



**Fluid forces on
non-streamline bodies
– Background notes and description of
the flow phenomena**

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FLUID FORCES ON NON-STREAMLINE BODIES – BACKGROUND NOTES AND DESCRIPTION OF THE FLOW PHENOMENA

1. INTRODUCTION

The purpose of this Item is to provide background information which will assist the user of the series of Data Items on the estimation of fluid forces on non-streamline (*i.e.* bluff)* bodies. This series of Data Items gives detailed numerical data for use in a wide range of problems in aeronautical, chemical, marine, mechanical and structural engineering associated with the flow of fluid around bluff bodies. The Items present the latest available information and contain numerical data for the effect of variations in all the parameters considered of importance. They include flow charts to guide the user through procedures that will enable him to obtain numerical results without requiring him to have a specialist's understanding of the physical phenomena that take place. This Item is intended to describe the physical phenomena for those who are not specialist aerodynamicists and want to understand the rudiments of the problem. It is mainly concerned with wind flow around bluff bodies, such as buildings, but the information is also applicable to other fluid flow problems providing the Reynolds number is sufficiently high. Further, more detailed, descriptions and mathematical analyses of the problem can be found in the References quoted in Section 12. A key word index is given in Section 13.

Fluid flowing around a bluff body exerts on that body forces which fluctuate with time. These forces can be resolved into a mean (time-averaged) component on which is superimposed a fluctuating component which varies with time. The first Data Items in the series are concerned with the estimation of the mean component; a knowledge of this alone is satisfactory for many problems such as the design of most structures, particularly those having high natural frequencies of vibration and high damping. These will be followed with Data Items concerned with the estimation of the fluctuating component. It should be remarked that, although it is possible to separate the mean component from the fluctuating component, time-varying phenomena, such as turbulence, affect both the mean and the fluctuating components of the force on the body. Consequently, a discussion of such time-varying phenomena is as relevant to an understanding of the mean component as to the fluctuating component.

2. NOTATION AND NOMENCLATURE

2.1 Notation

Three coherent systems of units are given below†.

		SI	British	
A	reference surface area	m^2	ft^2	ft^2
a	local speed of sound in fluid	m/s	ft/s	ft/s
C_D	drag coefficient, $D/(\frac{1}{2}\rho V_\infty^2 A)$			
C_F	force coefficient, $F/(\frac{1}{2}\rho V_\infty^2 A)$			
C_L	lift coefficient, $L/(\frac{1}{2}\rho V_\infty^2 A)$			

* Definitions of streamline and non-streamline (*i.e.* bluff) bodies are given in Section 2.3

† See Section 2.2

		SI	British	
$C_X; C_Y; C_Z$	force coefficients, $X/(\frac{1}{2}\rho V_\infty^2 A)$; $Y/(\frac{1}{2}\rho V_\infty^2 A)$, $Z/(\frac{1}{2}\rho V_\infty^2 A)$			
C_M	moment coefficient (see Section 6.1)			
C_p	pressure coefficient, $(p - p_{ref})/(\frac{1}{2}\rho V_\infty^2)$			
D	drag force (measured in free-stream direction)	N	pdl	lbf
F	force acting on body	N	pdl	lbf
f	centre frequency of narrow-band vortex shedding (see Section 11.1)	Hz	c/s	c/s
L	lift force measured normal to free-stream direction	N	pdl	lbf
$\left. \begin{matrix} L_x(u); L_y(u); L_z(u) \\ L_x(v); L_y(v); L_z(v) \\ L_x(w); L_y(w); L_z(w) \end{matrix} \right\}$	integral length scales of u , v and w components of turbulence along x , y and z axes respectively	m	ft	ft
l	representative body dimension	m	ft	ft
M	local Mach number, V/a			
p	local static pressure	N/m ²	pdl/ft ²	lbf/ft ²
p_o	total pressure	N/m ²	pdl/ft ²	lbf/ft ²
p_{ref}	reference pressure usually taken as p_∞	N/m ²	pdl/ft ²	lbf/ft ²
$\left. \begin{matrix} R_u(x, 0, 0); \\ R_u(0, y, 0); \\ R_u(0, 0, z); \end{matrix} \right\}$	correlation coefficient of u component of turbulence for two points situated on x , y or z axes respectively (see Section 10.3)			
r_u	correlation function of u component of turbulence (see Section 10.3)	m ² /s ²	ft ² /s ²	ft ² /s ²
Re	Reynolds number, $V_\infty l/\nu$			
$\left. \begin{matrix} S_u(n); \\ S_v(n); \\ S_w(n); \end{matrix} \right\}$	power spectral density functions of u , v and w components of turbulence (see Section 10.1)	m ² /s	ft ² /s	ft ² /s
St	Strouhal number, fl/V_∞			
t	time	s	s	s

