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Damping of structures
Part 1: tall buildings

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DAMPING OF STRUCTURES
Part 1: tall buildings

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DAMPING OF STRUCTURES
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1. NOTATION AND UNITS

Any consistent system of units may be used.

		SI Units	*Imperial Units*
C_D	local drag coefficient		
$\bar{C}_D$	averaged drag coefficient over building (see Section 4.2)		
c	viscous damping, translation or rotation	N s/m or N m s	lbf s/ft or lbf ft s
D	base dimension of building in direction of vibration	m	ft
F_j	generalised force for mode j	N	lbf
f_j	natural frequency for mode j	Hz	Hz
$f(t)$	time-dependent applied force	N	lbf
H	height of building	m	ft
j	mode number		
K_j	generalised stiffness for mode j	N/m	lbf/ft
k	rotational spring stiffness	N m/rad	lbf ft/rad
M_j	generalised mass for mode j	kg	lb
m	local mass/unit height	kg/m	*slug/ft
n,p	integers		
Q_j	dynamic magnification factor for mode j		
t	time	s	s
$u(t), v(t)$, $w(t)$	local instantaneous fluctuating velocity components along mean wind direction, normal to mean wind direction and in vertical direction respectively	m/s	ft/s
$V(t)$	local instantaneous wind speed along mean wind direction	m/s	ft/s
$\bar{V}_z$	mean-hourly wind speed at height z	m/s	ft/s
W	local width of building normal to mean wind direction	m	ft

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X_j	generalised deflection for mode j	m	ft
x_H	peak resonant component of fluctuating translational displacement at top of building (see footnote†)	m	ft
x_z	amplitude of cycle of decay (see Section 5.1)	m	ft
z	height above ground level	m	ft
α	power law exponent for mean-hourly wind speed, $(\bar{V}_z/\bar{V}_H) = (z/H)^{\alpha}$		
Δ_j	half-power frequency bandwidth for mode j	Hz	Hz
δ_j	damping logarithmic decrement for mode j		
ζ_j	modal damping ratio for mode j		
$(\zeta_a)_j$	modal aerodynamic damping ratio for mode j		
$(\zeta_s)j$	modal structural damping ratio for mode j		
$(\zeta_{so})j$	modal structural damping ratio at very small amplitude of vibration (taken as zero) for mode j		
$(\zeta'_s)_j$	rate of increase of modal structural damping ratio with normalised amplitude of vibration, x_H/H, for mode j		
n_j	damping loss factor for mode j		
θ_H	peak resonant component of fluctuating angular displacement at top of a building (see footnote†)	rad	rad
Λ	linear scale, ratio of model to full-scale		
$\mu_j(z)$	mode shape at height z for mode j (see Section 4.2)		
ρ_a	density of air	kg/m^3	*slug/ft^3
τ	time scale		

Additional Subscripts

fs	refers to full-scale building
H	refers to height H
m	refers to semi-rigid model

* 1 slug = 32.174 lb (pounds mass)

† Note that x_H (commonly referred to as the single-amplitude or half-amplitude of response in the single mode of vibration, and denoted by $g_R\sigma_{X_H R}\{j\}$ in ESDU 88019, Reference 29) and θ_H do not include the mean or non-resonant fluctuating components of deflection.

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2. PURPOSE AND SCOPE OF THIS ITEM

This Item provides damping data which may be used in the estimation of the response of tall buildings to fluctuating wind loads. Because damping in a building depends on many parameters such as the amplitude and frequency of vibration, the internal features and the detailed method of fabrication, it is not possible to assign a unique value of damping for a building of a particular size and shape. Although it may be possible to predict the overall damping by consideration of the contributions from individual members, using for example such data as those presented in Reference 12, it is generally more reliable to base the prediction on full-scale measurements from real buildings. Measured damping values, obtained using various measuring techniques for a range of buildings, exhibit considerable scatter. This scatter is well illustrated by collections of damping data published in the literature (*e.g.* Derivation 6 and Reference 15). The data presented in this Item are in the form of recommended ranges of damping values derived from those full-scale measurements where it has been possible to identify the effects of parameters such as amplitude. Such sets of data are comparatively rare (for example, few of the collected data presented in Reference 15 provide sufficient information by which the effect of amplitude can be reliably derived). The data are given in this Item for buildings of concrete or steel construction. In general, steel buildings exhibit lower damping than concrete buildings. The way in which these data may be used in the estimation of the response of a tall building to fluctuating wind loads is given in Reference 28.

