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Calculation methods for along-wind loading Part 2: response of line-like structures to atmospheric turbulence

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item, which supersedes in part ESDU 76001, 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 C. Scruton	— Independent
Mr R.E. Whitbread	— British Maritime Technology 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.

CALCULATION METHODS FOR ALONG-WIND LOADING Part 2: response of line-like structures to atmospheric turbulence

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CALCULATION METHODS FOR ALONG-WIND LOADING Part 2: response of line-like structures to atmospheric turbulence

1. NOTATION AND UNITS

		Units	
		SI	British
B_B, B_R^2	admittance factors accounting for departures from idealised response model (see Derivation 13)	—	—
b	effective width of line-like structure; equal to diameter for circular sections, overall width normal to both wind and long axis for solid sections, overall width $\times$ solidity ratio for lattice sections	m	ft
C_{Dm}	average drag coefficient (see Section 5.4); $C_{Dm} = \text{total drag} / (\frac{1}{2}\rho V_{hc}^2 bL)$	—	—
C_{Dr}	local drag coefficient (see Section 5.4); $C_{Dr} = (\text{drag per unit at } r) / (\frac{1}{2}\rho V_r^2 b_r)$	—	—
d	displacement height of wind speed profile zero-plane (see Section 5.5)	m	ft
E_{mean}	overall mean load effect, $E_{mean} = \int_0^L \frac{1}{2}\rho V_r^2 C_{Dr} b_r \beta_r dr$	*	*
F_j	mean mode-generalised force, $F_j = \int_0^L \frac{1}{2}\rho V_r^2 C_{Dr} b_r \mu_{jr} dr$	N	lbf
E_{ref}	reference mean load effect [†] , $E_{ref} = \int_0^L \frac{1}{2}\rho V_r^2 C_{Dr} b_r \beta_r dr$	*	*
g_B, g_R	peak response factors for background and resonant component respectively (see Derivation 13)	—	—
H	overall height of structure	m	ft
H_i	distance along vertical structure at which load effect is required	m	ft
h_c	height above ground of location at which $\mu_1 = 1$	m	ft
h_0	height above ground of lowest point on structure	m	ft
I_u	turbulence intensity of along-wind component of turbulence at height h_c ; $I_u = (\sigma_u/V_z)$	—	—
I_1	integral parameter; $I_1 = \int_0^1 m_r \mu_{1r} d(r/L)$	kg/m	[‡] slug/ft
I_2	integral parameter; $I_2 = \int_0^1 m_r \mu_{jr} \beta_r d(r/L)$	*	*
J_B	normalised background loading factor	—	—

For footnotes see end of the Notation Table.

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J_R^2	normalised resonant loading factor at frequency n_j	—	—
K_V^2	mean wind speed factor; $K_V^2 = \int_0^1 (V_z/V_{hc})^2 d(z/H)$	—	—
K_ζ	aerodynamic damping factor (see Table 4.1 and Appendix A)	—	—
L	length of line-like structure along its long axis; H for vertical structures, W for horizontal structures	m	ft
L_i	distance along structure at which load effect is required; H_i for vertical structures, W_i for horizontal structures	m	ft
$^x L_u$	integral length scale of along-wind component of turbulence, measured in along-wind, x , direction at height h_c	m	ft
$^y L_u, ^z L_u$	integral length scales of along-wind component of turbulence, measured in y and z directions at height h_c	m	ft
m	total mass per unit length of structure (see Section 5.1)	kg/m	$\ddagger$ slug/ft
m_{ej}	equivalent mass per unit length for mode j (see Section 5.1)	kg/m	$\ddagger$ slug/ft
m_j	mode-generalised mass per unit length for mode j (see Section 5.1)	kg/m	$\ddagger$ slug/ft
N_1, N_2	parameters in mode shape functions (see Table 6.1)	—	—
n_j	natural frequency of mode j	Hz	Hz
R_j	reference mode-generalised force **, $R_j = \int_0^L \frac{1}{2} \rho V_r^2 C_{Dr} b_r \mu_{jr} dr$	N	lbf
r	general dimension along axis of structure; y for horizontal structures and $z + d - h_0$ for vertical structures	m	ft
S_{FjFj}	mode-generalised force spectral density for mode j at frequency n_j	N ² /Hz	lbf ² /Hz
S_{uu}	mode-generalised spectral density of along-wind turbulence component at frequency n_j	m ² /s ² Hz	ft ² /s ² Hz
V	hourly-mean wind speed	m/s	ft/s
V_m	average hourly-mean wind speed; $V_m^2 = K_V^2 V_{hc}^2$	m/s	ft/s
W	overall width of structure	m	ft
x, y, z	system of rectangular cartesian co-ordinates with x -axis defined in mean wind direction and z -axis vertical, upwards	—	—
z	height above velocity profile zero plane (see Section 5.5)	m	ft

