

AXIAL PRESSURE COEFFICIENT DISTRIBUTIONS FOR SPHERICALLY BLUNTED SECANT OGIVE FOREBODIES OF FINENESS RATIO 1.0, 1.5 AND 2.0 AT ZERO INCIDENCE IN TRANSONIC FLOW

SUMMARY

This Memorandum presents charts of the axial distribution of forebody pressure coefficient for spherically blunted secant ogive forebodies (including the blunted cone) of fineness ratio 1.0, 1.5 and 2.0 over a Mach number range from 0.40 to 1.05. It complements T.D.Memo. 83017 which presents wave drag data for the same family of forebody shapes. Wave drag data and pressure coefficient distributions for the spherically blunted tangent ogive forebody, a member of the spherically blunted secant ogive family of forebodies, may be found in T.D.Memo. 79004 and 80008 respectively.

The charts were derived by use of a computer program developed at the Aircraft Research Association and based on a modified version of the South-Jameson finite-difference method which calculates the inviscid transonic potential flow around non-ducted axisymmetric bodies.

Although the calculations are for inviscid flow they are applicable to real flows of moderate to high Reynolds number where the boundary layers are thin and flow separations are absent.

NOTE

As explained in T.D.Memo. 89033⁶, potential flow solutions have proved extremely useful for predicting transonic flows with shock waves of moderate strength. However such flow solutions ignore the entropy changes and vorticity production associated with actual shock waves and tend to become less realistic as shock strength increases. Solutions based on the Euler equations (such as those utilised in T.D.Memo. 89033) do not ignore entropy changes and vorticity production, and, for cases of appreciable shock strength, yield more accurate results than potential flow solutions. For such cases, it is therefore recommended that, where possible, data based on solutions to the Euler equations are used in preference to data derived from potential flow solutions.

Indications of the significance of differences between data derived from solutions to the Euler equations and data from potential flow solutions may be obtained by comparing the results for wave drag of

- (a) blunted tangent ogive forebodies of fineness ratio 2.0 (using T.D.Memo. 89033 and T.D.Memo. 79004³), and
- (b) blunted conical forebodies of fineness ratio 2.0 (using T.D.Memo. 89033 and T.D.Memo. 83017¹).

1. INTRODUCTION

This Memorandum presents charts of the distribution of forebody pressure coefficient for spherically blunted secant ogive forebodies of fineness ratio 1.0, 1.5 and 2.0 for a freestream Mach number range from 0.40 to 1.05. Charts of wave drag coefficient for these forebodies may be found in T.D. Memo. 83017¹.

A particular member of the secant ogive family of forebodies is the tangent ogive, for which pressure distribution charts may be found in T.D. Memo. 80008² and related wave drag charts in T.D. Memo. 79004³. Thus this Memorandum supplements T.D. Memo. 80008, the Introduction to which provides brief comments on the application of the data provided, the method used in their derivation[†] and comparisons that have been made with experiment. In this last respect Figure 17 of T.D. Memo. 83017 is also relevant.

As with T.D. Memo. 80008 a primary purpose of this Memorandum is to illustrate the trends in the development of the pressure distributions as the principal parameters are varied. This purpose has been achieved using a selection of the pressure distribution data available in preference to presenting data for all the forebodies considered in T.D. Memo. 83017.

2. NOTATION

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

b	nose blunting ratio ($= d/D$)
C_p	pressure coefficient
C_p^*	pressure coefficient for local Mach number of unity
d	diameter of spherical nose blunting ($= 2r$)
D	diameter of cylindrical afterbody ($= 2R$)
D'	diameter of cylindrical afterbody of blunted tangent ogive forebody of length L' (see Sketch 3.1)
f	forebody fineness ratio ($= L/D$) (see Sketch 3.1)
L	forebody length
L'	length of a blunted tangent ogive forebody having the same value of ogive radius, R_0 , as the equivalent blunted secant ogive forebody of length L (see Sketch 3.1)
L_0	virtual length of an unblunted ogive forebody having the same value of ogive radius, R_0 , as a blunted ogive forebody of length L (see Sketch 3.1)
M	freestream Mach number
r	radius of spherical nose blunting
R	radius of cylindrical afterbody

[†] See the NOTE following the SUMMARY concerning the use of potential flow methods (such as used in this Data Item) for flows with shocks of appreciable strength.

