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Normal-force-curve and pitching-moment-curve slopes of forebody-cylinder combinations at zero angle of attack for Mach numbers up to 5

Associated software: ESDUpac A9034

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NORMAL-FORCE-CURVE AND PITCHING-MOMENT-CURVE SLOPES OF FOREBODY-CYLINDER COMBINATIONS AT ZERO ANGLE OF ATTACK FOR MACH NUMBERS UP TO 5

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NORMAL-FORCE-CURVE AND PITCHING-MOMENT-CURVE SLOPES OF FOREBODY-CYLINDER COMBINATIONS AT ZERO ANGLE OF ATTACK FOR MACH NUMBERS UP TO 5

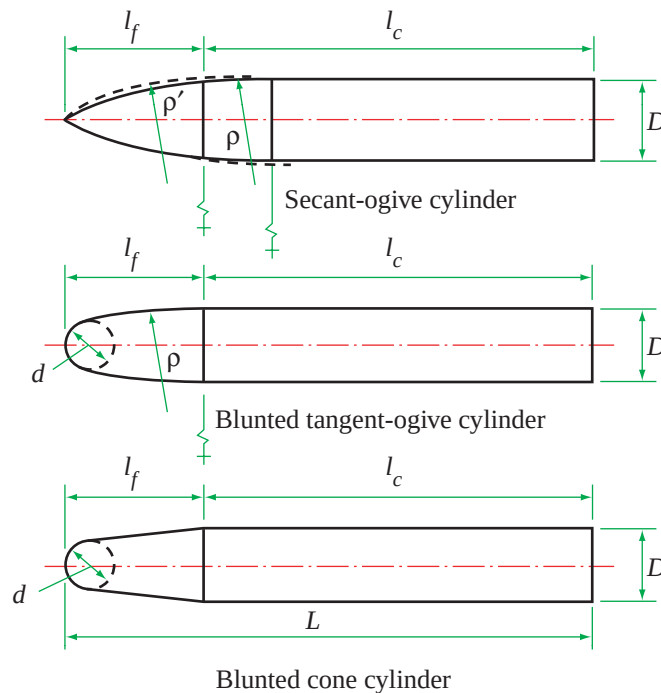
1. NOTATION AND UNITS

		SI	British
C_F	mean skin-friction coefficient for turbulent boundary layer		
C_m	pitching moment coefficient about axis $x = x_m$, (pitching moment)/ $\frac{1}{2}\rho V_\infty^2 S_{ref} D$, positive nose up		
$C_{m\alpha}$	pitching-moment-curve slope, $\partial C_m / \partial \alpha$, at zero angle of attack	rad ⁻¹	rad ⁻¹
$(C_m)_0$	pitching moment coefficient about nose ($x_m = 0$)		
$(C_m)_{0\alpha}$	pitching-moment-curve slope, $\partial (C_m)_0 / \partial \alpha$, at zero angle of attack	rad ⁻¹	rad ⁻¹
$\Delta[(C_m)_{0\alpha} / C_{N\alpha}]_i$	difference between $[(C_m)_{0\alpha} / C_{N\alpha}]_i$, for tangent-ogive forebody and forebody of interest as calculated by slender-body theory, see Section 3.		
$\Delta(C_m)_{0\alpha F}$	skin friction contribution to $(C_m)_{0\alpha}$	rad ⁻¹	rad ⁻¹
$\Delta(C_m)_{0\alpha\delta^*}$	boundary-layer displacement contribution to $(C_m)_{0\alpha}$	rad ⁻¹	rad ⁻¹
C_N	normal force coefficient, (normal force)/ $\frac{1}{2}\rho V_\infty^2 S_{ref}$		
$C_{N\alpha}$	normal-force-curve slope, $\partial C_N / \partial \alpha$, at zero angle of attack	rad ⁻¹	rad ⁻¹
$C_{N\alpha l}$	normal-force-curve slope, $C_{N\alpha}$, for long bodies with boundary-layer effects removed, see Section 3	rad ⁻¹	rad ⁻¹
$\Delta C_{N\alpha F}$	skin-friction contribution to $C_{N\alpha}$	rad ⁻¹	rad ⁻¹
$\Delta C_{N\alpha\delta^*}$	boundary-layer displacement contribution to $C_{N\alpha}$	rad ⁻¹	rad ⁻¹
C_{Vf}	volume (sometimes called "prismatic") coefficient of forebody, volume/($l_f \pi D^2 / 4$)		
D	body maximum diameter	m	ft
d	diameter of spherical nose blunting	m	ft
G	factor to allow for forebody shape		

