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Response of structures to galloping excitation

Background and approximate estimation

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Wind Engineering Panel. This Panel, which took over the work on wind engineering previously monitored by the Fluid Mechanics Steering Group, first met in 1979 and now has the following membership:

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Mr T.V. Lawson	—	Bristol University

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Mr C.W. Brown	—	Independent
Prof. J.E. Cermak*	—	Colorado State University, USA
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Dr W. Moores	—	Meteorological Office, UK
Dr G.A. Mowatt	—	Earl and Wright Ltd
Mr J.R.C. Pedersen	—	Independent
Mr R.E. Whitbread	—	BMT Fluid Mechanics Ltd
Mr G. Wiskin	—	British Broadcasting Corporation.

* Corresponding Member

The technical work involved in the assessment of the available information and the construction and subsequent development of the Data Item was undertaken by

Mr B.C. Freeman	—	Senior Engineer.

The person with overall responsibility for the work in this subject area is Mr N. Thompson, Head of the Wind Engineering Group.

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RESPONSE OF STRUCTURES TO GALLOPING EXCITATION BACKGROUND AND APPROXIMATE ESTIMATION

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Background and Approximate Estimation

1. NOTATION AND UNITS

		Units	
		SI	*British*
b	width of front face of structure	m	ft
C_D, C_L	wind-axis force coefficients	–	–
C_F	general force coefficient; (force per unit length)/($\frac{1}{2}\rho V^2 b$)	–	–
C_{FP}, C_{FQ}, C_{FR}	force coefficients in $0P$, $0Q$ and $0R$ directions	–	–
$C_{F_{pk}}$	local peak value of force coefficient (see Section 4)	–	–
F	general aerodynamic force	N	lbf
F_{Qj}	mode-generalised aerodynamic force	N	lbf
H	overall height of vertical structure (see Sketch 1.1)	m	ft
h_c	reference height (see Sketch 1.1)	m	ft
h_0	height above ground of lowest point on structure (see Sketch 1.1)	m	ft
L	structure length, H for vertical structure and W for horizontal structure	m	ft
l	distance along structure (see Sketch 1.1)	m	ft
M_j	overall mode-generalised mass for mode j	kg	*slug
n_j	natural frequency of mode j	Hz	Hz
$0P$, $0Q$, $0R$	system of right-handed rectangular principal structural axes	–	–
Q, $\dot{Q}$	general translational deflection and velocity	m *and* m/s	ft *and* ft/s

For Footnotes, refer to end of Notation Section

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Q_{oj}	general mode-generalised amplitude of motion in mode j	m	ft
P_j, $\dot{P}_j$, $\ddot{P}_j$ Q_j, $\dot{Q}_j$, $\ddot{Q}_j$	mode-generalised deflection, velocity and acceleration respectively for mode j, *i.e.* values at location where $\mu_j = 1$, for translational motion in $0P$ and $0Q$ directions	m, m/s *and* m/s^2	ft, ft/s *and* ft/s^2
p_j, $\dot{p}_j$, $\ddot{p}_j$ q_j, $\dot{q}_j$, $\ddot{q}_j$	deflection, velocity and acceleration respectively at location l on structure for translational motion in $0P$ and $0Q$ directions	m, m/s *and* m/s^2	ft, ft/s *and* ft/s^2
r	distance along $0R$ direction	m	ft
V	hourly-mean wind speed	m/s	ft/s
V_R	relative wind speed, resultant of hourly-mean wind speed and structure velocity	m/s	ft/s
V_z	hourly-mean wind speed at height z above wind-speed profile zero-plane	m/s	ft/s
W	overall length of horizontal structure (see Sketch 1.1)	m	ft
$0x$, $0y$, $0z$	system of right-handed rectangular wind axes with x-axis along mean wind direction and z-axis vertically upwards	–	–
z	height above wind-speed profile zero-plane	m	ft
z_0	terrain roughness parameter	m	ft
ζ_a	aerodynamic damping ratio	–	–
ζ_s	structural damping ratio, expressed as fraction of critical damping	–	–
θ	angular location in oscillation cycle; $2\pi n_j t$	rad	rad
μ_j	mode shape function describing deflected shape of structure in mode j	–	–
ρ	air density	kg/m^3	slug/ft^{3*}
ϕ	flow incidence	rad	rad
ϕ_P	angle between wind direction for which $C_L = 0$ and $0P$ axis (see Sketch A2.1)	rad	rad
$\Delta\phi_{pk}$	location of peak force coefficient relative to mean incidence (see Section 4)	degree†	degree†
$\Delta\phi_z$	location of $C_F = 0$ point relative to mean incidence (see Section 4)	degree†	degree†

For Footnotes, refer to end of Notation Section.