Some background information concerning the damping behaviour of tall buildings is given in Section 3 of this Item, and in Section 4 a method of estimating the damping ratios for the *first translational modes of vibration of tall buildings is presented. Ways of measuring experimentally the damping of a tall building are outlined in Section 5, and various means of increasing the modal damping are discussed in Section 6. In Appendix A, expressions for the generalised parameters required for the response calculations are developed. Guidance is given on the physical testing of a damped scale model of a building in Appendix B, and some other modal damping expressions, supplementary to the modal damping ratio expression used in this Item, are given in Appendix C. In Appendix D, the values of structural damping for a range of amplitudes of vibration of several identified buildings are presented for their first translational modes in the 2 orthogonal directions.

3. BACKGROUND NOTES

With the tendency towards the construction of tall, slender buildings of relatively high flexibility and low mass, a knowledge of the response of the building to dynamic excitation is often required at the design stage. The frequency content of the energy input to the building may be considered to be either "narrow-band" or "broad-band". With narrow-band excitation, for example that produced by offset rotating masses or vortex shedding in fluid streams, the building will respond at a single mode or a limited number of modes determined by the exciting phenomena. With broad-band excitation, such as that produced by atmospheric turbulence, the building may respond in a large range of modes, with energy present at each frequency for some of the time. In general, the fundamental mode of a building will be most susceptible to excitation by atmospheric turbulence, and most of the energy of the response will be contained in that mode.

In general, the response of tall buildings to broad-band, atmospheric turbulence may be characterised by small amplitude oscillations of low damping. The dynamic response of the building may be predicted using the modal superposition technique, in which the total response of the building is determined by combining the responses of the building in a number of modes of vibration. For each considered mode of vibration, the amplitude-dependent modal damping ratio is calculated from the response in that particular mode only. Usually, only the first few modes of vibration contain enough vibrational energy to be of interest, and a knowledge of the rate of dissipation of this energy (*i.e.* the damping) is required for each mode.

* The first translational modes of vibration are the flexural modes that have the lowest natural frequencies in each of the two principal orthogonal planes of the building.

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In response calculations, it may be necessary to investigate the dynamic behaviour of the building under wind excitation to ensure that the response satisfies all serviceability criteria, as well as to check the structural integrity under design wind speed conditions. Some data concerning the human response to vibration in buildings are given in References 14, 17 and 26.

3.1 Damping Definitions

In this Item, the damping of tall buildings is expressed by the modal damping ratio, ζ_j ,which is defined as

$$\zeta_j = \frac{c_j}{(c_{crit})_j}, \tag{3.1}$$

where c_j is the damping for mode j. The critical damping, $(c_{crit})_j$, for mode j is given by

$$(c_{crit})_j = 2\sqrt{K_j M_j}, \tag{3.2}$$

where K_j and M_j are the generalised stiffness and generalised mass for that particular mode. This approach is based upon the assumption of an equivalent viscous-type damping behaviour. It has been found that the magnitude of the modal damping ratio, ζ_j , is related to the mode shape, the mass of the building and the amplitude of response in that mode. In this Item, data are given for amplitudes of response typical of wind induced oscillations. The effect of increasing amplitude is to increase the modal damping of tall buildings up to a limiting value. An explanation of this effect is given in Section 3.3. Other damping terms which may be used for lightly damped tall buildings are given in Appendix C.