For footnotes see end of the Notation Table.

z_0	ground roughness parameter	m	ft
β	influence function (see Section 5.2 and Table 6.2)	*	*
ζ_a, ζ_s	aerodynamic and structural damping, expressed as fractions of critical damping (see Appendix A and Section 5.3)	—	—
μ_j	mode shape function describing deflected shape of structure in mode j (see Section 5.1 and Table 6.1)	—	—
ρ	air density	kg/m ³	‡slug/ft ³
σ_E	standard deviation of fluctuating load effect	*	*
σ_X	standard deviation of displacement at location where $\mu_j = 1$	m	ft
$\sigma_{\ddot{X}}$	standard deviation of acceleration at location where $\mu_j = 1$; $\sigma_{\ddot{X}} = (2\pi n_j)^2 \sigma_X$	m/s ²	ft/s ²
σ_x	standard deviation of displacement at location r ; $\sigma_x = \mu_{jr} \sigma_X$	m	ft
σ_u	standard deviation of along-wind component of turbulence	m/s	ft/s
ϕ_{uu}	normalised spectral function of along-wind component of turbulence at frequency n_j and height h_c ; $\phi_{uu} = n_j S_{uu} / \sigma_u^2$	—	—
ψ	angle between axis of structure and vertical, in plane normal to mean wind direction	degree	degree

Suffixes

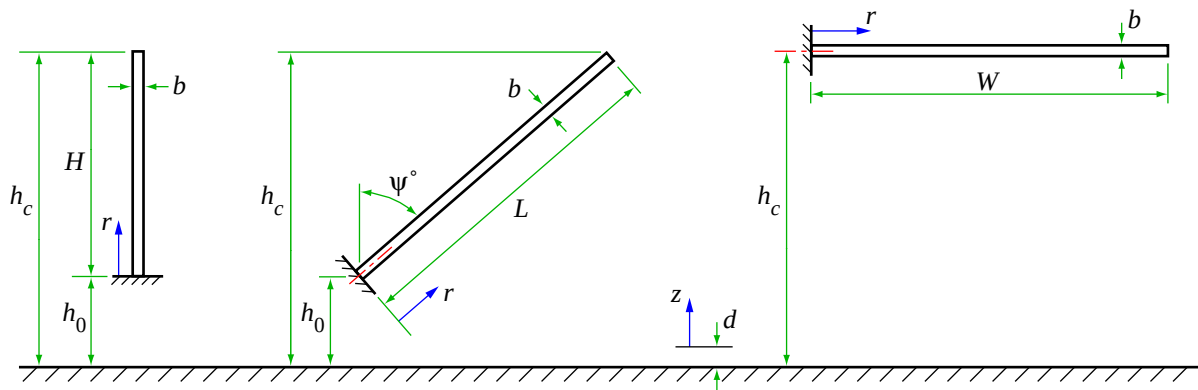
B	denotes quantity relating to non-resonant (or background) component
hc	denotes value at height h_c
$j, 1, 2$	denote values relating to general mode j and first and second modes
max	denotes expected maximum value
R	denotes quantity relating to resonant component
$r, r'; y, y'$ z, z'	denote values at locations r and r' , y and y' , and z and z' along structure
rms	denotes root mean square value

* Units depend on load effect considered.

