Refining the Prediction of Acceleration Response of Tall Buildings

W H Melbourne and J C K Cheung

Department of Mechanical Engineering
Monash University, Clayton, Vic 3168. Australia

Abstract – An example has been given which shows the importance of separating out the resonant component of the cross-wind response to use in the determination of building acceleration for human comfort considerations, when the building is operating at low reduced velocities.

1. INTRODUCTION

The response of a tall building to wind action is made up of a number of definable components. The acceleration response, to which occupancy comfort is related, is usually assumed to be dominated by resonant response in the first two sway modes, with or without a rotational component about a vertical axis as described by Melbourne and Palmer (1992).

For along-wind response it is relatively easy both analytically and experimentally to separate the resonant component from the mean and background component. However for the more important cross-wind acceleration response it is not so easy to separate out the resonant component and because most acceleration problems (ie exceedance of comfort criteria) have tended to occur when the building is operating near the peak of the cross-wind force spectrum it has been generally assumed that all the cross-wind response is resonant. This assumption is obviously conservative and hence satisfactory if it is just a matter of concluding that the building would not have occupancy comfort problems. However if the situation is marginal it becomes necessary to be much more precise about differentiating between background and resonant components of cross-wind response and the relativity of the two as a function of damping and turbulence. The latter has a direct relationship with the background response, but a very complex relationship with the resonant component, and depending also on the operating reduced velocity.

This paper will explore refinements in the prediction of acceleration response with particular emphasis on the cross-wind response, at reduced velocities well away from the peak of the cross-wind force spectrum.

2. PREDICTION OF ACCELERATION RESPONSE OF TALL BUILDINGS

The along-wind acceleration response can be obtained from the narrow band resonant component of the Gust Factor, and from which the peak acceleration for a building of uniform cross-section and density and linear mode can be given by

$$\hat{\ddot{x}} = \frac{3\overline{M}G_{res}}{m_o h^2} \qquad (1)$$

where $\overline{M}$ = mean base overturning moment.
m_o = mass per unit height.
h = height of building.
G_{res} = $2\frac{\sigma_V}{\overline{V}} g \sqrt{\frac{SE}{\zeta}}$ the resonant component of the Gust Factor.
$\frac{\sigma_V}{\overline{V}}$ = the turbulence intensity.
g = a peak factor.
S = a size reduction factor.
E = a gust energy factor.
ζ = damping as a fraction of critical.

There are many evaluations of these parameters given initially by Davenport (1967) and Vickery (1971), but the ones that will be used here come from the Australian Standard on Wind Loading AS1170.2-1989.

The cross-wind acceleration response has essentially been obtained from wind tunnel model measurements. Analytical methods have been developed based on wind tunnel model measured force spectra such as described by Melbourne and Cheung (1988), and from which, for a building of uniform cross-section and density, the peak acceleration can be given by

$$\hat{\ddot{y}} = \frac{1.5\, g\, \bar{q}\, b}{m_o} \sqrt{\frac{C_{f_s}}{\pi \zeta}} \qquad (2)$$

where $\bar{q}$ = is the mean dynamic pressure.
b = the building width.
C_{f_s} = the cross-wind force spectral coefficient.

Again the evaluations of the above in this paper will use parameters given by AS1170.2-1989.

The accelerations obtained from the above methods and from the measured model data will be compared with acceleration comfort criteria developed by Melbourne and Cheung (1988) and given in terms of a peak acceleration, $\hat{a}$, by

$$\hat{a} = \sqrt{2\, \ell n\, n\, T}\, (0.68 + \frac{\ell n R}{5})\ \exp(-3.65 - 0.41\, \ell n\, n) \qquad (3)$$

for $0.06 < n < 1.0$ and $0.5 < R < 10$

where n = frequency.
T = duration under consideration for evaluating a peak factor, (eg 10 min or 1 hour).
R = return period in years.

3. EXPERIMENTAL PREDICTION OF ACCELERATION RESPONSE

To give an example of the prediction of acceleration response of a building, and to explore the relative components contributing, some data from a model building with the following characteristics will be used.

height, h = 100m
windward face width, b = 15m
streamwise face width, d = 30m
1st and 2nd mode frequencies, $n_{1,2}$ = 0.5 Hz
building density, ρ_s = 270 kg m^{-3}
turbulence intensity, $\left(\frac{\sigma_V}{V}\right)_{100m}$ = 0.20
5 year return period mean wind speed, $\overline{V}_{100m} = 25\ \mathrm{ms}^{-1}$
operating Reduced Velocity. $V_r = \frac{V}{nb} = 3.3$