3.2 Components of Modal Damping

Various models have been suggested for the prediction of the modal damping of buildings. Three ways in which the energy present in a mode of vibration may be dissipated are:

(i) structural damping, $(\zeta_s)_j$, arising from the internal dissipation of energy between the elements and connections of the buildings;

(ii) aerodynamic damping, $(\zeta_a)_j$, arising from aerodynamic forces caused by the velocity of the vibrating building relative to the incident airflow;

and (iii) a foundation damping effect arising from the transfer of energy from the vibrating building to the soil.

In this Item, structural damping is modelled as having two components, a zero amplitude component and an amplitude-dependent component. The basis of this model is discussed in Section 3.3, and the estimation of the structural damping using this method is described in Section 4.1. In a typical building the structural damping term is generally responsible for most of the damping. The aerodynamic damping term is generally small except for very tall buildings of low density*. The amount of vibrational energy that is lost to soil/structure interaction is very difficult to quantify at the design stage (on-site measurements after completion of construction being the only reliable means of estimating the effects). However, foundation damping is often relatively small, and for the purpose of the experimentally-based damping correlations of this Item is not included in the structural damping representation. In general, shorter buildings lose a greater proportion of vibrational energy to the foundations than very tall buildings, especially in the lower-order modes of vibration. Guidance on the significance of soil/structure interaction in building vibrations is given in Reference 27.

* There are some flow patterns in which the aerodynamic damping may be negative. Further guidance on these occurrences is given in Reference 21.

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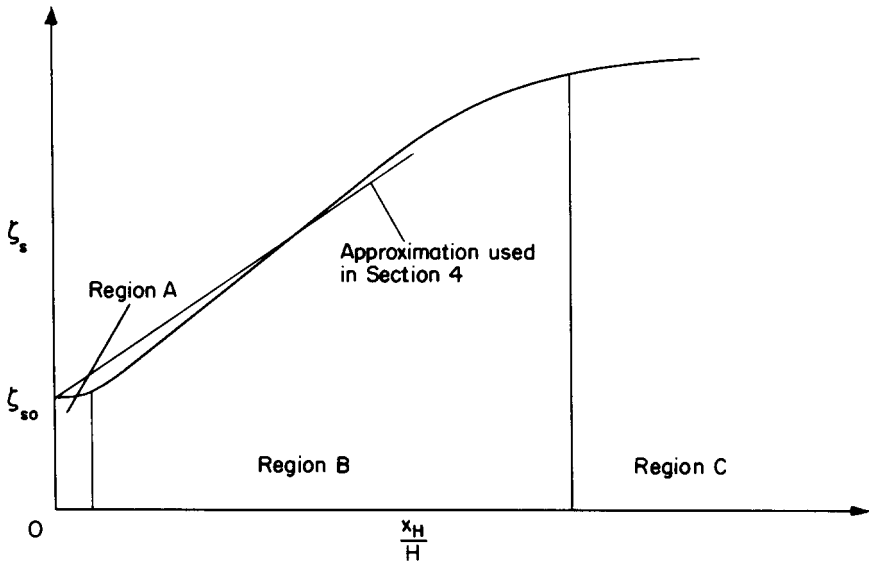
3.3 Effect of Amplitude on Structural Damping

The structural damping present in a natural mode of vibration has been shown for some existing buildings to be related to the peak resonant component of the vibratory amplitude associated with that mode (Derivations 2 to 9). The general form of the variation of structural damping ratio, ζ_S, with this amplitude is shown qualitatively in Sketch 3.1, and for some specific cases in Appendix D.