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k	factor on $C_{N\alpha l}$ to account for length of cylindrical section aft of tangent-ogive forebody		
L	body length	m	ft
l_c	cylinder length	m	ft
l_f	forebody length	m	ft
M_∞	free-stream Mach number		
R_L	Reynolds number based on body length		
S_{ref}	body maximum cross-sectional area, $\pi D^2/4$	m ²	ft ²
V_∞	free-stream velocity	m/s	ft/s
x	axial distance along body	m	ft
x_{cp}	axial distance along body of centre of pressure position	m	ft
x_m	axial distance from nose to pitching axis	m	ft
α	body angle of attack	rad	rad
δ^*	boundary-layer displacement thickness at base of body	m	ft
ρ	tangent or secant ogive radius of curvature, see Sketch 1.1	m	ft
ρ'	radius of curvature of tangent ogive having same length and maximum diameter as a given secant ogive or other forebody, see Sketch 1.1	m	ft
ρ_∞	free-stream density	kg/m ³	slug/ft ³
<i>Subscripts</i>			
i	denotes inviscid flow		
t	denotes tangent-ogive forebody		



Sketch 1.1 Body geometry

2. INTRODUCTION

This Item provides data on the normal-force-curve and pitching-moment-curve slopes of axisymmetric forebody-cylinder combinations with tangent-ogive and other forebodies at zero angle of attack*. The data are presented in graphical form in terms of forebody and cylinder fineness ratios, Mach number and Reynolds number.

The data may be used in stability calculations, or for the prediction of normal force and pitching moment at angle of attack when used in combination with the method of Item No. 89014 (Reference 13), which accounts for cross-flow effects.

The method, which was derived primarily for tangent-ogive cylinders, but has been extended to include bodies with other forebody shapes, is presented in Section 3. A guide to the accuracy and applicability of the method of this Item is given in Section 4, together with some remarks on the development of the method. The use of the Item is illustrated by means of two worked examples in Section 6.

A prediction method for the effects of conical boat-tailing on normal force and pitching moment characteristics of axisymmetric bodies is given in Item No. 87033 (Reference 12).

* The method of this Item is incorporated in the listing of a computer program written by the Computer Products Group of ESDU International (see Item No. 90034, Reference 14).

3. METHOD

The method of this Item assumes that both normal-force-curve and pitching-moment-curve slopes of forebody-cylinder combinations may be evaluated as the sum of three components. The major contribution arises as the result of the inviscid flow over the forebody at angle of attack which generates a loading distribution that may extend beyond the forebody onto the cylindrical section. The other two contributions both arise from the development of a viscous boundary layer along the length of the body. The first of these is caused by the modified flow associated with the displacement thickness of the boundary layer. The second boundary-layer contribution arises from the frictional force acting over the surface of the body. The method assumes that the boundary layer is fully turbulent along the length of the body. Section 3.1 presents the method for tangent-ogive cylinders and Section 3.2 extends this method to enable estimates to be obtained for other axisymmetric forebody-cylinder combinations.