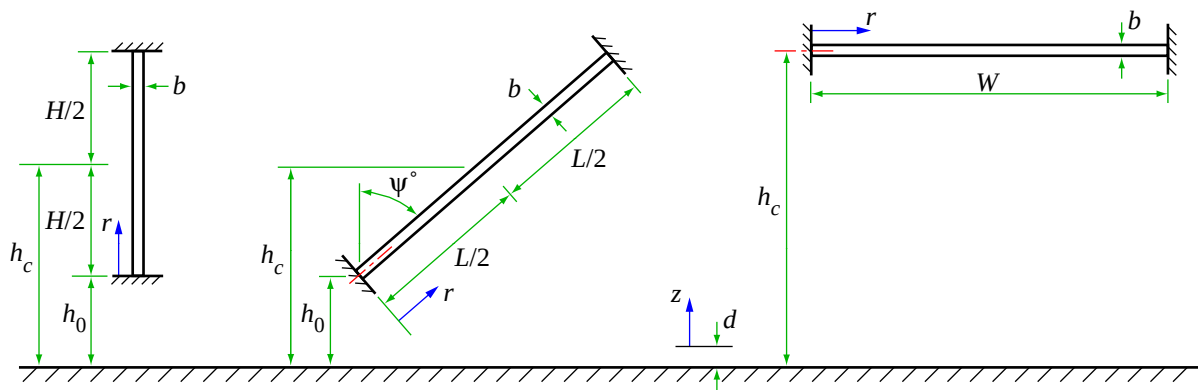
† The notation $|\beta_r|$ denotes the modulus or absolute value of β_r .

‡ 1 slug = 32.174 lb (pounds mass).

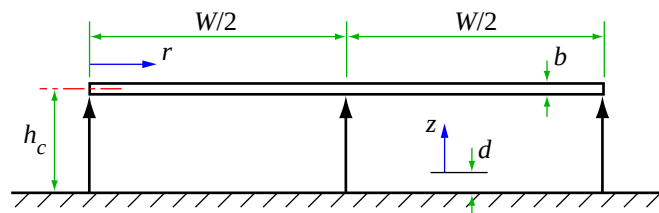
** The notation $|\mu_{jr}|$ denotes the modulus or absolute value of μ_{jr} .



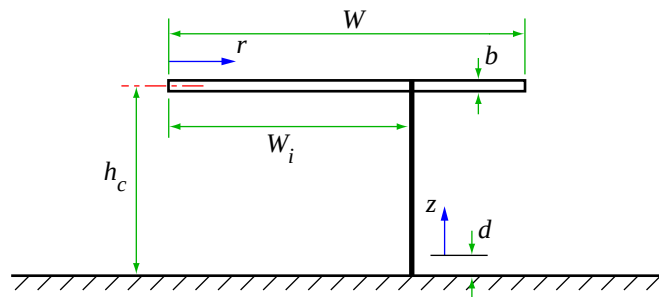
(a) Cantilever structures



(b) Structural members



(c) Two-span, bridge-type structures



(d) Structure on single support

Sketch 1.1 Geometrical parameters

2. INTRODUCTION

This Item is one of a group concerned with methods of calculating the along-wind loading and response of structures in the natural wind. Part 1 (Derivation 13) provides a background discussion of methods of calculation and their implementation. Part 2 (this Item) provides a calculation procedure for the along-wind loading or response of line-like structures and Part 3 (Reference 7) provides corresponding procedures for prismatic or plate-like structures. These three parts together supersede ESDU 76001. The principal change is to incorporate the updated wind properties given in Derivations 9, 10 and 12.

The along-wind loading or response of a structure in the natural wind can be expressed in terms of a mean component, due to the hourly-mean wind speed, and a fluctuating component, due to the turbulent fluctuations in wind speed about that mean. A full dynamic analysis for the fluctuating component is time-consuming but for most practical cases it can be replaced by an approximate method which treats the fluctuating response as the sum of a background (quasi-static) component and separate resonant components for each mode. This method is outlined in Derivation 13 and is described in more detail in Reference 2. It forms the basis of the calculation methods in this Item where it is further simplified by provision of precalculated loading factors for a range of wind and structure properties.

