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Fluid forces and moments on flat plates

Endorsed by
The Royal Aeronautical Society
The Institution of Chemical Engineers
The Institution of Structural Engineers
The Institution of Mechanical Engineers

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item which supersedes and extends Data Sheet Aero W.00.01.02, was monitored and guided by the following Working Party:

Mr J. Armit	— Central Electricity Research Laboratories
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on behalf of the Fluid Mechanics Steering Group which has the following constitution:

Chairman	
Mr W.F. Wiles	— Rolls Royce Ltd, Derby
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Mr E.C. Firman	— Central Electricity Research Laboratories
Mr B.H. Fisher	— Consulting Structural Engineer
Dr G. Hobson	— English Electricity – AEI Turbine Generators Ltd
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The Steering Group has benefitted from the participation of members from several engineering disciplines. In particular, Mr B.H. Fisher has been appointed to represent the interests of structural engineering as the nominee of the Institution of Structural Engineers and Mr E.C. Firman has been appointed to represent the interests of mechanical engineering as the nominee of the Institution of Mechanical Engineers.

The Item was accepted for inclusion in the Aerodynamics Sub-series by the Aerodynamics Committee which first met in 1942 and now has the following membership:

Chairman	
Prof. G.M. Lilley	— University of Southampton
Vice-Chairman	
Prof. D.W. Holder	— University of Oxford
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FLUID FORCES AND MOMENTS ON FLAT PLATES

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FLUID FORCES AND MOMENTS ON FLAT PLATES

1. NOTATION AND UNITS

Two coherent systems of units are given below. See end of notation for footnotes.

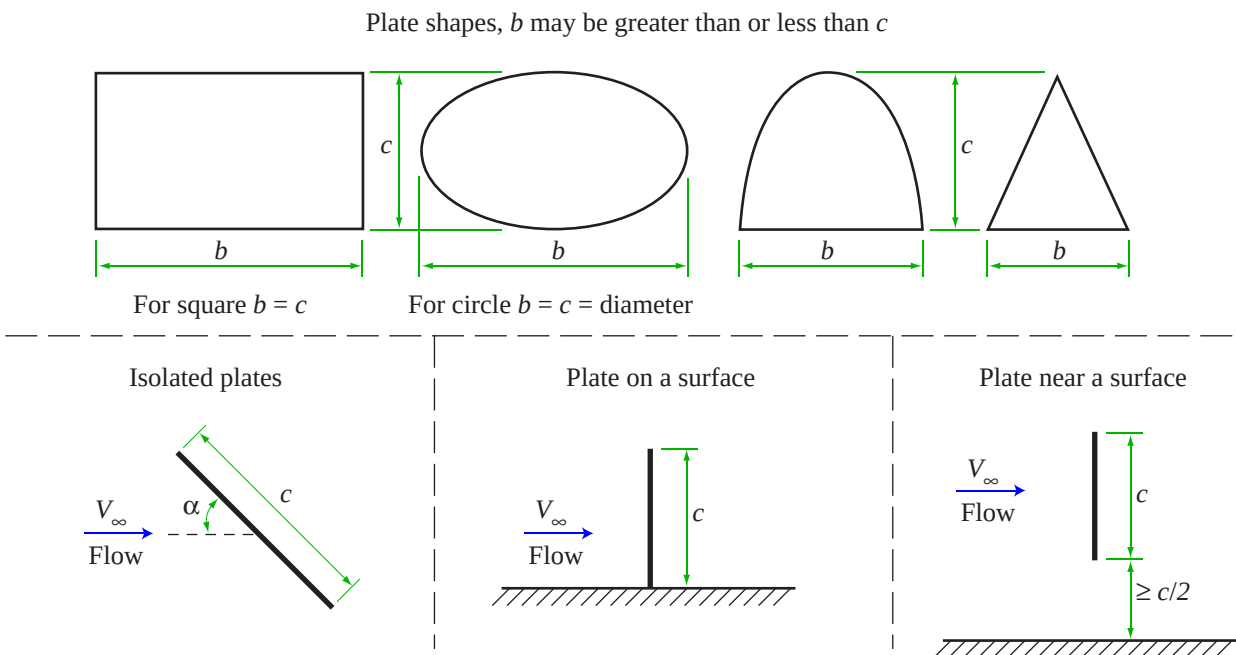
		<i>SI</i>	<i>British</i>
a	distance between two plates in series	m	ft
b	span of plate	m	ft
C_N	normal force coefficient in uniform flow, $N/1/2\rho V_\infty^2 S$		
c	chord of plate	m	ft
d_i, d_o	inner, outer diameter of circular plate with hole (see Figure 6)	m	ft
h	distance from datum in shear flow (Section 3.6)	m	ft
k_1, k_2	correction factors for effect of turbulence (Section 3.1)		
L_x	longitudinal integral scale of turbulence* in free stream	m	ft
N	normal force on plate	$^\dagger N$	lbf
n	constant defining velocity profile in shear flow (Section 3.6)		
Re	Reynolds number, $V_\infty c/\nu$		
S	area of plate	m ²	ft ²
S_f	open area of perforated plate	m ²	ft ²
s	spacing between plates in series (see Figure 4)	m	ft
V	velocity	m/s	ft/s
V_∞	average free-stream velocity in uniform flow	m/s	ft/s
V_{eff}	effective average velocity in shear flow (Section 3.6)	m/s	ft/s
$\sqrt{\overline{u^2}}$	root mean square value of longitudinal component of velocity fluctuations* due to turbulence in free stream	m/s	ft/s
x_{cp}	distance along centre line of centre of pressure behind leading edge of plate	m	ft

