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Fluctuating loads and dynamic response of bodies and structures in fluid flows – background information

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(Continued on inside back cover)

FLUCTUATING LOADS AND DYNAMIC RESPONSE OF BODIES AND STRUCTURES IN FLUID FLOWS – BACKGROUND INFORMATION

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FLUCTUATING LOADS AND DYNAMIC RESPONSE OF BODIES AND STRUCTURES IN FLUID FLOWS – BACKGROUND INFORMATION

1. NOTATION AND UNITS

Any coherent set of units may be used in the equations given in this Item. SI units are given below.

		SI Unit
A	reference area of body or structure, see Sketch 1.1	m^2
A_c	cross-sectional area of body in along-flow plane, see Sketch 1.1	m^2
a	depth, along-flow dimension of rectangular body, see Sketch 1.1	m
$a(\underline{r}; t)$	arbitrary function of position on body and time	*
b	width, across-flow dimension of rectangular body, see Sketch 1.1	m
$b(\underline{r}; t)$	arbitrary function of position on body and time	*
$C_{aa}(\tau)$	auto-covariance for fluctuating quantity $a(\underline{r}; t)$ at a single point with time delay τ	†
$C_{aa}(\underline{r}, \underline{r}'; \tau)$	cross-covariance for fluctuating quantity $a(t)$ at two points $\underline{r}$ and $\underline{r}'$ with time delay τ	†
$C_{ab}(\underline{r}, \underline{r}'; \tau)$	general cross-covariance between fluctuating quantities $a(\underline{r}; t)$ and $b(\underline{r}'; t + \tau)$ at points $\underline{r}$ and $\underline{r}'$ with time delay τ	†
C_{aj}	normal-mode generalised fluid-dynamic damping parameter, see Section 7	kg/s
C_D	along-flow or drag force coefficient, $D_F / \frac{1}{2} \rho \bar{V}^2 A$	–
C_F	force coefficient, $F / \frac{1}{2} \rho \bar{V}^2 A$	–
C_I	added mass coefficient; added mass/displaced mass, see Equation (7.29)	–
C_j	normal-mode generalised viscous damping parameter for structure in vacuo, oscillating in mode j only	–
C_L	across-flow or lift force coefficient, $L / \frac{1}{2} \rho \bar{V}^2 A$	–
C_M	moment coefficient, $M / \frac{1}{2} \rho \bar{V}^2 A D$	–
$\mathbf{C}$	damping matrix	kg/s
c	viscous damping parameter	kg/s
c_a	non-dimensionalised, normal-mode generalised fluid-dynamic viscous damping parameter, see Equation (7.9a)	–
c_{crit}	critical value of viscous damping parameter	kg/s

For footnotes see end of the Notation section

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c_s	non-dimensionalised, normal-mode generalised structural viscous damping parameter, see Equation (7.9b)	–
$\bar{c}$	along-flow characteristic dimension of streamlined body	m
D	characteristic dimension of body or structure, see Sketch (1.1)	m
D_F	along-flow or drag force	N
d_t	thickness of shell-structure wall, cable diameter (in relation to elasticity parameter, Section 5.2)	m
E	modulus of elasticity	N/m ²
$F(t)$	total fluctuating force on a body	N
$F(\underline{r}; t)$	fluctuating component of force on body element at $\underline{r}$	N
$F_{aj}(t)$	component of fluctuating normal-mode generalised force dependent on flow fluctuations	N
$F_j(t)$	normal-mode generalised force for mode j	N
F_{os}	amplitude of s^{th} component of fluctuating force expressed in Fourier series	N
g	acceleration due to gravity	m/s ²
$H(n); H(\omega)$	mechanical admittance functions in terms of frequency n and in terms of circular frequency ω respectively, see Equation (8.15)	–
$ H(n) \quad H(\omega) $	modulus or magnitude of admittance function, see Equation (8.16)	–
$H^*(n)$	complex conjugate of $H(n)$	–
$H_j(n); H_k(n)$	mechanical admittance functions for modes j and k respectively	–
h	height of structure, see Sketch 1.1	m
I	mass moment of inertia	kg m ²
i	$\sqrt{-1}$, operator rotating a vector through $\pi/2$ radians	–
j, k	mode numbers, $j = 1$ or $k = 1$ corresponds to the first or fundamental mode	–
K_{aj}	net normal-mode generalised fluid force component in phase with body displacement, see Section 7.1	‡
K_{fluid}	normal-mode generalised fluid dynamic stiffness	‡
K_j	normal-mode generalised structural stiffness for mode j , see Equation (8.40)	‡
$\mathbf{K}$	structural stiffness matrix	‡
k	structural stiffness parameter	‡

For footnotes see end of the Notation section

k_a	non-dimensionalised, normal-mode generalised fluid-dynamic stiffness parameter, see Equation (7.9b)	–
k_s	non-dimensionalised, normal-mode generalised structural stiffness parameter, see Equation (7.9b)	–
KE	kinetic energy	‡
$L(t)$	total fluctuating across-flow or lift force on body	N
l	length of a line-like structure, see Sketch (1.1); in Section 5 only, a characteristic dimension, not specifically equal to D	m
$\dot{l}_y, \ddot{l}_y, l_y$ $\dot{l}_\theta, \ddot{l}_\theta, l_\theta$	non-dimensionalised derivatives of across-flow force L with respect to cross-flow acceleration, velocity and displacement and torsional acceleration, velocity and displacement respectively	–
$M(t)$	total fluctuating moment on a body	N m
M_{add}	normal-mode generalised added mass ^{**} , see Section 7.1	kg
M_{fluid}	normal-mode generalised fluid inertia	kg
M_j	normal-mode generalised structural mass ^{**} , see Equation (8.36)	kg
$\mathbf{M}$	mass matrix ^{**}	kg
m	structural mass ^{**} per unit length of structure	kg/m
$m(r)$	structural mass ^{**} of an element of structure at location r	kg
m_e	equivalent mass ^{**} per unit length of structure, see Equation (8.38)	kg/m
m_s	non-dimensionalised, normal-mode generalised structural mass, see Equation (7.9b)	–
$\dot{m}_y, \ddot{m}_y, m_y$ $\dot{m}_\theta, \ddot{m}_\theta, m_\theta$	non-dimensionalised derivatives of moment M with respect to cross-flow acceleration, velocity and displacement and torsional acceleration, velocity and displacement respectively	–
N	index used in Equation (5.1)	–
n	frequency	Hz
n_j, n_k	effective frequencies of oscillation in normal modes j and k respectively for body in fluid flow, see Section 7.1	Hz
n_n	undamped natural frequency of oscillation of body in vacuo	Hz
n_s	vortex shedding frequency	Hz
PE	potential energy	‡
$Q_j(t)$	normal-mode generalised (normal) coordinate of normal mode j	††
Q_{oj}	amplitude of fluctuations in normal-mode generalised coordinate	††