An alternative, more approximate, approach is the gust method in which dynamic effects are ignored and a gust of an appropriate duration (dependent on the size of the structure) is assumed to act on the whole structure at a given time. The overall loading is then calculated on a quasi-static basis using the gust speed and gust velocity profile instead of hourly-mean values. This method is appropriate only for structures for which the resonant component of response is negligible and is used for certain classes of structure in some national Codes of Practice. This method is discussed further in Derivation 13.

Section 4 of the present Item gives a step-by-step method for calculating the along-wind loading or response, in terms of a mean component and rms fluctuating components. With the assumption that the fluctuating wind speed and the response to it are stationary random processes with normal (Gaussian) probability distributions, extreme values of the loading or response are then estimated for design purposes. The normalised loading factors required in the method are presented graphically and in equation form. The required input data are discussed in Section 5. Section 8 gives worked examples of the application of the method.

The overall response of an isolated structure in the wind is the result of several causes. The mean drag force causes a nominally steady along-wind loading and deflection; vortex shedding may lead to a fluctuating across-flow response and along-wind and across-wind turbulence components cause corresponding fluctuating responses. Vortex shedding also applies an along-wind loading but for typical structures in the natural wind this is usually small compared with the loading applied by the other causes mentioned. These various contributions are discussed in general terms in Reference 2. Calculation methods are considered in separate Items but the overall response is considered briefly in Derivation 13.

3. APPLICABILITY AND LIMITATIONS

The application of this Data Item is to single, isolated line-like structures of circular or non-circular cross section in the atmospheric wind. Such structures include chimney stacks, solid and lattice towers and masts, suspended pipelines and structural members such as tie rods. Only fundamental and some second mode responses are covered by the data presented but the method could be applied more generally by integration of the appropriate equations in Appendix A.

Interference between structures in groups may modify the buffeting response but this effect is not considered here.

The ranges of parameters covered by the data used to generate Figures 2 and 3 are given in Appendix A. The curves in this Item reproduce the calculated background loading factor, J_B , to within about ± 10 per cent over a practical range of parameters. The resonant loading factor, J_R , is reproduced to within about ± 20 per cent. This would allow the overall predicted response to be estimated to within about ± 10 per cent in the absence of other errors. However, there are few data on which to base the turbulence admittance factors (B_B and B_R) and their uncertainty cannot be reliably assessed. The uncertainty of the calculated response is also influenced considerably by the likely uncertainty in the input data, which cannot be quantified here.

For heights below about $1.5 \times d$ the wind properties, especially wind speed and direction, are subject to strong local effects. For structures which are wholly or largely below this height, results obtained from this Item should be applied with caution unless derived with wind data specific to the location considered.

4. CALCULATION PROCEDURES FOR ALONG-WIND LOAD EFFECT OR RESPONSE

Graph-based calculation procedures are given here, together with a Calculation Sheet on which the results may be recorded for vertical or horizontal structures. Equations for the curves are given in Appendix B and a computer program version (superseding ESDU 84034) is available in Reference 8. Background to the method is given in Appendix A. The input data are discussed in Section 5 and approximate values for some parameters are given in Section 6.

4.1 Parallel-sided Vertical or Horizontal Structures

4.1.1 Determine the input data

(1) The following input data are required:

