9. FORECOWL PARAMETERS

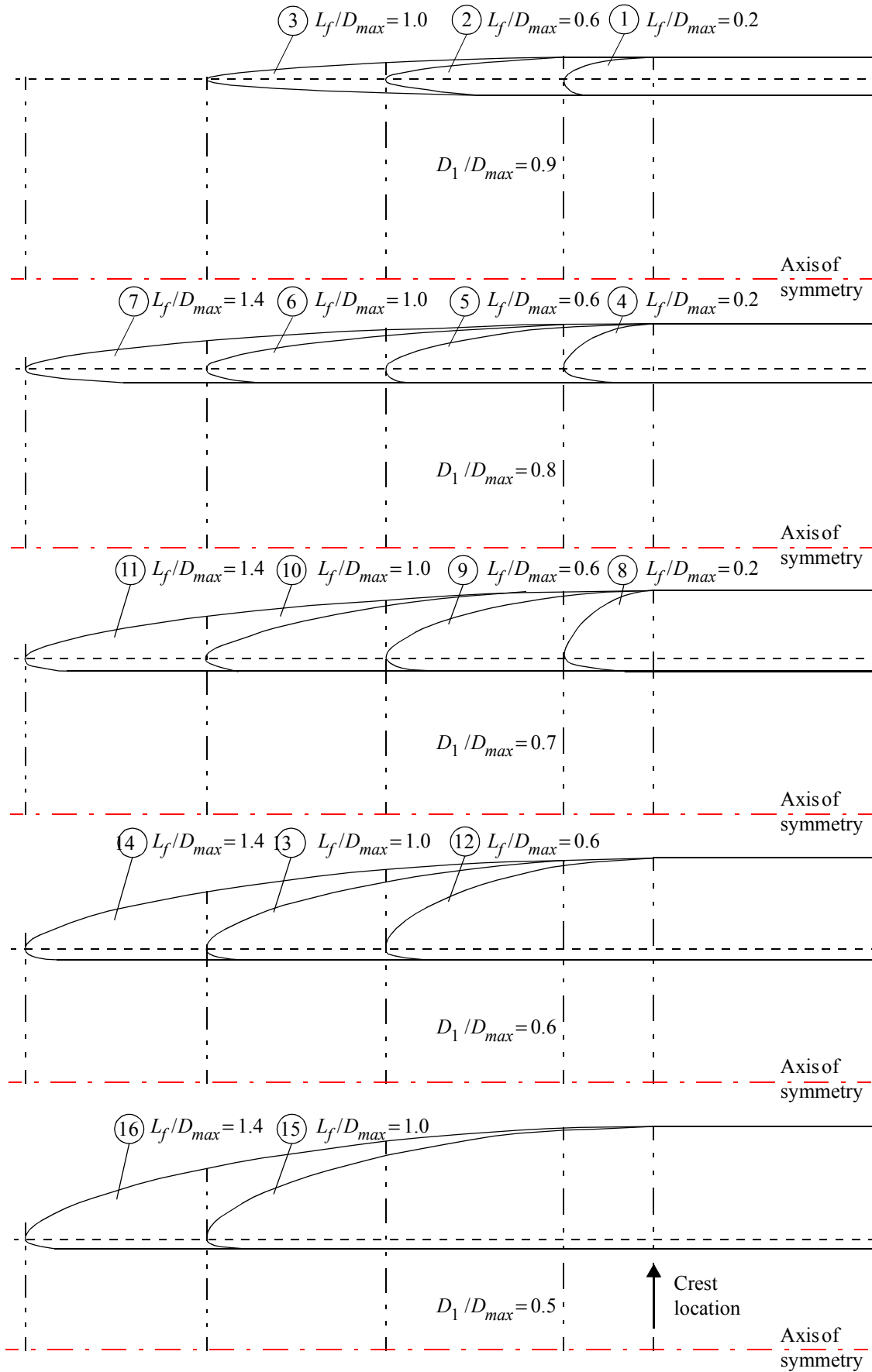
TABLE 9.1 FORECOWL PARAMETERS AND RELEVANT FIGURE NUMBERS

Forecowl Number*	External Profile†	D_1/D_{max}	L_f/D_{max}	x_{throat}/D_{max}	mfr_s	Figure Number†		
						C_{D_w}	$C_{\phi_{pre}}$	$C_{\phi_{cowl}}$
1	NACA 1-Series	0.9	0.2	0.0448	0.54	1a	1b	1c
2	NACA 1-Series		0.6	0.4036	0.82	2a	2b	2c
3	NACA 1-Series		1.0	1.1202	0.83	3a	3b	3c
4‡	NACA 1-Series	0.8	0.2	0.1743	0	4a	4b	4c
5	NACA 1-Series		0.6	0.0801	0.44	5a	5b	5c
6	NACA 1-Series		1.0	0.2225	0.58	6a	6b	6c
7	NACA 1-Series		1.4	0.4360	0.78	7a	7b	7c
8‡	NACA 1-Series	0.7	0.2	0.1525	0	8a	8b	8c
9‡	NACA 1-Series		0.6	0.1525	0.06	9a	9b	9c
10‡	NACA 1-Series		1.0	0.1525	0.41	10a	10b	10c
11	NACA 1-Series		1.4	0.1484	0.52	11a	11b	11c
12‡	NACA 1-Series	0.6	0.6	0.1307	0	12a	12b	12c
13‡	NACA 1-Series		1.0	0.1307	0	13a	13b	13c
14‡	NACA 1-Series		1.4	0.1307	0.24	14a	14b	14c
15‡	NACA 1-Series	0.5	1.0	0.1089	0	15a	15b	15c
16‡	NACA 1-Series		1.4	0.1089	0	16a	16b	16c
17	n = 0.35	0.8	1.0	0.2225	0	17a	17b	17c
18	n = 0.45		1.0	0.2225	0.60	18a	18b	18c
19	n = 0.55		1.0	0.2225	0.60	19a	19b	19c
20	n = 0.65		1.0	0.2225	0.64	20a	20b	20c

* Forecowl number and Figure number correspond up to 20.

† Profiles of Forecows 1 to 16 are shown in Sketch 9.1. Profiles of Forecows 6 and 19 are very similar. The variations of y/Y with x/X for Forecows 17 to 20 are shown in Sketch 3.2.

‡ For these forecows the internal profile is a quarter ellipse having $SR = 5.0$, see section 3.1.



