Engineering Structures 56 (2013) 766–778

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Estimation of stochastic crosswind response of wind-excited tall buildings with nonlinear aerodynamic damping

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ARTICLE INFO

Article history:
Received 8 March 2013
Revised 28 May 2013
Accepted 30 May 2013

Keywords:
Crosswind response
Vortex-induced vibration
Aerodynamic damping
Extreme value distribution
Peak factor
Wind loading
High-rise buildings

ABSTRACT

This study addresses the analysis of crosswind response of tall buildings and flexible structures at wind speed region higher than the vortex lock-in speed, where nonlinear negative aerodynamic damping effect is significant. The modeling of nonlinear aerodynamic damping as a function of time-varying velocity and/or displacement of vibration is established based on motion-induced aerodynamic force information obtained from forced-vibration model testing in wind tunnel, referred to as harmonic balance. Response time history simulations are performed by solving the nonlinear equation of motion to explore the unique hardening non-Gaussian characteristics of crosswind response and its extreme value distribution with reduced peak factor. The response time history simulations also provide a bases for assessing the performance of analytical predictions of root-mean-square (RMS) response using crosswind loading spectrum and equivalent aerodynamic damping models. The limitations of the equivalent aerodynamic damping models as functions of RMS response derived from harmonic balance and statistical linearization with an assumption of Gaussian response are revealed. This study, at the first time, by using the method of equivalent nonlinear equation, presents complete analytical solutions of crosswind response statistics, including not only the RMS response, but also response kurtosis, response probability distribution, peak factor and extreme value distribution. The comparison of the analytical predictions with response simulation results illustrates that the method of equivalent nonlinear equation is very accurate in predicting crosswind response statistics that are influenced by the nonlinear aerodynamic damping. The narrow band feature of response is further considered in this study in the calculation of crossing rate using amplitude process, which leads to even better predictions of extreme statistics. This general framework can also be readily adopted in design codes and standards for calculating vortex-induced vibration of towers and chimneys.

1. Introduction

Crosswind response excited by separation and vortex shedding of the wake flow is an important and often dominant component for wind-resistant design of tall buildings and flexible structures. With a decrease in structural frequency of super tall and flexible structures, the design reduced wind speed increases. As a result, crosswind response at wind speed region higher than the vortex lock-in wind speed must be addressed. The aerodynamic damping that is a nonlinear function of velocity and/or displacement of vibration plays an important role in the generation of crosswind response and determination of response characteristics. The crosswind response of tall buildings with various geometric configurations under boundary layer wind flows has been studied extensively in literature (e.g., [27,20,21,26,24,3,41,32,16,37]). The high-frequency-force-balance (HFFB) technique has widely been used to quantify crosswind base bending moment on a rigid building model, that is then used to estimate the generalized force with an empirical mode shape correction when the building mode shape is nonlinear (e.g., [22,38,8]). The synchronous measurement of multiple pressures on rigid building model surface in wind tunnel, on the other hand, provides more detailed description of spatio-temporally varying crosswind load on buildings (e.g., [37]). To characterize the motion-induced (self-excited) wind loading, forced-vibration test with harmonic vibration of building model is carried out, and the corresponding wind load is determined using HFFB measurement or pressure integration [41,31,29,11,18,19]. Aeroelastic model test in wind tunnel is a reliable tool for investigating crosswind response with aeroelastic effect, which can also be used to gain information on aerodynamic damping [3,17,18,9]. It should be emphasized that the aerodynamic damping is affected by wind characteristics especially the turbulence characteristics (e.g., [41,42]). These studies have greatly improved

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http://dx.doi.org/10.1016/j.engstruct.2013.05.044

our understanding on the generation mechanics of crosswind load and structural response, and enhanced our ability to predict crosswind response of tall buildings and flexible structures.

Predictive tools that allow estimations of crosswind response from wind load and structural characteristics are very useful and valuable especially in earlier stages of design. When wind speed is apparently lower than the vortex lock-in speed, the aerodynamic damping is positive and also not significant, thus its effect is often neglected in response analysis which is at least conservative (e.g., [20,3]). The root-mean-square (RMS) value or standard deviation (STD) of crosswind response can be readily estimated from loading power spectrum based on random vibration theory. The peak factor defined as the ratio of mean extreme response to RMS response can be calculated using Davenport's formula [12], generally ranging from 3.5 to 4.5. However, when the nonlinear aerodynamic damping effect is significant, the nonlinear damping must be represented in an equivalent damping as a function of RMS response in order to estimate the RMS response from the wind loading spectrum. The equivalent damping associated with a stochastic crosswind response is often calculated following the same model for harmonic vibration. A different damping model can also be derived based on statistical linearization scheme with a further assumption of Gaussian response. These aerodynamic damping models may not well represent the actual aerodynamic damping associated with stochastic crosswind response having non-Gaussian characteristic. As a result, the predicted RMS response is often not in good agreement with aeroelastic model testing.