R_0	secant ogive radius (see Sketch 3.1)
R'_0	radius of a blunted tangent ogive having the same value of fineness ratio, f , as the equivalent blunted secant ogive of radius R_0 (see Sketch 3.1)
$\bar{R}$	curvature ratio ($= R'_0/R_0$)
x	axial distance (see Sketch 3.1)
y	radial distance (see Sketch 3.1)

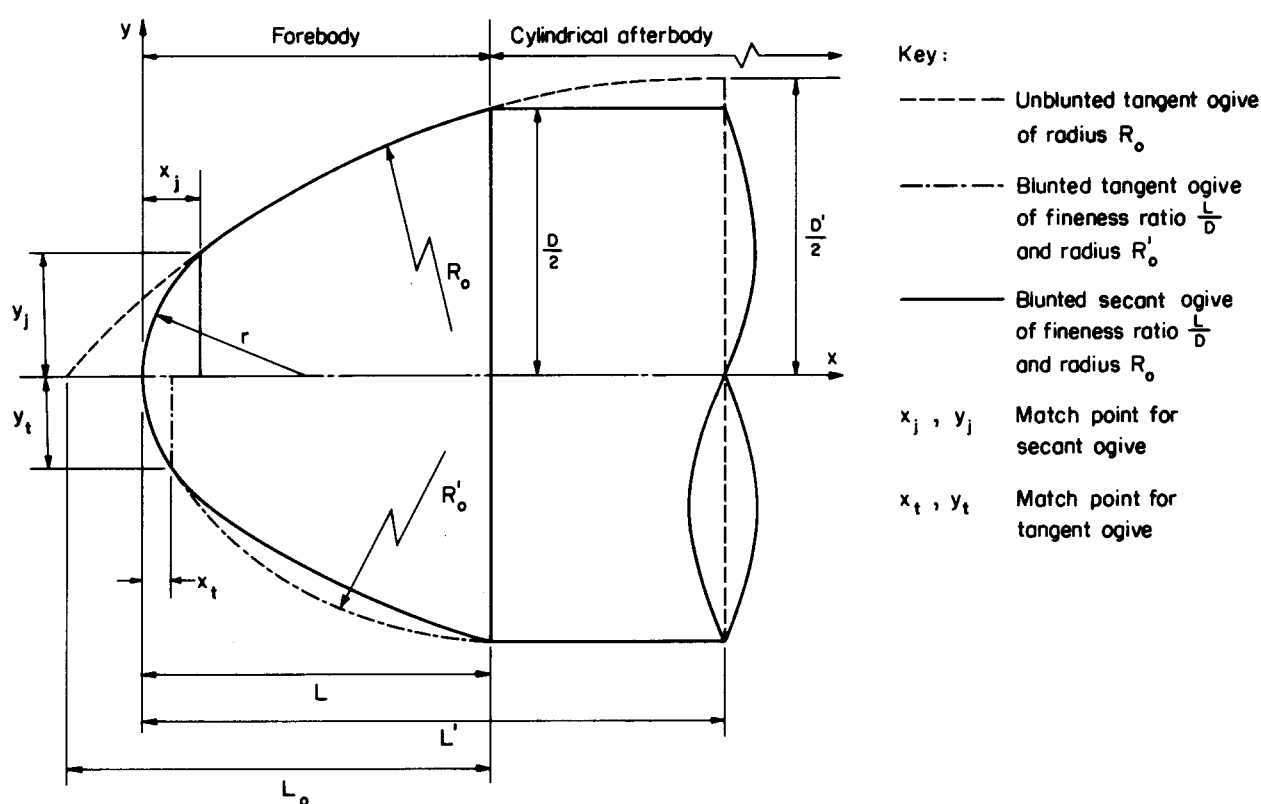
Subscripts

j	denotes match point between spherical blunting and ogive part of secant ogive 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, whilst the generating equations are detailed in T.D. Memo. 83017. Appendix A of that Item presents the listing of a computer program written in FORTRAN which generates the surface coordinates of the blunted secant ogive forebody and the values of the parameters L' , D' , R_0 , x_j and y_j . Values of these parameters for most of the forebodies considered in this Item are given, non-dimensionalised by R , in Appendix B of T.D. Memo. 83017.

This section describes the geometric features of the spherically blunted secant ogive forebodies that influence the development of the pressure distributions. Each blunted forebody is constructed from two generators comprising the spherical nose blunting portion and the ogival portion, which is followed by a cylindrical afterbody.



Sketch 3.1 Forebody geometry notation for spherically blunted secant ogives

The surface slope at the match point (junction between nose blunting and ogival portion) is continuous, but the curvature is discontinuous. Except for the special cases of the blunted tangent ogive and hemispherical forebodies, the surface slope at the shoulder (junction between forebody and afterbody) is discontinuous. Varying the parameters $f (= L/D)$ (fineness ratio), $\bar{R} (= R'_0/R_0)$ (curvature ratio) and $b (= d/D)$ (nose blunting ratio) affects the forebody geometric characteristics in the manner outlined in the following table.

