

PRESSURE DRAG AND LIFT CONTRIBUTIONS FOR BLUNTED FOREBODIES OF FINENESS RATIO 2.0 IN TRANSONIC FLOW ($M_\infty \leq 1.4$)

SUMMARY

This Data Item presents charts of forebody pressure drag coefficient at zero incidence (equivalent to wave drag coefficient) and charts, around the optimum blunting ratio, of normal pressure force coefficient and axial pressure force coefficient for incidences up to 10° . Viscous contributions to these coefficients are not included. Data are presented for spherically blunted tangent ogive and cone forebodies of fineness ratio 2.0, followed by a cylindrical afterbody, over the freestream Mach number range 0.70 to 1.40. An important part of the normal pressure force coefficient results from the pressure distribution over the cylindrical afterbody, and this part is included in the data presented.

The charts were derived using computer codes developed by British Aerospace (Filton) for inviscid flows around axisymmetric bodies and based on the Jameson method of solving the Euler equations; the forces were derived from the integration of surface pressures in the normal and axial directions.

Examples are provided which compare forebody pressure distributions and force coefficients with wind-tunnel data, whilst other evaluations which compare calculated results with experimental data are referenced.

1. INTRODUCTION

This Memorandum presents charts of forebody pressure drag coefficient at zero incidence (equivalent to wave drag coefficient) and charts, around the optimum blunting ratio, of normal pressure force coefficient and axial pressure force coefficient for incidences up to 10° . Viscous contributions to these coefficients are not included. Data are presented for spherically blunted tangent ogive and cone forebodies of fineness ratio 2.0, followed by a cylindrical afterbody, over the freestream Mach number range 0.70 to 1.40. The importance and applications of such data are discussed in the Introduction to T.D. Memo. 79004 (Ref. 1). The blunted tangent ogive and the blunted cone are the two limiting cases of the family of spherically blunted secant ogive forebodies defined in T.D. Memo. 83017 (Ref. 2). An important distinction between the blunted tangent ogive and the blunted cone is the existence in the latter of a discontinuity in slope at the forebody/afterbody junction (shoulder). Charts of forebody volume coefficient for the blunted tangent ogive and cone forebodies are presented in T.D. Memos 79004 and 83017.

The wave drag charts of T.D. Memos 79004 and 83017, restricted to zero incidence, were derived using a potential flow method (Ref. 3) whereas the charts presented here have been obtained using a method (Ref. 4) that solves the Euler equations. While potential flow solutions have proved extremely useful for predicting transonic flows with shock waves of moderate strength, the approximation of ignoring entropy changes and vorticity production cannot be expected to give acceptable accuracy when flight speed is increased into the upper transonic range. Solutions of Euler equations do not ignore these phenomena and, therefore, can be used to improve upon the previous charts as well as extending them to low supersonic speeds and incidence.

The solutions have been derived using computer codes (Ref. 5) developed by British Aerospace (Filton) for inviscid flows around axisymmetric bodies and based on the Jameson method (Ref. 4). The solutions yield surface pressures which are then integrated in the normal and axial directions to obtain the required forces. Examples are provided which compare forebody pressure distributions and pressure force coefficients with wind-tunnel data, whilst other evaluations which compare calculated results with experimental data are referenced.

In the calculations each forebody was followed by a long cylindrical afterbody (see Section 6). Note that, for real configurations such as missiles or aircraft fuselages, which are of finite length and usually close in a boat-tail, the change in entropy that occurs due to a shock may have an effect on the flow condition downstream of the shock resulting in changes in axial and normal force coefficients for the boat-tail.

The data in the charts may be used to calculate the forebody contribution to the pressure forces on bodies with the given forebody shape followed by a cylindrical midbody where the midbody is sufficiently long for the full effectiveness of the forebody to be achieved and for the interference effects between the forebody and the afterbody to be negligible. Where there are significant interference effects the forces on the complete body must be evaluated as an entity and a method such as that described in Ref. 5 can be used for this purpose.

2. NOTATION

In using this Item a consistent unit of linear dimension must be used.

b	nose blunting ratio (= d/D)
b_{opt}	optimum nose blunting ratio (see Section 4.5)
C_{A_p}	axial pressure force coefficient (based on πR^2)
C_{D_p}	pressure drag coefficient (based on πR^2)
C_{D_w}	wave drag coefficient (based on πR^2)
C_{L_p}	lift coefficient as defined by Equation (4.6) (based on πR^2)
C_N	normal force coefficient (based on πR^2)
C_{N_p}	normal pressure force coefficient (based on πR^2)
C_p	pressure coefficient
C_p^*	pressure coefficient for local Mach number of unity
c_a	local axial force coefficient as defined by Equation (4.2)
c_n	local normal force coefficient as defined by Equation (4.4)
D	diameter of cylindrical afterbody (= $2R$)
d	diameter of spherical nose blunting (= $2r$)
f	forebody fineness ratio (= L/D) (see Sketch 3.1)
L	forebody length
l_a	cylindrical afterbody length
M_∞	freestream Mach number
R	radius of cylindrical afterbody
R_0	radius of blunted tangent ogive (see Sketch 3.1)
r	radius of spherical nose blunting (see Sketch 3.1)
x	axial distance (see Sketch 3.1)
y	radial distance (see Sketch 3.1)

α angle of incidence (see Sketch 4.1)

ϕ roll angle (see Sketch 4.1)

