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Fluid forces, pressures and moments on rectangular blocks

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FLUID FORCES, PRESSURES AND MOMENTS ON RECTANGULAR BLOCKS

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FLUID FORCES, PRESSURES AND MOMENTS ON RECTANGULAR BLOCKS

1. NOTATION AND UNITS

Three coherent systems of units are given below.

		SI	British	
A	reference area, bc	m^2	ft^2	ft^2
A'	projected area of block normal to free stream [*] , wc	m^2	ft^2	ft^2
a, b, c	dimensions of block (see Sketch 1.1)	m	ft	ft
B	cross-sectional area of duct	m^2	ft^2	ft^2
C	side (or lift or cross-wind) component of total force on block; acts normal to free stream direction	$^{\dagger}N$	$^{\ddagger}pdl$	lbf
$C_C, C_D, C_F, C_X, C_Y, C_Z$	force coefficients in uniform flow, defined by $Force / \frac{1}{2}\rho V_{ref}^2 A$			
C_M	overturning moment coefficient for surface-mounted block in uniform flow, $M / \frac{1}{2}\rho V_{ref}^2 Ac$			
C_p	pressure coefficient, $(p - p_{\infty}) / \frac{1}{2}\rho V_{ref}^2$			
$C_{p \text{ int}}$	internal-pressure coefficient, $(p_{int} - p_{\infty}) / \frac{1}{2}\rho V_{ref}^2$			
D	drag component of total force on block; acts in free-stream direction	$^{\dagger}N$	$^{\ddagger}pdl$	lbf
F	$\frac{1}{2}\rho V_{eff}^2 AC_F$, see Section 4.2 and Equation (4.2)			
h	distance from datum in shear flow (Section 4.4)	m	ft	ft
k_1	correction factor for effect of low Re (Section 4.1), $C_{X(Re)} / C_{X(Re > 10^4)}$			
k_2	blockage correction factor (Section 4.2)			
k_3, k_4	correction factors for effect of turbulence (Section 4.3), $k_3 k_4 = C_{X \text{ (turbulent flow)}} / C_{X \text{ (smooth flow)}}$			

For footnotes see end of Notation Section

k_5	correction factor for effect of rounded edges (Section 4.7), $C_{X(\text{rounded edges})}/C_{X(\text{sharp edges})}$			
$L_x(u)$	integral length scale of longitudinal component of turbulence in free stream (see Table 8.1)	m	ft	ft
M	overturning moment on surface-mounted block, acting about an axis parallel to the Oy axis and at $x = a$	† N m	‡ pdl ft	lbf ft
Ma	Mach number, $V_{ref}/\text{speed of sound in free stream}$			
n	constant defining velocity profile in shear flow (Section 4.4)			
p	static pressure	† N/m ²	‡ pdl/ft ²	lbf/ft ²
p_{int}	internal static pressure	† N/m ²	‡ pdl/ft ²	lbf/ft ²
p_∞	free-stream static pressure	† N/m ²	‡ pdl/ft ²	lbf/ft ²
Re	Reynolds number, $V_{ref} b/\nu$			
r	edge radius on block	m	ft	ft
$\sqrt{\overline{u^2}}$	root mean square value of longitudinal component of velocity fluctuations ^{**} due to turbulence in free stream	m/s	ft/s	ft/s
V_{eff}	effective mean velocity in shear flow (Section 4.4)	m/s	ft/s	ft/s
V_{ref}	reference velocity of approaching free stream, = V_∞ in uniform flow, = V_{eff} in shear flow	m/s	ft/s	ft/s
V_∞	free-stream velocity in uniform flow	m/s	ft/s	ft/s
w	projected width of block normal to free stream, $a \sin \phi + b \cos \phi$ (see Sketch 3.2)	m	ft	ft
X, Y, Z	components of total force on block, acting in Ox, Oy and Oz directions respectively	† N	‡ pdl	lbf
x, y, z	distances along Ox, Oy and Oz directions	m	ft	ft
x_{cp}	distance of centre of pressure position from yOz plane	m	ft	ft

For footnotes see end of Notation Section

z_{cp}	distance of centre of pressure position from xOy plane (see Sketch 1.1)	m	ft	ft
δ	nominal boundary layer thickness on surface on which block is mounted	m	ft	ft
ε	effective roughness height			
ν	free-stream kinematic viscosity, μ/ρ	m^2/s	ft^2/s	ft^2/s
μ	free-stream dynamic viscosity	$^\dagger \text{N s/m}^2$	$^\dagger \text{pdl s/ft}^2$	lbf s/ft^2
ρ	free-stream density	kg/m^3	lb/ft^3	$^\dagger \text{slug/ft}^3$
ϕ	inclination of front face of block to free stream, in plane parallel to xOy (see Sketch 1.1)	degree	degree	degree

