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Fluctuating response of circular cylinders in small groups in fluid flows – discussion and guide to data available

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(*Continued on inside back cover*)

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FLUCTUATING RESPONSE OF CIRCULAR CYLINDERS IN SMALL GROUPS IN FLUID FLOWS – DISCUSSION AND GUIDE TO DATA AVAILABLE

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FLUCTUATING RESPONSE OF CIRCULAR CYLINDERS IN SMALL GROUPS IN FLUID FLOWS – DISCUSSION AND GUIDE TO DATA AVAILABLE

1. NOTATION AND UNITS

		SI Units
C_D	fluctuating drag coefficient (along flow)	
$\bar{C}_D$	time-mean drag coefficient (along flow)	
C_L	fluctuating side-force or lift coefficient (across flow)	
$\bar{C}_L$	time-mean side-force or lift coefficient (across flow)	
C_{aj}	absolute fluid-mechanic damping coefficient*	kg/s
C_{sj}	absolute structural damping coefficient*	kg/s
D	cylinder diameter	m
H	length of cylinder	m
I_u	turbulence intensity, $\sigma_u/\bar{V}$	
k	cylinder structural stiffness	N/m
${}^rL_u$	length scale of u-component of turbulence, in $r = y$ or z direction	m
m	mass per unit length of cylinder (including any enclosed fluid)	kg/m
m_e	equivalent mass (normal-mode generalised mass per unit length) of cylinder: for oscillation in mode j given by $\left[\int_0^H m\mu_j^2(r)\,\mathrm{d}r\right]/\left[\int_0^H \mu_j^2(r)\mathrm{d}r\right]$; for m uniformly distributed $m_e = m$	kg/m
n_j, n_k	natural vibration frequencies, in modes j and k respectively, of cylinder	Hz
n_s	frequency of shedding of complementary pairs of vortices	Hz
Re	Reynolds number, $\bar{V}D/\nu$	
Re_e	effective Reynolds number, $\lambda_R\lambda_T Re$	
r	distance along cylinder axis	m

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s	distance between cylinder centres (pitch)	m
s_l	along-flow distance between cylinder centres	m
s_t	across-flow distance between cylinder centres	m
St	Strouhal number, $n_s D/\bar{V}$	
$\bar{V}$	mean flow velocity	m/s
V_R	reduced velocity, $\bar{V}/n_j D$ (usually evaluated for $j = 1$)	
x, y, z	distance along $0x$, $0y$, $0z$ orthogonal axes respectively (see Sketch 1.1)	m
δ_x, δ_y	cylinder displacement (vibration amplitude centre to peak) in $0x$ and $0y$ directions respectively	m
α	flow incidence relative to $0x$ direction	degree
$\bar{\alpha}$	power law exponent for flow mean-velocity profile, $\bar{V}_z/\bar{V}_H = (z/H)^{\bar{\alpha}}$	
δ_s	logarithmic decrement of structural damping	
ε	effective roughness height of cylinder surface	m
ζ_s	structural damping ratio ($\approx \delta_s/2\pi$)	
η ; η_t ; η_x ; η_y	non-dimensional oscillation amplitudes: general (non-specific); total $\left(\sqrt{(\eta_x^2 + \eta_y^2)}\right)$; $\delta x/D$ (in $0x$ direction) and $\delta y/D$ (in $0y$ direction) respectively	
λ_R, λ_T	parameters determining effect of surface roughness and turbulence respectively[10, 20]	
$\mu_j(r)$	mode shape parameter for cylinder oscillating in mode j	
ν	fluid kinematic viscosity	m^2/s
ρ	fluid density	kg/m^3
ρ_s	cylinder density, $4m/\pi D^2$	kg/m^3
σ_u	root-mean-square value of longitudinal component of velocity fluctuations due to turbulence in approaching flow	m/s
ϕ	angle between $0x$ axis and line joining cylinder centres	degree