For footnotes see end of the Notation section

$q_j(\underline{r})$	contribution of normal mode j to actual generalised coordinate at position $\underline{r}$	††
q_r	r^{th} generalised coordinate	††
q_{rj}	contribution of normal mode j to r^{th} generalised coordinate	††
Re	Reynolds number, $\rho \bar{V} D / \mu$	—
r	distance along a line-like body	m
r_a, r_b	two locations on a body	—
$\underline{r}$	position vector describing location of point of interest on body	m, rad
$S_{aa}(n)$	spectral density of fluctuating quantity ^{††} $a(t)$ at a single point for frequency n	††
$S_{aa}(\underline{r}, \underline{r}'; n)$	cross-spectral density of fluctuating quantity ^{††} $a(t)$ at two points $\underline{r}$ and $\underline{r}'$ for frequency n	††
$S_{ab}(\underline{r}, \underline{r}'; n)$	general cross-spectral density of fluctuating quantities ^{***} $a(\underline{r}; t)$ and $b(\underline{r}'; t)$ for frequency n	††
St	Strouhal number, $n_s(D/\bar{V})$	—
t	time	s
T	time period	s
u, v, w	fluctuating components of natural wind velocity in Ox, Oy, Oz directions	m/s
V	fluctuating velocity	m/s
$\bar{V}$	time-mean flow velocity	m/s
$\bar{V}_c$	critical time-mean flow velocity at which flow induced oscillations are maximum, or minimum flow velocity for instability of body	m/s
$\bar{V}_D$	design value of time-mean flow velocity	m/s
V_R	reduced velocity, $\bar{V}/nD$	—
x	along-flow displacement from equilibrium	m
x_N, x_{N+1}	amplitudes of successive cycles of oscillation	m
Y_{oj}	normal-mode generalised amplitude of across-flow oscillation due to mode j	m
y	across-flow displacement from equilibrium	m
$y_r, \dot{y}_r, \ddot{y}_r$	across-flow displacement, velocity and acceleration respectively at position r	m, m/s, m/s ²
α	incidence angle of flow to structure	rad

For footnotes see end of the Notation section

$\gamma_{ab}^2(\underline{r}, \underline{r}'; n)$	coherence function for fluctuating quantities $a(\underline{r}; t)$ and $b(\underline{r}'; t + \tau)$ for frequency n , see Equation (7.35)	—
δ	logarithmic decrement of damping ($\approx 2\pi\zeta$)	—
δ_s	value of δ due to structure alone in vacuo	—
ζ	viscous damping ratio, c/c_{crit}	—
ζ_{aj}	normal-mode generalised fluid-dynamic damping ratio for normal mode j	—
ζ_s	viscous damping ratio for structure alone	—
η	hysteretic or structural damping parameter, see Section 8.4	—
θ	torsional displacement from equilibrium	rad
θ_{ab}	argument of coherence function	rad
$\theta_r, \dot{\theta}_r, \ddot{\theta}_r$	torsional displacement, velocity and acceleration respectively at position r	rad, rad/s, rad/s ²
μ	dynamic viscosity of fluid	N s/m ²
$\mu_j(\underline{r})$	value of mode-shape function at location $\underline{r}$ for oscillation in normal mode j	—
μ_{rj}	value of mode shape parameter for r^{th} generalised coordinate for oscillation in normal mode j	—
$\boldsymbol{\mu}$	normal-mode shape parameter matrix	—
ρ	fluid density	kg/m ³
ρ_s	structure density	kg/m ³
$\rho_{aa}(\tau)$	auto-correlation function for fluctuating quantity $a(\underline{r}; t)$ at a single point with time delay τ : $C_{aa}(\tau)/\sigma^2(a)$	—
$\rho_{aa}(\underline{r}, \underline{r}'; \tau)$	cross-correlation function for fluctuating quantity $a(t)$ at two points $\underline{r}$ and $\underline{r}'$ with time delay τ : $C_{aa}(\underline{r}, \underline{r}'; \tau)/\sigma^2(a)$	—
$\rho_{ab}(\underline{r}, \underline{r}'; \tau)$	general cross-correlation function for fluctuating quantities $a(\underline{r}; t)$ and $b(\underline{r}'; t + \tau)$: $C_{ab}(\underline{r}, \underline{r}'; \tau)/[\sigma(a)\sigma(b)]$	—
ν	frequency parameter, $\omega D/\bar{V}$ ($= 2\pi/V_R$)	—
$\sigma(a)$	standard deviation of quantity $a(t)$	***
$\sigma^2(a)$	variance or mean square of quantity $a(t)$	***
$\sigma_B^2(q)$	variance of background or non-resonant response to fluctuating loading	***
τ	time delay	s

For footnotes see end of the Notation section

$\varphi(\omega)$	argument or phase angle of admittance function $H(\omega)$, see Equation (8.17)	rad
ϕ_s	phase angle of s^{th} frequency component in Fourier series	rad
λ	exponent used in Equation (8.3)	–
ω	circular frequency, $2\pi n$	rad/s
ω_d	damped natural frequency of oscillation of body in vacuo	rad/s
ω_j	circular frequency of oscillation of body in normal mode j	rad/s
ω_n	undamped natural frequency of oscillation of body in vacuo	rad/s

Subscripts

j, k	relating to normal modes j and k respectively; normal-mode generalised with respect to modes j and k respectively
M	total number of normal modes considered
o	reference (zero time) value; maximum amplitude of oscillation
R	total number of generalised coordinates considered
$11, 12, 1R, R1$	denote row (first symbol) and column (second symbol) of a matrix element (Section 8)

Superscripts

'	denotes a second spatial location or a second generalised coordinate
–	(bar over) denotes a time averaged value (over some specified time)
$\dot{}, \ddot{}$	denote first and second derivatives with respect to time, $d()/dt$ and $d^2()/dt^2$
M, R	on summations denote number of normal modes and generalised coordinates considered

Other notation

$ $	denotes the modulus or magnitude of a quantity
$f()$	denotes that f is a function of the bracketed variable or is to be evaluated for the specified bracketed variable
$\int_A$	denotes an integral to be evaluated over the reference area of the body

* The units of these terms depend on the variables represented.