Sketch 9.1 Profiles of forecows 1 to 16 drawn to scale

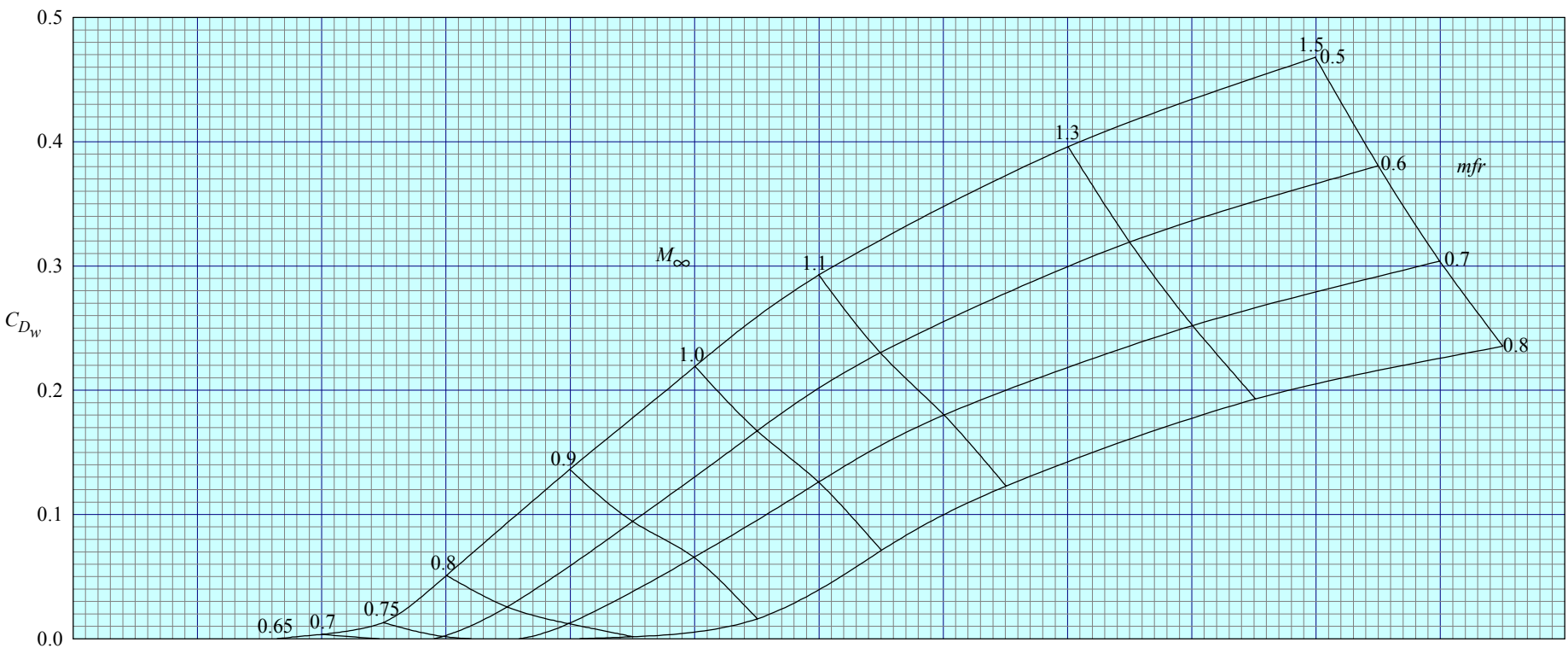


FIGURE 1a WAVE DRAG COEFFICIENT FOR FORECOWL 1 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.2$)

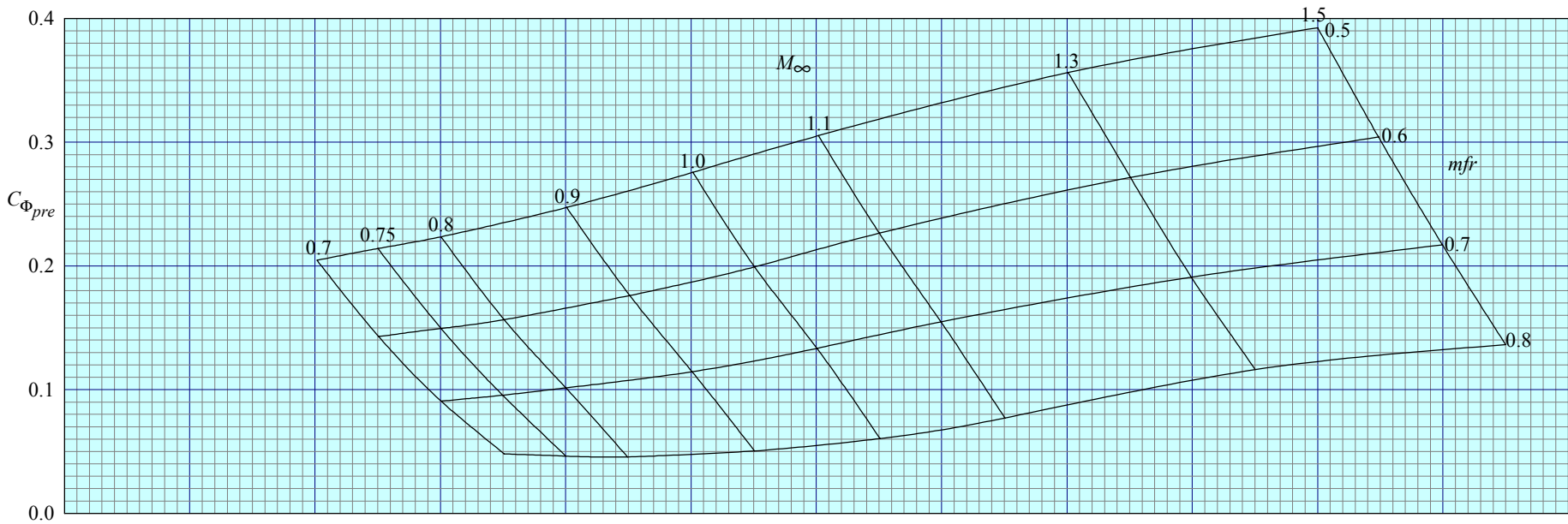


FIGURE 1b PRE-ENTRY FORCE COEFFICIENT FOR FORECOWL 1 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.2$)

