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Improved expression for across-wind aerodynamic damping ratios of super high-rise buildings

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ABSTRACT

To study across-wind aerodynamic damping ratios of super high-rise buildings, wind tunnel tests of multi-degree-of-freedom (MDOF) aero-elastic models with various aspect ratios and mass-damping parameters were carried out. The relationship between aero-damping ratio and reduced wind velocity (V_r), wind field roughness, aspect ratio, structural mass, structural damping as well as across-wind displacement was investigated systematically. It was found that the positive aerodynamic damping ratio is negatively correlated with the structural damping ratio and structural mass at V_r lower than critical reduced velocity of resonance (V_c). However, when V_r is close to or slightly bigger than V_c, the absolute value of negative aerodynamic damping ratio is positively correlated with structural damping but negatively correlated with structural mass. Therefore, the empirical function based on aerodynamic damping ratio alone cannot be reliably established, because the aerodynamic damping ratio alone is insufficient to assess aerodynamic effects. Thus, these considerations lead to a proposal of the concept of reduced damping ratio. This concept allows an improved empirical function of aerodynamic damping ratio to be established. Effects of the aspect ratio, reduced wind velocity, wind field terrain, structural damping and mass density were all considered in this empirical function.

1. Introduction

Current trend of increasing taller and slender buildings results in that they may be prone to significant oscillation at a wind velocity below design value. The level of these oscillations may not be severe enough to cause structural damage but likely causes discomfort to building occupants. As is known, accurate information concerning the aerodynamic damping ratio is a prerequisite for accurately estimating wind induced responses, especially for across-wind response. There have been a number of studies of aerodynamic damping ratios of tall buildings. For example, Kareem (1982, 1996) reconstructed across-wind force spectra and calculated wind induced response through pressure measurements of a square-shaped building. Hayashida et al. (1992) studied the across-wind aerodynamic damping ratio of a square cylinder with an aspect ratio of 7.5. Vickery and Steckley (1993) found that, with augment of aerodynamic damping ratio, across-wind response can be more accurately estimated for a square cylinder. Marukawa et al. (1996) investigated the aerodynamic damping ratio of rectangular-shaped buildings and found the aerodynamic damping ratio is positive in along wind direction for all models, and negative in across-wind direction for slender buildings with small side ratio. Li et al. (2003) conducted full-scale measurements on a tall building with 70 floors. It is observed from his study that the effect of amplitude-dependent damping on dynamic responses is significant for accurately predicting wind-induced vibrations of tall buildings. Meanwhile, Huang et al. (2013), Gu et al. (2015), Katagiri et al. (1998), Tamura and Suganuma (1996) also examined the characteristics of the aerodynamic damping ratio of super-tall buildings.

A few expressions for aerodynamic damping ratios have been proposed by researchers. The empirical aerodynamic damping ratio function proposed by Watanabe et al. (1997) takes into account some physical conditions such as tip-amplitude, aspect ratio, building shape and turbulence intensity. Cheng et al. (2002) proposed three empirical functions to estimate the aerodynamic damping ratio with different mass-damping parameter. In these functions, the aerodynamic damping ratio was regarded as a function of wind velocity and mass-damping parameter. Quan et al. (2005) studied the effects of reduced wind velocity, terrain type, and structural damping ratio on the aerodynamic damping ratio, which allowed researchers to derive functions for aerodynamic damping

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ratios of square super high-rise building. However, the aerodynamic damping ratio was mainly considered as a function of wind velocity in above studies.

In this paper, the authors used multi-degree-of-freedom aeroelastic models to study across-wind vibration behavior of isolated square cylinders with aspect ratios of 10, 13 and 16, respectively. The relationship between aerodynamic damping and reduced wind velocity, wind field roughness, aspect ratio, structural mass, structural damping as well as across-wind displacement was analyzed. A new empirical aerodynamic damping ratio function for super tall buildings is proposed, which can take into account the influence of aspect ratio, reduced wind velocity, structural damping and structural mass.

2. Wind tunnel test

The wind tunnel test was conducted in a boundary layer wind tunnel in Wuhan University, China. The cross-section of the wind tunnel was 3.2 m wide × 2.1 m high. Two terrain categories (i.e., suburban and city center in China's Code 2012) were simulated using a set of spires and roughness elements upwind of building models. Mean velocity and turbulence intensity profiles in the wind tunnel are illustrated in Fig. 1 for two categories. The power-law of terrain suburban and city center is 0.16 and 0.30 respectively.