† The units of these terms depend on the variables used to construct them.

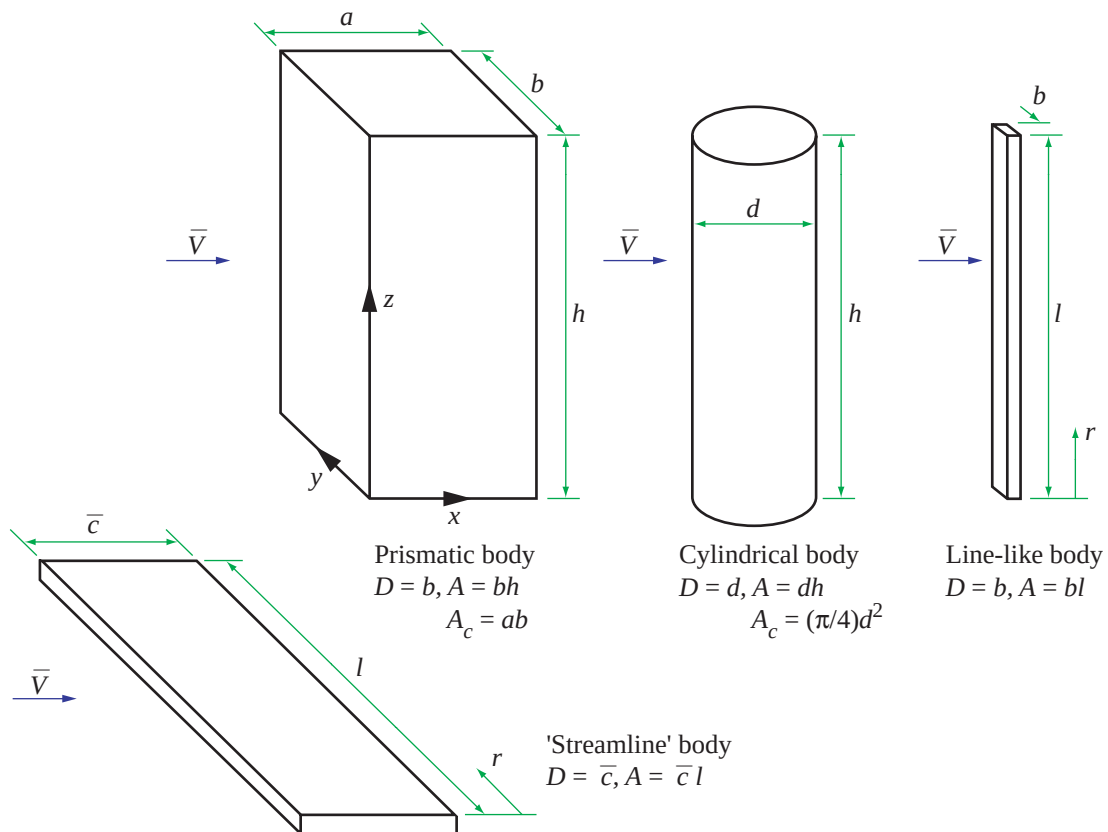
‡ The units of these terms depend on the generalised coordinate employed. For linear displacements, stiffness has units of N/m and KE has units of $\text{kg m}^2/\text{s}^2$; for angular displacement, stiffness has units of Nm/rad and KE of $\text{kg m}^4/\text{s}^2$.

** In the case of torsional oscillations the mass terms are replaced by mass moments of inertia.

†† The units of these terms depend on the choice of generalised coordinates.

‡‡ The quantities might be, for example, fluctuating forces for which the units of spectral density would be those of $(\text{force})^2/\text{Hz}$.

*** The units of these terms depend on the fluctuating quantity or generalised coordinate being considered.



Sketch 1.1

2. INTRODUCTION

The interaction between a fluid flow and a body* immersed in it is an unsteady phenomenon. Consequently the forces and pressures on the body and the distortions of the flow field which result from the interaction will vary with time. It is usual to analyse these effects in terms of a steady, time-mean component† upon which is superimposed a fluctuating component. This Data Item provides background information on the fluctuating component of force on a body and the response of that body, resulting from fluid flows. Other Data Items (e.g. References A20 and A21) provide data and calculation procedures for evaluating the effects of particular phenomena. Although much of the available information is for buildings and structures in the natural wind, the general procedures can be applied to other problems such as structures in water flows and bodies inside ducts. The problem of unsteady fluid loading caused by wave formation on a free surface is not discussed here (Reference A15 provides an introduction to this problem) but the methods discussed can be applied to sections of bodies well away from the free surface.

Some of the undesirable consequences of fluctuating loading and response of a body to it are discussed in Section 2.1. Section 3 provides a general description of some commonly distinguished phenomena and Section 6 provides some guidance on the types of body most susceptible to particular types or consequences of unsteady loading and gives sources of further discussion in this or other Data Items or elsewhere. Sections 4 and 5 discuss means of alleviating or avoiding problems and the use of model testing and experimental data. Sections 7 and 8 give a brief introduction to the basic principles of representation of the fluid forces and the analysis of structural vibration and bring these together to consider the essentials of solution of the complete governing equations. A list of selected sources of additional information is given in Section 9 and a glossary of some terms commonly encountered in the subject is given in Section 10.

