Combining Orthogonal Base Loads from the High-Frequency Base Balance

by George Vorobieff
Development Engineer, Concrete Structures
Cement and Concrete Association of Australia

SUMMARY

The current method of using the high-frequency base balance for the prediction of wind loading and response on high-rise buildings is to align the principal building stiffness axes with the orthogonal axes of the base balance device. Most base balance devices are designed to measure five load components at the base of the building. This paper discusses a method to combine the independent base loads, moments and torque in order for structural engineers to design structurally efficient high-rise buildings. Also, a technique is proposed to resolve the three rms acceleration components.

1 INTRODUCTION

The High-Frequency Base Balance Technique is used in Australia for many high-rise building projects to predict base wind loads and acceleration at the top of the building. It provides the base shear, base moments and torque (five load components in all), and root mean square (rms) acceleration at the top of the building using a combination of computational and testing methods (see Ref.2).

Similar to the aeroelastic model technique, the base balance device is designed to measure the orthogonal base wind loads of the scaled building model. The device base axes is generally aligned to the building principal axes. From this simple measuring system, design engineers are required to combine the independently measured loads for all wind azimuths tested, to estimate:

* the distribution of the base loads up the building. Which are then used in the analysis to estimate forces in the building structural elements.

* the maximum rms acceleration at the top of the building at different wind speeds and azimuths to assess the comfort for building users.

* the correlation between along-wind and cross-wind loads in order to design a structurally efficient building. This is usually difficult to assess when the wind direction is not aligned to the buildings principal axes.

The last issue is the theme of this paper because of the increasing need by design engineers to find a method which will combine the independently measured orthogonal base loads and predicted acceleration components from the simple base balance device.

2 BASE FORCES

Part 2 of the Loading Code covering wind loads (Ref.1) provides a useful discussion of the combination of along-wind and cross-wind responses in Clause F4.4.6. This discussion is of limited use since the equation which approximates $\hat{M}_R$ is for the case where $\bar{M}_c = 0$ and $\hat{M}_c > (G-1)\,\bar{M}_a$. In almost all base balance wind studies, $\bar{M}_c$ is not equal to zero and the Code equation is not applicable.

From studies on existing buildings and structures (Ref.3), the response displacement footprint, and the x and y-axis acceleration plot at the top of a building is usually shaped like an elliptical orbit. Thus, it is reasonable to assume that the quasi-static resultant base loads from the orthogonal base results may be a point on the elliptical curve, as shown in Figure 1. The resultant moment and the angle it occurs at may be determined by the maximum distance from the origin to a point on the elliptical curve.The rectangular box shown in Figure 1 represents a situation where the x and y base loads are perfectly correlated, that is the peak $\hat{M}_x$ and $\hat{M}_y$ occurs on the building simultaneously.

Once the resultant base moment is known, the next stage to combining the orthogonal loads is to estimate the load distribution with respect to building height about the building principal axes. The load distribution for each principal axis may be determined in the usual manner of considering the combined effect of the mean wind load and the fluctuating wind load, distributed in accordance with the vibration mode shape and building mass distribution.

