

# Validity of Wind Load Distribution based on High Frequency Force Balance Measurements

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**Abstract:** High frequency force balance (HFFB) measurements have recently been utilized to identify the distribution of spatiotemporally varying fluctuating wind loads on buildings. These developments, predicated on their ability to compute any response component of interest, based on actual building characteristics, attempt to offer a framework that eliminates the need for mode shape corrections generally necessary in the traditional HFFB technique. To examine the effectiveness of these schemes with significant practical implications to wind tunnel modeling technology, this technical note utilizes a recent approach to identify the alongwind loading on buildings. The predictions are compared to a widely utilized analytical loading model. It is noted that, akin to the traditional HFFB technique, the accuracy of these identification schemes clearly depends on the assumed wind loading model.

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## Introduction

Wind excited response of buildings can be separated into background and resonant components based on their spectral characteristics. The background response can be estimated through a quasistatic analysis under dynamic wind loading and is expressed in terms of respective influence function. This format implicitly includes the contributions of all structural modes to the background response thus offers more accurate response prediction in comparison with the format based on modal analysis involving only the fundamental structural mode. However, in practice, the background response of a high-rise building, like the resonant response, is often approximated by the fundamental mode response which can be estimated using a modal analysis scheme.

Within such a modal analysis procedure for background and resonant response, estimation of the generalized wind force is the critical element for response prediction. The generalized wind force can be characterized through simultaneously measured pressures on building model surfaces or by measured base forces on a model mounted on a high-frequency force balance (HFFB). High sensitivity pressure sensors available at low cost have allowed utilization of synchronous scanning of pressures over building models for capturing individual point pressure variations as well as the overall integral loads. While the pressure models are often

used in practice which provide a more detailed loading information, the HFFB technique remains a very effective tool for estimating the generalized wind forces on buildings with uncoupled mode shapes (e.g., Kareem and Cermark 1979; Tschanz and Davenport 1983; Reinhold and Kareem 1986; Boggs and Peterka 1989; Zhou et al. 2002). When the building has a translational mode shape that varies linearly over the building height, the measured base bending moment leads to an accurate estimate of the generalized wind force, while mode shape corrections are needed for the generalized forces associated with a torsional mode and a translational mode with a nonlinear mode shape. The correction for a torsional mode is generally larger than those required for the translational modes. Once the generalized wind force is available, it is then utilized to predict dynamic response for a wide range of structural characteristics.

By approximating both background and resonant responses of a high-rise building in terms of the fundamental mode response, and introducing the equivalent static loading framework which is realized by distributing the peak base bending moment response along the building height following the modal inertial load distribution, any peak response of the building can be expressed in terms of the peak base bending response (Boggs and Peterka 1989; Zhou and Kareem 2001; Zhou et al. 2002, Chen and Kareem 2004). Studies have shown that base bending moment response is rather insensitive to the mode shape, which makes the analysis framework based on the base bending moment to be very attractive (Boggs and Peterka 1989; Zhou and Kareem 2001; Zhou et al. 2002). Within this framework, the base bending moment can be first estimated for a virtual building that has identical geometrical features and building dynamics as the actual building with the exception of a linear mode shape (Zhou et al. 2002). A mode shape correction factor for the bending moment response is then introduced or even in some cases omitted for simplicity to estimate the base bending moment response of the actual building. Finally, other response components of the building are estimated through a static analysis under the equivalent static loading expressed in terms of the modal inertial loading of the actual building.

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When the actual building response with a nonlinear mode shape is directly evaluated from a stick type building model with a linear mode shape, mode shape correction factor for each individual response is required. A host of studies concerning the mode shape correction factor based on wind tunnel studies or analytical models have been reported in Vickery et al. (1985), Boggs and Peterka (1989), Xu and Kwok (1993) and Zhou et al. (2002), among others. It has been pointed out that the mode shape correction factors for different response components are related to each other (e.g., Chen and Kareem 2004). Although they have different values, the level of uncertainty associated with these factors is the same, which stems from the lack of spatiotemporal loading information since only the base forces are measured. The mode shape correction procedure has to rely on an empirical formulation or on a presumed analytical wind loading model that may not accurately describe the actual wind loads. An accurate estimation of the mode shape correction factor becomes even a more challenging task for buildings with complex geometries and three dimensional (3D) coupled mode shapes as well as for cases in which the mean wind directions are not normal to a building face. The application of HFFB measurements to buildings with 3D coupled modes have been studied in Irwin and Xie (1993), Yip and Flay (1995), Holmes et al. (2003), and Chen and Kareem (2005).