L	length of structure (H for vertical structures, W for horizontal structures)
b	width of structure normal to wind and long axis (for lattice structures, b = structure width $\times$ lattice solidity ratio)
L_i	location at which load effect is required or at which torsion axis is located
m	mass distribution (Section 5.1)
n_j	natural frequency (Sections 5.1 and 6.1)
μ_j	mode shape function (Section 5.1 and Tables* 6.1 and 6.3)
β	influence function (Section 5.2 and Table 6.2; for displacement or acceleration use $\beta = 1$)
ζ_s	structural damping (Section 5.3 and Table 6.4)
C_D	drag coefficient (Section 5.4)
h_c	[†] reference height (Sketch 1.1)
z_0	[†] ground roughness at site and upwind (Section 5.5)
d	[†] displacement height of wind-speed profile zero plane (Section 5.5)
V_{hc}	hourly-mean wind speed at height h_c
I_u	turbulence intensity at height h_c
^xL_u and ^yL_u or ^zL_u	turbulence length scales at height h_c
V_z -vs- z	hourly-mean wind-speed profile

for each case
(Section 5.5)

* If measured or calculated mode shapes are available those should be used. If mode shapes from Table 6.1 are used and m is constant along the structure, the required mode shape integrals may be taken from Table 6.3.

[†] These data are required in the calculation of the wind properties (Section 5.5)

Use x - and z -direction length scales for vertical structures, x - and y -direction length scales for horizontal structures.

The buffeting response will usually be required for several of wind speeds, including the design wind speed and wind speeds corresponding to serviceability criteria, and the calculations in Sections 4.1.2 to 4.1.4 should be carried out for each value of V_{hc} .

If accelerations only are required, Steps (3) to (6) may be ignored as usually only the resonant component contributes significantly. Continue at Step (7).

- (2) Calculate the mode-generalised mass from

$$m_j = \int_0^1 m_r \mu_{jr}^2 d(r/L).$$

4.1.2 Calculate the mean component of response

- (3) Calculate the mean load effect or the mean deflection as appropriate.

Calculate the mean load effect from

$$E_{mean} = \int_0^L \frac{1}{2} \rho V_r^2 C_{Dr} b_r \beta_r dr = L \times \int_0^1 \frac{1}{2} \rho V_r^2 C_{Dr} b_r \beta_r d(r/L)$$

(Where C_{Dr} is a local drag coefficient at location r) or, assuming constant width and C_D along the structure, from*

$$E_{mean} = \frac{1}{2} \rho V_{hc}^2 C_{Dm} b L \int_0^1 (V_r/V_{hc})^2 \beta_r d(r/L)$$

where C_{Dm} is an appropriate mean drag coefficient. For cantilever structures, if the load effect is required for $L_i \neq 0$, the integration limits should be taken from L_i to L (or L_i/L to 1) only.

For deflections, calculate the mean mode-generalised force from

$$F_j = \int_0^L \frac{1}{2} \rho V_r^2 C_{Dr} \mu_{jr} dr = L \times \int_0^1 \frac{1}{2} \rho V_r^2 C_{Dr} b_r \mu_{jr} d(r/L)$$

or, assuming constant width and C_D along the structure, from*

$$F_j = \frac{1}{2} \rho V_r^2 C_{Dm} b L \int_0^1 (V_r/V_{hc})^2 \mu_{jr} d(r/L).$$

The mean deflection is given by

$$X_{jmean} = \frac{F_j}{(2\pi n_j)^2 m_j L}.$$

For deflections, repeat Step (3) for a second mode response ($j = 2$) if required.

* For $\beta_r = 1$, the integral reduces to $\int_0^1 (V_r/V_{hc})^2 d(r/L) = K_V^2$ which may be obtained from Figure 1. If integration is necessary a Simpson's rule approximation will usually be adequate.

4.1.3 Calculate the background or non-resonant component

- (4) Calculate the reference mean load effect from

$$E_{ref} = \int_0^L \frac{1}{2} \rho V_r^2 C_{Dr} b_r |\beta_r| dr = L \times \int_0^1 \frac{1}{2} \rho V_r^2 C_{Dr} b_r |\beta_r| d(r/L)$$

or, assuming constant width and C_D along the structure, from

$$E_{ref} = \frac{1}{2} \rho V_{hc}^2 C_{Dm} b L \int_0^1 (V_r/V_{hc})^2 |\beta_r| d(r/L)$$

where $|\beta_r|$ denotes the modulus or absolute value* of β_r . If β_r is always positive, as is usual except for torsional moments, $E_{ref} = E_{mean}$. For cantilever structures, if the load is required for $L_i \neq 0$, the integration limits should be taken from L_i to L (or L_i/L to 1) only.