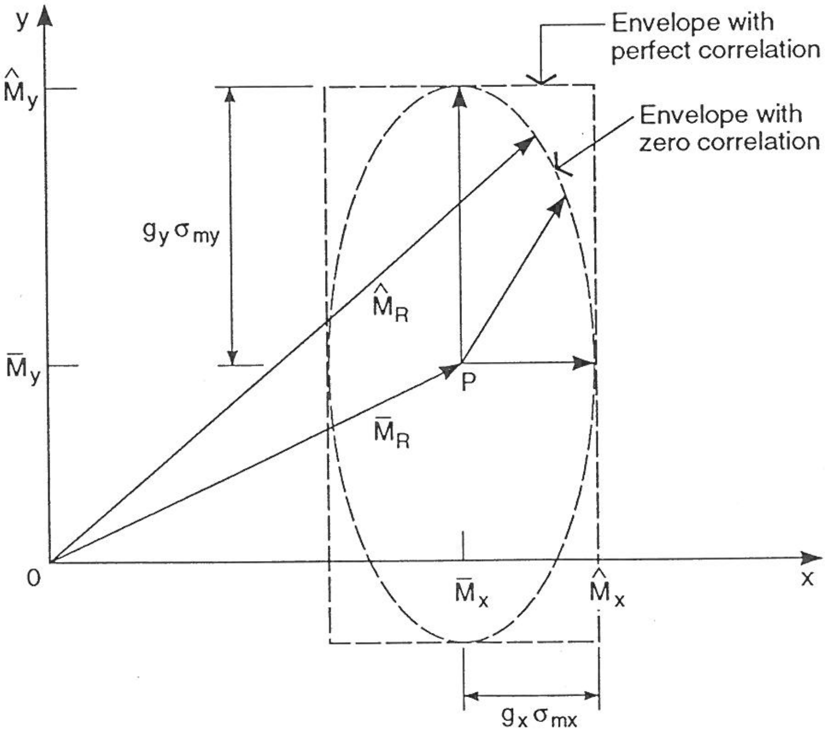

Figure 1 Vector response of mean and fluctuating components of x and y-axis base moments.

The peak base moment may be equated to a horizontal load at some height above the base and it is reasonable to assume the vertical centriod of the mean and fluctuating wind load should not change for each building principal axes when combining loads. Therefore, the resultant of the x-axis ($\hat{F}_x$) and y-axis ($\hat{F}_y$) base shear may be determined from vectors or trigonometry (see figure 2), with the resultant peak base shears $\hat{F}_{rx}$ and $\hat{F}_{ry}$ used to factor the load distribution on the building. The factors are $\hat{F}_{rx}/\hat{F}_x$ and $\hat{F}_{ry}/\hat{F}_y$ for each x and y axes respectively.

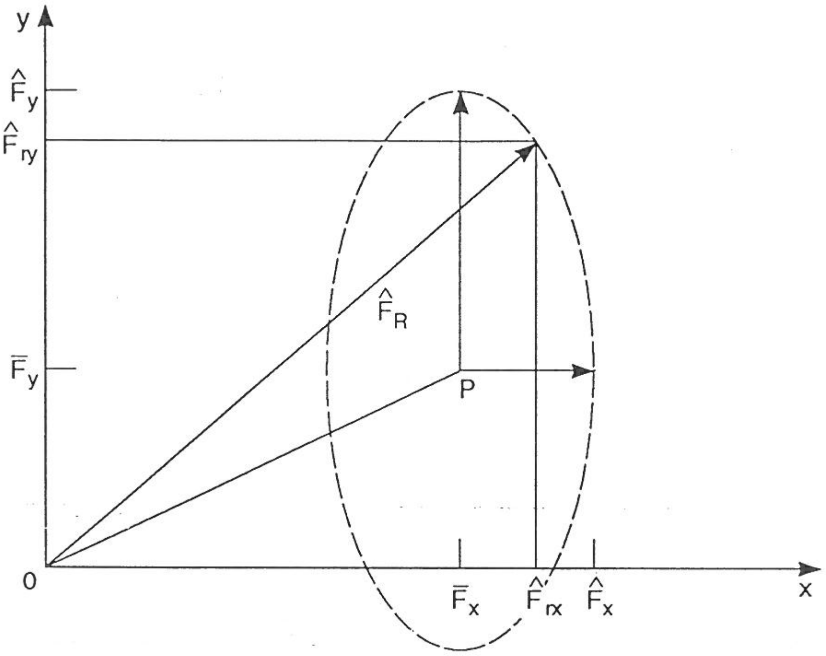

Figure 2 Vector response of peak components of x and y-axis base shear.

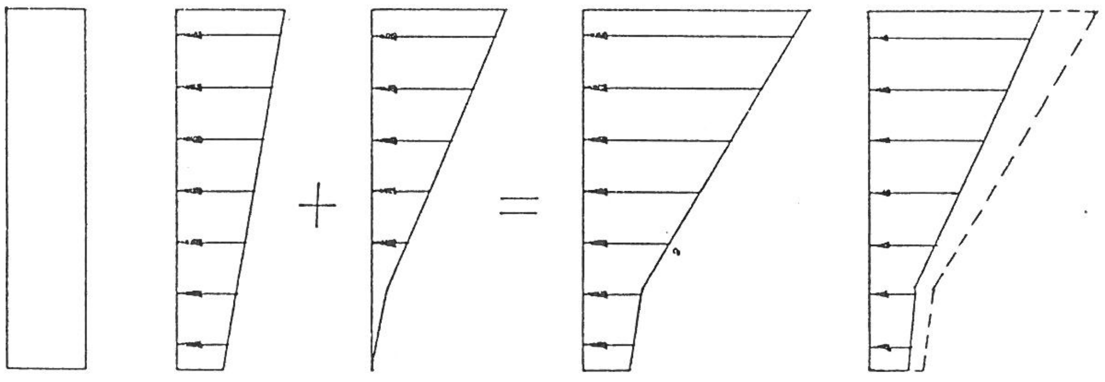

Figure 3 Typical distribution of peak wind load on the building face. Also shown dotted is the resultant peak load due to the combined along-wind and cross-wind response.