α	angle of incidence between plate and free stream	degrees	degrees
ν	free-stream kinematic viscosity [†]	m ² /s	ft ² /s
ρ	free-stream density	kg/m ³	slug/ft ³

* For explanations of this term see Item No. 83045 or Reference 2. Some typical values are given in Table 7.1.

[†] 1N = 1 newton = 102.0 × 10⁻³ kgf.

[‡] kinematic viscosity = dynamic viscosity/density.



Sketch 1.1

2. INTRODUCTION

This Data Item gives information on the normal forces and centre of pressure positions for thin flat plates of various shapes. The data are presented in terms of non-dimensional mean force coefficients, which are used in conjunction with pre-determined free-stream velocities (*e.g.* wind velocity) to determine the actual forces acting on a plate.

In addition to the normal force given by the Data Item, a plate at incidences of less than 90° will have a tangential force acting on it due to skin friction. However, the tangential force is not significant compared with the normal force except at incidences below about 10° and, within the accuracy of the data in this Item, may be neglected at all incidences.

In general, except at incidences below about 10° and near the stalling angle where the experimental data are less reliable, values of C_N to within ±5 per cent and values of the centre of pressure position x_{cp}/c to within ±0.05 may be obtained from this Data Item.

The data are predominantly for isolated plates in uniform flows. However, data for surface mounted rectangular plates are given in Section 3.5 and a method of allowing for the effects of a shear flow (*i.e.* an approach flow with a velocity gradient, such as a ground boundary layer) is given in Section 3.6.

For plates near a surface but not actually touching it, interference between the plate and the surface affects the forces and more especially the centre of pressure position. The data in this Item may be taken to apply for plates not less than half of one plate chord from a surface.

Where applicable, the method of Reference 1 has been used to correct experimental data for wind-tunnel blockage effects, making due allowance for any previously applied corrections. It is possible to extend the application of the data in this Item to plates in ducts by using blockage corrections, such as given in Reference 1, in reverse.

3. FLAT PLATES NORMAL TO THE FLOW

3.1 Basic Information for Isolated Plates

Figure 1, based on data from Derivations 4 to 8, 10, 18, 20, 22 and 25, shows the variation with b/c of the normal force coefficient for isolated rectangular plates, normal to a uniform flow. Over the range $1/30 < b/c < 30$, C_N is given by

$$C_N = 1.10 + 0.02(b/c + c/b). \quad (3.1)$$

For plates of other shapes the data of Figure 1 should give a reasonable approximation to the normal force coefficient, taking b/c as defined on Sketch 1.1 (Derivations 6, 9, 10, 13, 20 and 24).