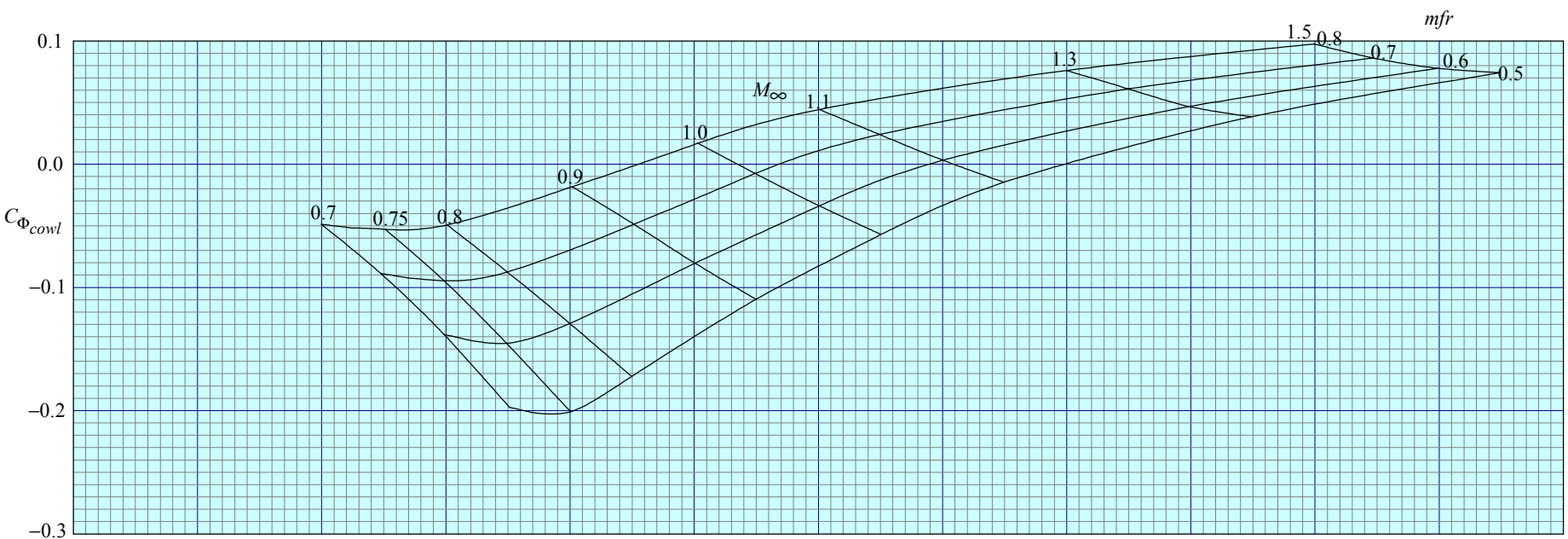


FIGURE 1c FORECOWL PRESSURE FORCE COEFFICIENT FOR FORECOWL 1 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.2$)