		SI	British	
$V(t)$	velocity; a time-dependent quantity	m/s	ft/s	ft/s
V	mean (time-averaged) velocity	m/s	ft/s	ft/s
u, v, w	components of fluctuating velocity along x, y and z axes respectively	m/s	ft/s	ft/s
X, Y, Z	component forces acting on body in direction of x, y and z axes respectively	N	pdl	lbf
x, y, z	system of rectangular cartesian coordinates; distances along x, y and z axes respectively	m	ft	ft
α	angle of inclination of free-stream direction to body longitudinal axis		degrees	
γ	ratio of specific heat capacity of fluid at constant pressure to that at constant volume			
ε	equivalent height of surface roughness (see Section 9)	m	ft	ft
μ	dynamic viscosity of fluid	N s/m ²	pdl s/ft ²	lbf s/ft ²
ν	kinematic viscosity of fluid, μ/ρ	m ² /s	ft ² /s	ft ² /s
ρ	density of fluid	kg/m ³	lb/ft ³	slug/ft ³
$\sigma^2(u)$	mean square value of $u, \bar{u}^2$	m ² /s ²	ft ² /s ²	ft ² /s ²

Subscripts

bl	denotes value in boundary layer
int	denotes internal value
∞	denotes free-stream value

2.2 Units

In the system of units known as *SI* the unit of force is the newton (N). A NEWTON is defined as the force required to impart an acceleration of 1 m/s^2 to a mass of 1 kg.

In the two coherent systems of British units given in Section 2.1 the units of force are respectively the poundal (pdl) and the pound-force (lbf). A POUNDAL is defined as the force required to impart an acceleration of 1 ft/s^2 to a mass of 1 pound. A POUND-FORCE (lbf) is defined as the force required to impart an acceleration of 1 ft/s^2 to a mass of 1 slug (which is 32.17 pounds) or, alternatively, as the force required to impart an acceleration of 32.17 ft/s^2 to a mass of 1 lb. Similarly, in the metric system, a KILOGRAMME-FORCE (kgf) is defined as the force required to impart an acceleration of 1 m/s^2 to a mass of 9.807 kg.

The units of pound-force and kilogramme-force must be distinguished from the local weights of bodies having masses of 1 lb and 1 kg respectively because the gravitational force or weight of the body is dependent on the local acceleration due to gravity which may be different from the assumed standard value of 32.17 ft/s^2 or 9.807 m/s^2 .

Some conversion factors between units are given below.

$$1 \text{ newton (N)} = 1 \text{ kg} \times 1 \text{ m/s}^2 = 102.0 \times 10^{-3} \text{ kgf}$$

$$1 \text{ poundal (pdl)} = 1 \text{ lb} \times 1 \text{ ft/s}^2 = 31.08 \times 10^{-3} \text{ lbf}$$

$$1 \text{ slug} = 32.17 \text{ lb.}$$

2.3 Definition of Streamline and Non-Streamline (Bluff) Bodies

A STREAMLINE BODY is defined as a body for which the major contribution to the drag force in the free-stream direction results directly from the viscous or skin friction action of the fluid on the body. A NON-STREAMLINE or BLUFF BODY is defined as a body for which the major contribution to the drag force is due to pressure forces arising from separation of the boundary layer flow adjacent to the surface over the rearward facing part of the body. For example, a body of circular or rectangular cross section is a bluff body and so is a flat plate or aerofoil inclined at a high angle to the oncoming flow. On the other hand, a thin flat plate lying parallel and edge on to the oncoming flow is a streamline body since the flow remains attached to the surface and skin friction accounts for up to 90 per cent of the total drag.

3. GENERAL

The force exerted by a fluid on a body can be resolved along the normal and tangential directions to the surface. In the normal direction the force per unit area is called the local **PRESSURE** (see Section 6.1) while in the tangential direction the force per unit area is called the **VISCOUS** or **FRICTION STRESS** (see Section 6.2).

