Shaping tall buildings to reduce aerodynamic excitation and response

by

W H Melbourne

Abstract: Background to the generation of perceptible accelerations in tall buildings is developed to demonstrate that these tend to be dominated by the cross-wind response to wake, vortex, excitation. A sensitivity analysis demonstrates the dependence on wind speed, damping, building massiveness and the cross-wind force spectrum. The remainder of the paper gives guidelines to the way in which the shape or configuration of a building may be directed to achieve reductions in the cross-wind force spectrum and hence reductions in acceleration response.

1. Introduction

The design of many tall buildings has become increasingly determined by the requirement to keep motion from wind action to within acceptable levels for human occupation. The most significant response in this respect is the cross-wind response driven by the wake (vortex) excitation mechanism. There are a number of ways of shaping or configuring a tall building to reduce the cross-wind excitation, such that it can be hypothesized that there should never be any need to incorporate auxiliary damping into a tall building which has been appropriately shaped. This paper will discuss the parameter sensitivity of tall buildings to cross-wind response and develop some guidelines for the shaping of tall buildings to avoid excessive response to wind action.

2. Parameter sensitivity and acceleration criteria

The more technical aspects of the mechanisms of tall building response to wind action and acceleration criteria have been covered in several papers by Melbourne et al (1988, 1992, 1998). For the purposed of this paper the essential background information will be summarised.

2.1 Response and excitation mechanisms

The response of tall buildings to wind action can be conveniently separated into along-wind and cross-wind motion in relation to two distinctly separate excitation mechanisms. The along-wind response is made up of a mean component and two types of fluctuating component, a low frequency response to background turbulence and a resonant response component. For the cross-wind response the mean component is usually small and the fluctuating components again have background and resonant response components. In terms of generating accelerations felt by building occupants it is only the resonant components which are significant, because the first cantilever bending modes have significantly higher frequencies than the main motions generated directly by the background turbulence. In the case of a tall building in a turbulent wind environment the resonant component can be relatively small which is the primary reason why along-wind response is rarely a problem in acceleration terms. The cross-wind resonant component can, however, be quite dominant particularly when the building is operating near the peak of the cross-wind force spectrum, only at lower Reduced Velocities does the background component tend to become significant. The dominance of the cross-wind resonant component in response to the relatively large amount of energy available from the vortex excitation is the main reason why acceleration levels tend to be dominated by the cross-wind response of the building. It follows then that shaping and configuring a tall building to reduce response acceleration levels essentially has to target reductions in vortex excitation.

2.2 Acceleration criteria

Acceleration criteria to achieve occupancy comfort in tall buildings have received somewhat varied attention over the past 20 years. The pioneering work of Chen and Robertson (1973) gave valuable information about human perception of sinusoidal excitation as a function of frequency, and they suggested using an occupancy sensitivity quotient which defines the ratio of the tolerable amplitudes of motions to the threshold motion for half the population. The work by Reed (1971) gave the first full-scale evaluation of occupants' responses to accelerations on two buildings and the first criteria in terms of standard deviation of acceleration for a return period for the frequencies of those buildings. Irwin, in a series of papers, further studied the responses of humans to sinusoidal acceleration over a range of frequencies. Through a number of unpublished full-scale studies of crane operators and building occupants he was primarily responsible for the standard deviation acceleration criteria in ISO 6897. He focused these on tall buildings in Irwin (1986). In North America some use appears to be made of an unreferenced peak acceleration criterion of 20 mg once in 10 years, with no reference to frequency.

Based on the above earlier studies and some full scale experience Melbourne and Cheung (1988) commenced the development of frequency-dependent criteria for peak accelerations rather than sinusoidal or normally distributed oscillations. This resulted in a single expression for peak acceleration for occupancy comfort in a building with dependence on the building frequency, and return period under consideration, and which allowed a peak factor dependent on the operating reduced frequency to be taken into account. This criterion or expression for peak acceleration which should not be exceeded to achieve acceptable occupancy comfort was

$$\hat{\ddot{x}} = \sqrt{2 \ln nT}\left(0.68 + \frac{\ln R}{5}\right)\exp(-3.65 - 0.41 \ln n) \qquad (1)$$

where

n = building resonant frequency

T = duration of experience of acceleration (usually put at 600 seconds)

R = return period in years.