Sketch 3.1 Typical variation of structural damping ratio with appropriate amplitude

Three amplitude-dependent regions can be identified, marked A, B, and C in Sketch 3.1. In Region A, at very small amplitudes of vibration, the magnitude of the structural damping ratio tends to show very little variation with amplitude and may be considered constant. The structural damping results largely from frictional interaction between the structural and non-structural elements of the building and by material hysteresis. Above a certain amplitude, shown by the boundary between Regions A and B, the forces in the building are sufficient to cause other dissipative effects in the building elements, such as bolt or joint slip, or local yielding, which increase the damping. Amplitudes within Region B are typical of those caused by wind excitation. Some data are available for the prediction of structural damping in this region (see Section 4.1.2). At higher amplitudes of vibration, in which most of the dissipative effects in the building elements are mobilised and in the absence of structural damage, the structural damping ratio tends to an upper limiting value. This upper limit is marked region C on Sketch 3.1. Although few data are available for the prediction of the amplitudes associated with this upper limit, there is some evidence to suggest that upper limit values encountered for wind engineering calculations are considerably lower than those measured for the very large deflections associated with earthquake excitation (Derivation 9). Non-reversible structural damage of the structural and non-structural building elements is generally responsible for the very high damping values measured in earthquakes: a limiting value of 10% of critical is sometimes used in earthquake engineering. Some large-amplitude data associated with earthquake excitation are presented in Reference 13.

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4. ESTIMATION OF MODAL DAMPING RATIO, ζ_j

As outlined in Section 3.2, the damping ratio for a particular mode of vibration of a tall structure may be given by the expression

$$\zeta_j = (\zeta_s)_j + (\zeta_a)_j, \tag{4.1}$$

where $(\zeta_s)_j$ is the structural damping ratio and $(\zeta_a)_j$ is the aerodynamic damping ratio at mode j. Means of estimating the modal structural and aerodynamic damping ratios of tall buildings of regular construction are given in Sections 4.1 and 4.2 respectively. The data for the structural damping ratio refer to the first translational modes of vibration. Insufficient data are available to allow predictions to be made of the structural damping ratio of torsional and higher-order translational modes of vibration. Some measured data for these modes are given for a selection of buildings in Appendix D.

4.1 Modal Structural Damping Ratio, $(\zeta_s)_j$, for First Translational Modes of Tall Buildings of Regular Construction

In this Item a relatively simple model for structural damping has been chosen, in which the structural damping ratio, $(\zeta_s)_j$, is expressed as the sum of two components. The first component is the damping ratio term corresponding to very small amplitudes of vibration $(\zeta_{so})_j$, and the second component provides the increase in damping ratio with increasing amplitude. Assuming Region A in Sketch 3.1 is very small, the structural damping ratio may be represented by the linear equation,

$$(\zeta_s)_j = (\zeta_{so})_j + (\zeta'_s)_j \frac{x_H}{H}, \tag{4.2}$$

where $(\zeta'_s)_j$ is the rate of increase of the structural damping with x_H/H, and x_H is the (single-amplitude) peak resonant component of the vibratory amplitude at the top of the building. Data for the estimation of $(\zeta'_s)_j$ that are particularly applicable to wind loading conditions are given in Section 4.1.2, and for several specified buildings in Appendix D.

4.1.1 Structural damping ratio at very small amplitudes of vibration, $(\zeta_{so})_j$

From Figure 1, based on a knowledge of the natural frequency of the mode, a range of possible values can be selected within which the structural damping ratio, $(\zeta_{so})_j$, at very small (nominally zero) amplitudes of vibration should lie. These values are applicable to the first translational modes of vibration of tall buildings of regular construction in which the predominant motion is parallel to one of the two orthogonal principal axes of flexure. The natural frequencies for most tall buildings may be estimated from References 19, 24 or 25. Alternatively, for the fundamental translational mode parallel to the major axis of flexure of the building, when only the height of the building is known, a quick approximate estimate of the range of possible values of $(\zeta_{so})_j$ can be made using Figure 2.

The data on Figures 1 and 2 relate to modal damping measurements taken mainly from forced vibration tests on a sample of tall buildings, of either concrete or steel construction, and generally of conventional design. Some data were obtained for a range of amplitudes, x_H, and extrapolated to zero amplitude to obtain $(\zeta_{so})_j$. These data are given for a range of height/width/breadth ratios and for the range of building heights indicated by Figure 2. Although significant torsional coupling was evident for several of these data, their measured values lie within the general scatter of the data.