- (5) Calculate H/L_u for vertical structures or W/L_u for horizontal structures and determine the normalised non-resonant loading factor, J_B , from the appropriate part of Figure 2.
- (6) Calculate the rms non-resonant component of load effect from

$$\sigma_{E,B} = E_{ref} \times 2 B_B I_u (1 + 0.5 I_u) J_B.$$

where the turbulence admittance factor, B_B , is approximately 0.95 (Figure 5).

If the deflection response is required, calculate $\sigma_{E,B}$ for $\beta = 1.0$ and the integral parameter I_1 from

$$I_1 = \int_0^1 m_r \mu_{1r} d(r/L).$$

Hence calculate the non-resonant contribution to the deflection, evaluated¹³ as a mode-generalised deflection in mode 1, from

$$\sigma_{X,B} = \frac{\sigma_{E,B}}{4\pi^2 n_1^2 I_1 L}.$$

4.1.4 Calculate the resonant component

- (7) Calculate the reference mode-generalised force from

$$R_j = \int_0^L \frac{1}{2} \rho V_r^2 C_{Dr} b_r |\mu_{jr}| dr = L \times \int_0^1 \frac{1}{2} \rho V_r^2 C_{Dr} b_r |\mu_{jr}| d(r/L)$$

* If β has both positive and negative values, the mean load effect, E_{mean} , can become very small or even zero, leading to computational difficulties in the evaluation of J_B . Use of $|\beta_r|$ in E_{ref} avoids this problem.

or, assuming constant width and C_D along the structure, from

$$R_j = \frac{1}{2} \rho V_{hc}^2 C_{Dm} b L \int_0^1 (V_r/V_{hc})^2 |\mu_{jr}| d(r/L)$$

where $|\mu_{jr}|$ denotes the modulus or absolute value* of μ_{jr} . If μ_{jr} is always positive, as is usual except for torsional modes, $R_j = F_j$.

- (8) Calculate $n_j L/V_{hc}$ and determine the normalised resonant loading factor, J_R^2 , from the appropriate part of Figure 3.
- (9) Calculate $n_j^x L_u/V_{hc}$ and determine the corresponding normalised spectral function, ϕ_{uu} , from Figure 4.
- (10) Calculate $n_j b/V_{hc}$ and determine the turbulence factor, B_R^2 from Figure 6.
- (11) Evaluate the spectral function of the resonant loading from

$$n_j S_{FjFj} = R_j^2 \times 4 B_R^2 I_u^2 J_R^2 \phi_{uu}.$$

- (12) Calculate the aerodynamic damping from

$$\zeta_a = \frac{R_j \times K_\zeta}{2\pi n_j m_j L V_{hc}}$$

where K_ζ is given by Table 4.1 on page 13 as $K_{\zeta H}$ for vertical structures and as $K_{\zeta W}$ for horizontal structures and m_j is given by Step (2).

- (13) For load effects calculate the resonant contribution from ¹³

$$\sigma_{E,R}\{j\} = \sqrt{\frac{\pi n_j S_{FjFj}}{4(\zeta_s + \zeta_a)}} \frac{I_2}{m_j}$$

where $I_2 = \int_0^1 m_r \mu_{jr} \beta_r d(r/L)$.

For deflections, calculate the mode-generalised deflection from

$$\sigma_{X,R}\{j\} = \sqrt{\frac{\pi n_j S_{FjFj}}{4(\zeta_s + \zeta_a)}} \frac{1}{(2\pi n_j)^2 m_j L}.$$

For accelerations, calculate the mode-generalised acceleration from

$$\sigma_{\ddot{X},R}\{j\} = \sqrt{\frac{\pi n_j S_{FjFj}}{4(\zeta_s + \zeta_a)}} \frac{1}{m_j L}.$$

* If μ has both positive and negative values, the mode-generalised force based on μ_{jr} can become very small or even zero, leading to computational difficulties in the evaluation of J_R^2 . Use of $|\mu_{jr}|$ in R_j avoids this problem.

