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Effects of the aerodynamic uncertainties in HFFB loading schemes on the response of tall buildings with coupled dynamic modes

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ABSTRACT

The wind loads on tall buildings can be estimated from the measurement of the base moments on rigid scale models with a high frequency force balance. Two main methods exist to this end, the most common of which is based on the definition of correction coefficients exploiting the close relation between the first three generalized forces and the base moments. In alternative, an approach based on calibrating spatio-temporal/-frequency models of the wind load distribution over the building height can be adopted. The main limitation inherent to both approaches consists in the introduction of uncertainties due to the lack of information concerning the wind load distribution. This source of error has not been sufficiently investigated especially in consideration of modern tall buildings characterized by complex profiles and coupled dynamic modes. The aim of this work is to study the errors induced in the response parameters by the aforementioned uncertainties. Results from specific wind tunnel tests are used to compare structural systems with both uncoupled and coupled dynamic modes and with geometrically simple and complex profiles. A quantitative evaluation of the error spread is proposed highlighting the significant sensitivity of irregular coupled buildings.

1. Introduction

The accurate estimation of the critical response parameters, such as top floor accelerations and displacements, is of fundamental importance when ensuring reliable designs of tall buildings. Methods to this end are typically set in a modal analysis framework and therefore require the estimation of the generalized forcing functions.

The estimate of the wind loads, and consequently the generalized forces, is typically obtained through specific wind tunnel tests made on rigid aerodynamic models. Two main methods exist to this end: one is based on the estimation of the external pressure field acting on the building through multiple point synchronous scanning of pressures (MPSSP), the other, in a simpler fashion, is based on the measurement of the base reactions with a high frequency force balance (HFFB). Both techniques have advantages and disadvantages. For instance an obvious advantage of the MPSSP is that it yields an estimate of the entire wind load acting on the building therefore allowing, among other things, the estimate of any number of generalized forces. However the HFFB technique, developed and employed since the early 1980s [1,2], is the most commonly adopted in design practice. This is not only because of its greater technical simplicity (therefore higher speed and considerably lower costs) compared to the MPSSP method, but also because it overcomes some technical difficulties inherent to the pressure measurement technique, namely the large number of pressure taps that are needed to adequately define the integrated wind load (in theory, an infinite number) and the fact that pressure taps are not capable of estimating the frictional component of the wind pressure field.

The most commonly adopted approach to using the HFFB measurements for defining the wind loads acting on tall buildings exploits the relation between the base moments and the first three (fundamental) generalized forces. Indeed, under certain ideal conditions, the two will coincide [3]. In general however, this coincidence does not hold and appropriate correction schemes must be defined. Over the past thirty years a number of these last have been proposed by several authors [4–8]. Apart from the earliest proposals, that were based on empirical considerations [9], a matrix of mode shape correction (MSC) coefficients is generally defined by assuming a wind loading model in the frequency domain. The inherent dependency of the matrix on frequency was neglected by the models proposed in [5–7] while more recently models have been proposed that are frequency-dependent [8,10]. Due to the inherent impossibility of estimating the generalized forces associated to the higher modes, the approaches based on MSC

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coefficients are generally considered suitable for giving estimates of the resonant components of the response parameters, but not for the background, where the contribution of the higher modes has seen to be important [11–14].

An alternative approach to the one outlined above attempts to identify spatio-temporal/-frequency varying wind loads over the building height calibrated from the experimentally measured base reactions [15–18]. In this approach, analytical wind loading models are defined or in the frequency domain [15,16,18] or in the time domain [17].

The fundamental difficulty of both approaches previously introduced and of any attempt to define the wind loads from a limited number of resultant measurements lies in the obvious need to assume at some point a wind loading model over the building height that may or may not coincide with the actual wind load distribution. The ultimate effect of this is the introduction of uncertainties (termed in this paper aerodynamic uncertainties) in the load estimation. The quantification of the errors induced by these aerodynamic uncertainties has not received attention over the years. This is partly due to the predominance of tall buildings with uncoupled dynamic modes where these errors are thought to be negligible. However modern tall buildings are often characterized by complex geometric forms and therefore coupled dynamic modes [19–22]. In this case the assumption of negligible errors could be unreasonable.

The aim of this paper is to investigate the propagation of the aerodynamic uncertainties, concerning the estimation of the wind loads from the base reactions, to the critical response parameters of fundamental importance for the structural design of tall buildings.

2. The use of HFFB measurements in the structural analysis of tall buildings

2.1. Wind-induced response in the frequency domain

For an n-story building modeled with three degrees of freedom for each story the equation of motion in terms of generalized coordinates $\{q\}$ can be expressed as:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{Q(t)\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the generalized matrices of masses, damping and stiffness respectively and $\{Q(t)\}$ is the generalized force vector, whose jth component is given by:

$$Q_j = \{\phi^j\}^T\{F\} = \{\phi^j_x\}^T\{F_x\} + \{\phi^j_y\}^T\{F_y\} + \{\phi^j_\theta\}^T\{F_\theta\} \tag{2}$$

where $\{\phi^j_s\},\ s = x, y, \theta$, is the $n \times 1$ sub-vector of the jth mode shape vector $\{\phi^j\}$ containing the components in the s direction and $\{F\}$ is the wind excitation time history vector (floor load vector). In the particular case that the mode shapes are characterized by displacements in only one of the directions x, y or θ, they are defined as uncoupled, while in general they will be coupled. In the frequency domain, the estimation of the spectra of the generalized forces $S_{Q_{jk}}$, $j,k = 1, \ldots, N$ (with $N = 3n$) allows firstly the estimation of the second order statistics of the generalized displacements, $\sigma^2_{q_{jk}}$, and then the determination of the RMS of the response parameter of interest. In particular, following the framework proposed in [3] (here briefly summarized for the sake of completeness), the resonant and background components of the variances $\sigma^2_{q_{jj}}$ of the generalized displacements can be expressed as:

$$\sigma^2_{q_{jjb}} \approx \frac{1}{k_j^2}\int_0^\infty S_{Q_{jj}}(f)df \tag{3}$$

$$\sigma^2_{q_{jjr}} \approx \frac{1}{k_j^2}\frac{\pi}{4\xi_j} f_j S_{Q_{jj}}(f_j) \tag{4}$$

where f is the frequency while k_j, f_j and ξ_j are the jth generalized stiffness, modal frequency and damping ratio respectively. Analogously, the background and resonant components of the covariances $\sigma^2_{q_{jk}}$ are given by:

$$\sigma^2_{q_{jkb}} \approx \frac{1}{k_j k_k}\int_0^\infty \mathrm{Re}[S_{Q_{jk}}(f)]df \tag{5}$$

$$\sigma^2_{q_{jkr}} = \mathrm{Re}\left[\int_{f'}^\infty \mathcal{H}_j(f)\mathcal{H}_k^*(f)S_{Q_{jk}}(f)df\right] \tag{6}$$

where $\mathcal{H}_j(f)$ is the complex transfer function:

$$\mathcal{H}_j(f) = \frac{1}{k_j[1-(f/f_j)^2 + 2i\xi_j f/f_j]} \tag{7}$$

and $\mathcal{H}_j^*(f)$ is the complex conjugate of $\mathcal{H}_j(f)$.

As for the correlation coefficients, the following expressions can be obtained for the background:

$$r_{q_{jkb}} = \frac{\int_0^\infty \mathrm{Re}[S_{Q_{jk}}(f)]df}{\sqrt{\int_0^\infty S_{Q_{jj}}(f)df}\sqrt{\int_0^\infty S_{Q_{kk}}(f)df}} \tag{8}$$

while the resonant correlation coefficient can be calculated through the expression given by Der Kiureghian [23]:

$$r_{q_{jkr}} = \frac{\mathrm{Re}[S_{Q_{jk}}(\bar{f})]}{\sqrt{S_{Q_{jj}}(\bar{f})}\sqrt{S_{Q_{kk}}(\bar{f})}}\rho_{jkr} = \alpha_{jk}\rho_{jkr} \tag{9}$$

where $\bar{f}$ is a frequency value equal to f_j or to f_k, and ρ_{jkr} is given by:

$$\rho_{jkr} = \frac{8\sqrt{\xi_j\xi_k}(\kappa_{jk}\xi_j + \xi_k)\kappa_{jk}^{2/3}}{\left(1-\kappa_{jk}^2\right)^2 + 4\xi_j\xi_k\kappa_{jk}\left(1+\kappa_{jk}^2\right) + 4\left(\xi_j^2+\xi_k^2\right)\kappa_{jk}^2} \tag{10}$$

where $\kappa_{jk} = f_j/f_k$. The combined correlation coefficient for the jth and kth generalized displacements is then expressed as:

$$r_{q_{jk}} = \frac{\sigma^2_{q_{jk}}}{\sigma_{q_j}\sigma_{q_k}} = \frac{r_{q_{jkb}}\sigma_{q_{jjb}}\sigma_{q_{kkb}} + r_{q_{jkr}}\sigma_{q_{jjr}}\sigma_{q_{kkr}}}{\sqrt{\sigma^2_{q_{jjb}} + \sigma^2_{q_{jjr}}}\sqrt{\sigma^2_{q_{kkb}} + \sigma^{2}_{q_{kkr}}}} \tag{11}$$

The second order statistical parameters of the generalized accelerations can be estimated again through approximate expressions. The background components can be considered negligible in comparison to the resonant components, hence $\sigma^2_{\ddot{q}_{jj}} \equiv \sigma^2_{\ddot{q}_{jjr}}$ and $\sigma^2_{\ddot{q}_{jk}} \equiv \sigma^2_{\ddot{q}_{jkr}}$. The following expressions holds (e.g. [24,25]):

$$\sigma^2_{\ddot{q}_{jj}} \approx \frac{\pi f_j}{4\xi_j m_j^2} S_{Q_{jj}}(f_j) \tag{12}$$

$$\sigma^2_{\ddot{q}_{jk}} = r_{q_{jkr}}\sigma_{\ddot{q}_{jj}}\sigma_{\ddot{q}_{kk}} \tag{13}$$

Once the second order statistics of the generalized displacements are estimated, it is possible to determine the variance and covariance of any response parameter of interest. First of all, through the modal superposition, the following equation:

$$\sigma^2_{spi} = \sum_{j=1}^N \phi^j_{si}\phi^j_{pi}\sigma^2_{q_{jj}} + \sum_{\substack{j=1 \\ j\neq k}}^N \sum_{k=1}^N \phi^j_{si}\phi^k_{pi} r_{q_{jk}}\sigma_{q_{jj}}\sigma_{q_{kk}} \tag{14}$$

for $s,p = x,\ y,\ \theta$ gives the variances ($p = s$) and covariances of the Lagrangian displacements at the reference center of the ith floor. Then, the Lagrangian displacement variance of a point C_i belonging to the same floor ($z = z_i$), whose coordinates (x,y) are (R_x,R_y), can be obtained from:

$$\sigma^2_{d_{C_i}} = \sigma^2_{xxi} + \sigma^2_{yyi} + \left(R_x^2 + R_y^2\right)\sigma^2_{\theta\theta i} - 2R_y\sigma^2_{x\theta i} + 2R_x\sigma_{y\theta i} \tag{15}$$

For the accelerations analogous expressions hold.