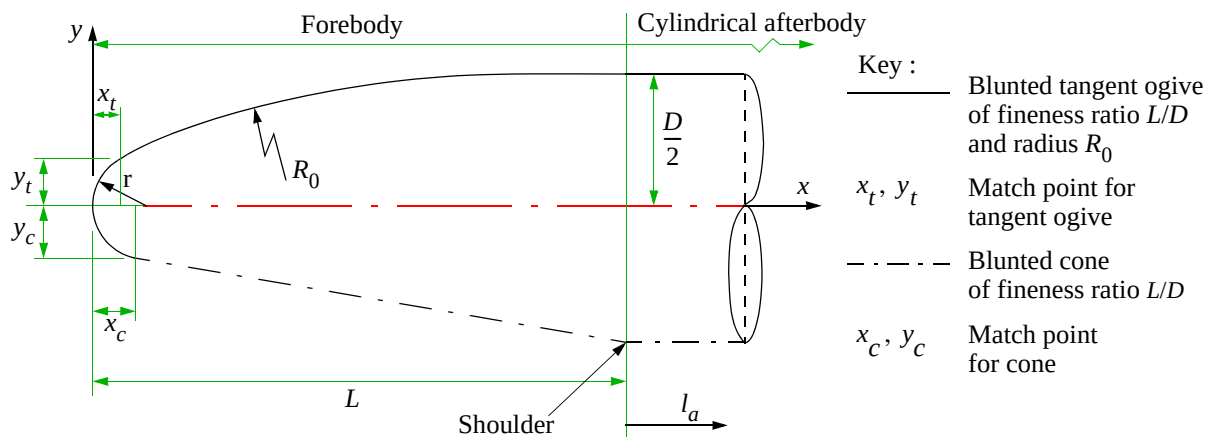
Subscripts

c denotes match point between spherical blunting and conical part of cone forebody (see Sketch 3.1)

t denotes match point between spherical blunting and ogive part of tangent ogive forebody (see Sketch 3.1)

3. GEOMETRIC CHARACTERISTICS OF THE FOREBODIES

The forebody geometry notation is given in Sketch 3.1. The generating equations for the spherically blunted tangent ogive and cone forebodies are included in the equations for the secant ogive detailed in T.D. Memo. 83017; the tangent ogive and the cone are the bodies at the limits of the range of the complete family of secant ogive forebodies. Appendix A of that Item presents the listing of a computer program written in FORTRAN which generates the surface coordinates of the forebodies and the values of the parameters R_0 , x_t and y_t or x_c and y_c . Values of the coordinates and the parameters from the program are output non-dimensionalised by R .



Sketch 3.1 Forebody geometry notation for spherically blunted tangent ogives and cones

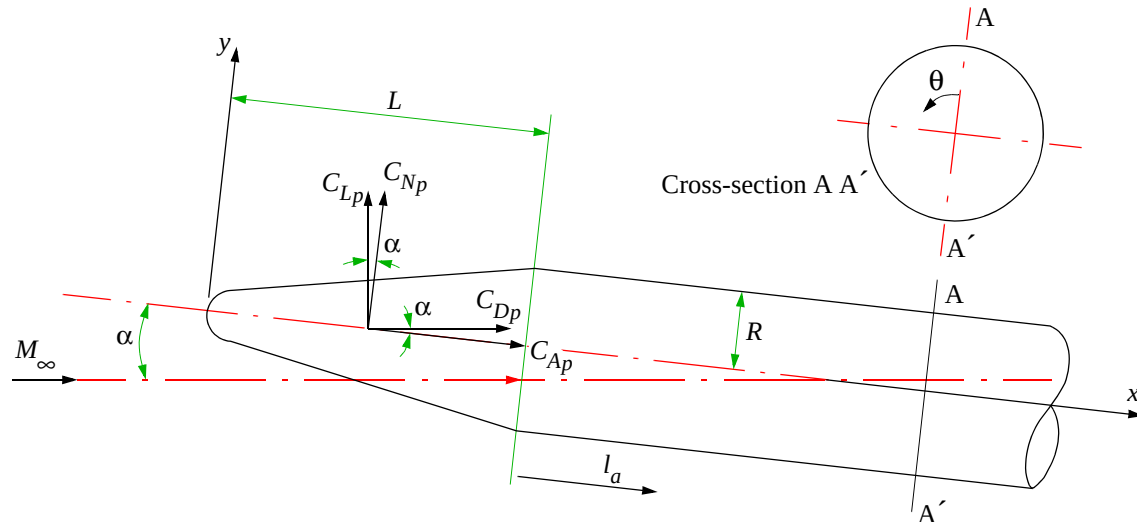
Each blunted forebody is constructed from two generators comprising the spherical nose blunting portion and the ogival or conical portion. The spherical nose blunting is tangential to the ogival or conical parts of the blunted tangent ogive or cone forebodies at the match point (x_t, y_t) or (x_c, y_c) , respectively; consequently the forebody surface slope is continuous at this point. The limiting values of nose blunting ratio are zero (corresponding to a pointed forebody – not included in the data of the present Item) and unity (corresponding to a hemispherical-headed forebody). For the blunted tangent ogive and hemispherical forebodies, the surface slope at the junction between forebody and afterbody is continuous whereas for the blunted cone the surface slope at the shoulder is discontinuous.

Figure 1 illustrates the effect on geometry of varying blunting ratio for (a) tangent ogive and (b) conical

forebodies, each with fineness ratio $f = 2.0$. It is these forebodies that are considered in this Memorandum.