<i>Effect on of an increase in</i>	<i>Axial distance of match point from nose (x_j/R)</i>	<i>Curvature discontinuity at match point</i>	<i>Curvature of ogival portion of forebody (R/R_0)</i>	<i>Slope discontinuity at shoulder</i>
Fineness ratio (f)	Increased	Increased	Decreased	Decreased
Curvature ratio ($\bar{R}$)	Decreased	Decreased	Increased	Decreased
Nose blunting ratio (d/D)	Increased	Decreased	Decreased	Decreased

These characteristics may also be observed in Appendix B of T.D. Memo. 83017.

Virtually all the charts presented here show the occurrence of a minimum pressure near the match point. The level of minimum pressure achieved and the strength of the subsequent pressure recovery are related closely to both the axial distance from the nose of the match point (x_j/R) and the curvature discontinuity there. Also x_j/R , through its relationship to y_j/R , defines the forward facing area of the spherically blunted portion of the forebody. Forebody wave drag can be attributed to the imbalance between the drag force, represented by positive C_p , and the thrust force, represented by negative C_p , acting on the forward facing areas⁴. A change in geometry will affect wave drag in two separate ways – namely through changes in the pressure distribution, and by the manner in which the cross-sectional area distribution varies in the streamwise direction.

The curvature of the ogival portion of the forebody is conveniently expressed by the ratio R/R_0 . This ratio has a relatively large value for the tangent ogive, but tends to zero as the ogival portion of the forebody tends towards a cone. It plays some part in determining the gradient of the pressure distribution between the match point and the shoulder.

The discontinuity in slope at the shoulder, together with the change in curvature at that location, has an important influence on the magnitude of the flow expansion at the shoulder.

4. CHARTS OF PRESSURE COEFFICIENT DISTRIBUTION

The charts were derived by use of a computer program⁵ developed by Baker at the Aircraft Research Association and based on a modified version of the South-Jameson finite-difference method which calculates the inviscid transonic potential flow around non-ducted axisymmetric bodies at zero incidence.

4.1 Presentation of the Charts

Figures 1–19 present charts of pressure coefficient distribution for varying freestream Mach number, Figures 20–26 present charts of pressure coefficient distribution for varying nose blunting ratio, Figures 27 and 28 present charts of pressure coefficient distribution for varying curvature ratio, and Figures 29 and 30 present charts of pressure coefficient distribution for varying fineness ratio. In Figures 1–19 sketches of the relevant forebody shapes are presented at the foot of the charts. The pressure distributions in Figures 20–30 do not correspond to single geometries but the variations in shape from curve to curve may be appreciated from Figures 3, 7 and 11 of T.D. Memo. 83017 which illustrate the effect on the forebody

geometry of varying nose blunting ratio whilst Figure 1 of that Item illustrates the effect of varying curvature ratio.

Details of the forebody fineness ratios, curvature ratios, nose blunting ratios and freestream Mach numbers considered in the pressure distribution charts of this Memorandum are given in Tables 6.1–6.4, together with the figure numbers of the relevant wave drag charts in T.D. Memo. 83017.

In the charts presented here axial distance is plotted in the form x/L in order to present, on the same chart, pressure distributions for forebodies of different fineness ratio. Thus the positions of the match point in the charts are given by $x_j/L = (x_j/R)/2f$ where values of x_j/R may be obtained from Appendix B of T.D. Memo. 83017.