In Figure 1 cross-wind standard deviation base moments ($C_{\sigma_M} = \frac{\sigma_M}{\frac{1}{2}\rho\overline{V}^2bh^2}$) are given as a function of reduced velocity, for two values of damping (defined by the critical damping ratio ζ) and with the background and resonant components separated out by means of high pass and low pass filtering of the total time series data. A spectrum of the total time series data is shown as an insert. When these two components are plotted as a fraction of the standard deviation squared (variance) as shown in Figure 2 a picture emerges of how the two components contribute to acceleration response. Acceleration is a function of frequency squared and the majority of the background component can be seen to be at frequencies about a tenth of the resonant frequency hence for similar component standard deviations the background contribution would be two orders of magnitude (one hundredth) below that from the resonant component. Hence it is concluded that only the resonant component contributes significantly to acceleration levels that would be felt by an occupant of the building. Referring now to Figure 2 it can be seen that at a damping ratio of 1% at the lowest reduced velocities the resonant and background components contribute almost equally whilst at a damping ratio of 3% the resonant component is damped out and the response is dominated by the background component. At the higher reduced velocities shown, (still 50% below the peak of the cross-wind force spectrum), it can be seen that the resonant component (as a square of the standard deviation) is rising to 60% of the total (and this would continue to rise to approach almost 100% at the peak of the cross-wind force spectrum).

At a reduced velocity of 3.3 and a damping ratio of 1%

$$C_{\sigma_{M_{\substack{\text{crosswind}\\\text{total}}}}} = 0.28 \quad C_{\sigma_{M_{\substack{\text{cross-wind}\\\text{resonant}}}}} = 0.20$$

and from other data not presented, $C_{\sigma_{M_{\substack{\text{along-wind}\\\text{total}}}}} \approx 0.08$

Even if the total along-wind component was considered it would contribute less than 10% to resultant acceleration and if only the resonant component were considered it would be much less. Hence only the cross-wind component will be considered further in this example.

For the 5 year return period the standard deviation base moments become

$$\sigma_{M_{\substack{\text{cross-wind}\\ \text{total}}}} = C_{\sigma_M} \bullet \tfrac{1}{2}\rho \overline{V}^2 bh^2 = 15.8 \text{ x } 10^6 \text{ Nm} \tag{4}$$

and $$\sigma_{M_{\substack{\text{cross-wind}\\ \text{resonant}}}} = 11.3 \text{ x } 10^6 \text{ Nm}$$

The inertial base moment for unit displacement and linear mode shape is

$$M_i = \frac{\rho bdh^2}{3}(2\pi n)^2 = 4.0 \text{ x } 10^9 \text{ Nm} \tag{5}$$

Therefore the standard deviation displacement at the top of the building becomes

$$\sigma_{y_{\substack{\text{cross-wind}\\ \text{total}}}} = \frac{\sigma_M}{M_i} = 0.0040 \text{ m} \quad \text{and} \quad \sigma_{y_{\substack{\text{cross-wind}\\ \text{resonant}}}} = 0.0028 \tag{6}$$

from which the standard deviation accelerations, σ_a , are given,

$$\sigma_{a_{\substack{\text{cross-wind}\\ \text{total}}}} = \sigma_y\,(2\pi\, n)^2 = 0.040 \text{ ms}^{-2} \quad \text{and} \quad \sigma_{a_{\substack{\text{cross-wind}\\ \text{resonant}}}} = 0.028 \text{ ms}^{-2} \tag{7}$$

In terms of peak accelerations, $\hat{a}$, multiplying by a peak factor for a 10 minute period,

$$g = \sqrt{2\,\ell n\, n\,T} = \sqrt{2\,\ell n\, 0.5 \bullet 600} = 3.34 \tag{8}$$

gives

$$\hat{a}_{\substack{\text{cross-wind}\\ \text{total}}} = g\sigma_a = 0.136 \text{ ms}^{-2} = 13.9 \text{ milli} - g$$

$$\hat{a}_{\substack{\text{cross-wind}\\ \text{resonant}}} = 0.095 \text{ ms}^{-1} = 9.7 \text{ milli} - g$$

This compares with the acceleration criterion from Equation 3 from which

$$\hat{a} = 0.117 \text{ ms}^{-2} = 11.9 \text{ milli} - g$$

From this example it can be seen that if the total standard deviation had been used to calculate the acceleration response the criterion would have been exceeded, but because of the low operating reduced velocity the resonant component primarily responsible for the acceleration response is only about 70% of the total and hence the building response comfortably meets the acceleration criterion for human occupancy comfort.

4. ANALYTICAL PREDICTION OF ACCELERATION RESPONSE

It is of interest to check the acceleration response predictions from Equations 1 and 2.

For the cross-wind acceleration response from Equation 2, and using a value of $C_{F_S} = 0.0016$ from AS1170.2-1989

$$\hat{a}_{\text{cross-wind}} = 0.053\ \text{ms}^{-2} = 5.4\ \text{milli} - \text{g}$$

This would have underpredicted the acceleration response in this case by quite a margin and the reason is that the experimental data used has come from a model building test where interference effects from another building were causing a significant increase in response.

For the along-wind acceleration response using Equation 1 with a mean moment coefficient of 0.4 and $G_{res} = 0.7$,

$$\hat{a}_{\text{along-wind}} = 0.039\ \text{ms}^{-2} = 4.0\ \text{mill} - \text{g}$$

Which is well under the criterion and in agreement with the along-wind acceleration response using the experimental total along-wind standard deviation moment coefficient given (ie 4.1 mill-g) but would be an overprediction if only the resonant component of the experimental data had been used.

