



ESDU 89014

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Supersedes ESDU 83039,
85025 and 86009

Normal force, pitching moment and side force of forebody-cylinder combinations for angles of attack up to 90 degrees and Mach numbers up to 5

**Associated software: ESDUpac A9034
See ESDU 90034**

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item which supersedes ESDU 83039, 85025 and 86009, was monitored and guided by the Aerodynamics Committee. This Committee first met in 1942 and now has the following membership:

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NORMAL FORCE, PITCHING MOMENT AND SIDE FORCE OF FOREBODY-CYLINDER COMBINATIONS FOR ANGLES OF ATTACK UP TO 90 DEGREES AND MACH NUMBERS UP TO 5

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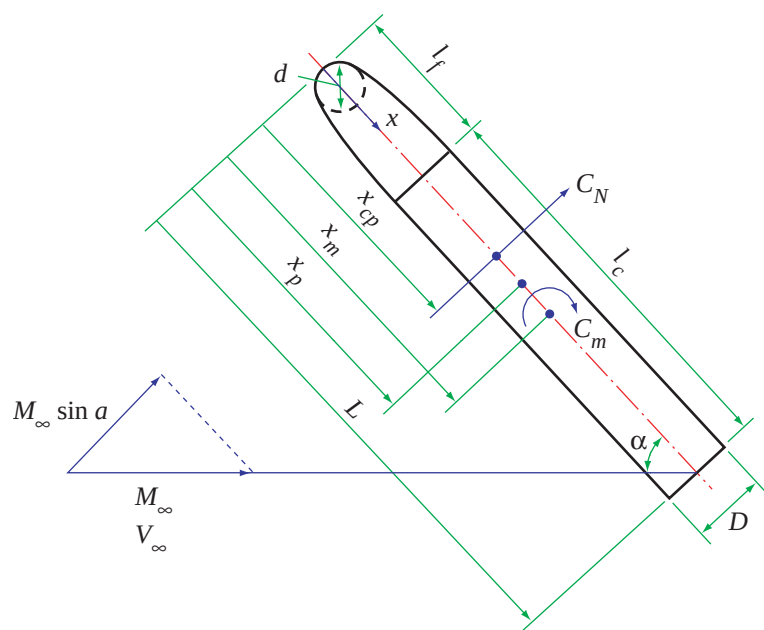
NORMAL FORCE, PITCHING MOMENT AND SIDE FORCE OF FOREBODY-CYLINDER COMBINATIONS FOR ANGLES OF ATTACK UP TO 90 DEGREES AND MACH NUMBERS UP TO 5

1. NOTATION AND UNITS

		SI	British
C_{CL}	centroid of planform area coefficient, $2x_p/L$		
C_m	pitching moment coefficient about axis x_m from body nose, (pitching moment)/ $\frac{1}{2}\rho_\infty V_\infty^2 S_{ref} D$		
$(C_m)_0$	pitching moment coefficient about axis through $x_m = 0$, see Equation (7.2)		
$(C_m)_{0\alpha}$	pitching-moment-curve slope, $\partial(C_m)_0/\partial\alpha$, at zero angle of attack	rad ⁻¹	rad ⁻¹
C_N	normal force coefficient, (normal force)/ $\frac{1}{2}\rho_\infty V_\infty^2 S_{ref}$		
C_{Nc}	cross-flow normal force coefficient, (cross-flow normal force)/ $\frac{1}{2}\rho_\infty V_\infty^2 S_p$		
$C_{N\alpha}$	normal-force-curve slope, $\partial C_N/\partial\alpha$, at zero angle of attack	rad ⁻¹	rad ⁻¹
C_{PL}	planform area coefficient, S_p/DL		
C_Y	side-force coefficient, (side force)/ $\frac{1}{2}\rho_\infty V_\infty^2 S_{ref}$		
C_y	local side force coefficient, (local side force per unit length)/ $\frac{1}{2}\rho_\infty V_\infty^2 D \sin^2\alpha$		
C_{Ymax}	maximum side force coefficient		
C_{ymax}	maximum local side force coefficient		
D	body maximum diameter	m	ft
d	diameter of spherical forebody blunting, see Sketch 1.1	m	ft
L	body length	m	ft
l_c	cylinder length	m	ft
l_f	forebody length	m	ft

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M_∞	free-stream Mach number		
R_D	Reynolds number based on free-stream flow conditions and body maximum diameter		
S_p	body planform area	m^2	ft^2
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 from nose	m	ft
x_{cp}	axial distance from nose to centre of pressure, see Equation (7.3)	m	ft
x_m	axial distance from nose to pitching axis	m	ft
x_p	axial distance from nose to centroid of planform area	m	ft
α	body angle of attack	deg	deg
ρ_∞	free-stream density	kg/m^3	slug/ft^3
ϕ	roll angle	deg	deg



Sketch 1.1 Body geometry

2. INTRODUCTION

This Item provides a simple, semi-empirical means of estimating the normal force and pitching moment of axisymmetric forebody-cylinder combinations at angles of attack up to 90 degrees and Mach numbers up to 5. The method requires estimates for the normal-force-curve and pitching-moment-curve slopes at zero angle of attack from Item No. 89008 (Derivation 39) and geometrical parameters from Item No. 77028 (Reference 46).