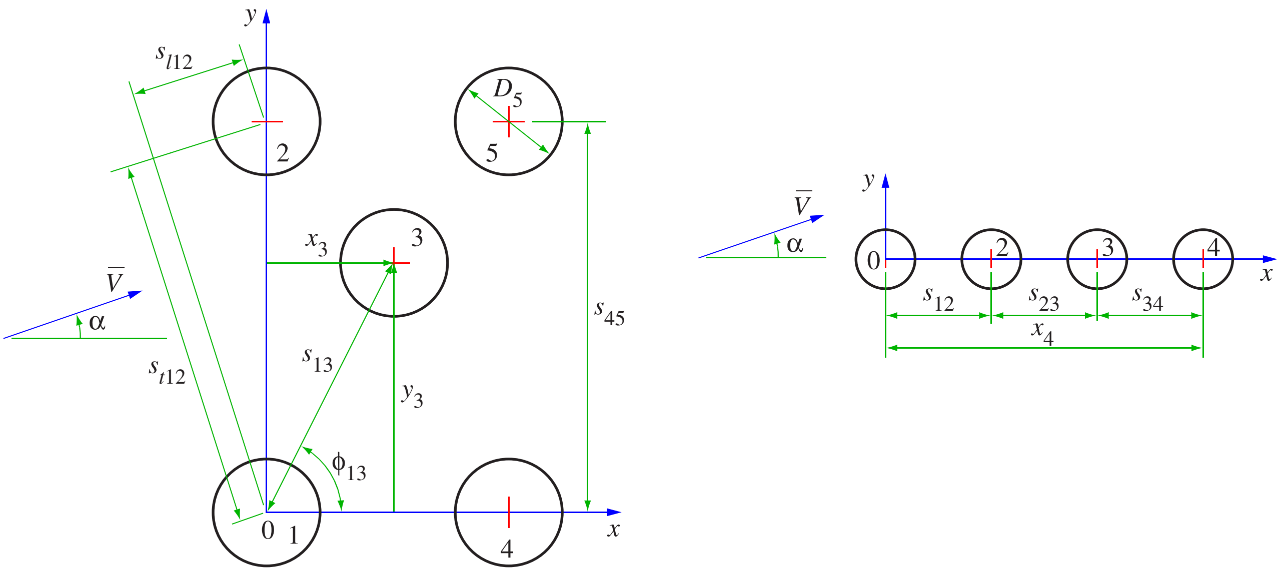
Subscripts

1, 2, 3, N, etc.	appertaining to cylinder number 1, 2, 3, N, etc. (see Sketch 1.1)

12, 13, 23, $1N$, etc.	appertaining to cylinder pairs 1 and 2, 1 and 3, 2 and 3, 1 and N, etc.
$base$	value at base of cantilever cylinder
$crit$	critical value
D	design value
H, r, z	value at locations H, r and z along cylinder
rms	root-mean-square value
tip	value at tip of cantilever cylinder

* See Equation (8) of Reference 20.

The individual cylinders are identified by numbering them in sequence starting with the front row as shown, for example, in Sketch 1.1. In this Item, for a single row of cylinders, $0x$ is always taken along the line of the row as in Sketch 1.1.



Sketch 1.1

2. INTRODUCTION

When two or more bodies or structures are close together in a fluid flow, the flow around any member of the group will usually differ from that around a similar isolated body. This leads to different forces, both time-averaged and fluctuating, on the body in a group compared with those arising when it is isolated and hence to a different response*. This Data Item is concerned with the effects of grouping on the fluctuating response; the effect on the time-averaged, or mean, forces is considered in Reference 36.

* Not always adversely different!

Groupings of circular cylinders occur in situations such as groups of chimney stacks, multiple pipe runs in chemical plant, grouped conductor power lines and tube banks in heat exchangers. This Item is concerned principally with small groups of up to 5 or 6 cylinders and does not specifically cover the tube bank* and power line† cases since these pose special problems resulting from the proximity of large numbers of tubes (and the confining walls) and from the very flexible nature of cables. Some information is, however, given on single and double rows of tubes in ducts. References 9 and 18 review the tube bank case and References 12, 16 and 27 provide an introduction to the grouped power conductor case which is predominantly a wake flutter response.