Both the pressure and viscous forces on the body are dependent on the local properties of the fluid at the point in question and these are affected by the history of the element of fluid at the point. Most theoretical investigations in the field of fluid dynamics are based on the concept of a perfect, frictionless and incompressible fluid. For streamline bodies this theory supplies in many cases a satisfactory description of real motions but it does fail completely to account for the force on a body in the free-stream direction (the drag force) which is, incorrectly, predicted to be zero. On a non-streamline body in particular this force depends upon so many parameters that a complete theoretical solution of the problem cannot at the moment be envisaged and most design data are of experimental origin.

If the results of one experiment, or of measurements at full-scale conditions, are to be related to another situation of a different scale, it is essential that the requirements for comparability are known in detail. Application of dimensional analysis to the problem, and other considerations, shows that the force exerted on a body divided by $(1/2)\rho V_\infty^2 A$ can be expressed as a function of a series of non-dimensional parameters relating to both the characteristics of the free stream and the body surface. The force acting on a body is conveniently presented in the form of a non-dimensional force coefficient defined as

$$C_F = F / (1/2 \rho V_\infty^2 A)$$

Thus a non-dimensional general relationship for force coefficient in terms of the most important parameters can be expressed as

$$C_F = f \left\{ Re, M_\infty, \frac{\sqrt{u^2}}{V_\infty}, \frac{L_x(u)}{l} \text{ etc.}, \frac{nS_u(n)}{\sigma^2(u)}, \frac{\varepsilon}{l}, \dots \right\}. \quad (3.1)$$

For the flow pattern around two geometrically similar bodies orientated identically to two fluid streams to be similar (*i.e.* for complete **DYNAMICAL SIMILARITY**), the values of all the non-dimensional parameters must be the same in both cases. In Equation (3.1) the important non-dimensional parameters are the Reynolds number (Re), the Mach number (M_∞), the free-stream turbulence intensity $(u^2)^{1/2}/V_\infty$, the free-stream turbulence length scale ratio ($L_x(u)/l$), the normalised power spectral density ($nS_u(n)/\sigma^2(u)$) and the surface roughness ratio (ε/l).

It is impracticable to obtain complete identity of all parameters: however, in every instance some of the parameters have little or no effect on the flow and can be ignored. One of the most difficult tasks in the analysis of fluid flow problems around bluff bodies is to determine which are the most important parameters. The following Sections attempt to draw guidelines for this process. Each of the items on the right-hand side of Equation (3.1) is discussed in Sections 7 to 10. Finally, in Section 11 the time-dependent characteristics associated with vortex shedding are described.

Before proceeding with a description of pressure and viscous forces the concepts of ideal (inviscid) and real (viscous) fluid flows will first be discussed.

4. INVISCID FLOW

A fluid which is inviscid is sometimes called IDEAL. It produces no tangential viscous or frictional stresses or a pressure drag in the direction of the free stream. All REAL FLUIDS are viscous and may involve chemical changes. In order to develop a theory for a real fluid flow it is usually necessary to assume that it is not only inviscid, but is also non-turbulent and chemically inert. In such a theory of fluid flow around a body, layers of fluid adjacent to each other experience no viscous forces and act upon the body surface with pressure forces, normal to the body surface at each point, only. When the flow is steady a simple relation exists between the pressure, density and velocity along a STREAMLINE*. This is obtained from the equation of motion for the fluid flow and is

$$\int_1^2 \frac{dp}{\rho} + \int_1^2 V dV + \left(\int_1^2 g dz \right)^\dagger = 0 \quad (4.1)$$

where z is measured vertically from a horizontal datum plane. If further it is assumed that the flow is INCOMPRESSIBLE, that is to say that the density, ρ , does not vary with pressure (and is therefore a constant throughout the flow), this equation integrates to the well known relationship known as Bernoulli's equation

$$p + \frac{1}{2}\rho V^2 + \rho gz = \text{constant} = p_o. \quad (4.2)$$

The value, p_o , is a constant along a streamline and is known as the TOTAL HEAD or STAGNATION PRESSURE. Its value can vary from streamline to streamline if the flow field upstream of a body is a turbulent shear flow. Since the surface of a body is a stream surface it follows that in inviscid, steady incompressible flow the relation between pressure and velocity on the body surface is given by Equation (4.2).

In practice – that is in a real fluid flow – it is found that Bernoulli's equation applies to most regions of an incompressible non-turbulent flow field except in the boundary layers (see Section 5.1) immediately adjacent to solid surfaces in the flow and in the near wake of a body.