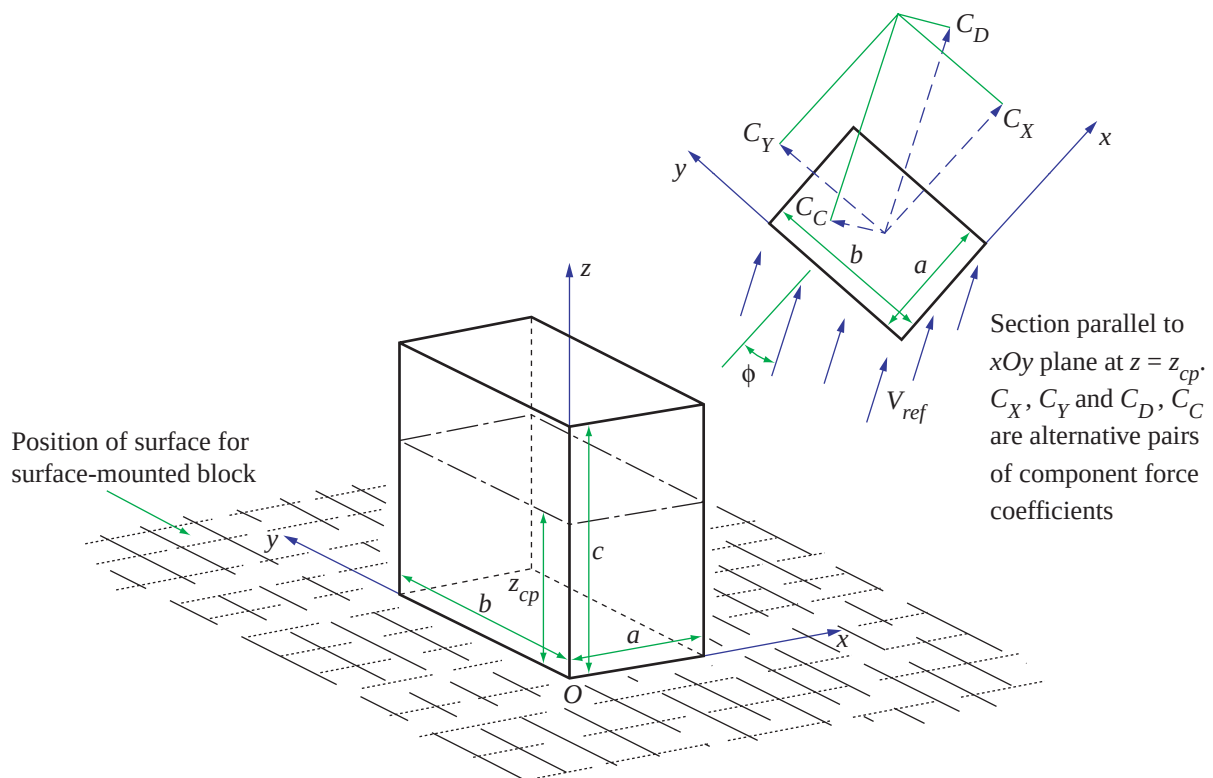
* The term 'free stream' means the undisturbed flow upstream of the block.

† 1 N = 1 newton = 102.0×10^{-3} kgf.

‡ 1 pdl = 31.08×10^{-3} lbf.

** For explanation of this term see Reference 3. Some typical values are given in Table 8.1.

$^\dagger \dagger$ 1 slug = 32.17 lb.



Sketch 1.1

2. INTRODUCTION

2.1 Scope and Application of the Data Item

Fluid flow around a rectangular block produces forces on the block which, in fact, vary with time. However, as is discussed in Sections 2.1.1 and 2.1.2, a knowledge of the mean (time-averaged) force coefficients is always required in an analysis of the loading on the block.

This Data Item provides mean (time-averaged) force, pressure and moment coefficients for use in estimation of forces, pressures and moments on single rectangular-sectioned blocks or prisms as a result of fluid flow past them. The information can be applied in a wide range of engineering problems concerned with fluid flow around rectangular blocks, such as in the design of buildings, in the evaluation of the effects of projections on buildings, on marine, road and flight vehicles and in ductwork, and in the analysis of such problems as blocks suspended from cables.

Section 3 presents the basic information on force and moment coefficients for solid or impermeable blocks with sharp edges in an unbounded, smooth, uniform, low-speed flow. These conditions are referred to in this Item as the 'datum conditions'. For the range of conditions covered by the Item, the tangential friction forces on the block are negligible within the accuracy of the data and no separate allowance for them is necessary. Some guidance is given in Section 4 on the effects of departures from datum conditions and Section 5 deals with the external pressure coefficients on blocks and with the internal pressures set up inside hollow permeable blocks such as buildings.