It is not currently possible to provide correlated data from which the response of a cylinder in a group can be calculated. A designer must consequently resort to an assessment of the most relevant data in the literature and perhaps to model testing. This Item therefore provides in Section 5 a list of "Sources of Data" currently available. Each entry includes a brief tabular summary of configurations covered, flow and structure properties and response data presented, to enable the user to locate appropriate Sources of Data. Where important data are omitted this is also noted. Since it is unlikely that any source will provide data for an exactly matching situation, Section 3.2 of the Item discusses how various parameters affect the response so that the user can assess the importance of differences between values of parameters in the sources and in his application. Such considerations will also be relevant in setting up model tests but References 2, 13, 17 and 20 consider the similarity scaling parameters for model testing in more detail. Section 4 of this Item reviews possible methods of reducing flow-induced oscillations by original design or remedial measures.

3. GENERAL DISCUSSION OF THE RESPONSE OF A CYLINDER IN A GROUP

This Section provides a general discussion of the problem and its relation to the response of an isolated cylinder. Section 3.1 describes the mechanisms causing flow-induced oscillations and characteristics of the response. Section 3.2 discusses the parameters affecting the response of a cylinder in a group with particular reference to the problems of using existing data to predict the response in a new situation.

3.1 Characteristics of Response to Different Forcing Mechanisms and Effects of Interference

A cylinder in a group will be subject to forcing mechanisms similar to those affecting an isolated cylinder but these will be modified by interference and additional forcing mechanisms may exist, caused solely by interference effects. Interference effects may result from:–

(i) direct buffeting of a cylinder by the wake of another,

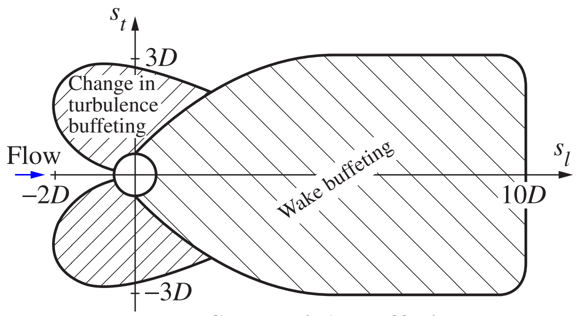
(ii) alteration in the strength and frequency of vortex shedding,

(iii) variations in the quasi-static forces on a cylinder as it oscillates relative to another (leading to wake flutter or wake galloping) and

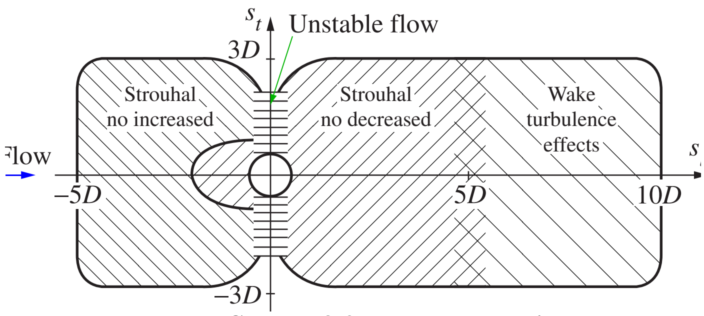
(iv) instability of the flow around one cylinder due to the presence of others (as in the jet switch mechanism).

Interference effects are not confined to a cylinder downstream of another since the flow around any cylinder may be affected by others nearby. Interference may increase or decrease the response compared with the response of an isolated cylinder. The shaded areas in Sketches 3.1 to 3.4 show approximately the regions in which interference effects may influence flow-induced oscillations of a second cylinder placed in the vicinity of the cylinder shown.

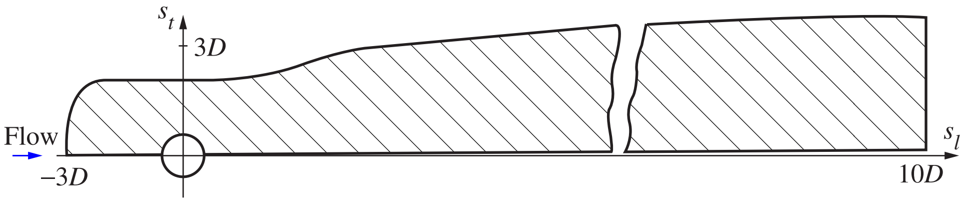
* Separate Data Items covering these topics are proposed.