When the flow is COMPRESSIBLE (*i.e.* for gas flows at high speeds) Equation (4.2) no longer applies and Equation (4.1) has to be integrated, allowing for the variation of density with pressure. Thus for the flow of a gas along a streamline, when the gas is inviscid and non-heat conducting, and when no heat is lost or gained from the adjacent flow, the relation between density and pressure is $p/\rho^\gamma = \text{constant}$. This is the isentropic relationship which applies since the thermodynamic process is reversible. Hence, for an isentropic gas flow, Equation (4.1) when integrated becomes

$$\frac{p_1}{p_2} = \left\{ 1 - \frac{\gamma - 1}{2} \frac{V_1^2 - V_2^2}{a_2^2} \right\}^{\gamma/(\gamma - 1)}.$$

* A STREAMLINE is a curve such that its tangent at any point is in the direction of the velocity of the fluid at that point at the time considered. For a steady flow it is the path traced by an element of fluid in its motion around a body.

† The contribution of the term $(g dz)$ in Equation (4.1) and (ρgz) in Equation (4.2) for gases can be ignored. In homogeneous liquid flows with no free surface the term ρgz does not affect the motion as it is simply the hydrostatic pressure field for the fluid at rest.

For $V_1 = 0$, $p_1 = p_o$ when the equation reduces to

$$\frac{p_o}{p} = \left\{ 1 + \frac{\gamma - 1}{2} M^2 \right\}^{\gamma/(\gamma - 1)} \quad (4.3)$$

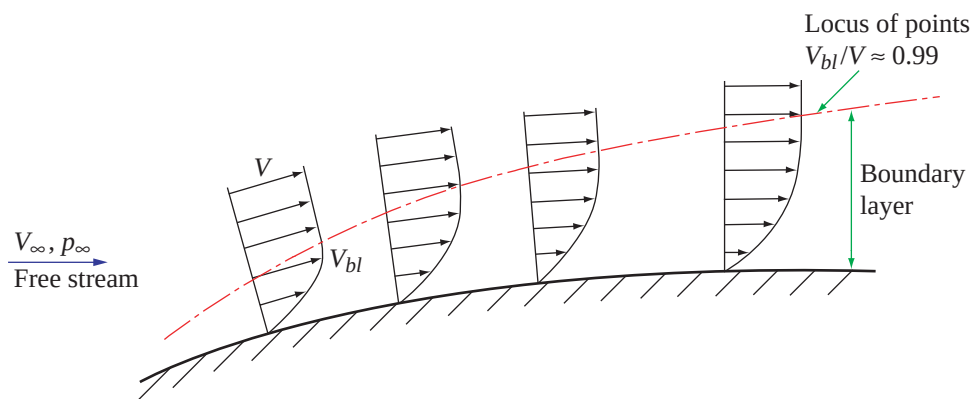
or, alternatively, for $V_2 = V_\infty$ and $p_2 = p_\infty$ it becomes

$$\frac{p}{p_\infty} = \left\{ 1 + \frac{\gamma - 1}{2} M_\infty^2 \left[1 - \frac{V^2}{V_\infty^2} \right] \right\}^{\gamma/(\gamma - 1)} \quad (4.4)$$

5. VISCOUS FLOW

5.1 Friction Forces, Boundary Layer, Separation

The FRICTION or VISCOUS force arises from the tangential shearing flow of a fluid along the surface of a body. The shearing forces are transmitted through the fluid shear layers adjacent to the surface as illustrated in Sketch 5.1. This layer of fluid in which a large velocity gradient exists normal to the surface is called the BOUNDARY LAYER and the flow in it is often referred to as a SHEAR FLOW. At the leading edge of a body, or more explicitly near the stagnation point (see Section 6.1), the boundary layer has only a small thickness. In general its thickness increases with distance along the surface, except in regions of high acceleration where its thickness can be reduced.



Sketch 5.1

In the boundary layer frictional forces act to slow down the fluid velocity relative to the body surface such that at the surface of the body there is no slip between the fluid and the body. When the boundary layer thickness is small compared with the body dimensions it is found that the pressure variation across the boundary layer normal to the surface can be neglected. Thus, in a real fluid, although Bernoulli's equation can only be applied outside the boundary layer, the pressure calculated at the edge of the boundary layer is also the pressure at the body surface when the boundary layer is thin.