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Crosswind response of tall buildings with nonlinear aerodynamic damping and hysteretic restoring force character

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ABSTRACT

This study deals with analysis of stochastic crosswind response of tall buildings with bilinear hysteretic restoring force character at the vicinity of vortex lock-in speed where nonlinear negative aerodynamic damping is significant. The nonlinear aerodynamic damping at a given wind speed and the hysteretic damping resulted from hysteretic restoring force are modelled as polynomial functions of amplitude of narrow-band building response. It permits analytical estimations of response statistics by using equivalent nonlinear equation (ENEL) approach, which include root-mean-square value, kurtosis, extreme value distribution and fatigue damage. Response history analysis is also performed to prove the accuracy of this analytical framework. A comprehensive parameter study is carried out to shed insights on the characteristics of inelastic crosswind response. This study also illustrates the advantage of the ENLE approach over the statistical linearization approach with assumption of Gaussian response distribution when applied to estimate inelastic crosswind response at wind speed region with negligible aerodynamic damping. This study not only presents an effective analytical approach but also sheds new insights towards improved understanding of inelastic crosswind response of tall buildings, contributing to a safer and more economical design of tall buildings against strong winds.

1. Introduction

Tall buildings and other flexible structures such as chimney and towers tend to be more flexible and more sensitive to crosswind loading caused by vortex shedding (e.g., Kareem, 1982; Kwok, 1982; Boggs, 1992; Kawai, 1992; Cheng et al., 2002; Repetto and Solari, 2006; Tanaka et al., 2012). With a decrease in structural frequency, the reduced wind speed increases such that the crosswind response at the vicinity of vortex lock-in wind speed needs to be carefully studied. At the vicinity of lock-in wind speed, crosswind response is affected by both self-excited and buffeting forces and the nonlinear aerodynamic damping effect resulted from the self-excited force becomes significant. The time variation of crosswind response is between a steady sinusoidal variation and a stochastic process and has a lower peak factor and fatigue damage than that of traditional buffeting response (e.g., Vickery and Basu, 1983; Basu and Vickery, 1983; Vickery and Steckley, 1993; Ohkuma et al., 1994; Chen, 2013, 2014a, 2014b). Chen (2013, 2014a) showed that the nonlinear aerodynamic damping effect drives the crosswind response to have hardening non-Gaussian distribution, which is responsible to the reduced peak factor and fatigue damage. The traditional effective damping approach for modelling the nonlinear aerodynamic damping cannot provide accurate estimations of root-mean-square (RMS) response, extreme value distribution and fatigue damage. Chen (2013) presented complete analytical solutions of crosswind response statistics using equivalent nonlinear equation (ENLE) approach, which include not only RMS response, but also response kurtosis, probability distributions of vibration displacement and amplitude, and extreme value distribution. The ENLE approach also gives closed-form estimation of fatigue damage (Chen, 2014b). Chen (2013, 2014a, 2014b) also presented approaches of estimating peak factor and fatigue damage using response kurtosis based on translational process theory.

Tall buildings and other structures with hysteretic dampers and base isolation systems have inelastic restoring force characteristics (Sato et al., 2008; Katagiri et al., 2014; Ikegami et al., 2014). The crosswind response of these structures at the vicinity of vortex lock-in wind speed is of interest in structural design. In addition, there is a need to push the envelope of current linear elastic design framework and to develop a better understanding of inelastic crosswind response of structures when aeroelastic effect is significant. Feng and Chen (2017) introduced statistical linearization approaches for estimating inelastic crosswind response where the nonlinear aerodynamic damping effect was not accounted. The results demonstrated that the crosswind response can be reduced considerably due to hysteretic damping associated with inelastic response.

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This study presents an analytical framework for estimating stochastic crosswind response of tall buildings with both nonlinear aerodynamic damping and bilinear hysteretic restoring force character. To obtain closed-form solutions, both the nonlinear aerodynamic damping and bilinear hysteretic damping are represented in terms of polynomial functions of amplitude of narrow-band response. This permits analytical estimations of response statistics using ENLE approach, which include RMS response, kurtosis, extreme value distribution and fatigue damage. The analytical estimations are compared with those from response time history simulations. The results demonstrate that the ENLE approach is able to give accurate estimation of response statistics. Using this newly established analytical framework, parametric studies are carried out to examine the inelastic crosswind response with consideration of nonlinear aerodynamic damping effect. This study also reexamines the inelastic crosswind response using the ENLE approach at wind speed region where the aerodynamic damping can be neglected. The results show the advantage of the ENLE approach over the statistical linearization approach for estimating narrow-band crosswind response.

2. Analytical framework

2.1. Equation of crosswind response

The equation of building motion under crosswind excitation in terms of first modal response is expressed as:

$$M_s\ddot{x}_1+2M_s\omega_s\xi_s\dot{x}_1+f(x_1,\dot{x}_1)=Q(t) \tag{1}$$

$$M_s=\int_0^H m(y)\phi^2(y)dy;Q(t)=1/2\rho U^2BH(\eta_{se}C_{Mse}(t)+\eta_bC_{Mb}(t)) \tag{2}$$

where M_s and ξ_s are generalized mass and damping ratio; ω_s is natural modal frequency calculated by using the initial generalized stiffness k, i.e., $\omega_s=2\pi f_s=\sqrt{k/M_s}$; $f(x_1,\dot{x}_1)$ is the generalized hysteretic restoring force; x_1 is generalized displacement, and is the building top displacement when mode shape $\phi(y)$ is normalized as $\phi(H)=1$; $Q(t)$ is generalized force, which is given by the base bending moment including self-excited (motion-induced) and buffeting components with mode shape correction factors η_{se} and η_b. For the linear mode shape, i.e., $\phi(y)=y/H$, $\eta_{se}=\eta_b=1$; $m(y)$ is building mass per unit height; ρ is air density; U is wind speed at building top; B is building width; H is building height; and $C_{Mse}(t)$ and $C_{Mb}(t)$ are self-excited (motion-induced) and buffeting components of base bending moment coefficient, which are determined by high-frequency-force-balance (HFFB) measurement in wind tunnel.