In subsonic and transonic flow at high angles of attack, asymmetric vortex flow may occur on the leeward side of the body. This phenomenon, which is known to depend on such minor factors as small imperfections at the nose, has the effect of producing an out-of-plane force distribution that can result in large side forces and yawing moments. A qualitative description of the nature of asymmetric vortex flow is given in Section 3 and an envelope of resulting maximum overall side force is given in Section 5.

Sections 4, 5 and 6 consider the effects of Reynolds number, Mach number and forebody blunting respectively, based on the work covered in Derivations 18, 22, 26, 27, 32, 33, 35 and 38 and References 41 to 45 and 47 to 50. Section 7 describes the predictions of normal force and pitching moment, which are illustrated by a worked example in Section 10. Section 8 provides a guide to the applicability and accuracy of the prediction method.

The effects of conical boat-tailing on normal force and pitching moment are given in Item No. 87033 (Reference 51). The method of this Item, together with the effects of conical boat-tailing, is incorporated in a computer program written by the Computer Products Group of ESDU International (see Item No. 90034; Reference 52), available on diskette in the Aerodynamics Software Volume and on CD-Rom.

3. THE NATURE OF FLOW AROUND AXISYMMETRIC BODIES

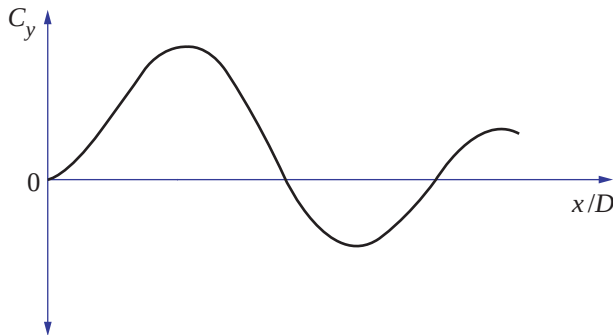
3.1 Types of Flow

In a full range of angle of attack from zero to 90 degrees a slender axisymmetric body may encounter four main flow regimes. These are briefly summarised below together with the approximate angles of attack at which they may occur.

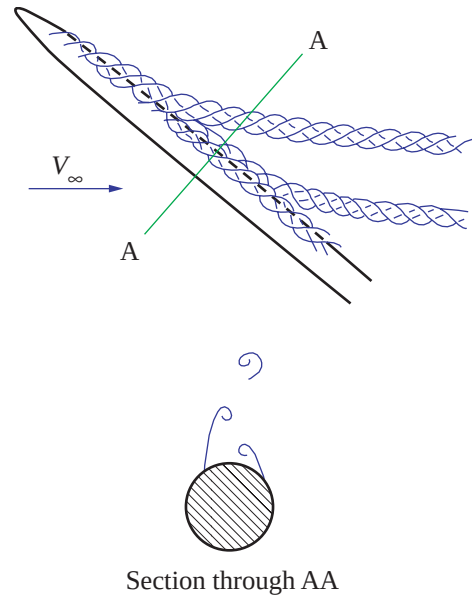
- (i) Attached flow. For angles of attack up to just a few degrees the flow around the whole body length remains attached.
- (ii) Symmetric vortex formation. With increasing angle of attack the flow around the body breaks away and rolls up on the leeward side to form a pair of symmetric vortices.
- (iii) Asymmetric vortex formation. At higher angles of attack, typically 20 to 30 degrees, the symmetric vortex flow becomes inherently unstable. The vortices then begin to develop asymmetrically and may detach alternately down the length of the body. As a result of this asymmetry a steady side force distribution can be developed along the body, the magnitude of which has been known to exceed that of the normal force at subsonic speeds.
- (iv) Unsteady wake flow. At around 60 to 70 degrees the asymmetric vortex flow starts to become increasingly unsteady and to weaken until the mean side force drops to zero before the angle of attack reaches 90 degrees.

3.2 Asymmetric Vortex Flow, Side Force and Normal Force

The side force distribution that develops on axisymmetric bodies as a result of asymmetric vortex flow alternates in sign along the length of the body. A typical axial distribution of this side force and an illustration of idealised asymmetric vortex flow are shown in Sketches 3.1 and 3.2.