4. DEFINITIONS

Sketch 4.1 shows the notation used to define the force coefficients which are obtained from integration of the calculated surface pressure coefficients. Since the computed flow is inviscid, viscous contributions to the force coefficients are not included.



Sketch 4.1 Forebody notation used to define force coefficients

4.1 Axial Pressure Force Coefficient

The axial pressure force coefficient is calculated as

$$C_{A_p} = \int_0^1 c_a d\left(\frac{y}{R}\right) \quad (4.1)$$

where

$$c_a = \int_0^1 2C_p\left(\frac{y}{R}\right)d\left(\frac{\phi}{2\pi}\right). \quad (4.2)$$

4.2 Normal Pressure Force Coefficient

The normal pressure force coefficient is given by

$$C_{N_p} = \int_0^\infty c_n d\left(\frac{x}{L}\right) \quad (4.3)$$

where

$$c_n = \int_0^1 2C_p\left(\frac{y}{R}\right)\left(\frac{L}{R}\right)\cos\phi d\left(\frac{\phi}{2\pi}\right). \quad (4.4)$$

In this Memorandum it has been found that all but a negligible amount of the contribution to C_{N_p} has been

generated by $x/L = 4$, i.e. $l_a = 3L$, so for practical reasons the upper limit of integration (∞) has been replaced by 4 (see Section 6).

4.3 Pressure Drag and Lift Coefficients

The inviscid flow contribution to pressure drag coefficient is given by

$$C_{D_p} = C_{A_p} \cos \alpha + C_{N_p} \sin \alpha \quad (4.5)$$

and the corresponding lift coefficient by

$$C_{L_p} = C_{N_p} \cos \alpha - C_{A_p} \sin \alpha. \quad (4.6)$$

4.4 Wave Drag Coefficient

In inviscid flow, for a body at zero incidence, the wave drag coefficient can be equated to the pressure drag coefficient. However, for a body at incidence, there will be a contribution to the pressure drag even in the absence of shock waves.

4.5 Optimum Blunting Ratio

For either type of forebody (i.e. blunted tangent ogive or blunted cone), the optimum blunting ratio, b_{opt} , is defined as the blunting ratio at which C_{D_p} is a minimum for given fineness ratio, M_∞ and α . Since (for either type of forebody) for given fineness ratio, M_∞ and α , the variation of C_{N_p} with blunting ratio is insignificant near the optimum blunting (see Section 5), b_{opt} is also the blunting ratio at which C_{A_p} is a minimum for given fineness ratio, M_∞ and α .

5. CHARTS OF AXIAL FORCE AND NORMAL FORCE COEFFICIENTS

5.1 Presentation of Charts

5.1.1 Blunted tangent ogive forebodies

Figure 2 presents the wave drag coefficient, C_{D_w} , at zero incidence (equivalent to the axial pressure force coefficient, C_{A_p} , at zero incidence) as a function of spherical nose blunting ratio, b , and freestream Mach number, M_∞ , for blunted tangent ogive forebodies with fineness ratio, f , of 2.0 in the range of freestream Mach number $0.7 \leq M_\infty \leq 1.4$.

Parts (a) of Figures 5 to 10 present the axial pressure force coefficient, C_{A_p} , as a function of spherical nose blunting ratio and incidence, α , for freestream Mach numbers $0.9 \leq M_\infty \leq 1.4$ for tangent ogive forebodies around the optimum blunting ratio at incidences up to 10° . Parts (b) of these figures provide the corresponding normal pressure force coefficient, C_{N_p} , as defined in Section 4.2.

Figures 11, 12 and 13 show the variation of the optimum blunting ratio, b_{opt} , with freestream Mach number for the tangent ogive forebodies at $\alpha = 0^\circ, 5^\circ$ and 10° , respectively. These figures also show blunting ratio limits corresponding to an increase in C_{A_p} of 0.001 above the optimum (which can also be regarded as an equal increase in C_{D_p} since, for a given incidence, C_{N_p} varies insignificantly around b_{opt}) either side of the value of C_{A_p} (or C_{D_p}) corresponding to optimum blunting. For $\alpha = 0^\circ$ a further limit corresponding to an increase in C_{A_p} of 0.005 above the optimum and a boundary marking approximately the end of wholly subcritical flow over the body have been added. Figure 14 presents the effect of incidence on the optimum

blunting ratio by showing the 0° , 5° and 10° optimum blunting curves together.

5.1.2 Blunted cone forebodies

Figure 15 presents, in a similar manner to Figure 2, the wave drag chart for spherically blunted cone forebodies at zero incidence.

Parts (a) of Figures 15 to 24 present, in the same manner as in Figures 5 to 10, the axial pressure force coefficient for the blunted cone forebodies but with the Mach number range $0.8 \leq M_\infty \leq 1.4$. Parts (b) of these figures provide the corresponding normal force coefficient.

Figures 25, 26 and 27 show the variation of optimum blunting ratio with freestream Mach number for the blunted cone forebodies at $\alpha = 0^\circ$, 5° and 10° , respectively. These figures contain boundaries equivalent to those in Figures 11 to 13. Figure 30 shows the effect of incidence on the optimum blunting ratio for the blunted cone forebodies.