2.1 The Need to Know

Failure of a system may be broadly classified as structural failure or as serviceability failure, the latter including both operational and environmental problems. Unsteady fluid loading may contribute to any of these and the following Sections give some examples. It is often found that serviceability problems impose more stringent limits than structural failure. The evaluation of the potential failures is beyond the scope of this Item but some of the References (Section 9) may assist in further evaluation.

2.1.1 Structural failure

Even when a structure does not oscillate significantly in response to fluctuating loading, that loading may be a significant part of the total. When the structure does oscillate the applied loading can be considerably amplified by inertia effects and the resulting stresses are then much higher than for static loading of similar magnitude. This may lead to direct failure due to overstressing. Excessive relative motion between individual structural components, caused by oscillation, may lead to collapse or cracking of joints and cladding. Fluctuating deflections can lead to wear failures such as for heat exchanger tubes passing through closely fitting baffles.

Structural members subject to repeatedly varying loading may fail, due to fatigue, at stresses well below the static failure stress. Where the loading cycle can be precisely defined it may be possible to estimate fatigue life. For random loading a very high uncertainty in the calculated life is inevitable and limiting the stresses to below the fatigue limit‡ (if one exists) may be preferable.

* The term 'body' is used in this Item to denote a general object which may be a simple geometrical shape or a complex construction, a complete structure or just one part singled out for consideration.

† For location of Data Items concerned with time-mean forces and pressures refer to the Engineering Sciences Data Index.

‡ For some materials, notably most steels, a stress level can be found below which the fatigue life is effectively infinite.

Joints in structures are particularly susceptible to failure due to repeated loading because of fatigue of welded joints and fatigue or loosening of other fasteners.

2.1.2 Serviceability failure

The large deflection amplitudes possible in the unsteady response of a structure (or element of a structure) in fluid flows can cause components of a system to interfere physically with each other or to move out of the alignment required for satisfactory performance. Examples of physical interference are the fretting of heat exchanger tubes on baffles and jamming of lifts (elevators) in their shafts. Oscillation of lift cables is another problem that has occurred. Close approach of conductors in power lines can lead to operational failure even if they do not touch. Precise alignment of objects such as radar reflectors, microwave antennae and telescopes can be difficult under unsteady loading conditions.

Instrumentation often requires a vibration-free environment for satisfactory operation and may indeed be in use to measure vibration of other components. Suitable choice and design of instruments can overcome many problems but a knowledge of the environmental vibration will be needed.

Swaying of tall towers or chimneys in the wind may cause alarm to people in the vicinity. Occupants of swaying buildings may be alarmed or annoyed by creaking partitions and cladding and may experience discomfort as a result of high local accelerations. Apart from noise caused by movement of structural components, the interaction of a bluff body with the flow, as in the case of wind flow past a prismatic tower block, may result in unacceptable aerodynamic noise. Noise^{*} generated by flow and body oscillations can be a problem for bodies in duct flows, especially if the duct itself amplifies the noise.

Human or instrument problems due to vibration usually occur at much lower levels than will cause serious structural damage.

The environmental consequences of the way in which a structure influences the flow are not considered in this Item but should not be overlooked. Examples are the wind environment around tall buildings and the flow in the lee of windbreaks.

* Extraneous noise may apply a fluctuating loading to a body through pressure fluctuations.

3. SOME COMMONLY DISTINGUISHED FLUCTUATING FORCE AND RESPONSE PHENOMENA

Fluctuating forces on bodies in fluid flows may arise from several mechanisms including fluctuations in flow approach velocity, oscillation of the body and from unsteadiness of the flow around and behind the body. Table 3.1 indicates the relative importance of various flow and body factors to the phenomena discussed qualitatively in the following Sections. The Table in Section 6 gives examples of particular structures that are likely to respond dynamically to particular phenomena. It should be remembered that the phenomena do not always occur in isolation and more than one may contribute to the response of a body under some circumstances.

3.1 Buffeting

Buffeting is caused by fluctuations in the flow velocity (such as the turbulence in the natural wind) which act directly to produce fluctuating forces on a body in the flow.

Turbulence buffeting occurs when the free stream is turbulent as in the natural wind. In this case the fluctuating velocities and consequent forces are random in character and have components both along and across the time-mean flow direction. A fluctuating torsional loading may also be caused. The magnitude of the fluctuating loading will be a function of the intensity of turbulence and its scale. The former determines the local magnitude of fluctuating forces while the latter, in relation to the body size, determines how well the fluctuations are correlated over the body.

TABLE 3.1
Relative Importance of Some Factors influencing Dynamic Loading and Response

<i>Influencing factor</i> <i>Phenomenon</i>	<i>Turbulent flow</i>	<i>Unsteady or periodic separation</i>	<i>Body oscillation</i>	<i>Several degrees of freedom</i>	<i>Asymmetry of body</i>	<i>Body in wake of another</i>
Turbulence Buffeting	*****	**	**	*	*	**
Wake Buffeting	*	***	**	*	*	*****
Torsion due to Buffeting	*****	*	**	*	***	**
Galloping	**	*	*****	**		***
Torsional Galloping	*		*****	**	***	**
Wake Galloping	*	***	*****	**		*****
Classical Flutter	*		*****	*****		***
Vortex Shedding	**	*****	***	**		**
Stall Flutter	*	*****	*****	*	***	*
Wake Flutter	*	***	*****	*****	*	*****

Key: ***** Fundamental cause of phenomenon
 *** Possible cause; large effect on magnitude of response
 ** Significant effect on magnitude of response
 * Small influence

The body may or may not oscillate significantly in response to the fluctuating loading. This will depend on the energy contained in those turbulent eddies whose average frequency of occurrence coincides with the natural frequency of the body. For the undisturbed atmospheric wind the higher frequency eddies contain less energy than those with a lower frequency of occurrence.

Significant fluctuating lift (and drag) forces can be generated on stranded cables in yawed (inclined) flow in the critical Reynolds number range (when transition from laminar to turbulent flow in the surface boundary layer occurs). The different lie of the strands on the upper and lower surfaces as presented to the yawed oncoming flow causes transition and flow separation to occur at different distances around the upper and lower surfaces of the cable. This asymmetry generates a lift (cross-flow) force which, in turbulent flow, fluctuates as a result of the fluctuations in both flow velocity and yaw angle.