A calculation chart, setting out a calculation procedure and giving a guide to the Figures, is included at the end of the Item.

2.1.1 Application to the estimation of wind loading on buildings

A particular application of the data in this Item is to wind loading on buildings. The response of a building to the fluctuating wind force can be resolved into a static component and a superimposed dynamic component. For buildings which have natural frequencies of vibration greater than about 0.4 Hz and damping greater than about 2 per cent of critical damping the dynamic component is usually small (less than about 10 per cent of the total loading).

When the building dimensions are of the same order of magnitude as, or smaller than, the length scale of turbulence in the wind (about 50 metres in the lateral plane and 60 metres in the vertical plane) then the building can be considered to be enveloped by whole gusts and no variation in gust speed over the face of the building due to separate gusts need be allowed for. The static loading on such a building can be estimated by using the coefficients in this Item in conjunction with a suitable velocity. This velocity is determined from an appropriate wind speed profile (such as is given in Table 8.1), scaled by the design gust velocity at the level of the top of the building.

For larger buildings and for other buildings where the dynamic component of loading is likely to be significant, the basic coefficient data in this Item can be used in conjunction with statistical methods for determining loadings, such as are given in Reference 2 for example. Such methods take into account the effects of variation in magnitude and structure of gusts over the face of a large building and also dynamic effects due to vibrations in the direction of the wind induced by the action of the wind. Oscillatory side or cross-wind forces associated with vortex shedding or other instability mechanisms, which may be considerable for tall slender structures, cannot be derived from the information in this Item. It is anticipated that such information will be issued in Data Item form in due course.

2.1.2 Application to rectangular blocks in general fluid flows

In principle, the methods outlined in Section 2.1.1 may be applied to the estimation of the loading on any block subject to fluid flow past it. However, the complete statistical description of the flow which is required is not often available and it is usual to assume that the loading may be derived by using a suitable reference or design velocity in conjunction with the basic mean coefficients. The reference velocity will usually be derived from the maximum anticipated free-stream velocity approaching one end of the block together with, where relevant, an appropriate velocity profile (see Section 4.4 and Table 8.1).

However, it should be noted that, as for buildings, blocks with low natural frequencies of vibration and low damping may be subject to significant additional dynamic components of loading due to both flow-induced vibrations in the free-stream direction and oscillatory side or cross-wind forces resulting from fluid dynamic instability.

2.2 Accuracy of Data Obtained from this Item

Under the datum conditions set out in Section 3.1 the user should allow for an uncertainty of about ± 0.15 on the force coefficients obtained from this Item. Under non-datum conditions an additional allowance of ± 20 per cent should be made for uncertainties in the corrected force coefficients. This is because there are few data on which to base the correction factors.

It is often difficult to define precisely the flow conditions for which the data are to be applied and the user is recommended to consider the effect of small changes in parameters such as turbulence level and inclination of the free stream and to take the most adverse estimate of forces and moments which results.

In the case of the pressure coefficient, small variations in flow conditions can change a local pressure by altering both the overall magnitude of pressures and also the distribution. The most adverse pressure likely to occur in the vicinity of the point of interest should therefore be taken into account.

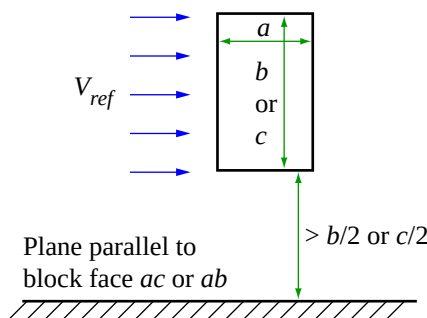
3. FORCE AND MOMENT COEFFICIENTS ON RECTANGULAR BLOCKS IN DATUM CONDITIONS

3.1 The Datum Conditions

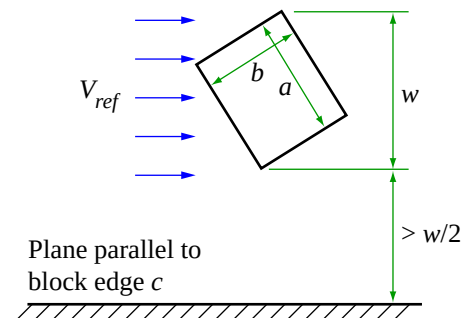
Sections 3.2 to 3.4 present data which have, as far as is practicable, been reduced to a set of datum conditions. These conditions together with their practical approximations are given below.