2.3 Determination of cross-wind response

One of the simplest ways of evaluating the cross-wind response, involving all the important parameters in the process of resonant response to wake excitation, is to use a mode-generalized force spectrum approach proposed by Saunders and Melbourne (1975). The method makes use of measured cross-wind displacement spectra to give a mode-generalized force spectrum (for the first mode) of

$$S_F(n) = \frac{(2\pi n_0)^4 m^2 S_y(n)}{H^2(n)} \qquad (2)$$

where

$S_y(n)$ = spectrum of cross-wind displacement at top of building

n_0 = first-mode frequency

m = modal mass

$H^2(n)$ = mechanical admittance; $1/\left\{\left[1-(n/n_0)^2\right]^2 + 4\zeta^2(n/n_0)^2\right\}$

ζ = critical damping ratio

For a linear mode, and if excitation by low frequencies is small and the structural damping low so that the excitation bandwidth is large compared with the resonant bandwidth, the standard deviation of displacement at the top of the building may be approximated by

$$\sigma_y = \left|\frac{\pi n_0 S_F(n)}{(2\pi n_0)^4 m^2 4\zeta}\right|^{1/2} \qquad (3)$$

and the standard deviation of acceleration is given by

$$\sigma_{\ddot{y}} = \sigma_y (2\pi n_0)^2 \qquad (4)$$

The force spectrum may be expressed in coefficient form by

$$C_{FS} = \frac{n_0 S_F(n)}{(\frac{1}{2}\rho \overline{V}_h^2 bh)^2} \qquad (5)$$

where

h = building height

b = building width normal to wind direction

$\overline{V}_h$ = mean wind speed at top of building.

Then in terms of this force spectrum coefficient the standard deviation of acceleration becomes

$$\sigma_{\ddot{y}} = \frac{\rho \overline{V}_h^2 bh}{4m} \sqrt{\frac{\pi C_{FS}}{\zeta}} \qquad (6)$$

For an average building density ρ_S and a linear mode, the modal mass is

$$m = \frac{1}{3}\rho_S bdh \qquad (7)$$

and the peak acceleration at the top of the building due to cross-wind response is given by

$$\hat{\ddot{y}} = \frac{3}{4}\frac{g\rho \overline{V}_h^2}{\rho_S d} \sqrt{\frac{\pi C_{FS}}{\zeta}} \qquad (8)$$

Corrections for mode shape, complex motion and background component have been discussed by Melbourne and Palmer (1992) and Melbourne and Cheung (1999).

2.4 Parameter sensitivity

Inspection of Equation (8) shows the obvious dependence of cross-wind response on wind speed building density, the cross-wind force spectrum and damping, but less obvious is the dependence on building shape. Firstly the acceleration is not, as one might intuitively think, directly dependent on height or aspect ratio but rather on planform size. Indirectly height is involved because wind speed is a function of height. Hence relatively tall slender buildings will have higher accelerations than low squat buildings, but the important relative parameters in the denominator are planform size and average density, i.e. massiveness. Secondly the value of the cross-wind force spectrum is a function of reduced velocity (V/nb) and the shape of the building. This relationship is quite complex and it is in the sensitivity of the cross-wind force spectrum to building shape that the key to developing tall buildings with reduced cross-wind response really lies.

3. Controlling the cross-wind force spectrum

With some understanding of the aerodynamic excitation mechanisms involved it is a short step to formulate some guidelines which will direct the shape of a tall building towards reduction of the cross-wind force spectrum.

The primary cause of the cross-wind excitation is the vortex shedding process. The strength of the cross-wind excitation depends primarily on the strength of the shed vortices, the height correlation of the vortex structures and the location of streamwise surfaces on which cross-wind acting pressure fields can develop with sufficient energy at the natural frequency of the building. For buildings only the first two cantilever bending modes are significant, but this does not follow for towers where sufficient energy may be generated to excite higher modes.

Whilst far from rigorously proven it is known that sharp edged structures will shed stronger and more coherent vortices than curved surfaces. Tapering the cross-section will broaden the frequency bandwidth of excitation and lower the peak, as will increased turbulence in most cases. Tapering also reduces massiveness. Bleeding flow through the body will weaken the vortex structure and tend also to broaden the bandwidth. With these few observations it can be simply concluded that guidelines for changes in building shape to achieve reductions in the cross-wind force spectrum are as follows:

1. Square or rectangular buildings should be made more circular, i.e. by cutting or rounding corners or adding features in the middle of sides.
2. Buildings should be tapered or stepped back with increasing height.
3. Porosity should be introduced across the building particularly over the upper levels and near the corners.

The remainder of this paper will give examples of the application of these guidelines.

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Professor W H Melbourne
Department of Mechanical Engineering, Monash University, Clayton, Vic 3800, Australia
Tel: 61(3)9905-3512 / Fax: 61(3)9905-3558 / Email: bill.melbourne@eng.monash.edu.au