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The dashed lines on Figures 1 and 2 represent "most probable" values of the structural damping ratio at very small amplitudes of vibration, derived from a fit to the data on Figure 1, and are based upon the expression

$$(\zeta_{so})_j = \frac{f_j}{100} \ . \tag{4.3}$$

The minimum lines show the expected lower limit of the structural damping ratio and are based upon the expression

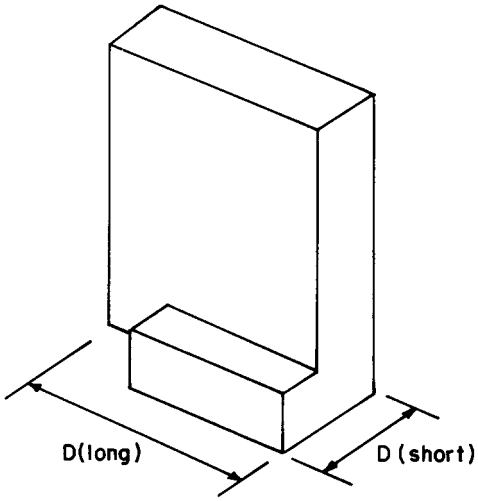
$$(\zeta_{so})_j = \frac{f_j}{250} \ . \tag{4.4}$$

In general, steel buildings exhibit lower values of this structural damping parameter than concrete buildings, and it is recommended that the lower values of the data be considered for steel buildings, and the whole range be considered for concrete buildings.

Tall buildings of particularly complex design, or with joints or structural interfaces which may allow more than the usual slip or relative movement of the structural or non-structural elements, may exhibit values of $(\zeta_{so})_j$ at the upper limit of the range of data on Figures 1 and 2. Conversely, particularly simple and well-constructed buildings, with few internal members, may exhibit values of $(\zeta_{so})_j$ approaching the minimum line.

4.1.2 Rate of change of structural damping ratio with amplitude, $(\zeta'_s)_j$

From Figure 3, an estimate may be made of the rate of increase of modal structural damping ratio, $(\zeta'_s)_j$, with peak resonant component of fluctuating displacement at the top of the building, x_H, in the first translational modes of vibration.



Sketch 4.1 Example building

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For this estimation, the value of a base dimension, D, in the direction of the mode of vibration, is required **and has the unit of metres.** This dimension is considered to be the linear structural dimension at ground level in the direction of translation, and includes the contribution of any attached structure. The values of D chosen for the two translational modes of vibration, in the long and short directions, of an example building are shown in Sketch 4.1. The data may be used to estimate the magnitude of the structural damping ratio at amplitudes of oscillation typical of the along-wind response of tall buildings excited by atmospheric turbulence. The dashed line on Figure 3 represents "most probable" values of $(\zeta'_s)_j$, derived from a fit to the data shown on that figure, and is described by the expression

$$(\zeta'_s)_j = 10^{(\sqrt{D}/2)}. \tag{4.5}$$

The second line on that figure represents an expected lower limit to $(\zeta'_s)_j$, and is described by the expression

$$(\zeta'_s)_j = 10^{(\sqrt{D}/2.5)}. \tag{4.6}$$

Buildings with numerous shear walls or a large number of active non-structural elements are likely to be best described by the "most probable" line. Conversely, simple and well-constructed buildings with few internal members and rigid foundations may be best described by the expected lower limit line. There is some evidence to suggest that the latter representation should be used for the estimation of $(\zeta'_s)_j$ for extremely tall buildings (Derivation 9). It is recommended that a range of values of $(\zeta'_s)_j$ are used in a series of calculations of the response of the building to wind excitation, unless experience suggests that other values of $(\zeta'_s)_j$ may be likely due to a feature of the construction or fabrication procedure. Data that have been used in the estimation of $(\zeta'_s)_j$ of a number of buildings are shown Appendix D.