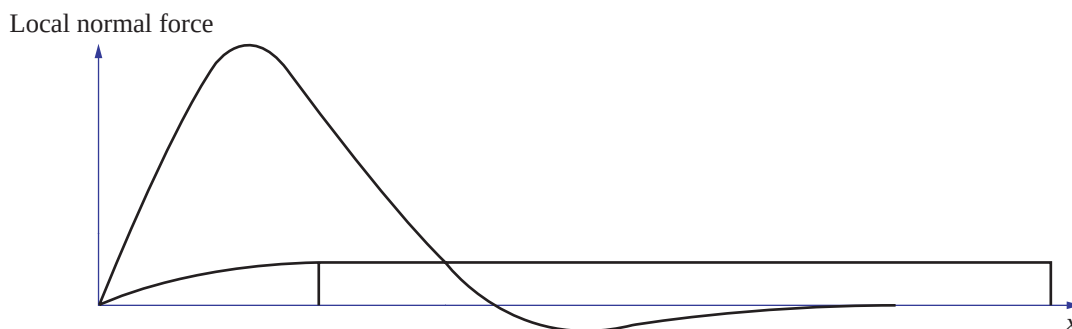
3.1 Tangent-ogive Forebody-cylinders

Normal-force-curve slope

The normal-force-curve slope of a tangent-ogive cylinder combination may be expressed as

$$C_{N\alpha} = kC_{N\alpha I} + \Delta C_{N\alpha\delta^*} + \Delta C_{N\alpha F}. \quad (3.1)$$

In Equation (3.1) $C_{N\alpha I}$ is the value of the inviscid contribution to normal force generated by the forebody when the cylindrical section of the body is sufficiently long to contain all of the carry-over load. Data for $C_{N\alpha I}$ are presented in Figure 1 in terms of forebody fineness ratio and Mach number. This Figure was obtained by removing the estimated contributions of the boundary layer from the data of Derivations 1 and 3 for long bodies. The factor k is applied to $C_{N\alpha I}$ to allow for cases where the cylindrical section is too short to contain all of the carry-over load. The results of second-order shock-expansion theory (as presented in Derivation 2) were used to generate theoretical estimates of k which were then modified empirically to give a better representation of the parametric sets of test data that show effects of cylinder length (Derivations 2 and 3) with l_c/D decreasing to zero. Figures 2a to 2d present k as a function of body geometry at Mach numbers of 2, 3, 4 and 5. Values of k at intermediate Mach numbers may be found by linear interpolation. Note that the value of k may exceed unity because at supersonic speeds the carry-over load onto the cylindrical section is followed by a region of negative loading, see Sketch 3.1. At speeds up to $M_\infty = 1$ the value of k may be taken as unity.



Sketch 3.1 Axial distribution of normal force at supersonic speeds

The second term of Equation (3.1) allows for an inviscid contribution arising from an apparent enlargement of the body cross-section as a result of boundary-layer displacement effect and may be estimated approximately by using slender-body theory.

Slender-body theory indicates that the normal-force-curve slope of a forebody-cylinder combination is given by

$$C_{N\alpha} = 2, \quad (3.2)$$

where the reference area is that of the body base (S_{ref}). If it is assumed that in the presence of the boundary layer the radius of the base is effectively increased by the displacement thickness, δ^* , then with reference to the true base area

$$C_{N\alpha} = \frac{2\pi(D/2 + \delta^*)^2}{\pi(D/2)^2} = 2(1 + 4(\delta^*/D) + 4(\delta^*/D)^2). \quad (3.3)$$

If the small term $4(\delta^*/D)^2$ is neglected, the contribution to $C_{N\alpha}$ of the boundary-layer displacement effect is given by

$$\Delta C_{N\alpha\delta^*} = 8\frac{\delta^*}{D}, \quad (3.4)$$

where δ^* is obtained from Figure 3, which is taken from Derivation 10.

The third term of Equation (3.1) allows for a skin-friction contribution to normal-force-curve slope and is derived on the basis of Derivation 10. The resulting contribution is

$$\Delta C_{N\alpha F} = 4C_F \frac{L}{D}, \quad (3.5)$$

where C_F is the mean flat-plate skin-friction coefficient. Figure 4, which is taken from Item No. 68020 (Derivation 6), gives C_F in terms of R_L for a fully turbulent boundary layer.