- (i) The free-stream* Reynolds number is between 10^4 and 10^6 .
- (ii) The flow is unbounded except by the surface-plane in the case of a surface-mounted block or by the end-planes in the case of approximately two-dimensional flow (see Section 3.2). Unbounded flow conditions are achieved approximately if a plane surface parallel to the free stream is located further from the block than the dimensions indicated in Sketches (3.1) and (3.2) or for a block in a duct if the area ratio A'/B is less than 0.02.

* The term 'free stream' means the undisturbed flow upstream of a block.



Sketch 3.1



Sketch 3.2

- (iii) The free stream is smooth or has a turbulence intensity, $\sqrt{u^2}/V_{ref}$, of less than 0.01.
- (iv) The free-stream velocity is uniform. This condition is sufficiently satisfied for surface-mounted blocks when $\delta/c < 0.2$, *i.e.* the velocity is constant over at least $0.8c$.
- (v) The flow may be considered incompressible. This applies for liquid flows and for gas flows for which the free-stream Mach number, Ma , is less than 0.2.
- (vi) The block is solid or impervious.
- (vii) The edges of the block are nominally sharp. A maximum radius ratio of $r/b = 0.01$ is allowed. Most blocks which do not have the edges deliberately rounded meet this condition.

3.2 Blocks in Two-dimensional Flow and between End-planes

Two-dimensional flow is said to occur when the mean flow patterns around all cross sections parallel to the xOy plane are identical, *i.e.* there is no flow in the Oz direction. This could occur for flow around an infinitely long block ($c/b = \infty$) but in practical terms is approximated when a finite-length block is mounted between end-planes. The end-planes do, however, interfere with the two-dimensional nature of the flow near the ends. Examination of the experimental data suggests that, provided the side ratio c/b is greater than unity and the end-planes are large enough*, the interference has a negligible overall effect on the flow. These data have application in such cases as enclosed bridges between buildings.

The curve for $c/b = \infty$ on Figure 1 shows the variation of the force coefficient C_X with side ratio a/b for blocks in two-dimensional flow and with the free stream normal to one face, based on an evaluation of data from Derivations 5, 7, 11, 13, 15, 21, 23, 36, 44 and 46. As the side ratio a/b increases, C_X rises to a maximum value at $a/b \approx 0.67$ and then falls again. This variation is associated with the extent to which the base of the block extends into the separation bubble and also with the influence of the block sides on the separated shear layer. At about $a/b = 2.8$ the sides are long enough for the flow to reattach (this value of a/b is influenced by turbulence, see Section 4.3).

Curves for $c/b = \infty$ on Figures 2 and 3 respectively give the component force coefficients C_X and C_Y for blocks of square cross section in two-dimensional flow at various inclinations, ϕ , to the free stream and curves on Figures 4 and 5 give the alternative component force coefficients C_D and C_C . Figures 2 to 5

* The minimum size required is approximately $3w$ downstream of the block, $\frac{1}{2}w$ upstream and a width of $2w$, where w is the maximum width of the block cross section normal to the flow direction (Derivation 21).

were derived by evaluating data for C_D and C_C from Derivations 4, 6, 15, 17, 20 and 21 and are related by the expressions:–

$$C_X = C_D \cos \phi - C_C \sin \phi \quad (3.1)$$

and
$$C_Y = C_D \sin \phi + C_C \cos \phi. \quad (3.2)$$

The variation with ϕ in the range 10° to 15° of the force coefficients on Figures 2 to 5 is associated with changes in flow separation and reattachment on the block sides.

A few values of C_C for blocks with $a/b = 1/2$ and 2, in two-dimensional flow and inclined to the free stream, are given in Derivation 17.

3.3 Isolated Blocks

A block may generally be considered isolated if the conditions for an unbounded flow are met and any supports are small in cross section compared with the block and not immediately upstream of it.

Figure 1 shows the variation of the force coefficient C_X with the side ratios c/b and a/b for isolated blocks with the free stream normal to one face, based on data from Derivations 4, 5, 21, 23, 27, 28, 38 and 41. The force coefficients C_Y and C_Z are zero when the free stream is normal to the front face.

Figures 4 and 5 show the effect on the force coefficients C_D and C_C of inclination, ϕ , of the free stream to the front face of isolated square-sectioned blocks. Data from Derivations 5, 21, 38 and 41 were evaluated to obtain Figures 4 and 5. For all values of ϕ , C_Z is zero. The data are presented in Figures 2 and 3 in terms of the alternative force coefficients C_X and C_Y obtained by using Equations (3.1) and (3.2).

3.4 Surface-mounted Blocks

The block is assumed to be mounted on a surface which is in the xOy plane and parallel to a uniform free stream.