So far, only the combination of base moments and shears have been considered. The torsional base load M_z may also be included and in this case, the curve is replaced by a surface in space ranging from a rectangular parallelepiped for the case of total correlation of all three axes to an ellipsoid for the case of no correlation. However, since the torsional wind loads are small for most high-rise buildings, it would be reasonable to assume full correlation between the resultant base moments M_x and M_y, and base torsion M_z.

The combination of the base moments, torque and shear as described above is applicable for wind directions aligned and not aligned to the building principal axes. For each wind azimuth, an elliptical curve may be drawn to estimate the combined base moment and base shear, and the results may be summarised as shown in Figures 4 to 6.

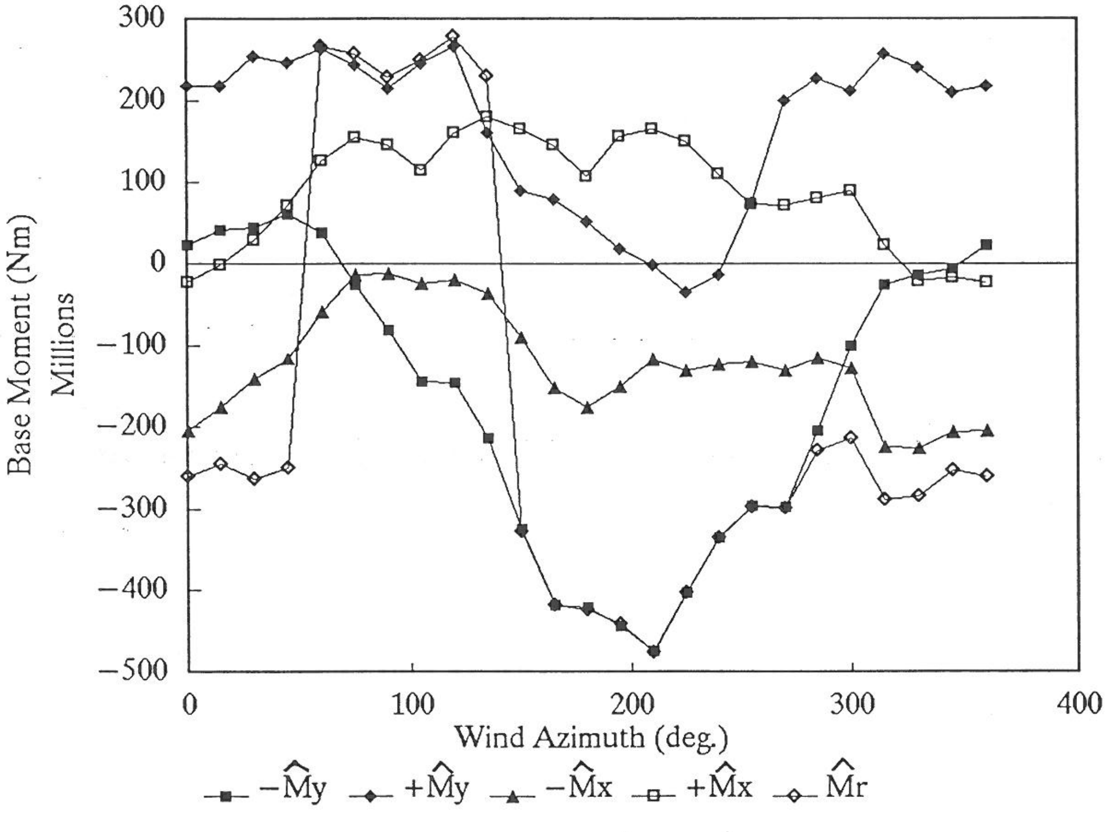

Figure 4 Plot shows the peak base moments $\hat{M}_x$ and $\hat{M}_y$, and the resultant moment $\hat{M}_r$ for 0 to 360 wind azimuths.

