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Experimental study of aerodynamic damping of a twisted supertall building

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ABSTRACT

The aerodynamic damping ratios and aeroelastic instability of a 180° helical supertall building with good aerodynamic behavior in both the along-wind and across-wind responses were investigated using an aeroelastic model test (rocking vibration model test). The aerodynamic damping ratios for the 180° helical and square models were evaluated using the random decrement technique. Furthermore, the effect of the triggering level and number of time segments on the evaluation of the aerodynamic damping ratio was also investigated. It was found that both the mean and fluctuating displacement responses of the 180° helical model in the along- and across-wind directions showed better aerodynamic behaviors than those of the square model. Aeroelastic instability of the 180° helical model was not observed at any of the reduced velocities considered in the study. In the along-wind direction, the aerodynamic damping ratios of the 180° helical model exhibit similar trends to those of the square model. However, in the across-wind direction, the aerodynamic damping ratios of the 180° helical model show significantly different trends than those of the square model. Furthermore, there was no effect of the variation in the wind direction on the aerodynamic damping ratio of the 180° helical model. We found that in the evaluation of the aerodynamic damping ratio, it is possible to adopt the triggering level at the value of the standard deviation or $\sqrt{2}$ times of the standard deviation of the displacement responses if the random decrement signature has a high number of triggering points.

1. Introduction

Supertall buildings have been constructed in many cities around the world to establish the cities' competency against other cities and for the improvement of their image, despite the economic depression that has been prevalent for many years. Further, supertall buildings are no longer being constructed in symmetrical shapes, such as rectangles, triangles, and circles; rather, there is an upsurge in the design of complicated sectional-shaped buildings in numerous countries. It is well known that supertall buildings are usually governed by their across-wind response rather than their along-wind response. The dynamic responses of tall buildings with corner modifications, such as chamfered, slotted, and tapered cross-sections (Davenport, 1988; Kwok et al., 1988; Kawai, 1998), and with complicated configurations, such as tapered, helical, and composite shapes (Cooper et al., 1997; Kim and You, 2002; Kim et al., 2008; Kim and Kanda, 2010; Tanaka et al., 2012) have been studied by many researchers for several decades. In particular, Tanaka et al. (2012) investigated the characteristics of aerodynamic forces and wind pressures acting on tall buildings to evaluate the most effective structural shape for wind-resistant designs of supertall buildings with various unconventional configurations (28 types of tall buildings), for example, corner modification, tapered model, helical model, opening model, and composite model, by conducting extensive wind tunnel tests. They found that helical- and composite-shaped tall buildings possessed the most effective structural shapes for reducing wind loads in both the along- and across-wind directions. Aerodynamic damping is one of the important factors for estimating the dynamic response of a super tall building. In the across-wind direction, the aerodynamic damping of a typical supertall building with a square cross-section rapidly decreases and becomes negative under certain conditions wherein the reduced wind velocity is over 9 (Haung et al., 2013). This results in a larger amplitude of the vibration experienced by the tall building in the across-wind direction. Majority of the previously reported studies have focused on wind forces and responses of tall buildings with an aerodynamic modification. Some researchers have examined the aerodynamic damping of tall buildings by conducting aeroelastic model tests (Holmes, 1996; Fukuwa et al., 1996; Marukawa et al., 1996; Tamura and Suganuma, 1996; Quan et al., 2005, 2016; Watanabe et al., 1997; Huang et al., 2013; Gu et al., 2014).

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Specifically, Holmes (1996) proposed a method based on the quasi-steady assumption to calculate the along-wind aerodynamic damping of a building with a square cross-section. Watanabe et al. (1997) formulated an empirical aerodynamic damping function including the effects of tip amplitude, aspect ratio, cross-section of the building, and turbulent intensity. The applicability of this function was examined by employing the aerodynamic damping values obtained from the wind tunnel tests for a square model. Huang et al. (2013) investigated the aerodynamic damping of tall buildings with various cross-sections (square, chamfered, corner-cut, and rectangular) by performing an aeroelastic model test. It is noticeable that most of the studies have only focused on the aerodynamic damping of typical tall buildings with a square or rectangular cross-section or slightly modified cross-sections. The aerodynamic damping of supertall buildings with complicated sectional shapes has rarely been evaluated.

In this study, the aerodynamic damping and aeroelastic instability of a 180° helical supertall building, which showed good aerodynamic behavior in terms of both along- and across-wind responses, as reported by Tanaka et al. (2012), is investigated through an aeroelastic wind tunnel test (rocking vibration model (RVM) test). The aerodynamic damping ratio of the supertall building is evaluated using the random decrement technique (RDT). Furthermore, the effect of the triggering level and number of time segments in the estimation of the aerodynamic damping ratio via RDT is also examined.

2. Wind tunnel experiments

2.1. Simulated natural wind

The wind tunnel tests were performed in a boundary layer wind tunnel at the Tokyo Polytechnic University, Japan. The test section of the wind tunnel was 2.2 m wide, 1.8 m high and 19 m long. In this study, the flow of the atmospheric boundary layer in the wind tunnel was interpreted on a geometrical scale of approximately 1/694. Using the spire-roughness technique with a power lay exponent of 0.2, the approach flow was determined to represent a suburban wind exposure corresponding to a flat terrain categorized as type III by the Japanese wind load code (AIJ-RLB, 2004). The wind velocity and turbulence intensity at the topmost point of the model in the wind tunnel were about 11.4 m/s and 12%, respectively, as shown in Fig. 1(a). The power spectrum density of the fluctuating wind velocity as a function of the turbulence length scale is presented in Fig. 1(b).

