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Investigation on the unstability of vortex induced resonance of high-rise buildings

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A B S T R A C T

Vortex induced vibration (VIV) as well as resonance were investigated by multi-degree-of-freedom (MDOF) aero-elastic models of supper high-rise buildings in a wind tunnel. The experimental data revealed that the structural displacement of the VIV was not ideally harmonic, and vortex induced resonance (VIR) occurred intermittently. Furthermore, it was showed that the vibration frequency did not lock the vortex shedding frequency completely in the VIV process, and the unstability of VIR was induced by the difference between the transient frequency of across-wind force and that of VIV displacement. In other words, the two frequencies cannot maintain equilibrium once they are equal to each other. Finally, a mathematical model considering multiple factors related to the VIV was established to predict the VIR occurrence probability of high-rise buildings.

1. Introduction

Flexible high-rise buildings may be exposed to the danger of vortex-induced resonance (VIR) if the vortex shedding frequency is close to the natural frequency of the building. As wind speed increases and reaches the critical wind speed at which the vortex shedding frequency is close to the natural frequency of the structure, the VIR occurs and violent vibration persists as long as wind speed is in a certain range. In this phenomenon, the ratio of these two frequencies remains close to unity, and then the vortex-induced vibration (VIV) can be approximately considered as a harmonic function (King and Prosser, 1972; Sarpkaya, 1978). Currently, several mathematic models to evaluate the VIR response have been developed on the assumption of the harmonic VIR response (Scruton, 1963; Kwok and Melbourne, 1981; Bearman, 2003). However, both of wind tunnel tests and full-scale measurements revealed that the VIR responses were unstable (Marris, 1964; Rumman, 1970; Vickery and Basu, 1983a,b). Unfortunately, the unstability of the VIR is less addressed in the wind engineering community.

During past forty years, single-degree-of-freedom (SDOF) aero-elastic models (King and Prosser, 1972; Sarpkaya, 1978; Vickery and Basu, 1983a,b; Larsen, 1995) have been widely used to investigate the aero-elastic phenomena as well as motion-induced forces of high-rise structures in VIV. Few studies, however, on VIV have been carried out by the multi-degree of freedom (MDOF) aero-elastic model. In fact, the SDOF aero-elastic model with a linear mode shape and the aero-elastic phenomena based on SDOF aero-elastic model are different from those of actual high-rise buildings. Recent investigation indicates, the coherence of wind pressures between two pressure transducers at upper and lower locations of the same side face, and that between two pressure transducers at opposite locations of two side faces, are much different for the SDOF aero-elastic model and the MDOF aero-elastic model (Wang et al., 2014). Fig. 1 illustrates the coherence functions of wind pressures for the SDOF aero-elastic model and the MDOF aero-elastic model when VIR takes place respectively.

The coherence function is defined as follows:

$$r_{ij}(n) = \frac{C_{ij}(n)}{\sqrt{S_{ii}(n)S_{jj}(n)}} \tag{1}$$

where $C_{ij}(n)$ is co-spectrum, which is the real part of the cross spectra $S_{ij}(n)$. Fig. 1 shows that absolute values of coherence functions at the frequency of VIR generally reach the maximum because of the strong aero-elastic effect. For SDOF aero-elastic model, the wind pressures of points 1and 3, which locate at the same side face and different heights, are almost fully and positively coherent; while the wind pressures of points 1and 2, which locate at opposite locations of two side faces and same height, are almost fully and negatively coherent. Compared with the coherence of wind pressures on the SDOF aero-elastic model, the coherence of wind pressures on the MDOF aero-model is rather weaker, no matter the coherence function is positive or negative. Obviously, the

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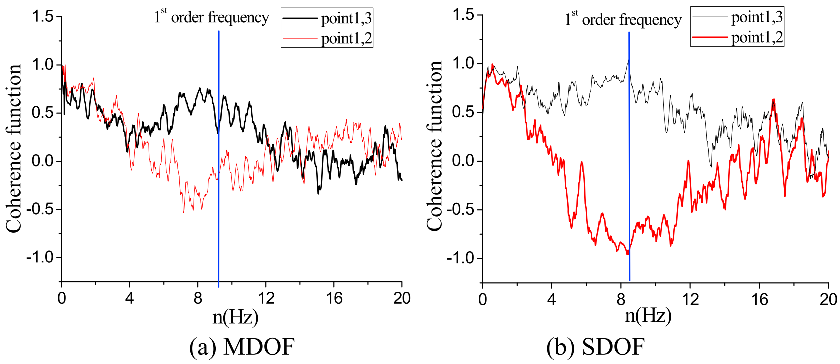

Fig. 1. Coherence function between wind pressures (locations of points 1–3 on models are illustrated in Fig. 2).