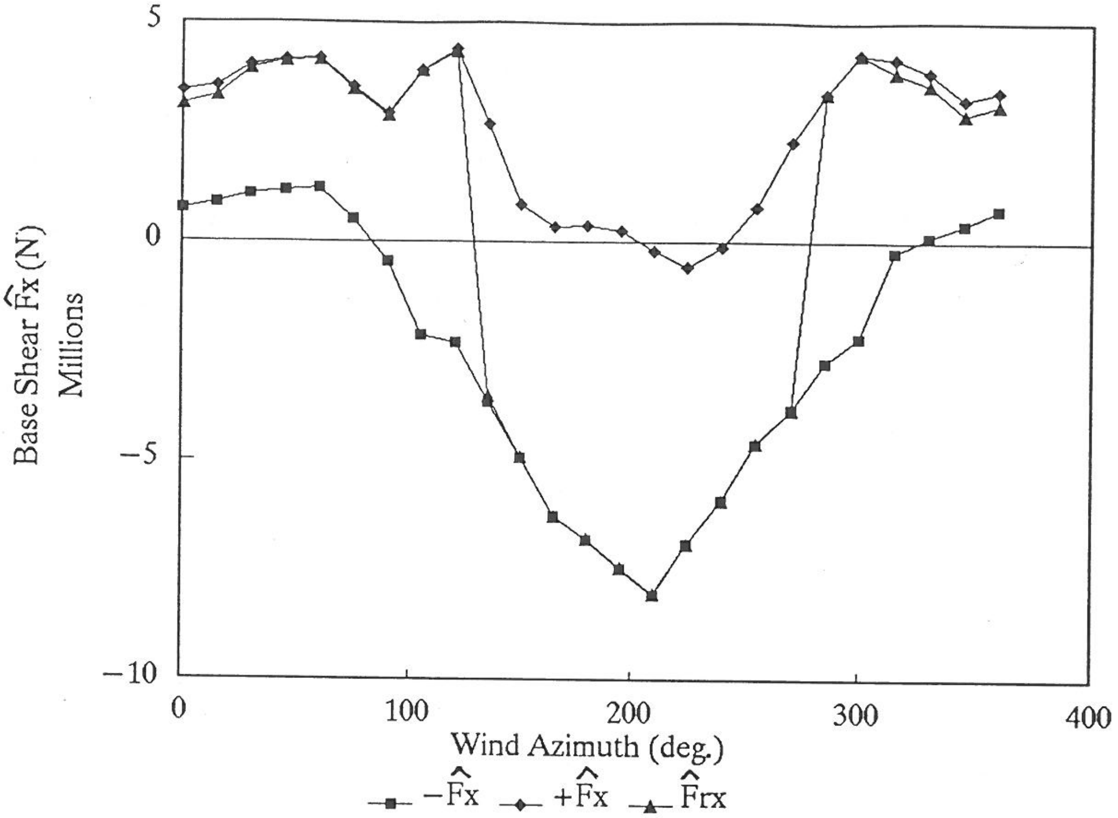

Figure 5 Plot shows the peak base shear ($\hat{F}_x$) and the resultant base shear ($\hat{F}_{rx}$) for the load combination effect.