5.2 Variation of Axial Pressure Force Coefficient with Freestream Mach Number

The wave drag coefficient due to a blunted tangent ogive or a blunted cone forebody at zero incidence (equivalent to axial pressure force coefficient at zero incidence) associated with increasing freestream Mach number, is shown by the carpet plots in Figures 2 and 15,

Generally the shapes of the curves in Figure 2 for fixed blunting ratio for the blunted tangent ogive forebodies fall into three categories. At values of blunting ratio less than 0.6 no wave drag is evident until $M_\infty = 0.85$ but by $M_\infty = 0.95$ C_{D_w} is increasing quite rapidly until $M_\infty = 1.05$, after which the rate of rise begins to decrease quite significantly as M_∞ increases towards 1.4. At $b = 0.7$ and 0.8 , however, wave drag is evident at $M_\infty = 0.8$ and 0.7 , respectively, but increases only slowly (drag creep) until M_∞ exceeds 0.95, when there is a rapid drag rise to $M_\infty = 1.05$. This is then followed by a more gradual rise to $M_\infty = 1.4$. At and above $b = 0.9$, the wave drag coefficient increases very rapidly once $M_\infty = 0.70$ has been exceeded. Once M_∞ has exceeded 1.05 the rate of increase is reduced.

For the blunted cone forebodies (Figure 15), the wave drag coefficient at zero incidence for low values of blunting ratio, $b < 0.4$, increases rapidly once M_∞ exceeds 0.80 reaching a maximum at about $M_\infty = 1.05$ and decreasing slowly thereafter. At $b = 0.4$ and $b = 0.5$, the shape of the curve is similar until about $M_\infty = 1.1$, just after which a local minimum is formed ('drag bucket'), followed by C_{D_w} resuming its rise with increasing Mach number but relatively slowly. For $b = 0.6$ the 'drag bucket' is much less evident. At $b = 0.7$ and 0.8 wave drag is evident at $M_\infty = 0.75$ and 0.7 , respectively, but increases moderately until about $M_\infty = 0.97$, after which there is a rapid increase in C_{D_w} until $M_\infty = 1.05$. Thereafter C_{D_w} increases less rapidly. At, and above, $b = 0.9$ the wave drag coefficient increases very rapidly once $M_\infty = 0.7$ has been exceeded but, again, the rate of increase is less rapid once $M_\infty = 1.05$ has been exceeded. There are slight inflexions in the curves for $b \geq 0.7$ between $M_\infty = 0.95$ and 1.0. These 'drag buckets' and inflexions are the result of the shock wave, developed on the nose of the forebody, moving rearwards and decreasing in strength as M_∞ increases. The increase in drag coefficient is then resumed because the contribution to drag from the bow shock (ahead of the body) becomes dominant.

5.3 Variation of Axial Pressure Force Coefficient with Nose Blunting Ratio

The variation of the wave drag coefficient at zero incidence with nose blunting ratio for fixed freestream Mach number is shown in the charts of Figures 2 and 15 and in more detail, for part of the range of blunting ratios considered, in parts (a) of Figures 5 to 10 for the tangent ogive and Figures 15 to 24 for the blunted cone. These latter sets of figures also provide, around the optimum blunting ratio, the variation of axial force coefficient with blunting ratio at $\alpha = 5^\circ$ and 10° .

As noted in T.D. Memo. 83017 (Ref. 2), the significant feature of the charts is that some degree of nose blunting can delay the rapid drag rise to a higher Mach number and reduce forebody pressure drag coefficient. For a given freestream Mach number and incidence it is possible to determine a nose blunting ratio that is optimum with respect to pressure drag. The reason for the drag reduction that is evident over a limited range of blunting ratio is discussed in T.D. Memo. 80008 (Ref. 6). For the tangent ogive forebody (Figure 2) at $M_\infty = 0.90$ and 0.95 , the inflexions between $b = 0.7$ and 0.8 in the C_{D_w} versus b curves are likely to be the first signs of this drag reduction occurring.

Generally, the variation of axial force coefficient with blunting ratio at incidences up to 10° , around the optimum blunting ratio, is similar to that at zero incidence.

5.4 Variation of Axial and Normal Pressure Force Coefficients with Incidence around the Optimum Blunting Ratio

The variation of the axial pressure force coefficient with incidence, around the optimum blunting ratio, is shown in parts (a) of Figures 5 to 10 and Figures 15 to 24. All the figures show a progressively more rapid reduction in C_{A_p} as incidence increases. This reduction in C_{A_p} is greatest at or below sonic freestream Mach number and at most, for a 10° increase in incidence from zero near the optimum blunting ratio, is 0.031 for the tangent ogive forebodies and 0.033 for the blunted cone forebodies.

For both types of forebodies, the pressure drag coefficient at $M_\infty = 0.6$ (*i.e.* no shock wave present) was found to be 0.0075 for $\alpha = 5^\circ$ and 0.0295 for $\alpha = 10^\circ$, irrespective of the blunting ratio. This is in accordance with slender body theory (Ref. 7) which states that the effect on drag of incidence is approximately α^2 where α is in radians (*i.e.* $\alpha^2 = 0.0076$ for $\alpha = 5^\circ$ and $\alpha^2 = 0.0305$ for $\alpha = 10^\circ$). This relationship is approximately true for $M_\infty < 1.0$ in the results presented in this Memorandum. However, for $M_\infty \geq 1.0$ there is a trend away from slender-body theory as the flow becomes complex and stronger shock waves are present, suggesting that the body can no longer be considered slender*.