2.2. High-frequency force balance test

To investigate the effect of unstable aerodynamic forces on the evaluation of the aerodynamic damping ratio, high-frequency force balance (HFFB) and RVM tests were conducted. Two types of rigid models were considered in the HFFB tests. One was a 180° helical model and the other was a square model. In this test, the wind direction was considered as $\theta = 0°$, because under this condition, the largest response in across-wind direction was observed for the square shaped tall building. In this test, the sample frequency was 1 kHz. The standard deviation of the response can be evaluated via the spectral modal analysis (Tschanz and Davenport, 1983).

$$\sigma_{x(y)} = \sqrt{\int_0^\infty S_{x(y)}(n)dn} = \frac{1}{k}\sqrt{\int_0^\infty |H(n)|^2 S_{fx(y)}(n)dn} \quad (1a)$$

$$= \sigma_{fx(y)}\sqrt{1 + \frac{\pi}{4}\frac{1}{\zeta_0}\frac{\chi_0 S_{fx(y)}(\chi_0)}{\sigma^2_{fx(y)}}} \quad (1b)$$

where, ζ_0 is the first mode damping ratio, $f_{x(y)}$ is generalized wind forces at x- and y-directions, respectively, $\chi_0 S_{fx(y)}(\chi_0)/\sigma^2_{fx(y)}$ is the normalized power spectral density of $f_{x(y)}$, $\sigma^2_{fx(y)}$ is the standard deviation of $f_{x(y)}$, and

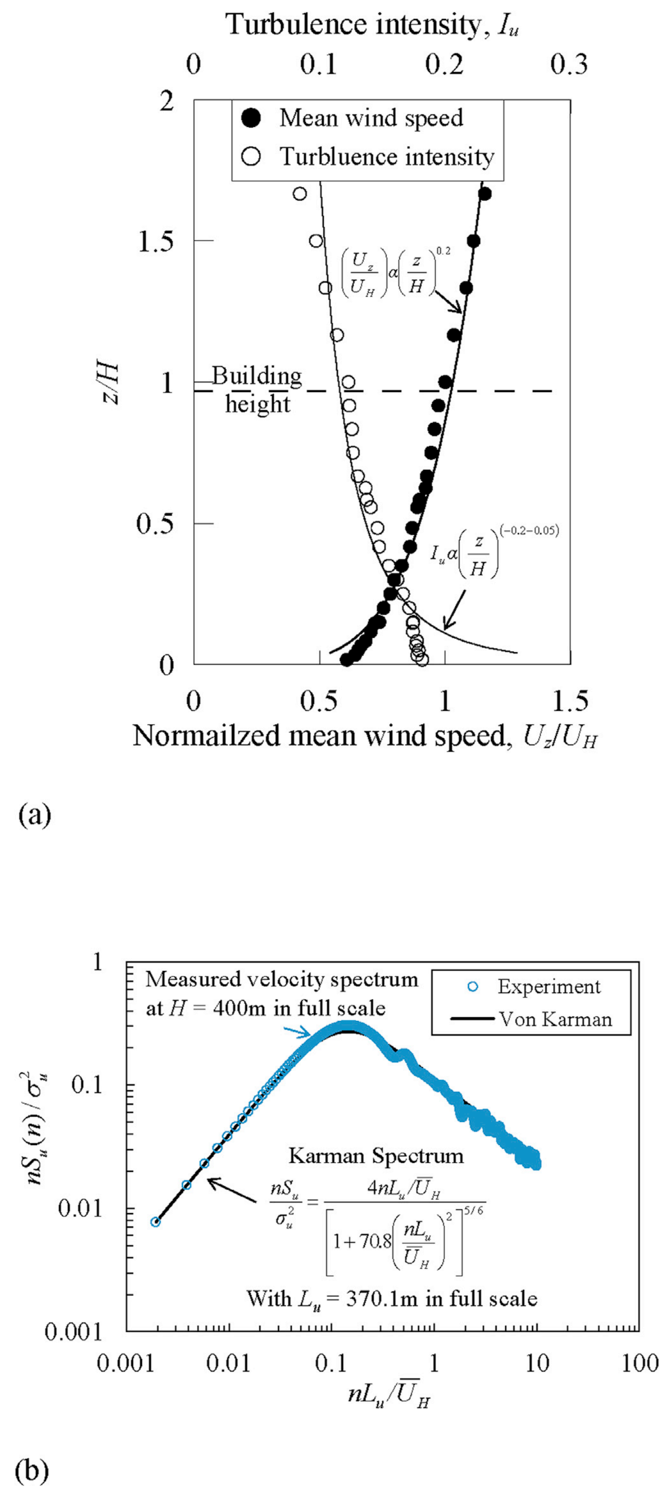

Fig. 1. Simulated wind parameters in the wind tunnel; (a) Normalized mean wind speed and turbulence intensity profiles; (b) Power spectrum density of the longitudinal velocity component at the topmost point of the model.

$|H(n)|^2$ is the mechanical admittance function that can be calculated as follows:

$$|H(n)|^2 = \frac{1}{\left(1 - (n/n_0)^2\right)^2 + (2\zeta_0 n/n_0)^2} \quad (2)$$

$\chi_0 = n_0 B/U_H$ is the reduced frequency, where n_0 is the natural frequency, B is the breadth of the building and U_H is the mean velocity at the top of