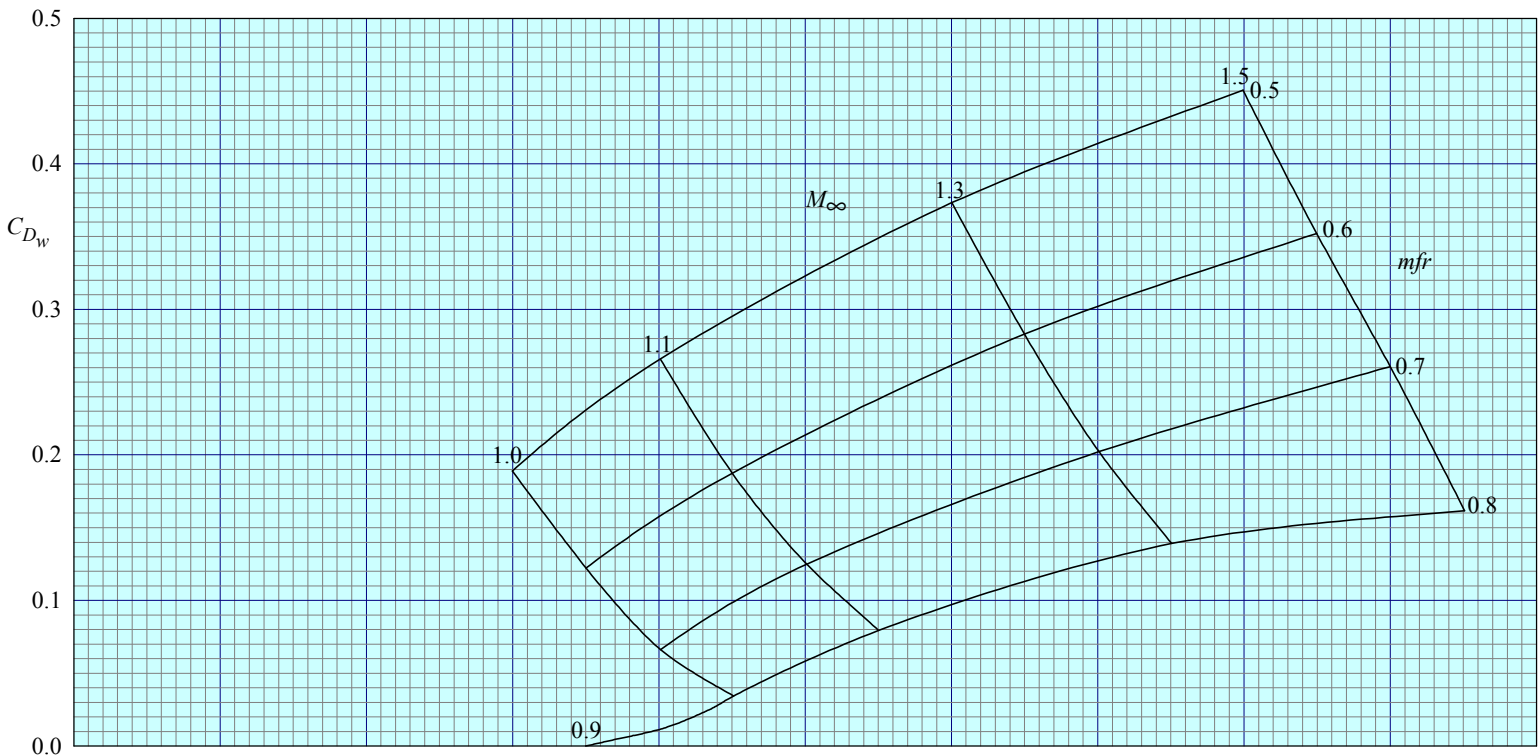


FIGURE 2a WAVE DRAG COEFFICIENT FOR FORECOWL 2 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.6$)