The along-wind peak resonant component of the amplitude response of a tall building under wind excitation may be estimated using Reference 28. Since the structural damping ratio is interrelated with the modal component of the amplitude of vibration, the estimation of $(\zeta_s)_j$ and x_H is an iterative calculation in which the value of $(\zeta_{so})_j$ can be used as a first approximation for $(\zeta_s)_j$.

4.1.3 Upper limit of structural damping ratio

It is possible that the upper limit of the structural damping ratio, described in Section 3.3, will be reached when performing building response calculations at extreme wind conditions. For this reason, and to prevent the estimation of excessively high values of $(\zeta_s)_j$ at large values of x_H/H, the value of $(\zeta_s)_j$ should not be extrapolated with x_H/H beyond a recommended upper limit dependent upon building height. This recommended upper limit, based upon information given in Derivations 6 and 9, is given by the expression

$$(\zeta_s)_j \leq \frac{60}{100H} + 0.013, \tag{4.7}$$

and is illustrated in Sketch 4.2.

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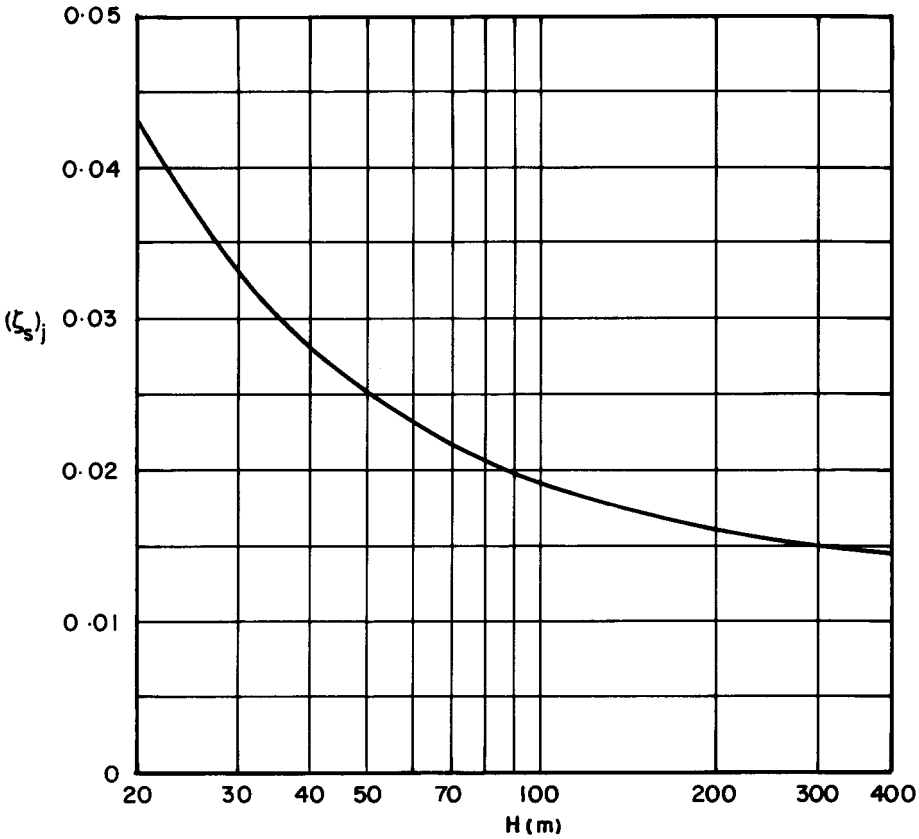