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ϕ_0	angle between mean wind direction at initial equilibrium and $0P$ axis (see Sketch A2.1)	rad	rad
ψ	angle between $0R$-axis of structure and vertical in plane normal to mean wind direction (see Sketch 1.1)	rad	rad

Suffixes

hc	denotes value at height h_c above ground
j	denotes value relating to mode j

* 1 slug = 32.174 lb (pound mass).

† The unit is strictly the radian, but degrees are used for convenience in the calculation method.

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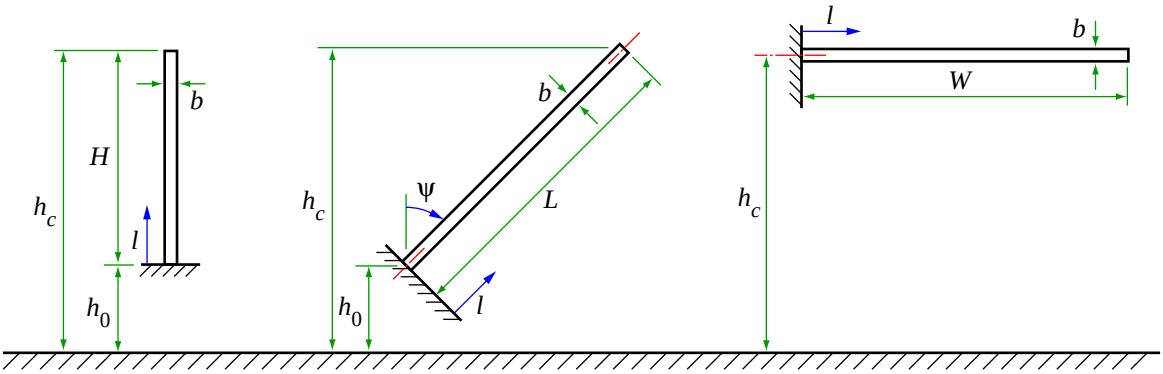
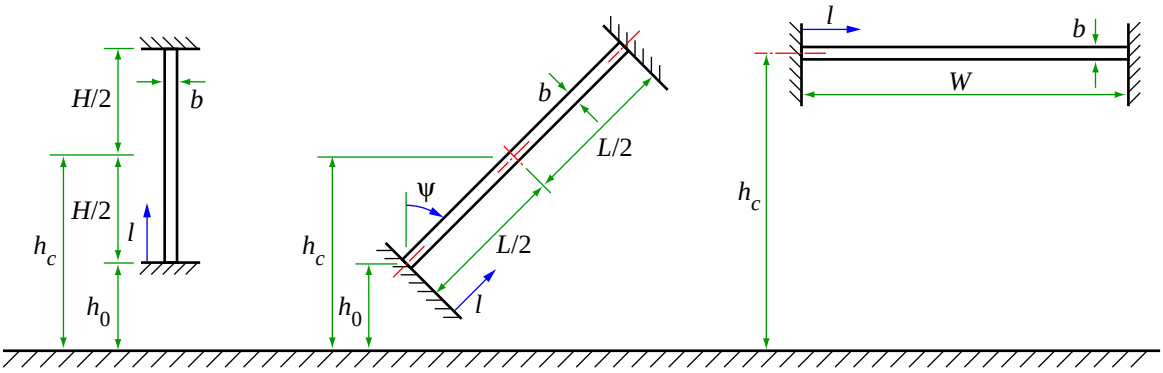
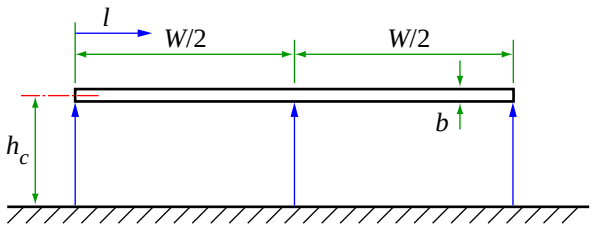