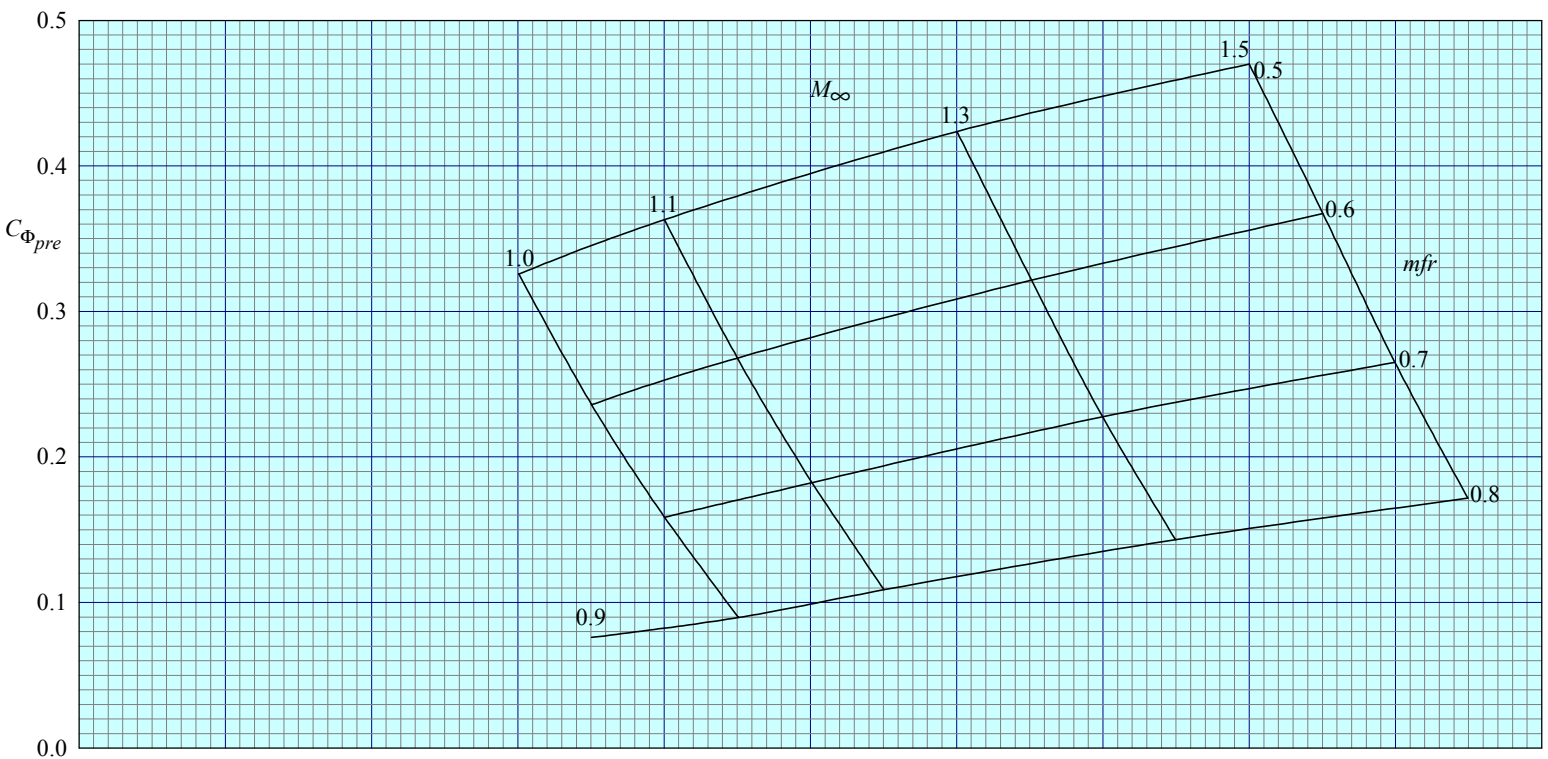


FIGURE 2b PRE-ENTRY FORCE COEFFICIENT FOR FORECOWL 2 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.6$)

