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Analysis of crosswind response of base-isolated tall buildings considering nonlinear aerodynamic damping

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SUMMARY:

This study deals with analysis of stochastic crosswind response of base-isolated tall buildings at the vicinity of vortex lock-in speed where nonlinear negative aerodynamic damping is significant. Based on self-excited aerodynamic force information obtained from forced-vibration model test of the corresponding fixed-base building with harmonic vibration in wind tunnel, the self-excited wind loads on base-isolated building in phase of vibration velocity is modelling as a function of time-varying displacement and velocity of vibration. The relation between shear force and displacement of the base-isolation system is described by Bouc-Wen hysteretic model. The crosswind response characteristics are investigated through a comprehensive parametric study using an example tall building of 260 m high, which include root-mean-square response, peak response, peak factor and response kurtosis. This study also carries out a comprehensive parametric study to explore the effects of base isolation parameters on building response. The results of this study help in developing improved understanding of crosswind vortex-induced vibration response of base-isolated tall buildings.

Keywords: base-isolated tall buildings, vortex-induced vibration, aerodynamic damping

1. INTRODUCTION

The wind-induced uncoupled and coupled responses of base-isolated tall buildings have been studied in literature (e.g., Kareem, 1997; Katagiri et al., 2014). It has shown that when the base layer response is in linear elastic range, the upper building response is greater than that of corresponding fixed-base building due the reduced building frequency. On the other hand, at higher wind speeds the inelastic response of base isolation system introduces additional hysteretic damping that leads to reduced upper building response. For tall flexible base-isolated buildings, the response at the vicinity of vortex lock-in wind speed needs to be carefully studied where the negative aerodynamic damping must be considered (Chen, 2013). This study presents an analysis framework of crosswind response of base-isolated buildings considering amplitude-dependent aerodynamic damping. The crosswind response characteristics are investigated through a comprehensive parametric study using an example tall building of 260 m high. The results of this study help in developing improved understanding of crosswind vortex-induced vibration response of base-isolated tall buildings.

2. ANALYSIS APPROACH

In this study, the upper structure of base-isolated building is in linear elastic, which response is given by first modal response. The shear force and displacement hysteretic relation is described by Bouc-Wen hysteretic model. The buffeting force component is calculated as fixed-base buildings. And the self-excited force component proportional to stiffness is neglected, only the component proportional to velocity in terms of aerodynamic damping is considered. The self-excited generalized modal force and shear force can be expressed as:

$$Q_{1se}(t)=\frac{1}{2}\rho U^2 BH\left[kH_{1b}^{*}(k)\left(\frac{\dot{x}_b}{U}\right)+kH_{1s}^{*}(k)\left(\frac{\dot{q}_1}{U}\right)\right] \tag{1}$$

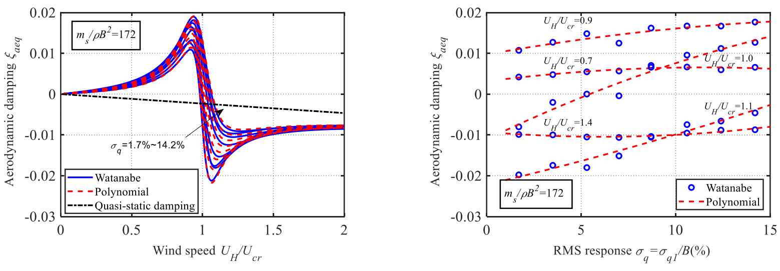
$$F_{se}(t)=\frac{1}{2}\rho U^2 BH\left[kH_{1Fb}^{*}(k)\left(\frac{\dot{x}_b}{U}\right)+kH_{1Fs}^{*}(k)\left(\frac{\dot{q}_1}{U}\right)\right] \tag{2}$$

Where ρ = air density; U = wind speed at building top; B = building width; H = building height; $k=\omega_s B/U$ is reduced frequency and U/fB = reduced wind speed; $\omega_s = 2\pi f$ is the first modal frequency; x_b = displacement of base slab relative to the ground; q_1 = the first generalized displacement; $H_{1b}^{*}(k), H_{1s}^{*}(k)$, $H_{1Fb}^{*}(k), H_{1Fs}^{*}(k)$ = aerodynamic derivatives are polynomial functions of both reduced frequency and displacement, which can be determined using forced-vibration test in wind tunnel (Vickery and Steckley, 1993; Watanabe et al., 1997).