Figure 6 shows the variation of the force coefficient C_X with the side ratios c/b and a/b when the free stream is normal to the front face. For values of $c/b \geq 1$ the data on Figure 6 are consistent with the application of the mirror image principle* to the data for isolated blocks from Figure 1. This is supported by experimental data from Derivations 4–10, 12, 19–22, 24–26, 36, 41 and 42.

Some data for the force coefficients C_D and C_C when the free stream is inclined to the front face are given in Figures 11 and 12. The data are also presented in terms of the force coefficients C_X and C_Y in Figures 7 and 8 respectively. Figures 7 and 8, and 11 and 12 are related by Equations (3.1) and (3.2). Figures 7 and 8 are based on data from Derivations 6–9, 12, 19, 20, 22 and 31 and apply for square cross sections, $a/b = 1$, only. Some data for other cross section shapes may be obtained from Derivations 8 and 12 for $\phi = 45^\circ$ and from Derivations 10 and 24 for a range of values of ϕ .

* The mirror-image (or reflection-plane) principle assumes that the surface on which a block is mounted may be taken as equivalent to the dividing streamline in the symmetrical flow past an isolated block of twice the length.

For a surface-mounted rectangular block, due to the asymmetry of the flow, a force component exists in the Oz direction. The main contribution to this force arises from the pressure on the free end and Figure 9 gives some data on the force coefficient C_Z derived from an integration of pressures on the free end of a number of blocks of square cross section. The curves are based on information from the same sources as were data in Figures 7 and 8 and again a few values for blocks of non-square cross section may be obtained from Derivations 8, 10 and 12. It should be noted that C_Z in Figure 9 is based on the reference area $A (= bc)$ whereas Figure 10 shows C_Z^* based on the end area ab , which may be more convenient to use in some cases.

Few data are available on the overturning moments for surface-mounted blocks. The moment coefficient about an axis through the lower rear edge of the block (*i.e.* an axis parallel to Oy at $x = a$ and $z = 0$) may be expressed in the form

$$C_M = C_X z_{cp}/c + C_Z(1 - x_{cp}/a)a/c. \quad (3.3)$$

Figures 13a and 13b show tentative estimates of z_{cp}/c and x_{cp}/a respectively based on data from Derivation 24 together with values derived from pressure distribution data. The force coefficient C_X is given by Figure 6 and, in the absence of better information, it is suggested that values of C_Z are taken from Figure 9 for all values of a/b .

4. EFFECTS OF DEPARTURE FROM DATUM CONDITIONS

This Section gives some guidance as to how the force coefficients given in Section 3 may be applied when the conditions do not match the datum conditions given in Section 3.1. Few data are at present available on which to assess the effects of departure from datum conditions and the information given, although generalised as far as possible, should be regarded more as examples of the effects which have been shown to occur in certain specified cases. Data for combinations of effects are almost non-existent, but it is unlikely that the results obtained by applying the corrections given will be subject to greater uncertainties than those given in Section 2.2.

4.1 Effect of Variation of Reynolds Number

The information in Section 3 is based on experimental data obtained for Reynolds numbers between 10^4 and 10^6 and, within the accuracy of the data, no significant trend or variation with Re over that range is apparent.

For Reynolds numbers below 10^4 the few data available are insufficient to establish the variation of the force coefficients. However, the flow around an isolated block, provided it is not long in the flow direction, resembles that around an isolated, thin, flat plate when both are normal to the approaching stream. The variation of C_X with Re for a block may therefore be expected to follow a similar trend to that found for a flat plate. This is shown in Figure 14, taken from Derivation 42. For blocks which are long in the flow direction or are inclined to the approaching stream, and for surface-mounted blocks, other influences of low Reynolds number, which do not arise in the flow around plates, are such that Figure 14 is less likely to apply.

For Reynolds numbers greater than 10^6 no significant effect of Re on the force coefficients is to be expected.

4.2 Effect of Bounded Flows (Blocks in Ducts)

If a block is near a single surface the presence of that surface will distort the flow past the block and hence alter the forces acting on it. The magnitude and sign of the change in force is dependent on how close the block is to the surface and also on the shape of the block. Data in Derivation 28, while insufficient to generalise, will give some guidance in a few cases.

If a block is surrounded by surfaces parallel with the free-stream direction, *i.e.* is enclosed in a duct, and its cross-sectional area normal to the stream is more than about two per cent of the duct cross-sectional area, a correction to the force coefficients given in Section 3 is required in order to allow for blockage effects.