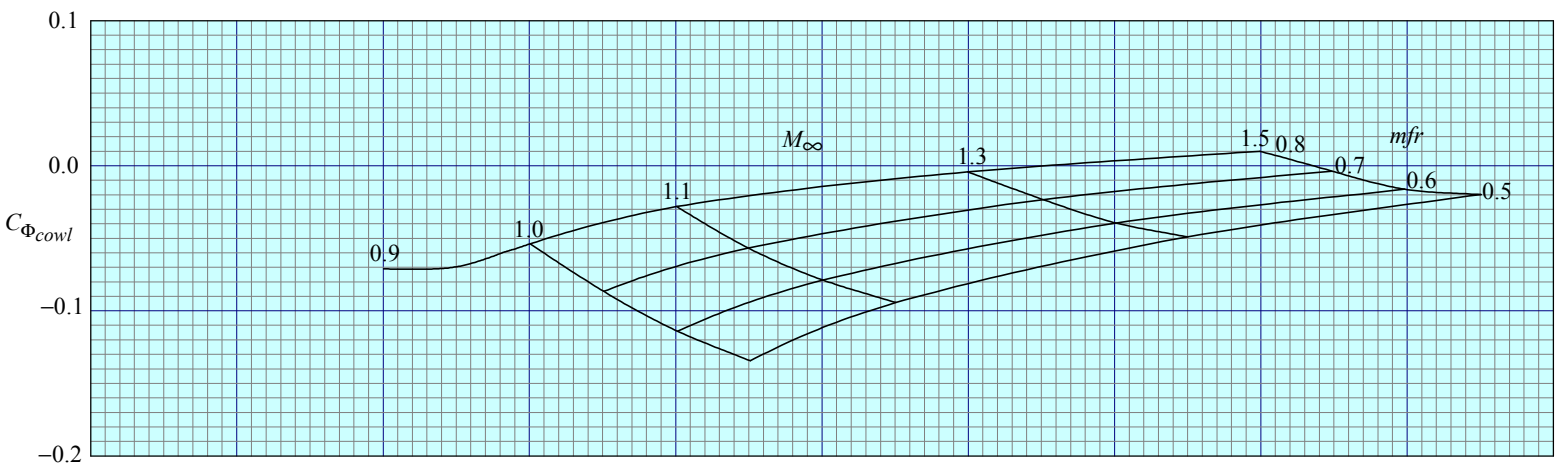


FIGURE 2c FORECOWL PRESSURE FORCE COEFFICIENT FOR FORECOWL 2 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 0.6$)