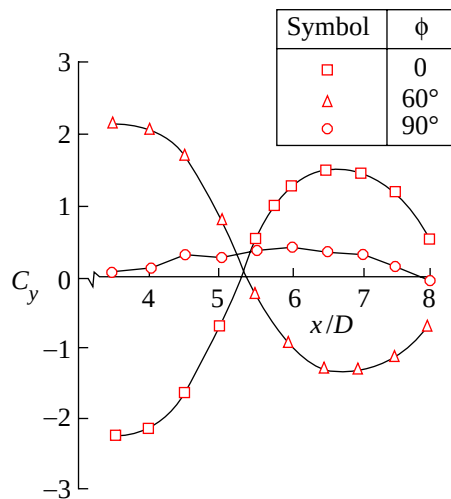
Sketch 3.1 Typical axial distribution of local side force coefficient due to asymmetric vortex flow



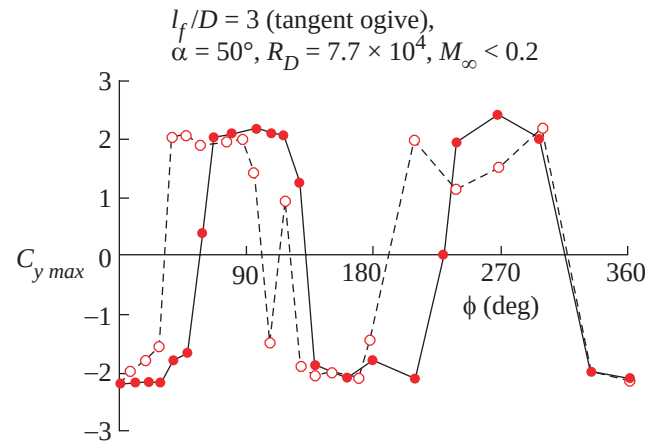
Sketch 3.2 Idealised asymmetric vortex flow

The magnitude, distribution and sense of the local side force are all highly dependent on minute asymmetries near the front of the forebody. Thus for a given angle of attack a wide range of distributions can be found as the roll angle, ϕ , is varied, as illustrated in Sketch 3.3. In varying roll angle the distributions fluctuate between two equal and opposite extreme states which may occur more than once in a 360 degree roll traverse. However, there is evidence (Derivations 27 and 32) that the distribution of local side force for the extreme states is similar for different forebodies of the same nominal geometry, and the steady peak values through a complete roll traverse are shown for two such forebodies in Sketch 3.4.

$l_f/D = 3$ (tangent ogive),
 $\alpha = 50^\circ$, $R_D = 7.7 \times 10^4$, $M_\infty < 0.2$



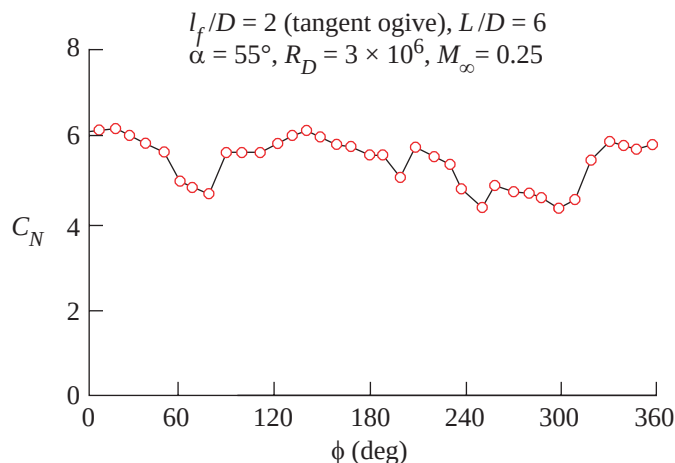
Sketch 3.3 Local side force distribution at different roll angles (Derivation 27)



Sketch 3.4 Maximum local side force variation with roll angle for two nominally identical forebodies (Derivation 27)

The extreme states correspond to the presence of greatest vortex flow asymmetry and consequently the greatest local side force. They also correspond to the maximum number of cycles or part-cycles occurring within a given length of the body and, in particular, they give the foremost location of the maximum local side force peak. At the higher angles of attack, up to around 55 degrees, the flows tend to be more polarised towards the extreme states with fewer occurrences of intermediate flows; also, the local side force peaks increase in number and generally become more compressed towards the front of the body. At angles of attack that are higher still, the vortex pattern becomes increasingly unsteady and the time-averaged side force eventually decreases to zero.

With asymmetric flow the high suctions producing the side force extend to the leeward side of the body and thus produce an increased local normal force. This implies that the normal force also has a variability that shows as a roll angle dependence and this is borne out by test data as illustrated in Sketch 3.5. The highest normal forces occur where the flow asymmetry is greatest and the lowest with symmetric vortices.



Sketch 3.5 Normal force variation with roll angle (Derivation 26)

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