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Evaluation of peak resultant response for wind-excited tall buildings

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ABSTRACT

The traditional peak factor approach and combination rules developed for Gaussian scalar combination effects are not applicable for vectorial combination effects which feature non-Gaussian characteristics. This paper addresses the evaluation of the peak value of a vectorial resultant response of a wind-excited tall building resulting from correlated three-dimensional responses with a special focus on building acceleration. The peak value of the resultant response over a given duration is analyzed based on the upcrossing theory for non-Gaussian processes and for vector-valued Gaussian processes. A parametric study including the correlation of response components and their derivative processes is conducted to identify the controlling parameters in estimating the upcrossing rate and peak resultant response. The accuracy of the current empirical combination approaches is evaluated. A practical combination scheme is proposed and demonstrated using a wind-excited tall building with three-dimensional mode shapes. The results show that the existence of eccentricity leads to coupled alongwind, crosswind and torsional accelerations, and considerably amplifies the peak resultant acceleration.

1. Introduction

Dynamic wind loadings on tall buildings generate building vibrations simultaneously in alongwind, crosswind and torsional directions. The response in each principle direction of a building with uncoupled one-dimensional (1-D) mode shapes can be determined independently through the fundamental modal response analysis. The peak (mean extreme) response over a given duration, say, one hour, is given as its standard deviation (STD) or root-mean-square (RMS) value multiplied by a peak factor [1]. The peak factor is calculated using a closed-form formula which was derived based on the upcrossing theory of Gaussian processes [2]. On the other hand, for buildings with coupled three-dimensional (3-D) mode shapes, the peak response in a principle direction is quantified by combining the peak modal responses using square-root-of-sum-square (SRSS) or complete-quadratic-combination (CQC) rules (e.g., [3,4]).

Assessment of building performance to strong winds involves the estimation of peak resultant effects contributed by coupled responses in principle directions. Most resultant responses, such as stresses at building columns, and building acceleration in a given floor location along a specific direction, are scalar combination effects, which can be assumed to be Gaussian processes. Their peak values can be determined from the peak responses in principle directions using SRSS or CQC or other simplified roles such as 40% and 75% rules. In the 40% rule, the peak value of two combined responses is estimated as the peak value of one response component plus 40% of the peak value of another component. On the other hand, the 70% rule estimates the peak value as 75% of the sum of the peak values of two response components. A number of studies concerning the scalar combination of alongwind, crosswind and even torsional wind load effects have been reported in literature [5–8]. These results have been reflected in current wind loading codes and standards (e.g., [9–11]).

However, some resultant responses of interest, such as the building acceleration at a given location regardless direction, are vectorial combinations of responses in principle directions. The vectorial combination effects are more relevant for wind-excited axi-symmetric structures such as chimneys and wind turbine towers. Most wind loading codes and standards have not explicitly addressed the assessment of peak vectorial combination effects. Concerning the resultant building acceleration which is critical for the assessment of building serviceability performance to strong wind, the approach reported by Isyumov [12] has been widely used in practice [13]. This approach combines the peak alongwind and crosswind accelerations using SRSS rule and then multiplies an empirical reduction factor for estimating the peak resultant

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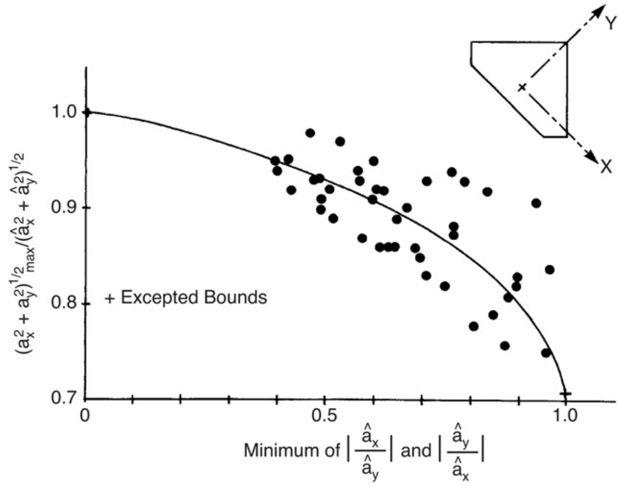

Fig. 1. Reduction factor for the extreme value of a combined tall building acceleration (From [12]).

acceleration. This reduction factor ranges between 0.7–1.0 and depends on the relative magnitudes of alongwind and crosswind components as shown in Fig. 1. A vectorial wind load effect from uncorrelated alongwind and acrosswind responses was discussed by Solari and Pagnini [7], in which the peak value was given as the length of the vector joining the origin of the alongwind and crosswind extreme response plane with the most distant point of a polygonal threshold. In these approaches, the influence of correlation between alongwind and crosswind responses, and the contribution of torsional response are not considered, while these can be considerably important for buildings with complex geometric configurations and 3-D dynamic characteristics.