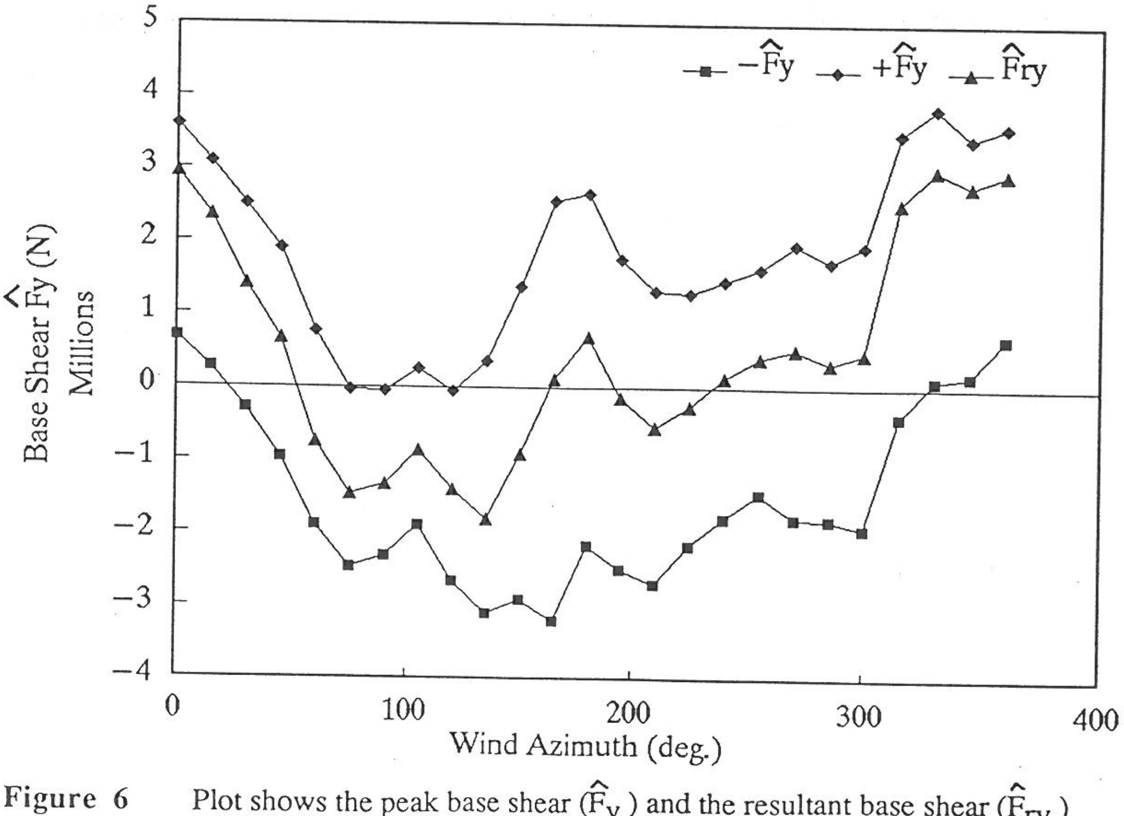

Figure 6 Plot shows the peak base shear ($\hat{F}_y$) and the resultant base shear ($\hat{F}_{ry}$) for the load combination effect.

3 ACCELERATIONS

The base balance technique is also used to predict the acceleration at the top of the building. Acceleration may be estimated by the same technique used to calculated base loads (see Ref.2). Unlike the requirement to calculate mean and peak loads, the rms acceleration is only estimated, since one of the most common criteria used to place an upper design limit on acceleration is based on rms acceleration (see Ref.4). The rms acceleration for each orthogonal axes is simple to compute from the base balance device, but the degree of correlation of the component accelerations is difficult to estimate.

A method previously established (Ref.2) uses equation 1 to estimate the resultant rms acceleration at the top of the building.

$$a_{r,rms} = \sqrt{a_x^2 + a_y^2 + (ra_o)^2} \quad [m/s^2] \tag{1}$$

where a_x = rms acceleration in the x axis [m/s^2]
a_y = rms acceleration in the y axis [m/s^2]
a_o = rms acceleration about the z axis [rad/s^2]
r = distance to the furthest location on the floor from the centre of twist [m]

Basically, this method uses the vector resultant of the three rms acceleration components and is conservative method.

Incorrect. This is not a conservative method. This is the correct method for combining standard deviation in a scalar form. It does not give any information on peak acceleration. Instantaneous peak acceleration is a vector sum.

It is proposed that an alternative method could be considered based on the principle that the rms torsional acceleration (ra_o) is correlated to the along-wind rms acceleration. Combined with the cross-wind rms acceleration at the top of the building, an elliptical orbit is assumed to represent the combined accelerations. Using this assumption, the resulting rms acceleration is the maximum point on the elliptical curve with respect to the origin, as shown in figure 7.