Repeat Steps (9) to (13) for a second mode response ($j = 2$) if required.

4.1.5 Estimate overall along-wind response

(14) The overall along-wind rms load effect is given by

$$\sigma_E = \sqrt{\sigma_{E,B}^2 + \sum_j (\sigma_{E,R\{j\}})^2}$$

where the contributions are taken at the same wind speed.

The overall along-wind expected maximum load effect is given by

$$E_{max} = E_{mean} + \sqrt{(g_B \sigma_{E,B})^2 + \sum_j (g_R \sigma_{E,R\{j\}})^2},$$

where $g_B \approx 3.5$ and $g_R \approx \sqrt{2 \ln(n_j T_o)} + \frac{0.577}{\sqrt{2 \ln(n_j T_o)}}$ (4.1)

and T_o is usually taken as 3600 seconds.

The overall along-wind rms deflection response at location r is given by

$$\sigma_X = \sqrt{(\mu_{1r} \sigma_{X,B})^2 + \sum_j (\mu_{jr} \sigma_{X,R\{j\}})^2}$$

where the contributions are taken at the same wind speed.

The overall along-wind expected maximum deflection is given by

$$x_{max} = \sum_j \mu_{jr} X_{jmean} + \sqrt{(g_B \mu_{1r} \sigma_{X,B})^2 + \sum_j (g_R \mu_{jr} \sigma_{X,R\{j\}})^2}$$

where $g_B \approx 3.5$ and g_R is given by Equation (4.1).

The overall along-wind rms acceleration at location r is given by

$$\sigma_{\ddot{x}} = \sqrt{\sum_j (\mu_{jr} \sigma_{\ddot{x},R\{j\}})^2}.$$

The overall along-wind expected maximum acceleration is given by

$$\ddot{x}_{max} = \sqrt{\sum_j (g_R \mu_{jr} \sigma_{\ddot{x},R\{j\}})^2}$$

where g_R is given by Equation (4.1).

4.2 Structures of Varying Width or Cross Section

Many structures are non-uniform in width or cross section. For example, stacks may be tapered or fitted with strakes or shrouds over part length, the solidity of lattice structures may vary and towers or masts may have step changes in section.

As a reasonable approximation it may be assumed that the method can be applied to structures of these types by amending Steps (3), (4) and (9) of the calculation procedure. The appropriate overall mean load effect, reference mean load effect and reference mode-generalised force should be evaluated by including the appropriate variations in V_r , C_{Dr} and b_r within the integrals giving E_{mean} , E_{ref} , F_j and R_j .

4.3 Inclined Structures

For structures which are normal to the mean wind direction but inclined in the y - z across-wind plane, the calculation procedure should be modified as follows¹³.

Step (1) The basic input data will be required together with the structure inclination to the vertical, ψ . Both ^yL_u and ^zL_u are required.

$$\text{Calculate } ^rL_u = \sqrt{(^zL_u \cos \psi)^2 + (^yL_u \sin \psi)^2}.$$

Step (5) Calculate $L/^rL_u$ and interpolate J_B between the curve for vertical structures and the curve for horizontal structures on the appropriate Figure 2.

Step (6) Calculate $\sigma_{E,B} = E_{ref} \times 2B_B I_u (1 + 0.5I_u) J_B$.

Step (8) Calculate $n_j L/V_{hc}$ and interpolate J_R^2 between the curve for vertical structures and the curve for horizontal structures on the appropriate Figure 3.

Step (10) Calculate $n_j b/V_{hc}$ and determine B_R^2 from Figure 6. If b_r varies an average value should be taken for b .

Step (11) Calculate $n_j S_{FjFj} = R_j^2 \times 4B_R^2 I_u^2 J_R^2 \phi_{uu}$.