3. CROSSWIND RESPONSE CHARACTERISTICS

3.1. Building Model

A 65-story tall base-isolated building with a square cross section in an urban area is considered. The building height is 260 m and width is 30 m. The building density is 192 kg/m^3. The story mass is assumed as a constant over the building height. The first modal frequency and damping ratio of upper building are 0.16 Hz and 1% with a linear mode shape. The damping matrix of upper building is assumed to be proportional to the stiffness matrix. The mass of the base isolation system is 4.08×10^5 kg. The initial stiffness of the base-isolation system is 402 kN/mm and the second stiffness ratio is 12%. The yield displacement is 0.025 m. The initial damping of the base-isolation system is ignored. The initial frequency with assumption of a rigid upper structure is 0.47 Hz. The first modal frequency of the base-isolated tall building is 0.15 Hz.



(a) ξ_{aeq} vs. U_H/U_{cr}

(b) ξ_{aeq} vs. σ_q

Figure 1. Aerodynamic damping of fixed-base building

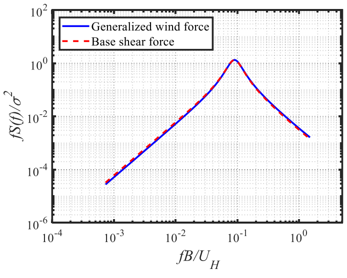


Figure 2. PSDs of the generalized wind force and base shear force

The aerodynamic damping ratio at each reduced wind speed is fitted into second order polynomial function of amplitude as (Chen, 2013)

$$\xi_{aeq1} = a_1(k) + a_2(k)\sigma_q + a_3(k)\sigma_q^2 \qquad (3)$$

where $\sigma_q = \sigma_{q_1}/B$ σ_{q_1} are RMS of building top displacement; a_1, a_2 and a_3 are independent of σ_q, but are functions of k. Fig.1a shows the equivalent aerodynamic damping ratio calculated using the empirical model introduced by Watanabe et al. (1997) based on wind tunnel data, where the σ_q ranges from 1.7% to 14.2%. In wind tunnel test, the power law exponent of mean wind speed profile was around 0.11, and turbulence intensity at the building height was about 6%. The Strouhal number is selected as S_t = 0.090. Fig.1b displays the equivalent aerodynamic damping ratio as a function of σ_q at various reduced wind speeds. The results from the curve-fitted polynomial function of σ_q (Chen, 2013) are also given for comparison. It is evident that the aerodynamic damping changes rapidly from positive to negative around the vortex lock-in speed, and remains negative at higher wind speeds.

3.2. Characteristics of Crosswind Response

Response history analysis is carried out at a given wind speed by solving the state-space equations using the Runge-Kutta method. The time step is 0.04 s and the duration is 13 min for each sample, where the first 3-min response is disregarded to eliminate potential transient response effect. The response of corresponding fixed-base building is calculated for comparison.

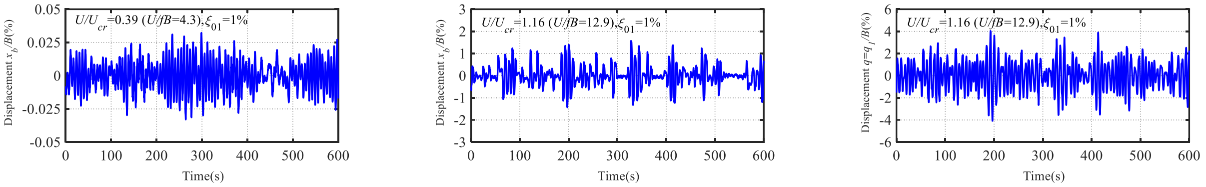
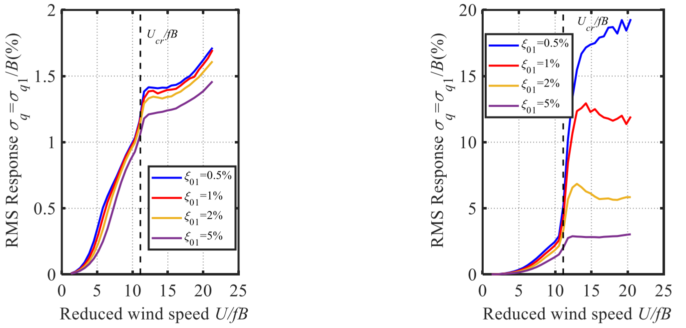