For a range of Reynolds numbers from 10^3 to 3×10^6 , the experimental data for rectangular and circular plates show that C_N does not vary significantly with Reynolds number. For $Re < 10^3$, data for circular discs are plotted in Figure 2 (Derivations 6, 9 and 24). In the absence of more specific data it should be assumed that Figure 2 may be applied for other plate shapes.

The limited information available on compressibility effects for air indicates that there is little variation in C_N for free-stream Mach numbers* up to 0.6 and thereafter a rise to a value about 10 per cent greater than the low speed value for a Mach number of 0.9 (Derivations 14 and 21).

The data available on the effects of turbulence (Derivations 12, 25 and 28) show effects due to both turbulence intensity† and to scale of turbulence†. As an approximation it may be taken that the increase in C_N due to turbulence is given by

$$C_{N(\text{turbulent})} = C_{N(\text{smooth})} (1 + k_1 k_2) \quad (3.2)$$

where k_1 and k_2 are taken from Figures 3a and 3b. Typical values of $\sqrt{u^2}/V_\infty$ and L_x are given in Table 7.1. The data from Derivation 25 show that the rate of increase of the effect of scale of turbulence falls off rapidly for L_x/c greater than 0.75 and, although no direct evidence exists, a corresponding trend for the effect of turbulence intensity may be expected.

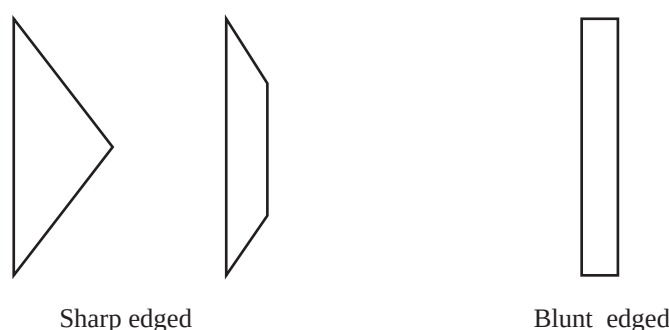
* The free-stream Mach number of a flow is the free-stream flow velocity divided by the speed of sound in the free stream.

† For explanations of these terms see Item No. 83045 or Reference 2. Some typical values are given in Table 7.1.

3.2 Approximation to Thin Plates

The available data suggest that, provided the edges of the plate are bevelled to a sharp edge and the flat surface faces the flow, the normal force coefficients for rectangular plates of maximum thickness up to one chord are approximately the same as for thin plates.

For blunt-edged plates, up to a maximum thickness of about $0.2c$, the effect of thickness on the normal force coefficient is insignificant. However, for thicker blunt-edged plates the thickness begins to have a significant effect and data for rectangular cross section cylinders (Reference 3) should be used.



Sketch 3.1 Plate cross section

3.3 Two Plates in Series

Figure 4 shows the effect on C_N of placing a plate in the wake of another identical plate, both in terms of the effect on the normal force coefficients of the individual plates and in terms of the overall coefficient. Figure 4 is based on data for circular plates and rectangular plates of $b/c = 2$ (Derivations 4, 5 and 22). The data do not apply when the plate thickness becomes significant compared with the spacing.

3.4 Perforated Plates

Figure 5 gives values of C_N for uniformly perforated plates, based on data for circular and square plates from Derivations 15 and 19 and for plates with $b/c = \infty$ (i.e. plates in two-dimensional flow) from Derivations 26 and 29. Data for grids of low b/c built up from crossed flat strips (Derivations 11 and 27) and from parallel flat strips (Derivation 11) and data for circular discs of wire mesh, all show similar trends although for the wire mesh the scatter of data about the mean curve is large.

Figure 6 gives values of C_N for circular plates with a circular central hole (Derivation 6). The step in the curve arises from a change from three-dimensional flow around the plate to an effectively two-dimensional flow across the annular ring.

It should be noted that in both Figures C_N is based on the total plate area and not on the remaining solid area.

3.5 Plates Mounted on a Surface

Figure 7 gives values of C_N in uniform flow conditions, for surface mounted flat plates normal to both the surface and the flow. For $b/c \leq 1$ these are based on the values of C_N for isolated plates of dimensions $b/2c$ (by application of the mirror image principle). However, for $b/c > 1$, the data (Derivation 27) suggest that C_N becomes constant at a value of about 1.2 and a tentative curve is shown dotted.