Recently, traditional HFFB measurements have been extended to identify spatiotemporally varying fluctuating wind loads through measured base forces (Ohkuma et al. 1995; Yip and Flay 1995; Solari et al. 1998; Xie and Irwin 1998). In these studies, an analytical wind loading model with unknown parameters is assumed. In the frequency domain, models in terms of the power spectral density (PSD) and cross PSD (XPSD) of loading (Ohkuma et al. 1995; Yip and Flay 1995; Solari et al. 1998), or in the time domain, models in terms of the load (pressure) distribution along the building height (Xie and Irwin 1998), are utilized. These unknown parameters are then identified by using the measured base force data. Once the external wind loads are determined, any response component of interest can be subsequently analyzed using actual building dynamics. These modeling schemes attempt to offer frameworks that eliminate the need for mode shape corrections.

To investigate the accuracy of these wind loading identification schemes, this study utilizes a recent approach used by Xie and Irwin (1998) to identify the alongwind loading on buildings, which is described by an analytical loading model. This study should by no means be considered as a criticism of the work reported in Xie and Irwin (1998), rather it is used as an example of the techniques in this context.

## Loading Identification Scheme

The alongwind loading and response of a building with one dimensional uncoupled mode shape in a translational direction is considered. In Xie and Irwin (1998), wind pressure over the building height is assumed to vary linearly. The wind pressure at height  $z$  above the ground, i.e.,  $p_x(z, t)$ , is given as

$$p_x(z, t) = p_{0x}(t) + p_{1x}(t) \left( \frac{z}{H} \right) \quad (1)$$

where  $p_{0x}(t)$  and  $p_{1x}(t)$  are assumed to be independent of location, and can be uniquely determined based on the measured base shear force, i.e.,  $F_x(t)$ , and base bending moment, i.e.,  $M_x(t)$ , as follows:

$$p_{0x}(t) = \frac{2}{BH^2} (2F_x(t)H - 3M_x(t))$$

$$p_{1x}(t) = \frac{6}{BH^2} (-F_x(t)H + 2M_x(t)) \quad (2)$$

where  $H$ =building height; and  $B$ =building width.

The generalized wind force, i.e.,  $Q_x(t)$ , associated with the mode shape  $\Theta_x(z) = (z/H)^\beta$  (where  $\beta$ =mode shape exponent ranging between 1.0 and 1.5 for typical buildings), is then expressed in terms of  $F_x(t)$  and  $M_x(t)$  as

$$Q_x(t) = B \int_0^H \left[ p_{0x}(t) + p_{1x}(t) \left( \frac{z}{H} \right) \right] \left( \frac{z}{H} \right)^\beta dz$$

$$= \frac{1}{H(\beta+1)(\beta+2)} [2(1-\beta)F_x(t)H + 6\beta M_x(t)] \quad (3)$$

and its PSD is given by

$$S_{Q_x}(f) = \frac{1}{H^2(\beta+1)^2(\beta+2)^2}$$

$$\times [4(1-\beta)^2 H^2 S_{F_x}(f)$$

$$+ 12(1-\beta)\beta H S_{F_x M_x}(f) + 36\beta^2 S_{M_x}(f)] \quad (4)$$

where  $S_{F_x}(f)$  and  $S_{M_x}(f)$ =PSDs of  $F_x(t)$  and  $M_x(t)$ ;  $S_{F_x M_x}(f)$ =XPSD between  $F_x(t)$  and  $M_x(t)$ .