Wake buffeting occurs when a body is located in the disturbed flow of the wake of some upstream (or adjacent) obstacle. In this case the applied loading will also be random but may contain dominant periodic components at, for example, a vortex shedding frequency of the upstream obstacle. When the dominant shedding frequency and the natural frequency of the downstream structure coincide, large amplitude oscillations may develop.

Another buffeting situation occurs when a significant part of a body is located within a wake or separated flow region created by the body itself upstream; for example the buffeting of glazing elements and cladding of buildings or the tail unit of an aircraft.

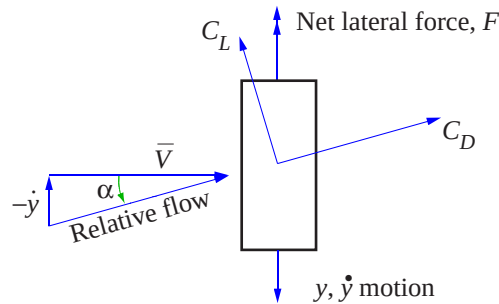
Flow fluctuations may also arise from the action of reciprocating pumps in internal flows. In this case the fluctuating loading is predominantly periodic and along the mean flow direction only.

3.2 Galloping

If a non-circular sectioned body is deflected across the flow it will experience an effective altered incidence which will change the side force on it. If the side force increases in the direction of motion the body will move further until the opposing stiffness force overcomes the fluid loading or until the side force begins to decrease again with increasing incidence. The body will then oscillate about the undeflected position. This is known as galloping and is initiated by body motion rather than flow fluctuations and can therefore occur even in steady, low turbulence flows.

The assumption is usually made that galloping oscillations are sufficiently slow that the problem can be analysed using force coefficients appropriate to a steady flow at the effective incidence, α , to the body. the condition^{J2} for potential instability is that rate of change of the net lateral force F ($F = 0$ at equilibrium) with increase in effective incidence, caused by the body motion $\dot{y}$, is negative, i.e. the resulting force acts to increase y further. For small displacements, so that $\cos \alpha \approx 1$ and $\sin \alpha \approx 0$, this criterion can be expressed as

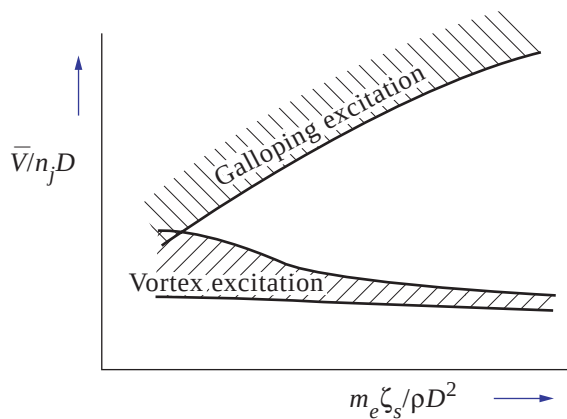
$$\frac{dC_F}{d\alpha} \approx \frac{dC_L}{d\alpha} + C_D < 0.$$



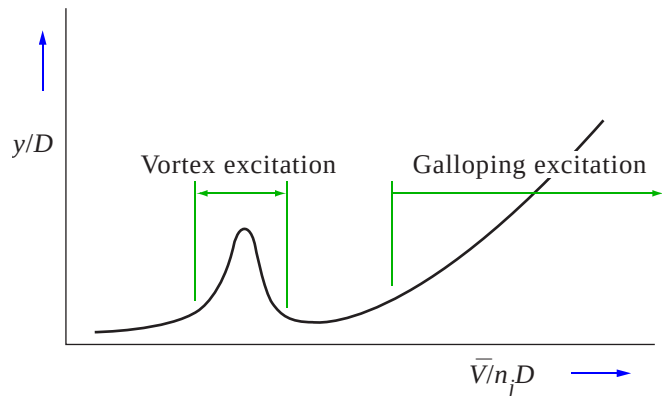
Sketch 3.1

Thus only cross sections for which $dC_L/d\alpha$ is negative can be susceptible to galloping but even nominally circular sections may be sufficiently asymmetric for this to be the case because of welds, fouling or icing.

Galloping oscillations are sustained once the flow velocity is high enough for the energy input from the flow to equal the energy dissipated by structural damping (i.e. the net damping is zero, see Section 7). For higher velocities the oscillation amplitude increases with increasing velocity. Sketches 3.2 and 3.3 show this schematically. Except at low damping the onset of galloping occurs at higher reduced velocities than significant oscillation due to vortex shedding. When this is not the case the use of steady-flow force coefficients is no longer valid.



Sketch 3.2



Sketch 3.3

Sketches illustrating vortex and galloping excitation of a square-sectioned cylinder

The oscillation of iced power conductor lines provides a classical example of galloping. It is also potentially a problem for tall, flexible prismatic towers.

The term galloping is usually applied to oscillation across the mean flow direction but a similar process may sometimes occur if a body is deflected torsionally about an axis normal to the mean flow direction. Coupling between these motions may occur, distinguished from classical flutter by the fact that the coupling is not essential to the motion.

A body in the wake of another may be liable to *wake galloping* which is described in Section 3.6.

3.3 Classical Flutter

Classical flutter is a coupled motion in at least two degrees of freedom at a single frequency, such as a combined bending and torsional motion or a combination of along-flow and across-flow motions. It is similar to galloping in that the fluctuating forces are controlled by the motion of the body but differs in the important respect that either or both of the motions would be positively damped were it not for cross coupling effects between the two degrees of freedom. Unlike galloping it can therefore only occur for bodies with at least two degrees of freedom. The cross coupling effects may arise from fluid force terms or from structural inertia or stiffness of freedom. the cross coupling effects may arise from fluid force terms or from structural inertia or stiffness terms. When the two motions are coupled fluid-dynamically, motion in one mode produces a fluctuating force influencing the other mode. For example if a body is oscillating torsionally its incidence to the free stream varies periodically, producing a fluctuating side force that will affect bending motions. The moment causing the torsional oscillation may equally be affected by the lateral oscillation. If the motions are coupled structurally, motion in one mode produces an unbalanced inertia or stiffness force causing motion in the other mode.