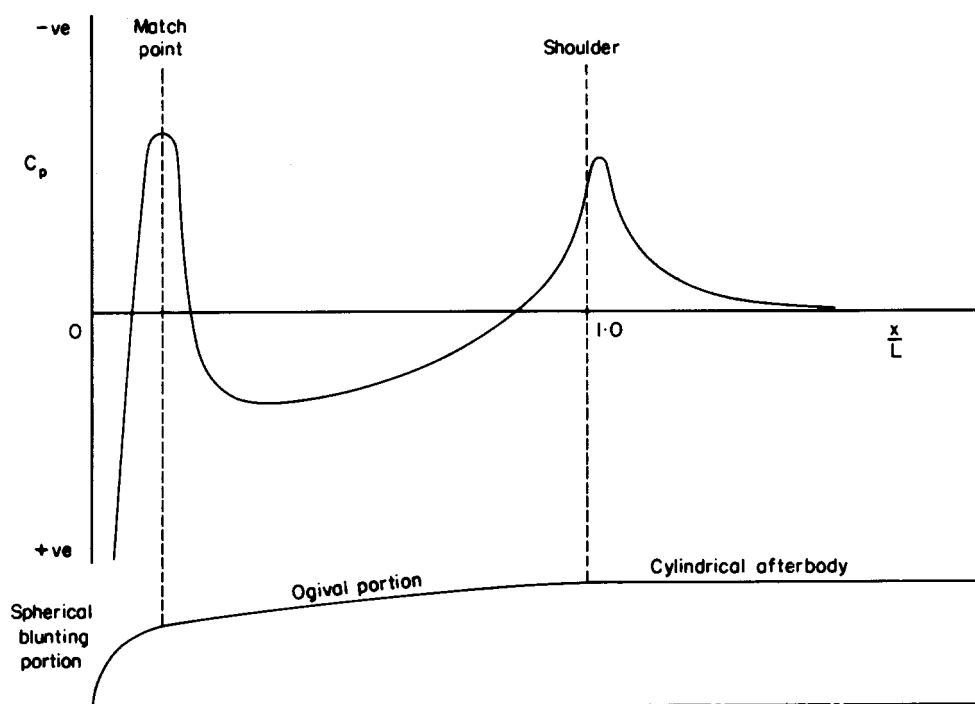
4.2 Values of C_p^*

Values of C_p^* (corresponding to a local Mach number of unity) are shown in the table below for the freestream Mach numbers for which results are presented in this Memorandum.

M	0.40	0.60	0.70	0.80	0.85	0.90	0.95	1.00	1.05
C_p^*	-3.66	-1.29	-0.78	-0.43	-0.30	-0.19	-0.09	0.00	0.08

4.3 General Features of the Pressure Distributions

A typical pressure coefficient distribution for a spherically blunted secant ogive forebody is shown in Sketch 4.1.



Sketch 4.1 Typical pressure coefficient distribution for a spherically blunted secant ogive forebody

At and immediately downstream of the stagnation point, C_p is positive and a drag force acts on the front portion of the nose blunting. The flow expansion from the stagnation point terminates in the region of the match point and some pressure recovery then occurs. Depending upon the geometry of the forebody the minimum pressure attained may or may not be less than the freestream static pressure (*i.e.* C_p may or may not become negative). In the event that C_p does attain negative values then this region of the forebody produces at least an element of thrust. The pressure recovery may be wholly isentropic or may be achieved at least in part through a shock wave whose location along the ogival portion of the forebody can vary considerably with geometry and freestream Mach number. Subsequent to this recompression a further flow expansion occurs, the gradient of which varies greatly according to the curvature of the ogival portion. This expansion becomes more rapid as the shoulder is approached. The discontinuity in slope at the shoulder accentuates this expansion, leading invariably to a suction peak so that the rearward part of the ogival portion produces at least a small region, but possibly a substantial region, of thrust. Downstream of the shoulder the flow finally recompresses, sometimes by means of a shock wave, back to freestream conditions.

4.4 Effect of Freestream Mach Number (Figures 1–19)

The major trends associated with the increase of freestream Mach number for the blunted tangent ogive forebody in the transonic regime have been described in Section 4.3 of T.D. Memo. 80008. The trends there are apparent also in the pressure distributions for blunted secant ogive forebodies presented here. Both the shock that initially can occur near the match point and the shock that initially can occur near the shoulder of the forebody move rearwards as freestream Mach number is increased at fixed nose blunting, curvature and fineness ratios (see, for example, Figure 6).

For low blunting ratios it is possible for the Mach number range to be traversed without the generation of a forward shock (see, for example, Figures 1, 3 and 17). Where a forward shock is present at subsonic Mach numbers, this may with increasing Mach number remain a feature of the flow whilst moving rearwards (Figure 6), or collapse into an isentropic compression (Figure 8) as the suction peak at the shoulder strengthens relative to the suction peak near the match point.

As the freestream Mach number increases to supersonic the occurrence of a bow shock wave marks a change in the flow pattern around the forebody. This shock wave contributes to the total wave drag of the forebody through further readjustments in the surface pressure distribution. Within the range of x/L that has been plotted, there is no longer a shock wave downstream of the shoulder but a shock wave may still be located at or just downstream from the match point, depending on the particular combination of R and d/D (see, for example, Figures 6, 11, 12 and 18).

4.5 Effect of Nose Blunting Ratio (Figures 20–26)

The main geometrical effects of varying the nose blunting ratio have been outlined in Section 3.

The figures to which this section relate are for a freestream Mach number of 1.00, with the exception of Figure 25, which is for $M = 0.90$.