More importantly, as revealed by aeroelastic model tests, full-scale measurements and analytical simulations of crosswind vibration, the nonlinear aerodynamic damping results in a unique distribution of extreme response with a peak factor much lower than that of Gaussian response [2,40,41,31,9]. Chen [6,7] pointed out that the non-Gaussian characteristic of crosswind response resulted from nonlinear negative aerodynamic damping is a primary contributor to cause the unique extreme response distribution. A practical framework was introduced in Chen [6] for calculating the peak factor and coefficient of variation (COV) of extreme crosswind response based on its kurtosis and bandwidth parameter. Another approach based on crossing rate analysis was also presented in Chen [7]. The effectiveness and accuracy of these frameworks have been illustrated by simulated crosswind response and full-scale measurement data. These frameworks are particularly useful when only a small number of response time history samples are available. However, it should be emphasized that an analytical framework, which enables estimation of peak factor and extreme value distribution of crosswind response directly based on prescribed nonlinear aerodynamic damping model, will be more useful for structural design applications and parametric studies. Such a predictive tool has not yet been developed.

In this study, the modeling of aerodynamic damping as a nonlinear function of time-varying displacement and/or velocity of building vibration is addressed based on motion-induced force information derived from forced-vibration testing with harmonic motion. The response characteristics of crosswind response with nonlinear damping effect is examined using time domain response simulations of a squared tall building. The limitation of current modeling of equivalent aerodynamic damping used for estimating RMS value of stochastic crosswind response is identified. The hardening non-Gaussian characteristic, reduced peak factor, and the effectiveness of the framework introduced by Chen [6] are examined. The method of equivalent nonlinear equation (ENLE) is applied to represent the system equation with nonlinear aerodynamic damping. It provides, at the first time, complete analytical solutions of crosswind response statistics, including not only RMS response, but also response kurtosis, response probability distribution, peak factor and extreme value distribution. The accuracy of the analytical predictions is illustrated through comparisons with time domain simulations. The framework can also be readily adopted in design codes and standards for calculating vortex-induced vibration of towers and chimneys. The framework presented for the analysis of stochastic crosswind response of nonlinear structural systems also lays a foundation for further considerations of uncertain structural and aerodynamic parameters (e.g., [23,28]).

2. Equation of motion of crosswind response

The equation of crosswind response of a wind-excited tall building in terms of first modal response is expressed as

$$M_s(\ddot{y}_1 + 2\xi_s\omega_s\dot{y}_1 + \omega_s^2 y_1) = Q(t) \tag{1}$$

$$M_s = \int_0^H m(z)\phi^2(z)dz; \quad Q(t) = \int_0^H L(z,t)\phi(z)dz \tag{2}$$

where M_s, $\omega_s = 2\pi f_s$, and ξ_s are generalized mass, modal frequency and damping ratio; y_1 is generalized crosswind displacement; $Q(t)$ is generalized crosswind force; $L(z,t)$ is crosswind force per unit height at elevation z above the ground; $\phi(z)$ is mode shape; and H is building height. When the mode shape is normalized such that $\phi(H) = 1$, the generalized displacement y_1 is the building tip displacement.

The HFFB technique is often used to quantify the generalized force through measurement of base bending moment in wind tunnel without knowing the spatial-temporally varying wind load $L(z,t)$. The base bending moment is separated into motion-induced (self-excited) and buffeting components, and expressed as

$$M(t) = \int_0^H zL(z,t)dz = \frac{1}{2}\rho U^2 BH^2(C_{Mse}(t) + C_{Mb}(t)) \tag{3}$$

where ρ is air density; U is wind speed at the building top; and B is building width; and $C_{Mse}(t)$ and $C_{Mb}(t)$ are motion-induced and buffeting components of base bending moment coefficient.

The generalized force is then estimated as

$$Q_{se}(t) = \frac{1}{2}\rho U^2 BH(\eta_{se}C_{Mse}(t) + \eta_b C_{Mb}(t)) \tag{4}$$

where η_{se} and η_b are empirical mode shape correction factors. It is evident that in the case of linear mode shape, i.e., $\phi(z) = z/H$, $\eta_{se} = 1$ and $\eta_b = 1$. In general, the mode shape correction factors depend on mode shape and also on the unknown distribution of dynamic wind loading $L(z,t)$, and thus are given empirically.

The self-excited moment coefficient $C_{Mse}(t)$ is often determined using forced-vibration model testing in wind tunnel, where the model is forced to have a harmonic vibration in terms of normalized non-dimensional displacement $y(t) = y_1(t)/B = y_{\max}\sin(\omega t)$ with a linear mode shape. The corresponding moment coefficient $C_{Mse}(t)$ is expressed as

$$C_{Mse}(t) = KH_1^*\frac{B\dot{y}}{U} + K^2H_4^* y \tag{5}$$

$$K^2H_1^* = \frac{\omega}{\pi y_{\max}}\int_0^{2\pi/\omega} C_{Mse}(t)\cos(\omega t)dt \tag{6}$$

$$K^2H_4^* = \frac{\omega}{\pi y_{\max}}\int_0^{2\pi/\omega} C_{Mse}(t)\sin(\omega t)dt \tag{7}$$

where $K = \omega B/U$ is reduced frequency; and H_1^* and H_4^* are aerodynamic derivatives and are functions of reduced frequency, representing out-of-phase (damping) and in-phase (stiffness) components with displacement, respectively. At the vicinity of vortex lock-in region, the self-excited force shows clear nonlinearity with respect to vibration amplitude $y_{\max} = y_{1\max}/B$. Therefore, the aerodynamic derivatives H_1^* and H_4^* are functions of both reduced frequency and amplitude $y_{\max}$, i.e., $H_1^* = H_1^*(K, y_{\max})$ and