Accordingly, the root-mean square (RMS) value of any dynamic response component of the building  $R(t)$ , i.e.,  $\sigma_R$ , can be estimated by modal analysis and is expressed as

$$\sigma_R = \frac{\int_0^H m(z) \Theta_x(z) \mu_x(z) dz}{\int_0^H m(z) \Theta_x^2(z) dz} \sqrt{\int_0^\infty S_{Q_x}(f) df + \frac{\pi}{4\xi_1} f_1 S_{Q_x}(f_1)}$$

$$(5)$$

where  $\mu_x(z)$ =influence function;  $m(z)$ =mass per unit height; and  $f_1$  and  $\xi_1$ =fundamental frequency and damping ratio (including aerodynamic damping) of the building, respectively.

## Analytical Loading Model

The analytical wind loading model, which forms the basis of most building codes and standards, is used to investigate the accuracy of the scheme used by Xie and Irwin (1998). Utilizing strip theory, the alongwind fluctuating wind load per unit height at height  $z$  above the ground, i.e.,  $P_x(z, t)$ , can be related to the wind fluctuations in the same direction. Assuming that the mean wind speed varies according to the power law as

$$U(z) = U_H \left( \frac{z}{H} \right)^\alpha \quad (6)$$

and assuming that the drag coefficient, aerodynamic admittance function and standard deviation of turbulence are uniform over the building height, the XPSD of wind loading per unit height is given as

$$S_{P_{xx}}(z_1, z_2, f) = \frac{S_p(f)}{H^2} \left( \frac{z_1}{H} \right)^\alpha \left( \frac{z_2}{H} \right)^\alpha \exp\left( -\frac{k_z f}{U_H} |z_1 - z_2| \right) \quad (7)$$

$$S_P(f) = 4q_H^2 I_u^2 S_u^*(f) |\chi_D(f)|^2 |J_y(f)|^2 \quad (8)$$

where  $q_H = 0.5\rho U_H^2 C_D B H$ ;  $\rho$  = air density;  $C_D$  = drag coefficient;  $S_P(f)$  = PSD of wind load at the building top normalized by  $H^2$ ;  $U_H$  = mean wind speed at the building top;  $\alpha$  = wind load profile coefficient;  $k_z$  = decay factor in the vertical direction;  $S_u^*(f) = S_{u0}(f)/\sigma_{u0}^2$  = normalized PSD of wind fluctuation with respect to its mean square value  $\sigma_{u0}^2$ ;  $\sigma_{u0} = \sqrt{\int_0^\infty S_{u0}(f) df}$  and  $I_u = \sigma_{u0}/U_H$  = RMS turbulence and turbulence intensity at the top of the building;  $|\chi_D(f)|^2$  = aerodynamic admittance function; and  $|J_y(f)|^2$  = joint acceptance in the horizontal direction given by

$$\begin{aligned} |J_y(f)|^2 &= \frac{1}{B^2} \int_0^B \int_0^B \exp\left(-\frac{k_y f}{U_H} |y_1 - y_2|\right) dy_1 dy_2 \\ &= \frac{2}{\lambda_y} \left(1 - \frac{1}{\lambda_y} + \frac{1}{\lambda_y} e^{-\lambda_y}\right) \end{aligned} \quad (9)$$

and  $\lambda_y = k_y B / U_H$ ; and  $k_y$  = decay factor in horizontal direction.

The PSDs of the base bending moment, i.e.,  $M_x(t)$ , base shear force, i.e.,  $F_x(t)$ , and the generalized wind force, i.e.,  $Q_x(t)$ , are given by the following:

$$S_{M_x}(f) = \int_0^H \int_0^H z_1 z_2 S_{P_{xx}}(z_1, z_2, f) dz_1 dz_2 = \frac{H^2 S_P(f)}{(2 + \alpha)^2} |J_z(\alpha, 1, f)|^2 \quad (10)$$

$$S_{F_x}(f) = \int_0^H \int_0^H S_{P_{xx}}(z_1, z_2, f) dz_1 dz_2 = \frac{S_P(f)}{(1 + \alpha)^2} |J_z(\alpha, 0, f)|^2 \quad (11)$$