Parts (b) of the above figures show the corresponding variation of the normal pressure force coefficient with incidence. At zero incidence and for subsonic freestream Mach numbers, the slope of the normal pressure force coefficient versus incidence plot is close to the value 2.0 per radian given by slender-body theory but increases above this value as both M_∞ and α increase. It is important to remember that in the results given here the contribution to normal force due to viscous effects is not included. There is no significant effect on C_{N_p} of varying blunting ratio around b_{opt} . From Equation (4.5), this suggests that the behaviour of C_{D_p} will follow closely the behaviour of C_{A_p} in the region of optimum blunting.

5.5 Variation of Optimum Blunting Ratio with Freestream Mach Number and Incidence

Figure 11 shows that for the blunted tangent ogive at $\alpha = 0^\circ$ and $M_\infty = 0.9$ the optimum blunting ratio is about 0.31, and thereafter it increases rapidly to a value of 0.72 at about $M_\infty = 0.97$. The optimum blunting ratio then decreases almost linearly to a value of about 0.35 at $M_\infty = 1.4$. Similar trends are observed at $\alpha = 5^\circ$ and 10° , but with lower values of maximum optimum blunting ratios, 0.7 and 0.65, respectively (Figures 12 and 13).

The effect of incidence on optimum blunting ratio for the blunted tangent ogive forebody (summarised in Figure 14) is to reduce b_{opt} as α is increased for a given M_∞ . At low Mach number, $M_\infty < 0.93$, there is little effect of incidence but it becomes of increasing significance as M_∞ exceeds 0.95. The maximum effect occurs at about $M_\infty = 0.97$ where there is a difference between the values of b_{opt} at 0° and 10° of about 0.07. This difference decreases gradually to about 0.01 at $M_\infty = 1.3$.

For the blunted cone forebody at $\alpha = 0^\circ$ (see Figure 25), the optimum blunting ratio is constant at 0.52

* For supersonic speeds, a body is slender when it lies well within the Mach cone from the vertex (see Ref. 8).

until $M_\infty = 0.95$, after which b_{opt} rapidly increases to about 0.7 at $M_\infty = 0.99$. The optimum blunting ratio then decreases quite rapidly to 0.53 at $M_\infty = 1.1$. Thereafter, b_{opt} decreases at a slower rate to a value of 0.3 at $M_\infty = 1.4$.

In Figures 26 and 27, between $M_\infty = 0.8$ and 0.95, the optimum blunting ratio for the cone forebody increases from 0.5 to 0.54 for $\alpha = 5^\circ$ and from about 0.46 to 0.52 for $\alpha = 10^\circ$. As at zero incidence (Figure 25) b_{opt} increases rapidly between $M_\infty = 0.95$ and 1.0. For $M_\infty > 1.0$ the trend in b_{opt} with increasing M_∞ at $\alpha = 5^\circ$ and 10° is similar to that at $\alpha = 0^\circ$ but with reduced values of b_{opt} . The most noticeable differences between optimum blunting ratios at $\alpha = 0^\circ$ and 10° occur at $M_\infty = 0.8$ and 0.99 and are about 0.06 and 0.04, respectively (Figure 30).

Although the precise value of b_{opt} can vary significantly with M_∞ and α , the changes in C_{A_p} around the optimum can be relatively small as indicated by the curves for $C_{A_p}(\min) + 0.001$ in Figures 11 to 13 and Figures 25 to 27.

6. DERIVATION OF CHARTS

The charts were derived using two computer codes (Ref. 5) developed by British Aerospace (Filton) for inviscid flows around axisymmetric bodies and based on the Jameson method (Ref. 4) of solving the Euler equations. One of the codes was used for calculations on axisymmetric bodies at incidence, the other code was developed as a sub-program of the incidence code and used for calculations on bodies at zero incidence. The programs are described in more detail in Refs 5 and 9.

A 'C' type grid was used for the blunted bodies to define the flow field and the body surface in the xy -plane. This grid was constructed of contour lines spreading successively further out into the flow field and, generally, following the forebody shape. These intersect with lines emanating from the body surface and perpendicular to the contour lines to form the computational mesh. The computational mesh in the cross-sectional plane was defined by circles concentric with the body and radial lines ('O' type grid), the area between adjacent radial lines constituting a radial sector. The grid in the xy -plane consisted of 100×30 points. For the cases considered in this Memorandum, this provided sufficient points for the streamwise pressure distributions to be satisfactorily predicted. At zero incidence the flow in the cross-sectional plane is independent of ϕ and it is necessary to compute the flow only in a single radial sector with the knowledge that all other sectors are identical; the smaller the included angle of the sector the more accurate should be the computation. Here the included angle was taken as 2° . For non-zero incidence the flow in the cross-sectional plane is symmetrical about the axis AA' (Sketch 4.1) and it is necessary to compute the flow only in the half-plane ($0^\circ < \phi < 180^\circ$). The permissible included angle of the radial sector is restricted by considerations of computer (CRAY-1S) memory and CPU time. Here a radial sector of 15° included angle was used which was determined to be sufficient to define the cross-flow adequately (see Ref. 10). The difficult cases, those around sonic freestream Mach number, required 1800 time steps to obtain satisfactory convergence. In the calculations the forebodies were followed by a cylindrical afterbody of 4 forebody lengths.