Derivation 33 shows that corrections derived for application to wind-tunnel test results for thin flat plates normal to the free stream may also be applied to results for rectangular blocks, provided that the flow does not reattach to the block sides downstream of the main separation points. In practice this restricts the correction to cases where, approximately, $a/b < 2.5$ and $\phi < 10^\circ$ or $\phi > 25^\circ$. Although the correction was derived to obtain the equivalent force coefficients in unbounded flow from those measured in duct flows, it may be applied in reverse. The correction is given by

$$C'_F = C_F / (1 - k_2 A' / B) \quad (4.1)$$

where C_F is the force coefficient* in unbounded flow (given in Section 3) and C'_F is the corresponding coefficient for duct flow. The correction factor k_2 depends on the shape of the block and is given in Figure 15. The data of Derivation 33 suggest that this method of correction will give good results where the correction is up to 30 per cent of C_F .

4.3 Effect of Free-stream Turbulence

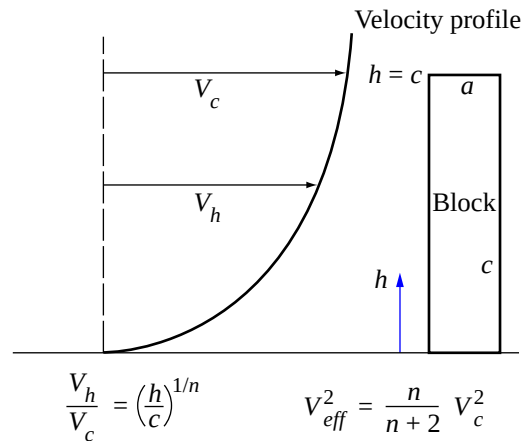
Free-stream turbulence affects the flow past a rectangular block primarily by its influence on the shear layer dividing the separated flow region from the separation bubble. For a surface-mounted block a second influence may be introduced via the effect of turbulence on the development of the boundary layer on the surface.

The effects of free-stream turbulence, although of importance, have not to date been widely investigated and it is therefore not possible to present data generalised for a wide range of situations. However, as an example, Figure 16 shows a tentative evaluation of the effects of turbulence on the force coefficient C_X for square-section blocks in two-dimensional flow and for isolated cubes, in both cases with the free stream normal to a face (Derivations 39, 40 and 41). Figure 16a shows the correction factor k_3 for the effect of turbulence intensity on C_X for both the two-dimensional flow case and the isolated cube. Figure 16b shows the correction factor k_4 for the effect of scale of turbulence for the two-dimensional flow case. For the isolated cube, data were available only up to $L_x(u)/a = 1$; over that range $k_4 \approx 1$. Data from Derivation 35 suggest that some values of k_3 for c/b between 1 and ∞ may lie outside the range enclosed by the two curves on Figure 16a but there is insufficient information to allow generalisation. It has been noted experimentally (Derivation 41) that increased turbulence tends to promote reattachment of the flow to the side of the block and therefore a smaller effect may be expected for a block length which is of the same order as or greater than that for which reattachment occurs in a smooth stream, that is for a/b greater than about 2.5.

* The symbol C_F is used to denote a general force coefficient and should be replaced by the appropriate individual coefficients as required.

4.4 Effect of Shear Flows

Few experimental data are available on the effect of shear flows (*i.e.* a flow with a velocity gradient) on the forces and moments on blocks. The following method of allowing for this effect is described in Derivation 34 and is supported by information from Derivations 24 and 45.



Sketch 4.1

The forces on a block in a shear flow are given to a good approximation by

$$F = \frac{1}{2} \rho V_{eff}^2 A C_F \quad (4.2)$$

where C_F is the value applying to uniform flow.

The value of the constant n in the velocity profile equation depends on the flow conditions upstream of the block and some typical values are given in Table 8.1. The velocity measured at a distance of $0.4c$ from the surface corresponds approximately to V_{eff} for most typical boundary layer profiles.

4.5 Effect of Compressibility

When the free-stream Mach number, Ma , is less than 0.2 the effect of compressibility on force coefficients may be assumed negligible²⁹. Insufficient reliable data are available to determine the effects of compressibility for higher Mach numbers.

Even for a Mach number as low as 0.2, the free-stream kinetic pressure will be high (about 2750 N/m² for air at standard sea level conditions) and the forces on a rectangular-sectioned block will also be high (*i.e.* 2750 C_F N/m²) and a more streamlined cross section may be preferable.

4.6 Effect of Permeability of Block

Provided that the open area of a permeable block does not exceed about 5 per cent of the total surface area, and is not concentrated on a front face, then the effect of permeability is only to change the internal pressure (Section 5.2) and there is no resultant change in the overall force coefficients.