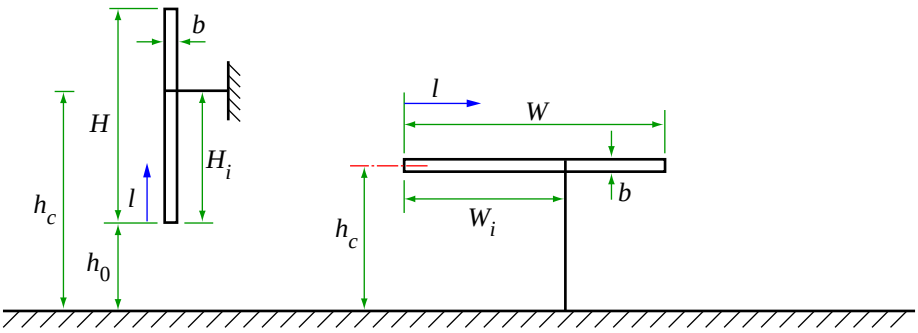
(a) Cantilever structures



(b) Single-span structures



(c) Two-span, bridge-type structures



(d) Single-support structures

Sketch 1.1 Geometrical Parameters

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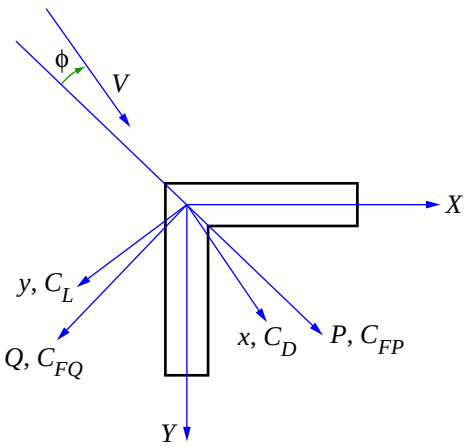
1.1 Axis Systems and Definitions

The wind properties are described in terms of a wind axis system, 0*x*, 0*y*, 0*z* of right-handed Cartesian coordinates. The 0*x* axis is aligned along the mean wind direction and the 0*z* axis is vertically upward.

The structural geometry is often described in terms of a body axis system, 0*X*, 0*Y*, 0*Z*, of right-handed Cartesian co-ordinates. The 0*X* axis will usually be aligned with an axis of symmetry if one exists or along a dominant feature. The 0*Z* axis will often be aligned along the 'long' axis of a structure if one dimension is much larger than the others.

The structural response is more conveniently described in terms of response in normal modes of vibration along the principal axes 0*P*, 0*Q*, 0*R*. These again form a right-handed Cartesian co-ordinate system. This system may coincide with the body-axis system but does not necessarily do so.

Sketch 1.2 shows the systems applied to an equal angle cross-section with the simplifying assumption that 0*z*, 0*Z* and 0*R* are coincident.



Sketch 1.2 Axis systems

1.2 Force Coefficients

Force coefficients in the wind axis system are the drag coefficient, C_D, along the 0*x* direction and the lift or across-wind coefficient C_L in the 0*y* or 0*z* direction depending on whether the structure is predominantly vertical or horizontal.

In the present Item the wind incidence is taken as the angle between the 0*x* axis projected onto the 0*PQ* plane and the 0*P* axis, positive in the sense of clockwise rotation of the wind about the 0*R* axis. Zero incidence is defined as a condition for which $C_L = 0$. There may be more than one condition for which this occurs, each effectively defining a different structural system and care should be taken to use a consistent value throughout. In the particular case in Sketch 1.2, zero incidence could be taken along 0*P* (as shown) or along – 0*P*, for example.

Care should be taken that data used for force coefficients conforms to the sign convention shown. In particular, the convention of C_L opposite to that shown is often used elsewhere.

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2. INTRODUCTION

Galloping is an aeroelastic response mechanism in which the fluid-dynamic loading results from the velocity of motion of the structure.

Galloping can affect lightly-damped, flexible structures or elements such as lighting standards, cables and stays of both circular and non-circular cross section. It is unlikely to be a problem for conventional buildings but can affect less rigid or lightly-damped rectangular-sectioned towers and structural elements.

Section 3 of this Item provides background to the phenomenon of galloping and the basis for its analysis. Brief mention is included of other aeroelastic phenomena such as classical flutter.

Section 4 provides a simplified method of analysis of galloping response of structures with force coefficient variations representative of sharp-edged sections. Consideration is given firstly to assessment of the potential for galloping and secondly the estimation of approximate response amplitudes. The method is also implemented for more general force coefficient variation in a computer program in Reference 6.

Since galloping response is usually undesirable, Section 5 outlines methods of reducing or eliminating it.

Section 6 provides a worked example of the application of the method in Section 4.

The basis of the analysis for the method is given in Appendix A and that specific to the simplified methods of Section 4, in Appendix B.

The analysis in this Item (in common with that widely used elsewhere) assumes that the flow is quasi steady, *i.e.* the wind loading can be determined from the instantaneous effective incidence and relative wind speed using mean force coefficient characteristics. Typically this is valid if $n_j b/V$ is less than about 0.1. For higher frequency parameter the effects of vortex shedding, which produces peak responses for $n_j b/V$ of around 0.15 to 0.25, will lead to variation in the mean loading also. At still higher values, around 0.5 to 1, the flow distribution may lag behind the appropriate condition for the instantaneous incidence*. If sufficient information were available the general method could be modified to include this time lag.

* This can lead to across-wind galloping of circular sections since the wind load then has a lateral component

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