The bilinear hysteretic restoring force $f(x_1,\dot{x}_1)$ as shown in Fig. 1 can be expressed as (e.g., Lutes and Sarkani, 2004):

$$f(x_1,\dot{x}_1)=\alpha kx_1+(1-\alpha)kz_1 \tag{3}$$

$$\dot{z}_1=\dot{x}_1\{1-u(z_1-x_{y1})u(\dot{x}_1)-u(-z_1-x_{y1})u(-\dot{x}_1)\} \tag{4}$$

where α is ratio of the second stiffness to initial stiffness k; z_1 is hysteretic displacement; $u(\bullet)$ is unit step function; and x_{y1} is yield displacement. For linear system, $\alpha=1$, and $z_1(t)=x_1(t)$.

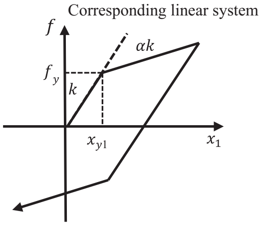

Fig. 1. Bilinear hysteretic force model.

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 $x(t)=x_1(t)/B=x_{max}\sin(\omega t)$ with a linear mode shape. The measured moment coefficient $C_{Mse}(t)$ is expressed in terms of vibration displacement and velocity as

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

where $K=\omega B/U$ is reduced frequency and $2\pi/K=U/fB$ is reduced wind speed; H_1^* and H_4^* are aerodynamic derivatives and are functions of reduced frequency and vibration amplitude, representing aerodynamic damping and stiffness effects, respectively.

The influence of aerodynamic stiffness on structural frequency is negligibly small, thus the equation of motion in terms of non-dimensional displacement is represented as

$$\ddot{x}+2\omega_s(\xi_s+\xi_a)\dot{x}+\alpha\omega_s^2x+(1-\alpha)\omega_s^2z=\frac{1}{2}\left(\frac{\rho B^2}{m_s}\right)\left(\frac{U^2}{B^2}\right)\eta_b\eta C_{Mb}(t) \tag{6}$$

$$\dot{z}=\dot{x}\{1-u(z-x_y)u(\dot{x})-u(-z-x_y)u(-\dot{x})\} \tag{7}$$

$$\xi_a=-\frac{1}{4}\left(\frac{\rho B^2}{m_s}\right)\eta_{se}\eta H_1^* \tag{8}$$

$$m_s=\frac{M_s}{\int_0^H\phi^2(y)dy};\eta=\frac{H}{\int_0^H\phi^2(y)dy} \tag{9}$$

where $x=x_1/B;z=z_1/B;x_y=x_{y1}/B$ are non-dimensional displacements; ξ_a is aerodynamic damping ratio; m_s is effective building mass per unit height; η is a non-dimensional parameter related to mode shape, and $\eta=3$ in the case of linear mode shape.

Introducing the non-dimensional parameters and variables:

$$t^*=\omega_st;x^*(t^*)=\frac{x(t)}{x_y};z^*(t^*)=\frac{z(t)}{x_y};x^{*'}(t^*)=\frac{dx^*(t^*)}{dt^*}=\frac{\dot{x}(t)}{\omega_sx_y};$$
$$x^{*''}(t^*)=\frac{d^2x^*(t^*)}{dt^{*2}}=\frac{\ddot{x}(t)}{\omega_s^2x_y};z^{*'}(t^*)=\frac{dz^*(t^*)}{dt^*}=\frac{\dot{z}(t)}{\omega_sx_y} \tag{10}$$

the equation of motion is then expressed as:

$$x^{*''}+2(\xi_s+\xi_a)x^{*\prime}+\alpha x^*+(1-\alpha)z^*=\frac{1}{8\pi^2x_y}\left(\frac{\rho B^2}{m_s}\right)\left(\frac{U}{f_sB}\right)^2\eta_b\eta C_{Mb} \tag{11}$$

$$z^{*'}=x^{*'}\{1-u(z^*-1)u(x^{*'})-u(-z^*-1)u(-x^{*'})\} \tag{12}$$

This non-dimensional equation clearly reveals the influencing non-dimensional parameters on crosswind response. For instance, the influence of building frequency on response is reflected by the reduced wind speed U/f_sB.

2.2. Modelling of nonlinear aerodynamic damping

The aerodynamic damping ratio in Eq. (8) determined from forced-vibration testing with harmonic motion is denoted as ξ_{aeq}. At a given reduced frequency K, ξ_{aeq} is a nonlinear function of vibration amplitude x_{max} or RMS response $\sigma_x=x_{max}/\sqrt{2}$, and can be expressed as follows for $\xi_{aeq1}=m_s\xi_{aeq}/\rho B^2$:

$$\xi_{aeq1}(x_{max})=a_1+a_2x_{max}+a_3x_{max}^2 \tag{13}$$

where a_1, a_2 and a_3 are independent of amplitude x_{max}, but are function of reduced frequency K. While the second-order polynomial function for the aerodynamic damping is used here, the analysis framework can be readily extended to the case with a higher-order polynomial function.

An aerodynamic damping model as a nonlinear function of time-varying velocity and/or displacement is required for a stochastic response analysis. The nonlinear aerodynamic damping in terms of