Figure 3. Crosswind response time history samples



(a) Base-isolated building

(b) Fixed-base building

Figure 4. RMS of top displacement

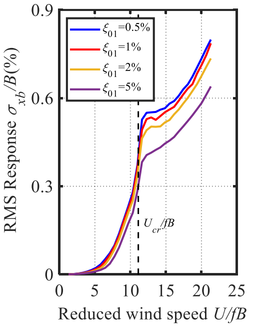
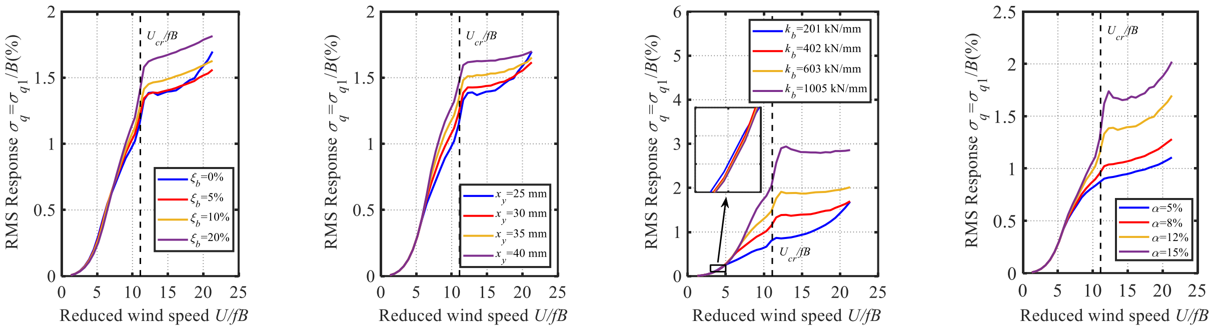


Figure 5. RMS of base displacement of base-isolated building

Fig.2 shows the PSDs of the generalized wind force and base shear force. Fig.3 displays typical response time history samples. The RMS responses are calculated from one hundred samples, and their ensemble averaged values are plotted in Fig.4-5. It is observed that compared with the fixed-base building, the top displacement response of the base-isolated building is significantly reduced. The base displacement response trends the same as that of the top. With the increase in structural damping, the effect of aerodynamic damping reduces. The displacement of base-isolated building is less sensitive to upper building damping. This is because the isolation layer is inelastic at higher wind speeds, damping ratio is primarily determined by the hysteretic damping and is less affected by upper building damping and aerodynamic damping. Fig.6 shows the influence of isolation layer parameters (including damping ratio, yield displacement, initial stiffness and second stiffness ratio) on the response of base-isolated tall buildings. The results show that the variation of parameters of isolation layer results in the change of the damping of isolation layer and hysteretic damping, which makes the response not monotonous with the increase of parameters. Therefore, in the design of base-isolated tall buildings, the scheme of choosing the proper the parameters of isolation layer for the reduction of upper building displacement is very important.



(a) Damping ratios (b) Yield displacement (c) Initial stiffness (d) Second stiffness ratio

Figure 6. RMS of top displacement under different parameters of base isolation system

4. CONCLUSIONS

This paper presents a framework for estimating the crosswind response of base-isolated tall buildings with amplitude-dependent aerodynamic damping. The results show that the system damping is increased by the hysteretic damping, leading to a reduction of crosswind response, and the influence of aerodynamic damping and structural damping is also reduced. The influence of parameters of base isolation system indicate that the increase of base displacement leads to an increase in hysteretic damping thus helps to reduce the effect of negative aerodynamic damping on building response.

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