In extreme cases the feedback or coupling between the motions may be sufficient to cause divergence (usually in torsion) which is a non-oscillatory motion in which the displacement increases without limit. In such a case the effective stiffness (see Section 7) is zero. This may also occur when only one degree of freedom is possible.

Classical flutter is a design criterion for aircraft wings* but may also occur for the decks of long span suspension bridges. Grouped or bundled power conductors may be subject to *wake-induced classical flutter* (see Section 3.6).

3.4 Vortex shedding

Except at very low Reynolds numbers, bluff bodies of all cross sections immersed in a flowing fluid, or moving in a stationary fluid, shed vortices, usually alternately from each side of the body (Sketch 3.4). This process induces regions of low pressure alternately on each side of the body which in turn results in a net cross-flow force which alternates in direction as vortices are shed and an along-flow force which fluctuates in magnitude.



Sketch 3.4 Alternate vortex shedding

The natural dominant frequency of shedding of complementary pairs of vortices (one from each side) is given by the Strouhal number, $St = n_s(D/\bar{V})$. typically St is of the order of 0.1 to 0.4 but this depends on the cross-sectional shape and Reynolds number. For rounded bodies at Reynolds numbers below the critical value (defined as the value at which the time-mean drag coefficient drops rapidly) the shedding is predominantly periodic at this characteristic frequency. At supercritical Reynolds numbers it becomes more random but reverts again to a more periodic form for Reynolds numbers above about 10^7 . Vortex shedding from sharp cornered sections is more-or-less independent of Reynolds number.

* The study of the aircraft flutter problem is a specialised subject in its own right, see for example Reference H2.

If the shedding occurs naturally at frequencies near a natural frequency of a body free to vibrate (especially when the damping is small) motion of the body tends to cause the shedding frequency to 'lock on' to the body frequency over a range of flow velocities. When the amplitude of vibration is significant (*i.e.* greater than about 1 or 2 per cent of the body width) the local forces due to vortex shedding are amplified and additionally the correlation of forces over the body is increased, further increasing the effective force on the body. The shedding frequency can also be influenced by strong shedding by upstream obstacles and then may occur at that frequency.

The alternate vortex shedding gives rise to significant cross-flow fluctuating forces and, in air flows, motion is usually in this direction only. If the density parameter $m_e/(\rho D^2)$ is low, usually in more dense fluids, along-flow forces (at twice the cross-flow frequency) may become sufficient to cause motion. Torsional forces are also produced by the alternating pressure distribution.

Vortex shedding oscillations have significant amplitudes over a specific range, see Sketches 3.2 and 3.3, for flow velocity in the region of $St/n_j D$ (in contrast to galloping for which there is no upper limit). there may be more than one range if oscillations in higher modes than the first become important.

A common situation where vortex shedding may be a problem is the circular steel chimney in the natural wind. In this case motion caused by the vortex-induced instability is not usually a problem when the height to diameter ratio is less than about 8.

In some circumstances simultaneous shedding^{E8} of pairs of vortices, (Sketch 3.5), one from each side has been noted, principally with bodies oscillating significantly along the flow direction. The fluctuating force is then along-flow^{E13,E18} only but is of greater significance than the along-flow force for alternate shedding. A short distance downstream the vortex street for simultaneous shedding reverts to the alternating pattern.



Sketch 3.5 Symmetrical vortex shedding

Whilst lattice structures are not usually prone to vortex induced oscillations, individual members may be. Oscillations are more likely in structural members connected by friction-grip bolts or welding, rather than those joined by riveting or black bolts, due to lower damping.

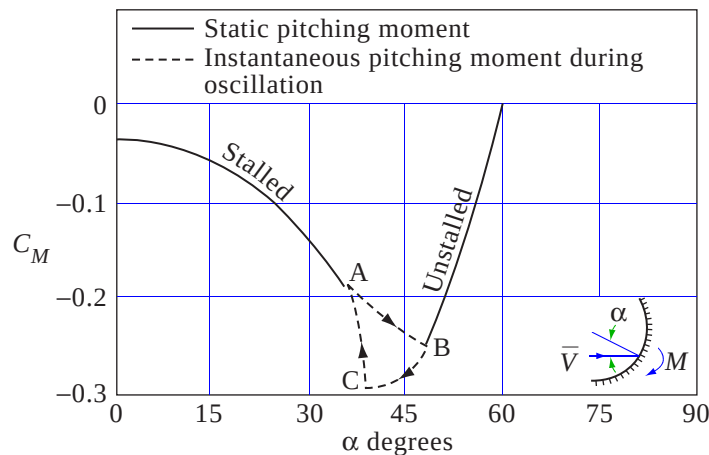
3.4.1 Owalling oscillation

Another consequence of vortex shedding is that the pressure distribution around a section varies periodically. This can lead to periodic distortion of an unstiffened thin-walled cross section such as a large diameter steel chimney. This is usually termed 'ovalling' (from the distorted shape of circular sections which are most vulnerable) or 'breathing'.

3.5 Stall Hysteresis Flutter

The term stall flutter or stall hysteresis flutter has been applied to motion sustained by hysteresis effects on separation and reattachment of flow on a body. For many body shapes, the curves of force or moment coefficient versus incidence are different in the stalling incidence region according to whether the flow starts from a stalled or an unstalled state. Additionally, motion of a body may alter the flow around it so as to delay stall for one direction of motion and advance it in the other.

Sketch 3.6^{A4} adapted from data in Reference H3 shows an example for a reflector bowl oscillating about a mean incidence in the region in which the changeover between stalled and unstalled flow takes place. As the incidence increases from A, the pitching moment coefficient follows a 'stalled' curve to B where recovery from the stall occurs; as incidence decreases again from B, C_M follows a different 'unstalled' curve to C where the flow again stalls and the moment rapidly drops back to A again. The clockwise path round the hysteresis loop ABC indicates that energy is fed from the flow to the structure in this case, sustaining motion.



Sketch 3.6

The exact shape of the loop will depend on the body shape and may also be influenced by the rate of change of incidence.