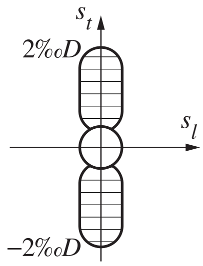
Sketch 3.1 Buffeting



Sketch 3.2 Vortex shedding



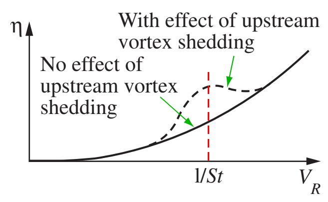
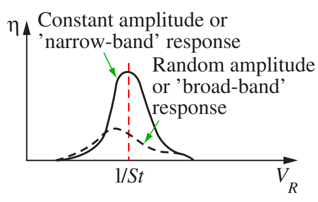
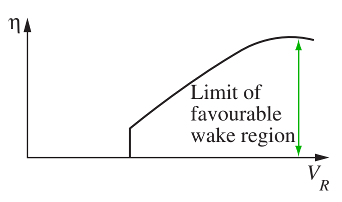
Sketch 3.3 Wake flutter and wake galloping



Sketch 3.4 Jet switch

Although there is often interaction between the various forcing mechanisms and responses, it is useful to consider their separate causes and characteristics separately. Table 3.1 sets out some of the principal characteristics of the response to turbulence and wake buffeting, vortex shedding and wake flutter and wake galloping. Sections 3.1.1 to 3.1.3 discuss these further and Section 3.1.4 considers some possible oscillations arising from flow instabilities. Reference 20 also gives some background discussion of the mechanisms involved.

TABLE 3.1 Characteristics of Response to Particular Forcing Mechanisms

	Turbulence and Wake Buffeting	*Vortex Shedding*	*Wake flutter and Wake Galloping*
Typical Response Curves			
Critical Conditions	If an upstream structure is shedding vortices a hump in the response curve may occur because there is then a dominant fluctuation frequency in the turbulence spectrum.	Response peaks when V_R gives $n_s \approx n_j$, narrow band response may "lock on" to this condition for about $\pm 20\%$ of exact value. For tapered structure $n_s D_r / \bar{V}$ $\approx$ constant along structure, response peaks when $n_s \approx n_j$ at some critical height.	Onset of flutter or galloping when $\bar{V}$ is high enough to provide energy to overcome that dissipated by damping. Occurs only over certain parts of a wake. May require an initiating disturbance in some wake areas, self-starting in others.
Direction of Motion	Along and across flow often of similar magnitudes.	Across flow unless ρ_s/ρ or ζ_s is low when along flow oscillation at a flow velocity corresponding to shedding of individual vortices (i.e. $n_j = 2n_s$) may occur.	Both along and across flow but former usually dominant.
Amplitude Limits	No limit, η increases with increasing $\bar{V}$.	Limited by fluid-elastic feed-back to $\eta \leq 1$.	Limited by areas of wake in which forces of appropriate sign are generated. Confined to one half of wake only. Larger amplitudes possible further downstream where wake is wider.

3.1.1 Turbulence buffeting and wake buffeting

Buffeting is caused by fluctuations in the flow velocity which produce fluctuating forces on a cylinder in that flow. Various factors, including distortion of the turbulence by the cylinder in its vicinity, combine to modify the direct relationship between velocity and force fluctuations. In Reference 19 these distortion effects are accounted for by the use of "turbulence admittance" factors.

If a cylinder is freely exposed to the oncoming turbulent flow, Reference 19 may be used to estimate the along-flow component of turbulence buffeting response. The across-flow component may be calculated by a similar method but turbulence admittance values accounting for the distortion of the lateral component of turbulence are not currently available, although they are likely to be nearer to unity than for the along-flow case.