Due to the lack of effective combination rules for estimating vectorial resultant responses, time domain approach has been increasingly utilized in practice to estimate the peak value directly from its time history samples. This approach, however, requires sufficient numbers of response samples for a robust estimation. Therefore, when the response is obtained from a wind tunnel testing, it leads to excessive wind tunnel time and data analysis efforts. In addition, the time domain approach may not be very suitable for full-scale field measurement data, where a sufficiently long time history record at a stationary wind condition is often not available. Furthermore, the time domain approach is not effective when the wind loadings are defined in terms of power spectra models, as it requires a Monte Carlo simulation of the time histories of wind loadings and subsequent step-by-step response analysis.

This paper addresses the estimation of peak value of a vectorial resultant response of wind-excited tall buildings with correlated 3-D responses with a special focus on building acceleration. The statistical moments and probability distribution function (PDF) of the resultant response are analyzed, which reveal its non-Gaussian characteristics. The peak value of resultant response over a given duration is analyzed based on the upcrossing theory for non-Gaussian processes and for vector-valued Gaussian processes. The upcrossing theory has been widely used in reliability analysis of structural systems over structural lifetime under dynamic loadings known as first-passage probability problem (e.g., [2,14–23]). The focus of this study, however, is placed on the mean extreme value of the resultant response over a relatively short duration, which has not been extensively addressed for wind-excited structures. A parametric study including the correlation of response components and their derivative processes is conducted to identify the controlling parameters in estimating the upcrossing rate and peak resultant response. The accuracy of the current empirical combination approach reported by Isyumov [12] and other simplified combination rules is evaluated. A practical combination scheme is proposed and demonstrated using a wind-excited tall building with 3-D coupled mode shapes.

2. Building response in a principle direction

A wind-excited tall building with 3-D coupled mode shapes is considered. A cartesian coordinate system with two orthogonal translational axes x and y and vertical axis z with the origin at the ground is used for describing the building system. The 3-D building response at the location with a coordinate $(0, 0, z)$ is denoted as $a_x(t)$, $a_y(t)$ and $a_\theta(t)$, respectively (Fig. 2). These response components are generally regarded as Gaussian processes, and are quantified through a dynamic analysis in either time or frequency domain under given wind loadings (e.g., [24–26,3,4]) or through wind tunnel or field measurements (e.g., [27,28]). The response $a_s(t) (s = x, y, \theta)$ is expressed in terms of the generalized displacements of the three fundamental modes $q_i(t)$ $(i = 1, 2, 3)$ as

$$a_s(t) = \phi_{1s}q_1(t) + \phi_{2s}q_2(t) + \phi_{3s}q_3(t) \tag{1}$$

where ϕ_{is} $(i = 1, 2, 3;\ s = x, y, \theta)$ is the participation coefficient of ith mode.

The variance of $a_s(t)$ is given by

$$\sigma_{as}^2 = \sum_{i=1}^{3}\sum_{j=1}^{3}\phi_{is}\phi_{js}\rho_{ij}\sigma_{q_i}\sigma_{q_j} \tag{2}$$

where $\sigma_{q_i} (i = 1, 2, 3)$ is the STD of ith generalized displacement; and ρ_{ij} is the correlation coefficient between ith and jth modes, which depends on not only the modal frequencies and damping ratios, but also the coherency of the generalized forces [3,4].

The CQC combination rule of Eq. (2) is often approximately extended to the peak value as follows when the peak factors for different modal responses are not distinctly different:

$$a_{s\max} \approx \left(\sum_{i=1}^{3}\sum_{j=1}^{3}\phi_{is}\phi_{js}\rho_{ij}g_i g_j\sigma_{q_i}\sigma_{q_j}\right)^{1/2} \tag{3}$$

where g_i is the peak factor for ith modal response given as [1]

$$g_i = \sqrt{2\ln(\nu_{0i}T)} + \frac{\gamma}{\sqrt{2\ln(\nu_{0i}T)}} \tag{4}$$

$\nu_{0i} = \sigma_{\dot{q}_i}/(2\pi\sigma_{q_i})$ is the mean upcrossing rate of $q_i(t)$ at the zero mean; $\sigma_{\dot{q}_i}$ is the STD of the derivative process $\dot{q}_i(t)$; T is the duration; and $\gamma = 0.5772$ is the Euler's constant. When the resonant modal response is dominant, $\sigma_{\dot{q}_i} \approx (2\pi f_i)\sigma_{q_i}$ and $\nu_{0i} \approx f_i$ where f_i is the ith modal frequency.

It should be mentioned that the proceeding peak factor formula was derived based on one-sided upcrossing (so-called "B-type barrier") of Gaussian process. In the case where the peak value of the absolute response process is considered, the double-sided upcrossing ("D-type barrier") should be used in which ν_{0i} in Eq. (4) is replaced by $2\nu_{0i}$.

When the acceleration is of concern, the generalized modal displacements should be replaced by the modal accelerations in the aforementioned formulations. The modal acceleration is a narrow band process with a central frequency of the corresponding modal frequency. The STD of the ith modal acceleration is calculated as $\sigma_{\ddot{q}_i} = (2\pi f_i)^2\sigma_{q_i}$.

3. Resultant response as a scalar combination effect

Consider a resultant response $V(t)$ which is related to the responses along principle directions as

$$V(t) = B_x a_x(t) + B_y a_y(t) + B_\theta a_\theta(t) \tag{5}$$

where B_s $(s = x, y, \theta)$ is the contribution coefficient of principle response.