Calculations were performed at freestream Mach numbers, $M_\infty = 0.6, 0.7, 0.8, 0.85, 0.95, 0.97, 1.0, 1.02, 1.05, 1.1, 1.2, 1.3$ and 1.4. The nose blunting ratio was varied between 0.1 and 1.0 in steps of 0.1 with sufficient suitable intermediate values to determine the optimum blunting ratio within 0.01 of b . Furthermore, in the case of the blunted tangent ogive at $\alpha = 0^\circ$, the points of inflexion between $b = 0.7$ and 0.8 in the variation of C_{D_p} with b at $M_\infty = 0.9$ and 0.95 were determined by successive calculations incrementing b by 0.01. Additional calculations to determine b_{opt} were also carried out at $M_\infty = 0.96$ for the tangent ogive and at $M_\infty = 0.99$ for the blunted cone.

In the charts, the computed pressure drag coefficient at zero incidence has been adjusted such that C_{D_p} at

$\alpha = 0^\circ$ is zero at low subsonic Mach number, typically $M_\infty = 0.6$, so as to eliminate any small residual error that occurs in the numerical integration of the calculated pressure coefficients. This residual error was within ± 0.0050 for blunted tangent ogive forebodies and within ± 0.0100 for blunted cone forebodies.

An adjustment is also made to the axial pressure force coefficient at incidences other than 0° . Since a better definition of the cross-sectional flow field is used in the $\alpha = 0^\circ$ case than for $\alpha > 0^\circ$, a small adjustment equal to the difference between the value of C_{D_w} at $\alpha = 0^\circ$ with the better cross-sectional definition and that value with the poorer cross-sectional definition is made to C_{A_p} for $\alpha > 0^\circ$ to merge the two sets of results together. This further adjustment was less than $+0.005$ for both types of forebodies.

It was found that a small residual value of local normal force coefficient, c_n , persisted over the rear part of the afterbody, even in wholly subcritical flow, rather than c_n tending to zero as would be expected for inviscid flow. Therefore in calculating C_{N_p} , c_n has been adjusted by removing a residual amount equal to the value of c_n occurring at $x/L = 4.0$ for $M_\infty = 0.6$. Typically, the residual amount was 0.003 for $\alpha = 5^\circ$ and 0.009 for $\alpha = 10^\circ$. The assumption that c_n tends to zero far downstream is not strictly justified for a body at incidence in inviscid supersonic flow if a shock wave is present.

At lower freestream Mach numbers ($M_\infty \leq 0.95$), where wave drag is small, the contribution from surface pressure coefficients to the normal pressure force coefficient is negligible for $x/L \geq 2.0$, *i.e.* with afterbody length $l_a \geq 1.0L$. At higher Mach numbers, where shock waves producing significant wave drag exist and significant entropy changes occur, the contribution to C_{N_p} can persist beyond $x/L = 2.0$.

7. EXPERIMENTAL VERIFICATION OF THE METHOD

Calculated pressure distributions, wave drag coefficients, axial pressure force coefficients and normal pressure force coefficients for typical tangent ogive and cone forebodies have been compared in Refs 9 and 10 with experimental data. It has been found that, in general, the Euler code results compare very favourably with experimental results. Furthermore, the Euler code predicts the experimental pressure distribution and wave drag coefficient at zero incidence better than Baker's solution of the Full Potential equation (used in Refs 1 and 2). Example comparisons are provided in Figures 31 to 38.

Figure 31 compares the pressure distributions on a blunted tangent ogive ($f = 2.0$, $b = 0.6$) at $\alpha = 0^\circ$ and $M_\infty = 1.05$ (the upper limit of M_∞ in Refs 1 and 2). The present method (Euler code) shows a significant improvement over Baker's method in predicting the experimental pressure distribution obtained by Ward (Ref. 11). However, there is an unexpected divergence of the experimental pressures over the rear part of the cylindrical afterbody. Ward (Ref. 12) has suggested this may be due to some drifting of the tunnel speed while pressure measurements were being obtained. Figure 32 provides a comparison of the pressure distributions over the blunted cone ($f = 2.0$ and $b = 0.6$) at $M_\infty = 1.20$. The Euler code predicts the pressure distributions generally very well, with some local differences in the pressure rise behind the blunted nose and in the region of the shoulder where a rapid expansion of the flow occurs.

Computed wave drag coefficients at zero incidence are directly compared with those derived from experiment* (Refs 12 and 13) in Figures 31 and 32 for the blunted tangent ogives ($b = 0.3, 0.6, 0.7, 0.8$) and blunted cones ($b = 0.3$ and 0.6), respectively. In both figures the Euler code is generally observed to predict the experimental results significantly better than Baker's method. Except at low values of wave drag coefficients ($C_{D_w} < 0.1$), all but one of the Euler code results lie within $\pm 5\%$ of the experimentally determined values of C_{D_w} .

For the bodies at incidence, comparison of the pressure distributions at $\phi = 15^\circ$ and $\phi = 165^\circ$ on the

* To derive wave drag at zero incidence or axial pressure force at incidence from the measured force, the subtraction of a value for the skin friction contribution was required. The value chosen was, in all cases, that determined for zero incidence.

blunted tangent ogive ($f = 2.0$, $b = 0.6$) and blunted cone ($f = 2.0$, $b = 0.3$) at $M_\infty = 0.97$ and $\alpha = 10^\circ$ are provided in Figures 33 and 34, respectively. The pressure distributions from the Euler code compare well with those from experiment over the forebody but there are some noticeable differences over the rear part on the cylindrical afterbody, especially at $\phi = 15^\circ$. These differences may be due to viscous effects becoming important at this incidence where the differences are likely to be more pronounced on the leeward generator than the windward generator since the boundary layer of the former will be thicker.