Step (12) Calculate $\zeta_a = \frac{R_j}{2\pi n_j m_j L V_{hc}} (K_{\zeta H} \cos^2 \psi + K_{\zeta W} \sin^2 \psi)$

where $K_{\zeta H}$ and $K_{\zeta W}$ are the appropriate values of K_ζ for vertical structures and horizontal structures respectively, from Table 4.1.

TABLE 4.1

Mode Shape								
Cantilever, first mode, $\mu_1 = (r/L)^{N_1}$	Vertical	N_1	1.0	1.5	2.0	2.5		
	Horizontal	$K_{\zeta H}$	0.71	0.67	0.64	0.62		
Cantilever, second mode, $\mu_2 = (r/L)(N_2 r/L - N_2 + 1)$	Vertical	N_2	3	4	5			
	Horizontal	$K_{\zeta W}$	0.54	0.62	0.77			
Structural member, first mode, pinned or clamped ends	Vertical	$K_{\zeta H}$	0.78					
	Horizontal	$K_{\zeta W}$	0.78					
Structural member, second mode, pinned ends	Vertical	$K_{\zeta H}$	0.80					
	Horizontal	$K_{\zeta W}$	0.78					
Two-span bridge-type structures	Horizontal	$K_{\zeta W}$	0.78					
Torsion mode	Horizontal	W_i/W	0.5	0.6	0.7	0.8	0.9	1.0
		$K_{\zeta W}$	0.66	0.59	0.61	0.64	0.66	0.67

4.4 Calculation Sheet for Estimation of Along-wind Buffeting Response of Vertical or Horizontal Line-like Structures

TABLE 4.2

(1)	$L = H \text{ or } W$	m	(4)	n_j	Hz	(6)	ζ_s
(2)	b	m	(5)	μ_j		(7a)	β
(3)	$H_i \text{ or } W_i$	m					
(8a)*	$\int_0^1 (V_z/V_{hc})^2 \beta_r d(r/L)$						
(8b)*	$\int_0^1 (V_z/V_{hc})^2 \beta_r d(r/L)$						
(9a)*	$\int_0^1 (V_z/V_{hc})^2 \mu_{jr} d(r/L)$						
(9b)*	$\int_0^1 (V_z/V_{hc})^2 \mu_{jr} d(r/L)$						
(10)†	$m_j \text{ (Section 5.2)} = \int_0^1 m_r \mu_{jr}^2 d(r/L) \text{ kg/m}$						
(11)	V_{hc}	m/s					
(12)	I_u						
(13a)	$^x L_u$	m					
(13b)	$^z L_u \text{ or } ^y L_u$	m					
(14)	C_{Dm}						
(15)‡	$E_{mean} = \frac{1}{2} \rho \times (11)^2 \times (14) \times (2) \times (1) \times (8a)$						
(16)‡†	$F_j = \frac{1}{2} \rho \times (11)^2 \times (14) \times (2) \times (1) \times (9a)$						
(17)‡†	$X_{jmean} = (16) / [4\pi^2 \times (4)^2 \times (10) \times (1)]$						
(18)	$E_{ref} = \frac{1}{2} \rho \times (11)^2 \times (14) \times (2) \times (1) \times (8b)$						
(19)	$H/{}^z L_u \text{ or } W/{}^y L_u = (1)/(13b)$						
(20)	J_B (Figure 2) for (19) and β function						
(21)	B_B (Figure 5) (≈ 0.95)						
(22)	$\sigma_{E,B} = 2 \times (18) \times (20) \times (12) \times (21) \times [1 + 0.5 \times (12)]$						
(23)‡	$I_1 = \int_0^1 m_r \mu_{jr} d(r/L)$						
(24)‡	$\sigma_{X,B} = (22) / [4\pi^2 \times n_1^2 \times (23) \times (1)]$						

(continued)

* If β is always positive, (8b) = (8a) and if μ is always positive, (9b) = (9a). If response is required for $L_i > 0$ on cantilever structures, the limits should be replaced by L_i/L to 1 in Steps (8a) and (8b).

† Repeat these steps for second mode contributions if required.

‡ Select steps appropriate to required response.