Pitching-moment-curve slope

The pitching-moment-curve slope of a tangent-ogive-cylinder combination may be expressed as

$$(C_m)_{0\alpha} = kC_{N\alpha} \left[\frac{(C_m)_{0\alpha}}{C_{N\alpha}} \right]_{i,t} + \Delta(C_m)_{0\alpha\delta^*} + \Delta(C_m)_{0\alpha F}. \quad (3.6)$$

In Equation (3.6) the ratio $[(C_m)_{0\alpha}/C_{N\alpha}]_{i,t}$ is the limiting centre of pressure position as $\alpha \rightarrow 0$ in the absence of boundary-layer effects and is given in Figure 5. This Figure was derived on the basis that the load on the forebody acts at the point given by slender-body theory ($x_{cp} = 0.46l_f$) and that the effect of the presence of the cylindrical body is consistent with the distribution of normal force aft of the forebody/cylinder junction implied by Figure 2. Therefore, for all bodies at Mach numbers up to unity and for forebodies alone at all Mach numbers, the value of $[(C_m)_{0\alpha}/C_{N\alpha}]_{i,t}$ is $-0.46 l_f/D$, and in all other cases $[(C_m)_{0\alpha}/C_{N\alpha}]_{i,t}$ may be obtained from Figure 5, which presents a series of carpet plots at Mach numbers of 2, 3, 4 and 5. Values at intermediate Mach numbers may be found by linear interpolation.

The term in Equation (3.6) arising from the boundary-layer displacement effect may be estimated with the simple assumption that $\Delta C_{N\alpha\delta^*}$ acts at the body mid-point and is thus given by

$$\Delta(C_m)_{0\alpha\delta^*} = -4 \frac{\delta^*}{D} \frac{L}{D}, \quad (3.7)$$

where δ^* is obtained from Figure 3.

The term in Equation (3.6) arising from the skin-friction forces is obtained by assuming $\Delta C_{N\alpha F}$ also acts at the body mid-point and is thus given by

$$\Delta(C_m)_{0\alpha F} = -2C_F \left(\frac{L}{D}\right)^2, \quad (3.8)$$

where C_F is obtained from Figure 4.

The pitching-moment-curve slope about an axis located at $x = x_m$ may be calculated from

$$C_{m\alpha} = C_{N\alpha} \left[\frac{x_m}{D} + \frac{(C_m)_{0\alpha}}{C_{Na}} \right]. \quad (3.9)$$

3.2 Forebody-cylinders of Other Shapes

Normal-force-curve slope

In order to extend the method of Section 3.1 to other forebody shapes comparisons were made between data for tangent-ogive bodies and bodies with cone, secant ogive, blunted tangent-ogive and blunted cone forebodies (Derivations 1 to 5, 7 and 9). The comparisons showed that the values for $C_{N\alpha}$ were very similar except for the cone and blunted cone bodies with little or zero cylindrical section. In those cases the values of $C_{N\alpha}$ were less than that of the tangent-ogive forebody-cylinders of the same length. In order to extend Equation (3.1) to allow for this effect an additional factor, G , has been introduced to cater for short bodies with a discontinuity in slope at the forebody-cylinder junction so that the expression for normal-force-curve slope becomes

$$C_{N\alpha} = GkC_{NaI} + \Delta C_{N\alpha\delta^*} + \Delta C_{N\alpha F}. \quad (3.10)$$

Experimentally derived values of G have been calculated from the cone test data which show that, within the scatter of the test data, G is a function only of cylindrical section fineness ratio. As no data were available for secant-ogive bodies with zero or small cylinder lengths a simple linear interpolation in terms of radius ratio, ρ'/ρ , (see Sketch 1.1) is suggested between the value of G for the cone ($\rho'/\rho = 0$) and the tangent ogive ($\rho'/\rho = 1$). Values for G may be found in Figure 6. For forebody shapes other than those mentioned above, see Section 4.2.

The boundary-layer terms in Equation (3.10) are the same as those in Section 3.1 and are thus given by Equations (3.4) and (3.5).