The variations with incidence of the calculated axial pressure force coefficients are compared with those from experiment[†] (Ref. 13) for the blunted tangent ogive ($f = 2.0$, $b = 0.6$) at $M_\infty = 0.97$ and for the blunted cone ($f = 2.0$, $b = 0.6$) at $M_\infty = 1.10$ in Figures 35 and 36, respectively. These provide comparisons for incidences up to $\alpha = 20^\circ$. The values of C_{A_p} and the trend of C_{A_p} with incidence are predicted well by the Euler code. Furthermore, because the viscous contribution to the axial force at zero incidence is removed from the measured force to obtain C_{A_p} , the comparisons suggest that there is no significant change in viscous effects from that at zero incidence*.

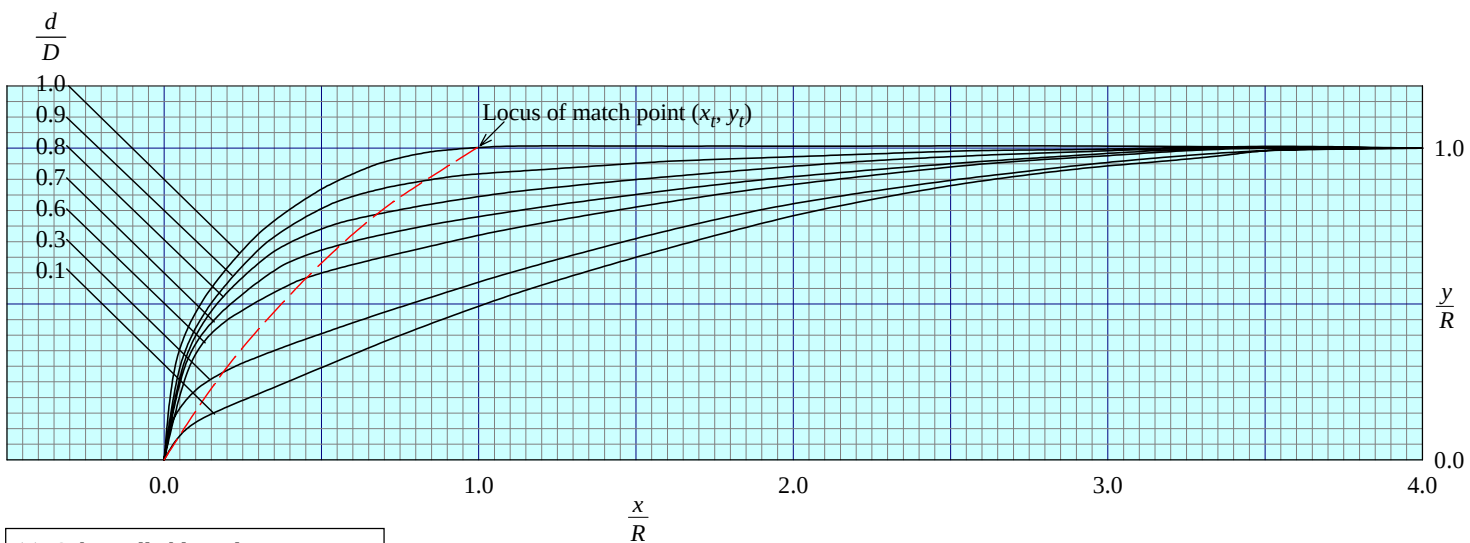
The corresponding normal force coefficients are compared in Figures 37 and 30, respectively. The Euler method predicts the C_N versus α curve well at low incidence. The comparisons suggest that the viscous flow contributions to C_N for $\alpha \leq 10^\circ$ are less than 15% of the total. As incidence increases beyond $\alpha = 10^\circ$, the viscous flow contributions to C_N become increasingly significant.

8. REFERENCES

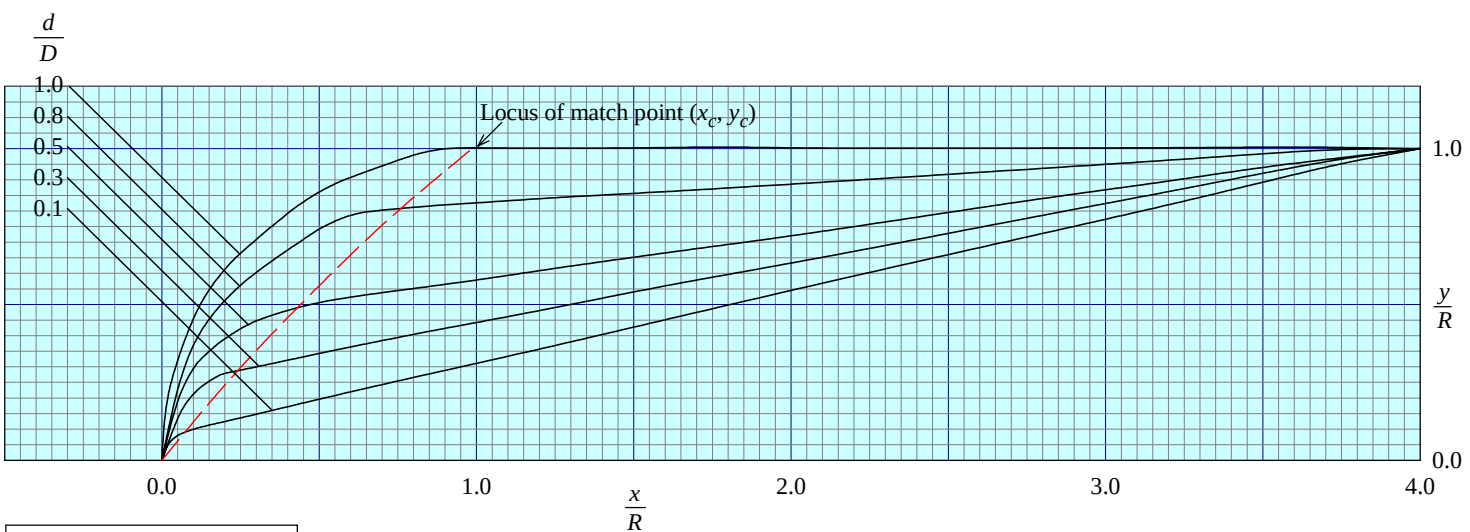
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* To derive wave drag at zero incidence or axial pressure force at incidence from the measured force, the subtraction of a value for the skin friction contribution was required. The value chosen was, in all cases, that determined for zero incidence.