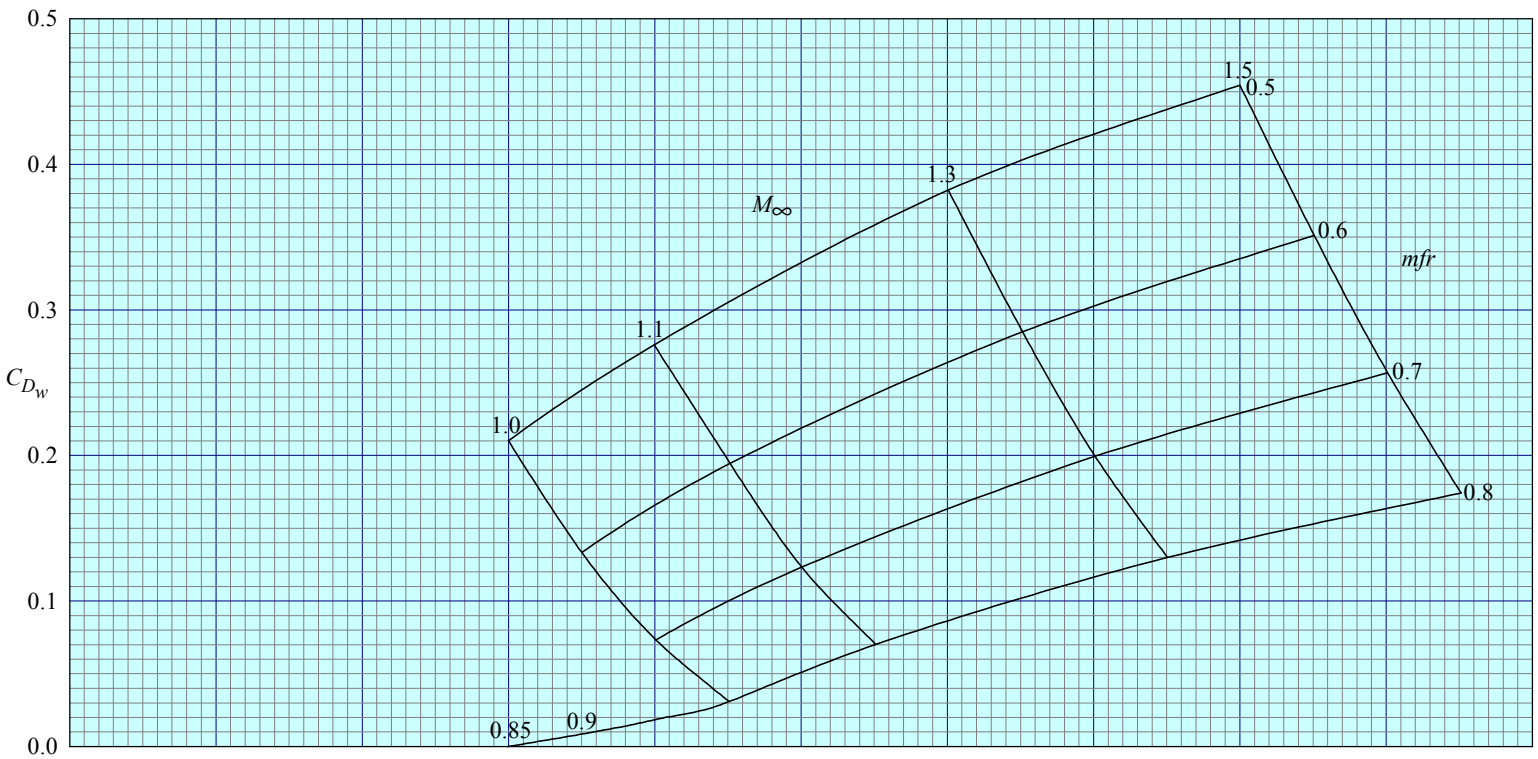


FIGURE 3a WAVE DRAG COEFFICIENT FOR FORECOWL 3 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 1.0$)