Stall hysteresis flutter is a potential problem for bowl-shaped reflector structures, compressor or turbine blades and plate type structures at high mean incidences to the flow, such as lock gates.

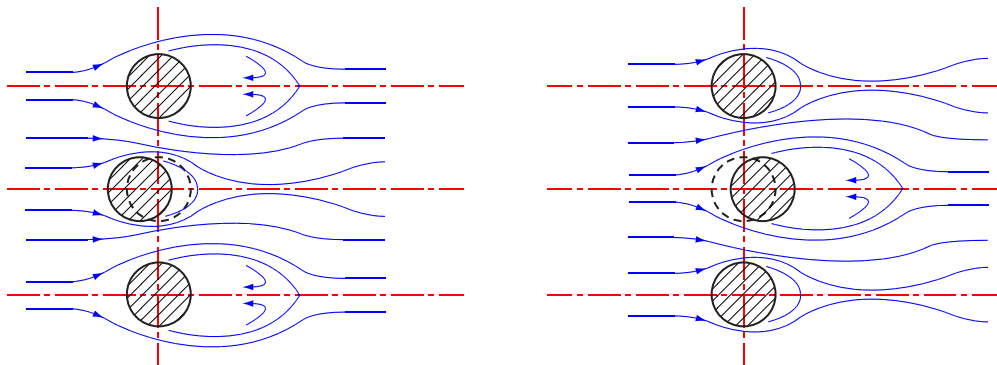
3.6 Interference between Bodies

When several bodies are grouped close together, the proximity of one body to another can influence the flow around, and forces on, both bodies or several members of the group. The effects are often particularly marked for groups of similar bodies such as a line of chimneys since the fact that all have the same natural frequency makes each very susceptible to flow disturbance caused by the others. The interference pattern may change if an body oscillates as a result of any of the previous discussed mechanisms and therefore the effects of interference may also alter. Significant changes in the time-mean forces may also be induced by interference effects.

The wake shed by a body can exert strong influences on a downstream body. A particular example, wake buffeting, has been discussed in Section 3.1. Another example is the enhancement of vortex shedding forces on the downstream stack or stacks in a row (see References in Section 9.5). In this case peak enhancements can occur when the wind is nearly normal to ^{E14}, or parallel to ^{E16}, the line joining the stacks but there seems to be some conflict as to which case is more critical. Reference E16 indicates that interference (enhancement) exists for spacings of less than 20 diameters (at 2/3 height) and is a maximum at a spacing of 5 diameters with the wind at an angle of 15°. When a body moves in the wake of another body it may experience fluctuations in loading caused both by its motion and by variations in flow velocity across the wake. This may lead to either *wake galloping* or *wake flutter* oscillations. For bodies of cross sections liable to galloping (Section 3.2) the velocity fluctuation across the wake can add a further destabilising effect. For circular-sectioned bodies, the wake velocity profile can cause asymmetry of the separation points on the

two sides of the section giving rise to cross-flow forces, so that a circular cylinder may gallop in a wake flow although not in a uniform free stream. For stiff structures the motion will usually be a single degree of freedom cross-flow galloping oscillation. For very flexible bodies the changes in along-flow force, induced by motion either along or across the mean flow direction, may be adequate to sustain along-flow oscillations. Motion may then occur in two coupled degrees of freedom, along and across the mean flow direction. This is termed *wake galloping* if the motion would be self-sustaining in either degree of freedom without coupling or *wake flutter* if the coupling effects are the cause of sustained oscillation. Bundled power conductors are liable to these problems, usually wake flutter of the downstream conductor for spacings typical of power lines. The conductor follows an elliptical path with its major axis nearly horizontal. When spacers are incorporated between cables flutter can occur between the spacers (sub-span oscillation). Flutter or galloping of a cable bundle with spacers as a single unit can also occur as a result of effects of the wake of upstream conductors on those downstream.

Interference effects are not confined to the downstream body. The presence of a body in or near its wake can considerably influence the flow around the upstream body or an adjacent one. A classic example of interference in all directions is the case of heat exchanger tube bundles. This is a very complex example of interference effects including wake buffeting effects and jet switching. The latter occurs when, because of along-flow tube motion, the pattern of alternate wide and narrow wakes behind closely spaced tubes switches sideways so that any one tube has alternately a wide and a narrow wake producing a fluctuating force. Sketch 3.7 shows this schematically.



Sketch 3.7 Jet switching (cylinder motion exaggerated)

4. METHODS OF REDUCING FLOW-INDUCED OSCILLATIONS

There are three main methods of reducing potentially undesirable flow-induced oscillations. First, since an important parameter governing the occurrence or onset of an instability is the 'reduced velocity', $\bar{V}_c/(n_j D)$ which is approximately constant for a given set of conditions), an increase* in n_j will cause an increase in the critical flow velocity, $\bar{V}_c$, at which the instability occurs; if $\bar{V}_c$ is greater than the maximum flow velocity expected to occur (e.g. the maximum design wind speed) the flow-induced instability will not generally be a problem. Secondly, the geometry of the structure can be changed either by modifying the structure shape or by adding aerodynamic devices that reduce the strength of the flow mechanisms producing the instability. Thirdly, the inherent structural damping can be increased by artificial means (see Section 4.9). This is often the only practical means of reducing the oscillatory response.

The following sections summarise various methods of reducing the severity of particular types of flow-induced oscillation but it should be borne in mind that more than one type of instability may occur for particular structures.

4.1 Vortex-induced Oscillations (Isolated Bodies)

4.1.1 Change in natural frequency, stiffness or mass

An increase in the natural frequency* (or dimension D) will cause an increase in the critical flow speed, $\bar{V}_c$, for maximum amplitude oscillations since $\bar{V}_c = n_j D / St$ (where St , the Strouhal number is approximately a constant but depends on body shape and, for rounded bodies, on Reynolds number). Note that although an increase in the diameter of stack will also increase its natural frequency this method will not often be sufficient to put the critical wind speed beyond the range of the maximum design wind speed.

An increase in structural stiffness (and damping) can be obtained using guy wires although this method may not eliminate oscillations completely and may introduce new problems through oscillations of the guys themselves.