Three types of MDOF aeroelastic models were installed in the wind tunnel respectively. The models were square prisms with aspect ratios (λ) 10, 13, and 16, respectively. The models were fabricated as six-lumped-mass systems to simulate super-high-rise buildings of 600 m, 780 m, and 900 m high, respectively. The skeleton of MDOF models consisted of aluminum columns and rigid plates. Striking a balance between blockage ratio requirements and an easy operation, a length scale of 1: 600 was adopted. The same model scale was used for all three models, and is shown in Table 1.

Fig. 2 shows a model with an aspect ratio of 10. Holes were drilled in each of the model's rigid plates. The model was fitted with five fitted aluminum columns, including one thick column in the center and four flexible columns at four edges. Copper billets were fixed on each plate to adjust the required mass and mass moment of inertia. Damping was added by energy-dissipation material attached to the corners of each plate. The dynamic properties of each MDOF model are presented in Table 2.

$$M = \frac{\int_0^H m(z)\phi^2(z)d_z}{\int_0^H \phi^2(z)d_z} \tag{1}$$

Table 1
Similarity parameters.

Property	Modeling parameters	Similarities
Length	l_m/l_p	1/600
Time	n_m/n_p	100
Velocity	V_m/V_p	1/6
Density	ρ_m/ρ_p	1

Note: The subscript m and p denote the model and prototype building, respectively.

$$Sc = \frac{2M\xi_s}{\rho_a D^2} \tag{2}$$

where $m(z)$ and $\phi(z)$ are the mass per unit length and mode shape of MDOF model, respectively; H is the total height of MDOF model; ξ_s, ρ_a, and D is the structural damping ratio, air density and width of MDOF model, respectively.

The energy dissipation materials are light and flexible foam strips. As shown in Fig. 3, the rigid plate of each floor is square with chamfering angles, and there are six grooves on each foam strip. The foam strips were connected to rigid plates by chamfering angles and grooves. Various damping can be simulated by changing the geometry size of the foam strips. The foam strips are very light and flexible, so it can be assumed that the stiffness and mode shape of MDOF model was not influenced by the supernumerary added foam strips.

The dynamic parameters were determined by free vibration and wind induced vibration of the MDOF models. As an example, the time history of free vibration displacement, power spectrum, and wind induced acceleration spectrum of test conditions 1 and 4 were shown in Figs. 4–6 respectively. It can be seen, the 2nd order frequency is about 2.3–3.0 times of the 1st order frequency, and the wind induced vibration is dominated by the first order vibration for most conditions. The mode shapes of MDOF model were shown in Fig. 7.

3. Across-wind response of MDOF model

This section considers the standard deviation (STD) of the cross-wind displacement response (σ_y) due to vortex induced vibration (VIV) of MDOF model. As is known, vortex induced resonance (VIR) may occur when vortex shedding frequency is sufficiently close to natural frequency of vibration (Bearman, 2012; Larsen, 1994; Melbourne, 1997). In other words, VIR may occur when reduced velocity V_r defined in Eq. (3) is close to critical reduced velocity of resonance, which is about 10.5 for square prisms in smooth flow.

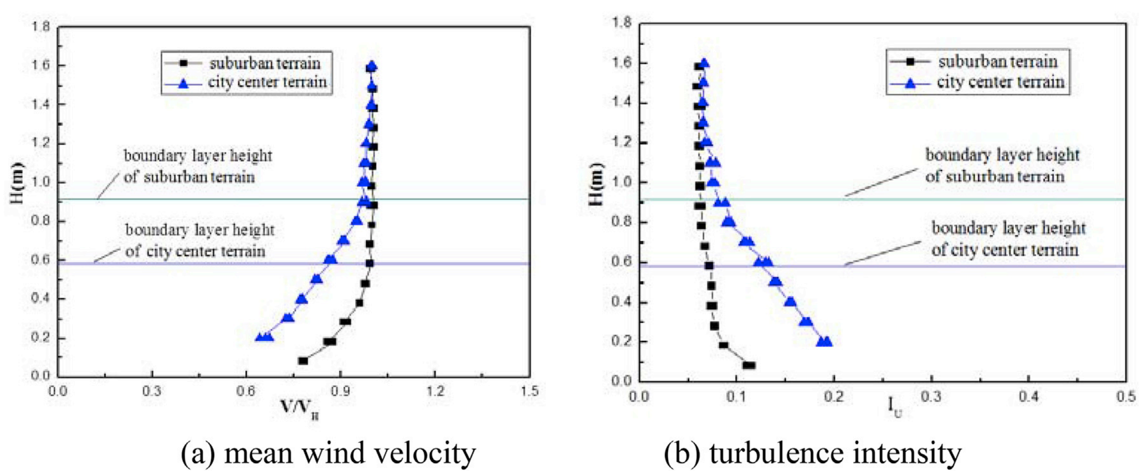

Fig. 1. Mean wind velocity and turbulence intensity.