5. CONCLUSIONS

An example of the evaluation of the acceleration response of a building has been given using experimental data and currently available analytical methods. It has been shown that for a building operating at relatively low reduced velocities it is necessary to separate out the resonant component of the cross-wind response to use in the acceleration response determination to avoid over prediction.

References

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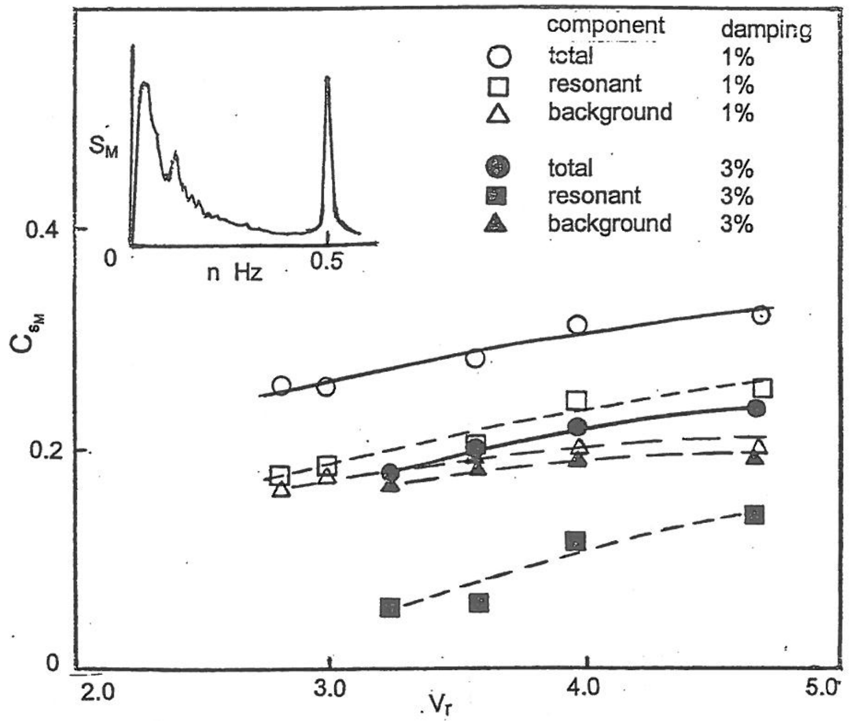

Figure 1 Standard deviation cross-wind base bending moment coefficients as a function of reduced velocity and damping with resonant and background components obtained by high-pass and low-pass filtering.

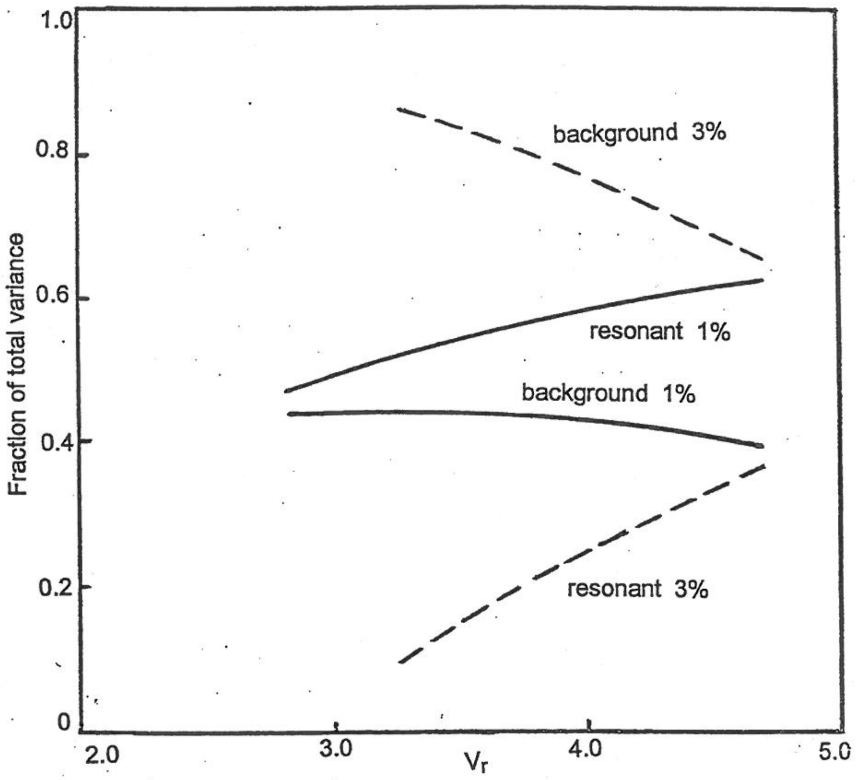

Figure 2 Fraction of total variance of the cross-wind resonant and background components as a function of reduced velocity and damping.