$$\begin{aligned} S_{Q_x}(f) &= \int_0^H \int_0^H \Theta_x(z_1) \Theta_x(z_2) S_{P_{xx}}(z_1, z_2, f) dz_1 dz_2 \\ &= \frac{S_P(f)}{(1 + \alpha + \beta)^2} |J_z(\alpha, \beta, f)|^2 \end{aligned} \quad (12)$$

where  $|J_z(\alpha, \beta_0, f)|^2$  ( $\beta_0 = 0, 1, \beta$ ) = joint acceptance function that captures the load reduction due to the loss of vertical spatial coherence in wind loads, and is expressed as

$$\begin{aligned} |J_z(\alpha, \beta_0, f)|^2 &= \frac{(1 + \alpha + \beta_0)^2}{H^2} \int_0^H \int_0^H \left(\frac{z_1}{H}\right)^{\alpha + \beta_0} \left(\frac{z_2}{H}\right)^{\alpha + \beta_0} \\ &\quad \times \exp\left(-\frac{k_z f}{U_H} |z_1 - z_2|\right) dz_1 dz_2 \end{aligned} \quad (13)$$

In the case of zero correlation in wind loads when  $k_z f / U_H \rightarrow \infty$ , Eqs. (10)–(12) reduce to

$$S_{M_x}(f) = \frac{H^2 S_P(f)}{2\alpha + 3} \quad (14)$$

$$S_{F_x}(f) = \frac{S_P(f)}{2\alpha + 1} \quad (15)$$

$$S_{Q_x}(f) = \frac{S_P(f)}{2\alpha + 2\beta + 1} \quad (16)$$

In the case of full correlation in wind loads when  $k_z f / U_H = 0$ , Eqs. (10)–(12) reduce to

$$S_{M_x}(f) = \frac{H^2 S_P(f)}{(2 + \alpha)^2} \quad (17)$$

$$S_{F_x}(f) = \frac{S_P(f)}{(1 + \alpha)^2} \quad (18)$$

$$S_{Q_x}(f) = \frac{S_P(f)}{(1 + \alpha + \beta)^2} \quad (19)$$

## Validation of Loading Identification Scheme

For the purpose of validating the effectiveness of the wind loading identification scheme used in Xie and Irwin (1998), the base bending moment and base shear force given by Eqs. (10) and (11), associated with the analytical loading model, are taken as the HFFB measurements. The PSD of the generalized wind force derived from the loading identification scheme [Eq. (4)], is then compared to its true value which can be directly calculated from the analytical loading model [Eq. (12)]. In Eq. (4),  $S_{F_x M_x}(f)$  is expressed as

$$\begin{aligned} S_{F_x M_x}(f) &= \frac{S_P(f)}{H} \int_0^H \int_0^H \left(\frac{z_1}{H}\right)^{\alpha+1} \left(\frac{z_2}{H}\right)^\alpha \\ &\quad \times \exp\left(-\frac{k_z f H}{U_H} |z_1 - z_2|\right) dz_1 dz_2 \end{aligned} \quad (20)$$

which in the case of zero correlation reduces to

$$S_{F_x M_x}(f) = \frac{HS_P(f)}{2\alpha + 2} \quad (21)$$

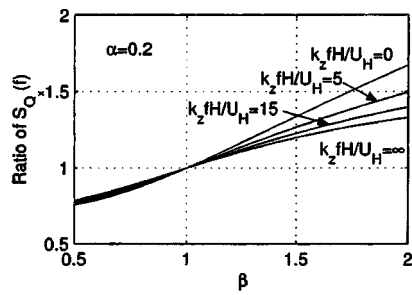
and in the case of full correlation to

$$S_{F_x M_x}(f) = \frac{HS_P(f)}{(1 + \alpha)(2 + \alpha)} \quad (22)$$

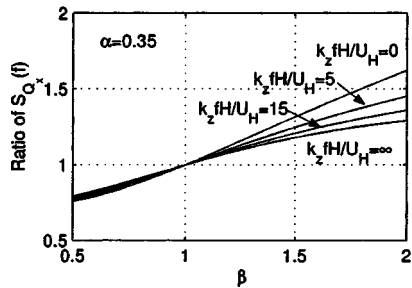
The ratio of  $S_{Q_x}(f)$  determined by Eq. (4) to that given by Eq. (12) serves as a measure of the accuracy of the scheme given in Xie and Irwin (1998). This exercise has no intention to question this practical scheme, rather an attempt is made to initiate a discussion on the accuracy of these wind loading identification schemes.