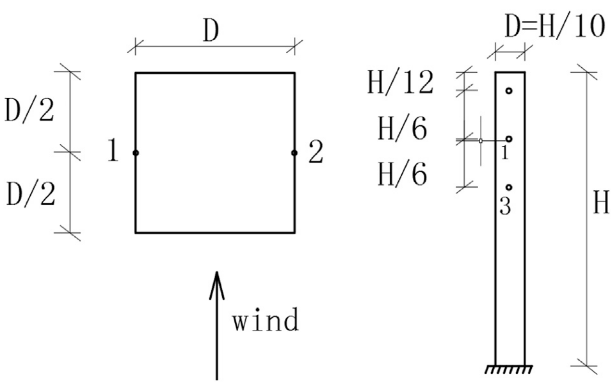

Fig. 2. Locations of pressure transducers.

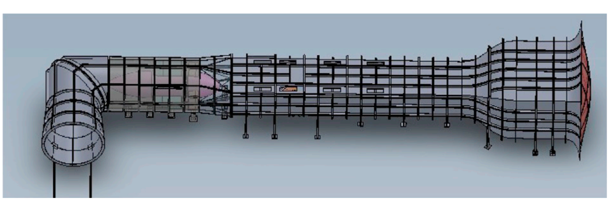

Fig. 3. Aerodynamic contour of the wind tunnel.

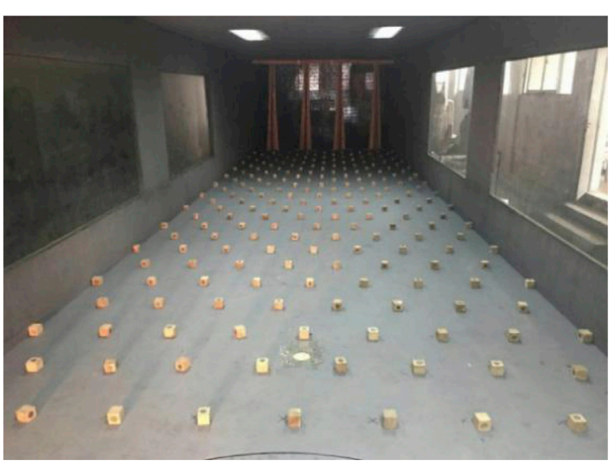

Fig. 4. Simulation of the turbulent wind field in the wind tunnel.

stronger coherence of wind pressures on the two side faces of the SDOF aero-elastic model of course will make its VIR much more violent and stable than that of the MDOF aero-model. The difference between the wind pressure coherences and that between VIRs of these two kinds of aero-elastic models are mainly due to the difference of their mode shapes. Actually, the homogeneity of the mode shape of the SDOF aero-elastic model is much better than that of MDOF aero-elastic model. On the other hand, the mode shape of the MDOF aero-elastic model, as well as the simulated wind pressure coherence and VIR, are much close to the reality of real high-rise buildings. Consequently, the test result of VIR by SDOF aero-elastic model, which is much closer to ideal harmonic than that by MDOF aero-elastic model, was not sufficiently accurate and reliable (Melbourne, 1997; Tamura and Dias, 2003; Wang et al., 2015).

As mentioned above, although phenomena of unstability of VIR have been reported in a few references, the investigation is seldom conducted by the MDOF aero-elastic model, which is considered as a more accurate and sophisticated experimental approach. Moreover, the mechanism of the unstability and occurrence probability of VIR of high-rise buildings has not yet been systematically investigated by the MDOF aero-elastic model. In this paper, wind tunnel tests of MDOF aero-elastic models were carried out to investigate the unstability of VIR of supper high-rise buildings, and the mechanism and the occurrence probability of VIR of high-rise buildings were discussed based on the wind tunnel data.

2. Wind tunnel test

The test was conducted in the boundary layer wind tunnel of Wuhan University, China. The cross-section of the wind tunnel is 3.2 m wide × 2.1 m high. The turbulent wind fields under two terrains (i.e., terrain categories B and D in China's Code, 2012) were simulated using a set of spires and roughness elements. The aerodynamic contour and simulated turbulent wind field of the wind tunnel are illustrated in Figs. 3–4. The mean velocity and turbulence intensity profiles in the wind tunnel are illustrated in Fig. 5 for the two terrain categories.

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

Fig. 6 shows the model with an aspect ratio 10. Holes were drilled in each of the model's floors, and five fitted aluminum columns, including one thick column in the center and four slender columns at the four edges, through the holes at the floors constituted the structure of the model. A copper billet was fixed on each floor to adjust the required mass and mass moment of inertia. The structural damping was simulated by attaching energy-dissipation material to each floor. The dynamic properties of each MDOF model are presented in Table 2, where the equivalent mass (M) and Scruton number (Sc) are expressed as