Sketch 4.2 Recommended upper limit on structural damping ratio

4.2 Modal Aerodynamic Damping Ratio, $(\zeta_a)_j$

The aerodynamic damping ratio for mode j is shown in Appendix A to be

$$(\zeta_a)_j = \frac{\rho_a \overline{V}_H}{4\pi f_j M_j} \int_{z=0}^{H} W C_D(z, f_j) \mu_j^2(z) (z/H)^{\overline{\alpha}} dz, \tag{4.8}$$

where ρ_a is the air density, $\overline{V}_H$ is the mean-hourly wind speed at the top of the building, H is the height of the building, z is the height above ground level, f_j and M_j are the natural frequency and generalised mass for mode j, and W is the width of the structure normal to the mean wind direction under consideration, $C_D(z, f_j)$ is the *local drag coefficient, $\mu_j(z)$ is the mode shape function (describing the deflected shape of the structure in mode j with a maximum value of unity) and α is the power-law exponent for mean-hourly wind speed. Guidance on the determination of these terms is given in References 10 and 17. For tall buildings, assuming a linear mode shape (applicable to the first translational modes only), invariance of W with z, and invariance of C_D with both z and f_j, this equation may be simplified to give,

$$(\zeta_a)_j = \frac{\rho_a \overline{V}_H \overline{C}_D W}{4\pi f_j m} \cdot \frac{3}{3+\alpha}, \tag{4.9}$$

* The local drag coefficient $C_D(z, f_j)$, is a function of the height, z, and the natural frequency vibration, f_j, or the mode under consideration (see Reference 17). The variation with frequency is due to the disturbance of the aerodynamic wake of the oscillating building.

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where m is the mass per unit height of the structure, and $\overline{C}_D$ is the average mean drag coefficient taken over the height of the building.

5. MEASUREMENT OF MODAL STRUCTURAL DAMPING

The amount of structural damping present in any natural mode of vibration of a building may be measured by a variety of techniques.* The most popular techniques are the free decay (logarithmic decrement) technique and the half-power bandwidth technique. These techniques are outlined below, and may help the user appreciate the limited accuracy of measured damping data.

5.1 Free Decay Technique

For this technique the building is vibrated to an appropriate amplitude level at the frequency of the natural mode under investigation, and the excitation forces removed to allow the amplitude of oscillatory vibrations of the building to die away. An accurate estimate of the modal damping may be determined from the shape of the envelope of vibrational amplitude decay assuming viscous type damping. A typical time/response record for a tall building is shown in Sketch 5.1. The envelope of vibrational decay is assumed to be of the exponential form and the modal damping for lightly damped buildings is given by

$$\zeta_j = \frac{1}{2\pi(p-n)} \ln\left\{\frac{(x_z)_n}{(x_z)_p}\right\}_j, \tag{5.1}$$

where $(x_z)_n$ refers to the amplitude of a cycle of decay, n, at a suitable position in the building, and $(x_z)_p$ refers to the amplitude at the same level of a following cycle, p. In practice, successive amplitudes of oscillation are plotted on a logarithmic basis (see Sketch 5.2). A line is drawn through the points and the modal damping ratio at any amplitude is taken as the local tangent to the line. This procedure has the advantage that, as the amplitude of oscillation decreases, the variation of modal damping with amplitude can be simply determined.

5.2 Half-powered Bandwidth Technique

For this technique the amplitude, velocity or acceleration response of the building to an oscillatory load, which increases in frequency through a frequency band encompassing the resonance frequency under consideration, is measured. An estimate of the modal damping ratio may be determined from the shape and height of the response peak corresponding to a natural mode. A typical amplitude response record for the fundamental translational mode of vibration of a tall building is shown in Sketch 5.3. The damping may be determined by selecting the two positions of "half-power", that is the two frequencies at which the response is $1/\sqrt{2}$ of the maximum amplitude of response. The frequency interval between these two half-power frequency positions is termed the half-power bandwidth, Δ_j, and the modal damping ratio may be obtained from the expression

$$\zeta_j = \frac{\Delta_j}{2f_j}, \tag{5.2}$$

* In order to obtain good estimates of the modal structural damping, the damping measurements must be made in calm, still conditions. In such conditions, the aerodynamic damping contribution to the measured modal damping may reasonably be neglected except for very tall, light buildings. If the aerodynamic damping is significant, the modal structural damping may be expressed by the difference between the measured modal damping and the calculated modal aerodynamic damping.

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