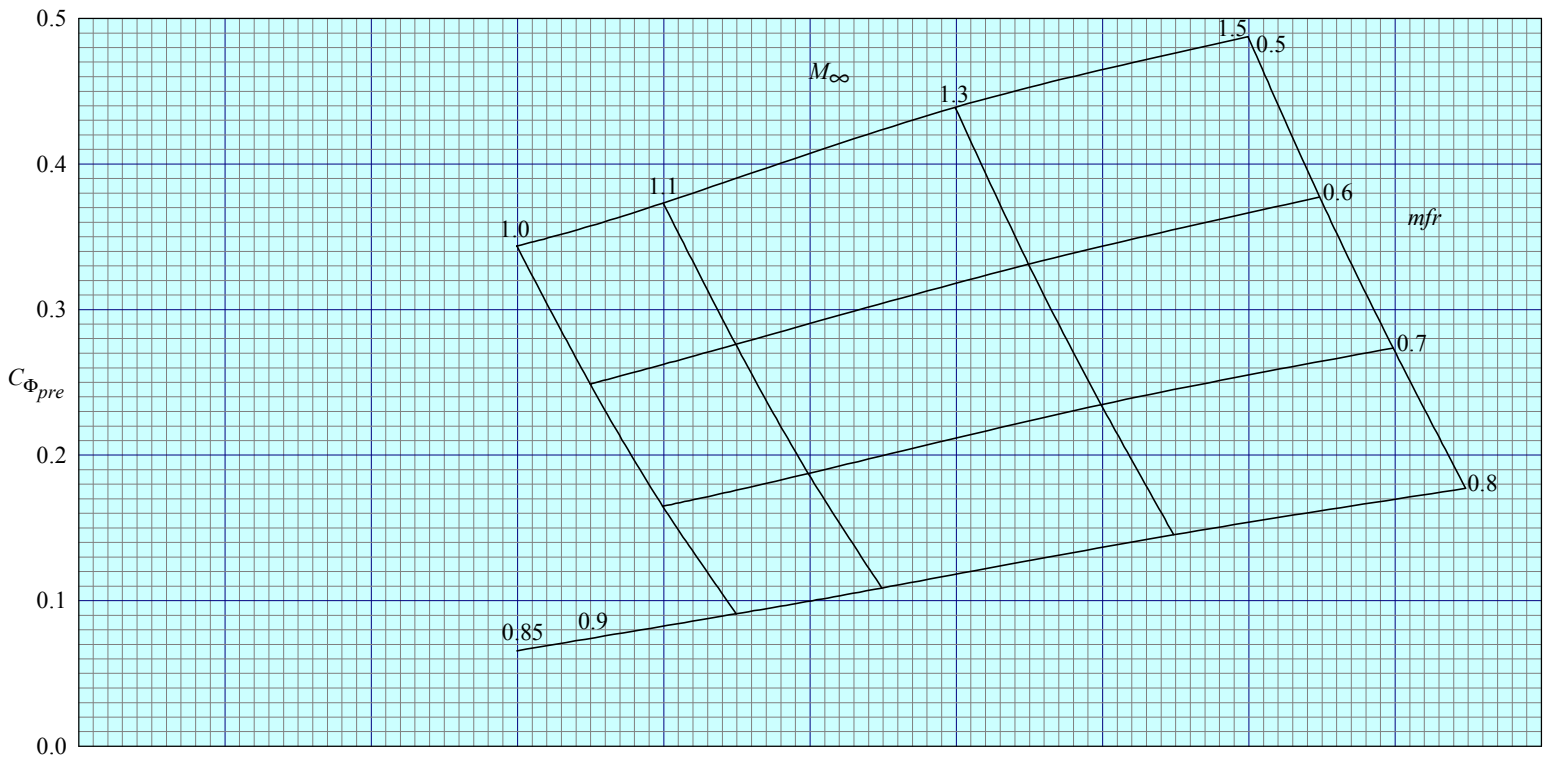


FIGURE 3b PRE-ENTRY FORCE COEFFICIENT FOR FORECOWL 3 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 1.0$)

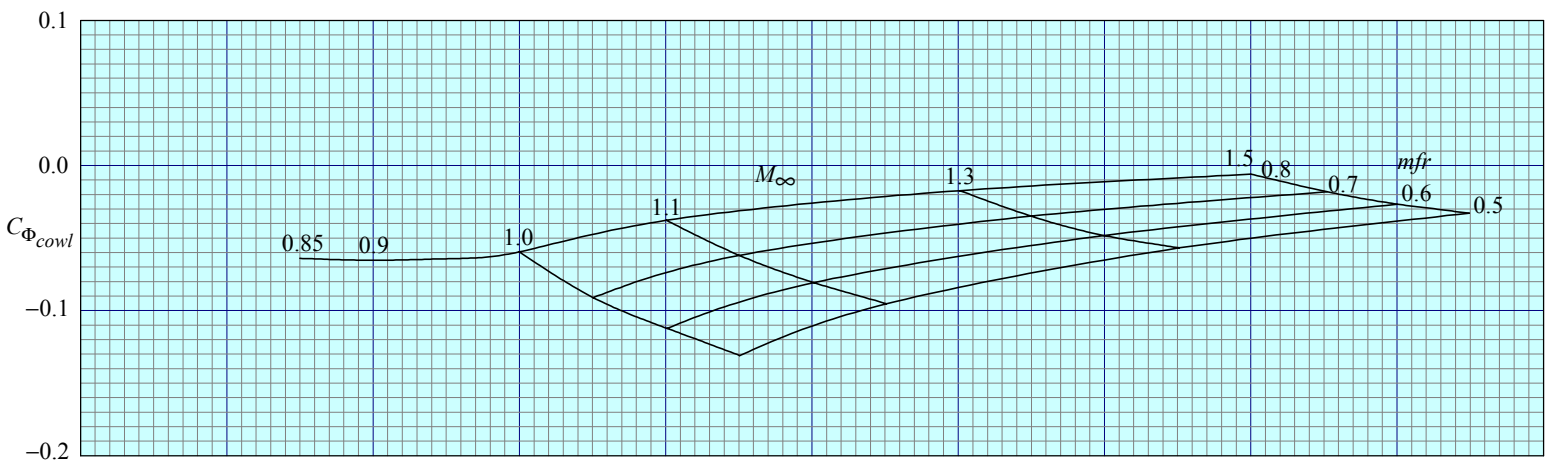


FIGURE 3c FORECOWL PRESSURE FORCE COEFFICIENT FOR FORECOWL 3 (NACA 1-SERIES, $D_1/D_{max} = 0.9$, $L_f/D_{max} = 1.0$)