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(a) Spherically blunted tangent ogive



(b) Spherically blunted cone

FIGURE 1 FOREBODIES OF FINENESS RATIO 2.0 SHOWING THE EFFECT OF VARYING NOSE BLUNTING RATIO

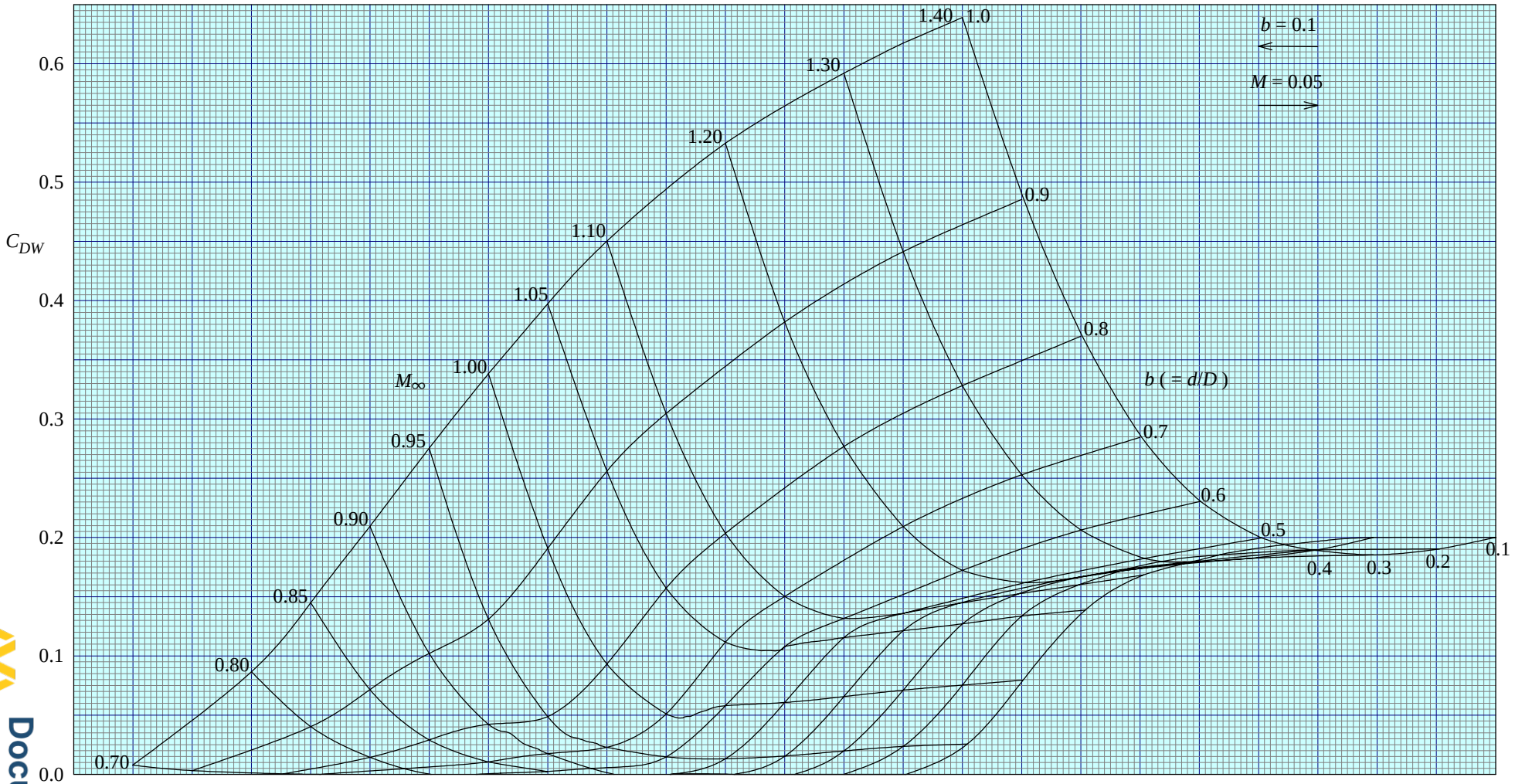


FIGURE 2 WAVE DRAG COEFFICIENT FOR BLUNTED TANGENT OGIVE FOREBODY ($f = 2.0$) AT $\alpha = 0^\circ$