The simplest method of reducing ovaling oscillations of shell structures such as stacks is to incorporate stiffening rings near the tip.

An increase in non-structural mass (i.e. a mass which does not change the stiffness of the structure) can be used to decrease the amplitude of oscillation for the following reason. The response is controlled by the balance between the energy input by the flow (which usually increases with increasing $\bar{V}_c$) and the energy absorbed by the structure through damping. This balance can be expressed in terms of the net value of the damping coefficient of the velocity of the motion, $C_s + C_a$ (see Section 7.1), where C_s is the structural damping coefficient and C_a is the fluid-dynamic damping coefficient which is negative when there is an energy input by the flow. An increase in non-structural mass will not change C_s (although it will change δ_s or ζ_s) but the consequent reduction in the natural frequency† will reduce the critical flow speed, $\bar{V}_c$, so that $(-C_a)$ is reduced and the net damping coefficient, $C_s + C_a$, becomes larger resulting in smaller amplitude oscillations. This technique has been used, for example, to reduce oscillations of a tubular railway gantry tower^{H1} and it has also been used to inhibit vibration in pin-jointed tie rods^{J17} by filling them with sand although in this case the sand also increased the damping.

It is important to note that a reduction of natural frequency by increasing the mass may reduce the frequency of a higher mode of oscillation to a value at which the critical flow speed for this mode comes within the

* An increase in n_j can be obtained by increasing the stiffness alone but this should be attempted with caution since the mass will usually be increased also with the net result that there may be no significant change in n_j .

† A reduction of structural stiffness will also reduce the natural frequency but this action is not recommended because of its effects on other instabilities.

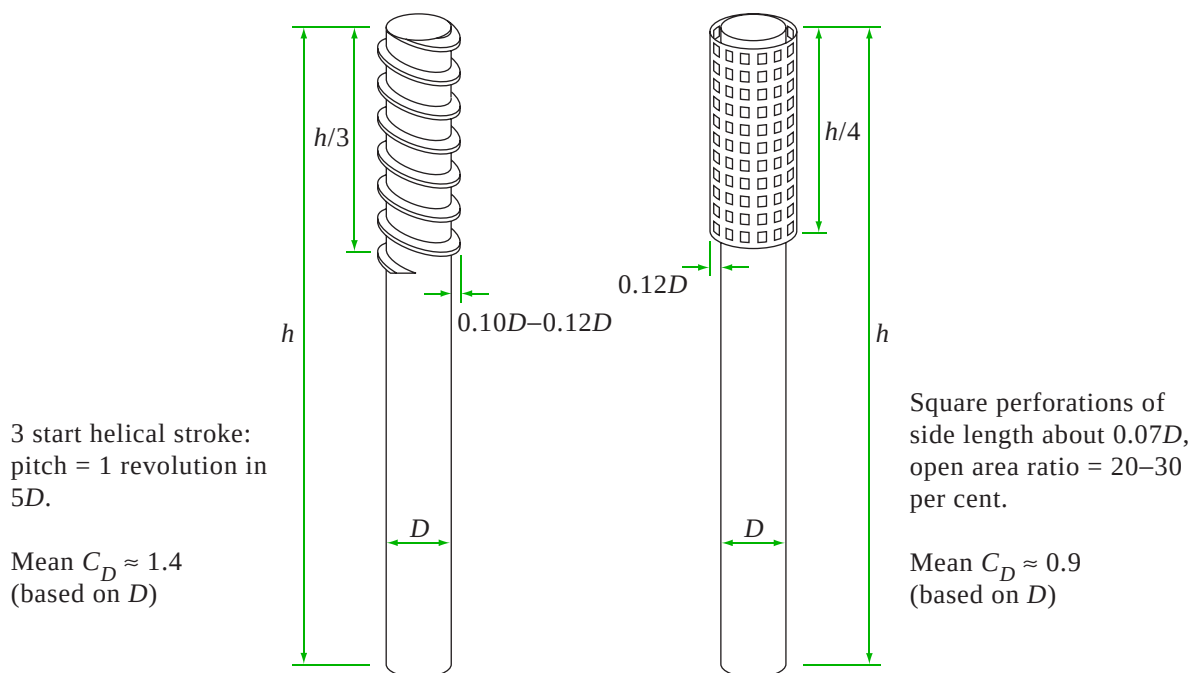
range of flow speeds which the structure will experience. However, if the mass is incorporated at the nodal^{*} point of, say, the second mode, this frequency of oscillation is unaffected and that of the first mode oscillation is reduced^{J9}.

4.1.2 Change of shape, aerodynamic devices

Modifications to the shape are not usually acceptable although there are cases where fairings have been added to make the cross-sectional shape more streamlined; for example, wedge-shaped fairings have been added to box-like cross sections of suspension bridge decks^{G5}. For tower buildings, a decrease in aspect ratio can usually be accompanied by an increase in stiffness and such modifications at the design stage can, in particular, be used to alleviate any problems due to sensitivity of occupants to building oscillations. A decrease in the aspect ratio of a tower to a value less than about 8 will tend to eliminate vortex-induced oscillations.

For some shell-like structures (e.g. a multi-flue stack) perforations in the shell can be conveniently incorporated in the upper 25 per cent of the shell; this reduces the excitation by reducing the strength of the vortex discharge^{C17,J7}. A similar effect is obtained by fitting a perforated shroud to the top 25 per cent of a stack. The perforations must be square and an effective design^{J7} is shown in Sketch 4.1. There is also evidence of an improvement in effluent dispersal when a shroud is fitted^{J9}. Perforated shrouds have also been suggested^{C8,J13} for use on towers of square cross section.

Helical strakes (see Sketch 4.1 for an effective design)^{J5} are widely used in preventing vortex-induced oscillations of steel stacks; they are effective in reducing the correlation of the vortex-induced forces along the upper part of the stack thereby reducing the excitation forces. Note, however, that helical strakes (and shrouds) increase the mean drag forces, thereby increasing the along-wind response to turbulence at the design wind speed.



Sketch 4.1

* A nodal point is a point along a structure at which the oscillation amplitude in a particular mode is always zero.