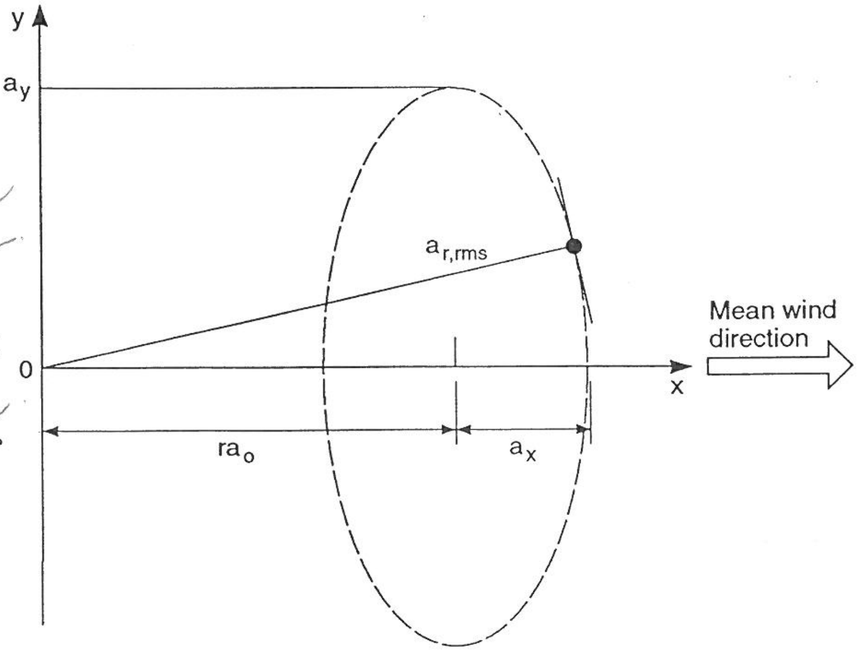

Figure 7 Proposed technique shown graphically to resolve the three rms acceleration components.

To compare this latter approach to that of equation 1, a study was carried out on a proposed 120-metre high office building. The results for 4 azimuths are listed in Table 1. The results indicate that a higher rms acceleration is predicted using the vector resultant method (no.1) than the proposed method (no.2) if torsion is similar in magnitude to the along-wind acceleration. For 210^o wind azimuth, the second method predicts 10% more in acceleration than the estimate using method no.1

The preliminary study indicates the second approach produces lower estimates of the resultant rms acceleration than the vector resultant method in most cases. It is recommended that further research work is required to assess the proposed method to combine the rms acceleration from along-wind, cross-wind and torsional excitation.

Table No.1 A comparison of the two methods to estimate the resultant rms acceleration at two locations at the top of a building. The location (A) is on the top floor of the building at the centre of twist, and location (B) is 27 metres from the centre of twist (i.e. corner office).

Loc.	Wind Azimuth (deg.)	RMS acceleration Components Along-wind (m/s^2)	Cross-Wind (m/s^2)	Torsion (m/s^2)	Resultant RMS Accel. Using Method1	Using Method 2
A	30	0.0041	0.0022	0.0001x0	0.0047	0.0041
B	30	0.0041	0.0022	0.0001x27	0.0054	0.0068
A	120	0.0028	0.0096	0.0002x0	0.0100	0.0096
B	120	0.0028	0.0096	0.0002x27	0.0115	0.0111
A	210	0.0116	0.0051	0.0001x0	0.0127	0.0116
B	210	0.0116	0.0051	0.0001x27	0.0130	0.0143
A	300	0.0039	0.0072	0.0001x0	0.0082	0.0072
B	300	0.0039	0.0072	0.0001x27	0.0086	0.0079

4 CONCLUSION

The high-frequency base balance technique provides five load components, base shear (F_x and F_y), base moment (M_x and M_y), and base torque (M_z). This paper has discussed a method of combining the independently measured base moments and shear loads from the orthogonal axes of the base balance device assuming that the combination of orthogonal loads may be represented by an elliptical curve (see figure 1). The method also suggests that the wind load distribution for each building principal axes may be estimated be vector scaling the resultant base moment M_R. This is applicable for each wind azimuth tested in the wind tunnel.

Most tall buildings are governed by the building response at the serviceability limit state and using a conservative approach to assess the combined effect of the three components of acceleration (a_x, a_y and a_o) may unnecessarily produce structurally inefficient design solutions. It is currently proposed that the three components of acceleration are combined using the second approach detailed in section 3 (see figure 7). Although the second approach will in most cases predict lower rms acceleration than from equation 1, it is suggested that further research is carried out on existing high-rise buildings to verify that the method does not unduly underestimate the maximum rms acceleration.

5 REFERENCE

1 Standards Australia **SAA Loading Code Part 2: Wind Loads** AS1170.2-1989

2 Vorobieff, G and Cochran, L **A New Wind Tunnel method For Direct Determinations of Design Loads: The High Frequency Base Balance** Second National Structural Engineering Conference, I.E.Aust., Adelaide, October, 1990.

3 Kwok, K.C.S and MacDonald, P.A **Wind-Induced Response of Sydney Tower** First National Structural Engineering Conference, I.E.Aust., Melbourne, August, 1987.

4 ACI-ASCE Committee 442 **Response of Concrete Buildings to Lateral Forces** ACI Manual of Concrete Practice, Part3, 1990.