4.7 Effect of Rounded Edges

Rounding the edges of a rectangular block may significantly affect the flow around the block and the forces on it. In common with other rounded bluff bodies, the rounded-edge block exhibits a critical Reynolds number regime³ in which the force coefficients change rapidly with changing Reynolds number. As $r/b \rightarrow 0.5$, a square section, $a/b = 1$, becomes increasingly similar to a circle and, for certain combinations of Reynolds number and radius ratio, circular cylinder data^{50,51}, which include guidance on the effects of turbulence and surface roughness on the critical flow regime, can be applied.

The information given is based on data for blocks with all four z-direction edges rounded. However, since much of the effect of the rounded edge is to "streamline" the shear layers separating from the upstream edges of the block, the upstream edges will generally exert most influence. The downstream edges become more important for long blocks (*i.e.* having $a/b > 2.5$) or for blocks at incidence ($\phi > 10^\circ$) when the flow may reattach to the block sides.

4.7.1 Blocks normal to two-dimensional flow, $c/b = \infty$

Figures 17a and 17c give a correction factor, k_5 , for the effect of edge radius on C_X , (or C_D) for blocks normal to flow, for subcritical and supercritical flow. These are based on data from Derivations 13, 14 and 44. In Figure 17c, data are available for smooth surfaces only and have been tentatively extrapolated using circular cylinder data as a guide at $r/b = 0.5$. Values of ϵ , the effective roughness height, may be found from Derivation 50.

Figure 17b shows the range of Reynolds number within which the critical flow³ regime may occur, based on data from Derivations 13 and 14. The force coefficients in this range of Re are unlikely to exceed that given for subcritical flow but may be lower than those for supercritical flow in some circumstances. As a tentative guide it is suggested that the subcritical and supercritical flow values be taken to apply up to, and beyond, respectively, the full line on Figure 17b.

The data suggest that for $r/b > 0.25$ circular cylinder data⁵⁰ may be used to obtain C_D values for rounded square sections ($a/b = 1$) at all Re although within the critical flow regime the uncertainty is large.

4.7.2 Blocks inclined to two-dimensional flow, $c/b = \infty$

Figure 17d shows the correction factor, k_5 , for a square section at 45° to the flow, based on data from Derivations 13 and 14. Note that for this case $C_X = C_Y$ (but $C_D = \sqrt{2}C_X$) and is based on the reference area bc . The circular cylinder data⁵⁰ may be applied for square sections with $r/b > 0.3$ in supercritical flow only in this case.

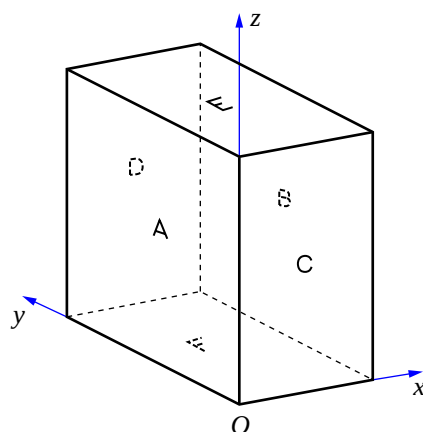
Figures 18a and 18d shows the dominant trends in the variation of k_5 (for corrections to C_X) and k_6 (for corrections to C_Y) with incidence for square sections (Derivation 14). Data for sections with $a/b = 2/3$ and $1\frac{1}{2}$ show broadly similar trends. The critical Reynolds number region for these cases also is within the band defined on Figure 17b. Note that k_6 changes sign between subcritical and supercritical flow cases; this is a result of changes in the separation and reattachment patterns of the shear layers around the side faces of the block.

4.7.3 Three-dimensional blocks, $c/b < \infty$

It is suggested that, in the absence of specific data the factors k_5 and k_6 from Figures 17 and 18 be applied for short rectangular blocks, $c/b < \infty$. The few data in Derivations 20, 47, 48 and 49 for flow normal to the block and at 45° and the similarity of the variation of C_D with c/b for square-section blocks and circular-section blocks qualitatively support this approach.

5. SURFACE PRESSURE COEFFICIENTS

5.1 External Pressures



Sketch 5.1

The data given in this Section are average pressures on a complete face of a block (Section 5.1.1) and distribution of pressure over the face (Section 5.1.2). For convenience in reference to a particular face, the faces of a block have been lettered as in Sketch (5.1) and the appropriate letter is added as a suffix to C_p in referring to the pressure coefficient on a particular face. For a surface-mounted block, face F is on the surface; for a block between end-planes (two-dimensional flow), faces E and F are on the planes. The free stream is parallel to xOy and for $\phi = 0^\circ$ it is normal to face A while for $\phi = 90^\circ$ it would be normal to face C.