Figs. 1(a and b) show the ratio of the generalized forces for  $\alpha = 0.2$  and  $0.35$ , respectively, as a function of the mode shape parameter  $\beta$  and loading correlation parameter  $k_z f H / U_H = 0, 5, 15, \text{ and } \infty$ . Examination of the results suggests that this ratio is not sensitive to typical values of  $k_z f H / U_H$  and  $\alpha$ . Furthermore, it is not surprising to observe that this ratio becomes unity for the case of a linear mode shape. This is due to the fact that Eqs. (3) and (4) result in  $Q_x = M_x / H$  and  $S_{Q_x} = S_{M_x} / H^2$ , which is universally valid for a linear mode shape irrespective of the wind load distribution. However, when a building mode shape departs from linear, this scheme may significantly overestimate the generalized wind load and associated response for typical buildings with  $\beta$  ranging from 1.0 to 1.5. In order to compensate for this discrepancy, an additional correction factor needs to be introduced in this scheme, which is similar to the mode shape correction procedure for the traditional HFFB technique. However, this is exactly contrary to the premise of this approach which was motivated by a need for circumventing the mode shape correction.

It is worth noting that the loading model used in Xie and Irwin (1998) is equivalent to the following frequency domain model:



(a)  $\alpha = 0.2$



(a)  $\alpha = 0.35$

Fig. 1. Ratio of power spectral densities of generalized wind forces

$$S_{p_x}(z_1, z_2, f) = S_{p_{0x}}(f) + S_{p_{0x}p_{1x}}(f) \begin{pmatrix} z_1 \\ H \end{pmatrix} + S_{p_{1x}p_{0x}}(f) \begin{pmatrix} z_2 \\ H \end{pmatrix} + S_{p_{1x}}(f) \begin{pmatrix} z_1 \\ H \end{pmatrix} \begin{pmatrix} z_2 \\ H \end{pmatrix} \quad (23)$$

where  $S_{p_{0x}}(f)$  and  $S_{p_{1x}}(f)$  = PSDs of  $p_{0x}(t)$  and  $p_{1x}(t)$ ;  $S_{p_{0x}p_{1x}}(f) = S_{p_{1x}p_{0x}}^*(f)$  = XPSD between  $p_{0x}(t)$  and  $p_{1x}(t)$ ; the superscript \* = complex conjugate operator. It is obvious that the assumed loading model is different from the analytical loading model.

It is reiterated that a limited number of base force measurements generally fail to provide sufficient information to completely describe the overall distribution of fluctuating wind loads. Akin to the mode shape correction procedure, accuracy of the techniques for identifying wind loading distribution based on measured base forces strongly depends on the proper choice of the presumed analytical loading model. Measured base force data fitted to a presumed loading model does not always guarantee the ability of the resulting loading distribution to predict other wind load effects. Simply, this is due to the fact that different loading models may produce the same or almost the same base forces but may result in apparently different wind load effects at other locations. Therefore, like the mode shape correction procedure, better understanding and modeling of the fluctuating wind loads based on the measured pressure fields are critical to ensure the accuracy of the predicted wind loads and their effects.

## Conclusion

The effectiveness of the techniques for identifying the wind loading distribution on buildings derived from the measured base forces was discussed. It is noted that, akin to the mode shape correction procedures for traditional high frequency force balance technique, the accuracy of these techniques depends on the presumed loading models. Using a loading model that departs from

the actual distribution may result in remarkable errors in response predictions. It was noted that a better understanding and modeling of wind loads on buildings based on measured spatiotemporally varying pressure fields are essential prerequisites for enhancing the accuracy of response predictions, particularly, for buildings in a cluster of surrounding buildings and those with complex geometries and 3D mode shapes under wind excitation not normal to one of the building faces.

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