An increase in nose blunting ratio leads to decrease in minimum pressure near the match point and initially accentuates the pressure rise through the rapid flow recompression (which may constitute a shock wave) immediately downstream of the minimum (Figure 22). This behaviour is closely related to the position of the match point and the curvature discontinuity there. For the higher values of blunting ratio there is some difference in the nature of the total recompression from the minimum pressure depending on freestream Mach number. At Mach numbers of 1.00 or 1.05 the recompression has a region of less severe pressure gradient as d/D approaches 1.0 and ultimately at $d/D = 1$ any shock wave that may have been present is replaced by an isentropic compression. At a subsonic freestream condition ($M = 0.9$) Figure 25 shows, for a blunted cone of fineness ratio 2.0, that a shock is present at value of d/D of 0.6 but, now, as blunting ratio

is increased the shock persists, moves downstream and is stronger at $d/D = 1.0$ than at $d/D = 0.6$. Figures 29 to 31 and 34 to 36 of T.D. Memo. 80008 show similar behaviour for a spherically blunted tangent ogive body, namely that at $M = 0.70, 0.80$, and 0.90 a shock wave remains present in the flow for $d/D = 1.0$.

As nose blunting ratio increases the flow acceleration following the recompression near the match point, when a sharp recompression is present, becomes less severe on the ogival portion of the forebody since the curvature there is decreased (Figures 20 and 21), whilst near the shoulder, since the slope discontinuity there becomes less marked, there is a weaker expansion which leads in turn to a less strong peak suction (Figures 25 and 26).

T.D. Memo. 80008 gives an explanation of why moderate amounts of nose blunting on the tangent ogive forebody can reduce forebody wave drag coefficient and delay drag-rise, in terms of shock wave behaviour. As mentioned in Section 4.3 of T.D. Memo. 83017 this explanation also has validity for forebodies of lower curvature ratio. For example (see Figures 15 of T.D. Memo. 83017) secant ogive forebodies of fineness ratio 1.0, for all curvature ratios, have a wave drag minimum at a blunting ratio of about 0.8. Figures 3 and 4 of this Item present pressure distributions for forebodies of fineness ratio 1.0 and curvature ratio 0.4 for blunting ratios of 0.5 and 0.8 respectively whilst Figure 13 of T.D. Memo. 80008 presents the pressure distribution on the hemisphere (limiting geometry for all fineness and curvature ratios). The strong shock downstream of the shoulder for the forebody of blunting ratio 0.5, and downstream of the match point for the hemisphere, is replaced at high subsonic Mach numbers for the forebody of blunting ratio 0.8 by two relatively weak shocks, yielding a reduction in wave drag. Similarly, Figure 25 shows that for a cone of fineness ratio 2.0 at a Mach number of 0.90, a strong shock near the shoulder for low bluntings, and near the match point for high bluntings, is replaced for blunting ratios in the region 0.5 to 0.7 (the optimum as far as wave drag is concerned) by two weaker shocks.

4.6 Effect of Curvature Ratio (Figures 27 and 28)

The main features associated with curvature ratio are most readily appreciated by considering cases where the forward shock has not collapsed. Typical cases are shown in Figures 27 and 28.

A decrease in curvature ratio causes a marked increase in the magnitude of the suction peak at the match point and of the subsequent pressure recovery. This is closely related to the corresponding increase in axial distance of the match point from the nose (x_j/R) and also in the curvature discontinuity at the match point.

In cases where the pressure recovery is partially negotiated by means of a shock wave, the magnitude of this shock wave also tends to increase with decreasing curvature ratio (Figure 27). This could account very largely for the high wave drag coefficient associated with forebodies of low curvature ratio, such as the blunted cone.

The flow acceleration following the pressure recovery is smaller at lower curvature ratios since the curvature of the ogival portion is less. At the forebody shoulder, the higher slope discontinuity associated with the lower value of $\bar{R}$ induces a larger flow expansion; the tangent ogive, which has no slope discontinuity at the shoulder, has no such flow expansion. An important consequence of these factors for forebodies of low curvature ratio, such as the cone, is that the value of pressure coefficient just upstream of the rapid flow expansion near the shoulder is substantially higher than for forebodies such as the tangent ogive (Figures 27 and 28). For the cone in Figure 28, in fact, a drag force acts over almost the entire "ogival" portion.

4.7 Effect of Fineness Ratio (Figures 29 and 30)

Figure 29 shows the main effects of varying fineness ratio. An increase in fineness ratio leads to a lower value of pressure coefficient at the forebody match point and a much more pronounced pressure recovery. This is commensurate with the increase in curvature discontinuity at the match point. The flow acceleration