5.1.1 Average pressure coefficients

The basic data for uniform flow will be subject to uncertainties similar to those quoted in Section 2.2 for force coefficients. The data for shear flows and turbulence effects, however, give approximate guidance only. The following relationships between pressure and force coefficients apply:

$$C_X = C_{pA} - C_{pB} \quad (5.1)$$

$$C_Y = (C_{pC} - C_{pD})ac/(bc), \quad (5.2)$$

and for surface-mounted blocks only,

$$C_Z = (-C_{pE})ab/(bc), \quad (5.3)$$

whereas $C_Z^* = -C_{pE}$. For isolated blocks in uniform flow $C_{pF} = C_{pE}$ and $C_Z = 0$.

Figure 19 shows the variation with side ratio a/b of the average pressure coefficients on the faces of rectangular blocks for two-dimensional flow* normal to face A. The coefficient C_{pB} is often referred to as the 'base-pressure' coefficient. The peak which occurs in the force coefficient curve (Figure 1) is reflected in a trough in the base-pressure coefficient curve. The front-face coefficient, C_{pA} , is approximately independent of a/b . Data from Derivations 7, 32, 36 and 46, adjusted so that values of C_X given by Equation (5.1) are consistent with Figure 1, were used to obtain Figure 19.

* For explanation of this term see Section 3.2.

When the flow is inclined to face A, the pressure distribution changes with changes in inclination angle ϕ such that face C becomes a “front” face as well as face A, and face D becomes in effect part of the base. The variations of the average pressure coefficients on the four faces A, B, C and D with inclination angle, ϕ , are shown in Figure 20 for two-dimensional flow past a square-sectioned block. Data from Derivations 7, 17 and 32, adjusted so that values of C_X and C_Y given by Equations (5.1) and (5.2) are consistent with Figures 2 and 3, were used to obtain Figure 20.

Figures 21 and 22 show the variation with inclination angle, ϕ , of the average pressure coefficients for isolated blocks of square cross section with $c/b = 5$ and 1. Figures 23 and 24 show the corresponding data for surface-mounted blocks. Data from Derivations 6, 7, 8, 12, 22 and 31, adjusted so that values of C_X and C_Y given by Equations (5.1) and (5.2) are consistent with Figures 2 and 3 and Figures 7 and 8, were used to obtain Figures 21 to 24.

Data for other surface-mounted rectangular blocks may be obtained by integration of pressure distributions given in Derivations 8, 10, 12, 22 and 24. It should be noted that the depth of boundary layer on the surface on which these blocks were mounted was not the same in all tests and may lead to inconsistencies in the results obtained. Integration of pressure distributions obtained by the methods given in Figure 30 may be used but, because of the approximation involved in generalising the data, will give less reliable results.

5.1.2 Distribution of local pressure coefficient on block faces

This Section gives some approximate guidance on the distribution of pressure on the faces of rectangular blocks under the datum conditions as set out in Section 3.1. Departures from the datum conditions will change both the local pressures and their distributions but the available information does not enable much guidance to be given on this.

On rear facing surfaces and surfaces parallel with the free stream the pressure coefficient, C_p , is negative and the region of negative C_p extends a short distance past the corners onto the forward facing surfaces. On forward facing surfaces both positive and negative pressures may be found, the distribution depending on the inclination to the free stream.

The pressure distribution around a square-sectioned block with two-dimensional flow normal to face A ($\phi = 0^\circ$) is shown in Figure 25a (Derivations 7, 17 and 45). For rectangular-sectioned blocks C_{pA} is almost independent of side ratio a/b but the distribution of $-C_{pB}$ across the base tends to become more peaked at the centre for values of a/b in the region of 0.67 as shown in Figure 25b. For large values of a/b , the distributions on the sides and the base remain similar to those on the square section but values of C_p are generally less negative as shown by Figure 25c. When the free stream is inclined to face A, the pressure distributions change in shape as shown in Figure 26 (Derivation 7).

Figure 27a shows the approximate distribution of pressure on the faces of a surface-mounted cube ($a/b = 1$, $c/b = 1$) with a nominally uniform free stream normal to face A, based on data from Derivations 7, 8, 12, 22 and 31. In a completely uniform flow a stagnation point ($C_p = +1$) would occur at the centre of the lower edge of face A. The presence of a boundary layer on the surface lifts the stagnation point further up the face and in practice, since the measured C_p is a time-averaged value of a fluctuating quantity, a value of $C_p = 1$ is often not actually recorded.

The effect of inclination of the free stream to face A is shown in Figures 27b, c and d. Features of note are the initial ($\phi \leq 15^\circ$) rise in negative pressure coefficient near the front of face C as ϕ increases and the relatively high negative values near the front corner of face E for all values of ϕ .

Figures 28 and 29 give some further examples of pressure distributions on blocks in uniform flows, based on data from Derivations 7, 10, 19, 24 and 26.