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Effects of aerodynamic modification mechanisms on interference from neighboring buildings

Yuan-Lung Lo [a], Yong Chul Kim [b,*], Akihito Yoshida [b]

[a] Department of Civil Engineering, Tamkang University, Taiwan, ROC
[b] Department of Architecture, Tokyo Polytechnic University, Japan

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ABSTRACT

This paper investigates the effect of the single and multiple aerodynamic modification mechanisms on the dynamic behavior of the principal building that is interfered by a very closely located building. For the study, aeroelastic vibration tests and high-frequency force balance tests are conducted to compare responses and wind forces in a well-simulated turbulent boundary layer flow. The principal building is manufactured with three different building configurations to represent the single and multiple aerodynamic modification treatments; the neighboring building which produces interference effects is made into a square prism model. Results show that the multiple modification treatment is efficient in reducing wind forces in all interference location series. However, it is also found that in certain critical conditions, such treatment is sensitive to reduced velocity, and may amplify the interference effect and result in larger displacements.

1. Introduction

Buildings that undergo interference effects caused by neighboring buildings require an improved wind load resistant design different from those for isolated buildings. However, the interference effects are considered very difficult to be integrated into regulations or codes due to their complex nature and huge number of disturbances. This issue with the interference effects remains one of the most difficult research topics in the field of wind engineering.

Over the past decades, researchers have adopted various methodologies to investigate the interference effects on overall or local wind loads of high-rise buildings. There are a large number of discussions regarding possible wind force-affecting factors, which include the approaching flow characteristics, wind directions, relative location of neighboring buildings, cross sectional shapes and aspect ratios, Scruton numbers, Strouhal numbers, modal frequency, and mode shapes. (Saunders and Melbourne, 1979; Surry and Mallais, 1983; Bailey and Kwok, 1985; Blessmann and Riera, 1985; Kareem, 1987; Taniike and Inaoka, 1988; Sakamoto and Haniu, 1988; Taniike, 1991, 1992; Yahyai et al., 1992; Zhang et al., 1994, 1995; Sun and Gu, 1995; Khanduri et al., 1998, 2000; Luo et al., 1999; Thepmongkorn et al., 2002; Tang and Kwok, 2004; Xie and Gu, 2004, 2007; Huang and Gu, 2005; Zhao and Lam, 2008; Lam et al., 2008, 2011; Hui et al., 2012, 2013a, b; Fang et al., 2013; Kim et al., 2011; 2013; 2015a, b; Mara et al., 2014; Yu et al., 2015; Lo et al., 2016). Among these research works, square or rectangular prisms, as well as cylindrical prisms, chimneys, storage tanks, or cladding structures were common choices for discussions (Kareem et al., 1998; Niemann and Kasperski, 1999; Wang et al., 2014; Uematsu et al., 2015). In most cases, interference effects were discussed based on the evaluation of distorted wind forces to indicate critical interference locations. However, it has been pointed out that different critical interference mechanisms could occur at certain interference locations, either upstream or downstream, to generate significant responses (Bailey and Kwok, 1985; Yahyai et al., 1992; Lo et al., 2016), especially in areas very close to the principal building. In some related studies, the aeroelastic vibration test was considered more intuitive to observe the interfered dynamic responses rather than high-frequency force balance tests.

At the same time, the aerodynamic modifications that can efficiently reduce the wind force acting on high-rise buildings are reported in some recent works. Changing the geometrical appearance of the building shape may be the easiest form of aerodynamic modifications. Kim et al. (2014; 2015a, b; 2016) conclude that two simple but efficient treatments, which are changing the number of sides of the cross section and changing the helical angle to twist the building, promise lower wind forces. Surprisingly, these treatments sometimes happen to meet architects' imagination and design of the buildings bear. For example, the taper and twisting features of modern skyscrapers have become more and more attractive nowadays.

* Corresponding author.
E-mail addresses: yllo@mail.tku.edu.tw (Y.-L. Lo), kimyc@arch.t-kougei.ac.jp (Y.C. Kim), yoshida@arch.t-kougei.ac.jp (A. Yoshida).

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This study intends to investigate the effects of single and multiple aerodynamic modification treatments on the interfered responses and wind forces by comparing the experimental results from aeroelastic vibration tests and high frequency force balance tests. Three principal models that consist of a square prism model, a taper model and a helical taper model are made for the modifications. Closed interference locations are selected to cover those critical interference mechanisms either from the upstream or the downstream locations. Response trajectories, wind force spectra, force interference factors and response buffeting factors are estimated to examine the treatments' effectiveness in reducing or amplifying the unfavorable dynamic behavior of the target principal building.

2. Experimental setup

Both the aeroelastic vibration test and the high-frequency balance test are conducted in the 18 × 1.8 × 2.2 m boundary layer wind tunnel at Wind Engineering Research Center at Tokyo Polytechnic University. A 1/400 scale turbulent flow over a sub-urban terrain with a power law index exponent for mean velocity profile of 0.19 is simulated with properly equipped spires, saw barriers, and roughness blocks (Photo 1). The vertical flow characteristics are shown in Fig. 1.

For the aeroelastic vibration test, three rigid base-pivoted aero-elastic models are manufactured for the role of the principal building as shown in Fig. 2. The square prism model is 0.07 m in both width (B) and depth (D) and 0.56 m in height (H), which make the aspect ratio (H/B) 8. The tapered model is 0.04 m in width on the roof-top and 0.10 m in width on the bottom. The height is the same as the square one and the aspect ratio (height to the averaged width) is also 8. The helical tapered model has the same geometrical appearance as the tapered model but has a helical twisting angle of 180° from the bottom to the top. All the three principal models are manufactured in the same volume in order to have a basic comparison level. Both the tapered and the helical tapered models have been proven to efficiently reduce the projected wind force when they are isolated (Kim et al., 2014; 2015a, b; 2016). The tapered model and the helical tapered model in this study are referred to as Model IV and X by Kim et al. (2016). The setup of the aeroelastic vibration test is illustrated in Fig. 3. The tapered and the helical tapered models were chosen for this study because the buildings with tapered shape and twisting features are becoming more and more popular in the modern skyscraper designs; however, there has not been matching number of discussions related to these two features. It is also the authors' interest to investigate the consequences with the consideration of interference effects.

The fundamental modal information of the three principal models is listed in Table 1. The fundamental frequencies in along-wind (longitudinal) and across-wind (lateral) directions are tuned to 6.5 Hz based on free vibration tests. The damping ratios are kept under or equal to 1% in both directions for all three models and the generalized masses are about 0.11 kg. The corresponding mass-damping parameter is determined by

$$\delta = \frac{M\xi}{\rho B^2 H} \tag{1}$$

where ρ is the air density. M is the generalized mass. ξ is the damping ratio. For the rigid base-pivoted aeroelastic model in this study, the mass-damping parameters for the three models are between the range of 0.23–0.33, which is slightly lower than the range of typical full scale high-rise buildings (0.4–0.6) and can be converted to Scruton numbers ranged from 0.7 to 1.0 based on the linear mode shape assumption of its rigid elastic feature. Generally speaking, in this range of lower Scruton numbers, the across-wind response of an isolated square prism model will increase significantly when the reduced velocity rises to values larger than 9 or 10. Furthermore, as shown in Table 1, the parameters in these three models are intentionally made the same or similar in order to minimize the possible differences in reducing wind forces or dynamic response. In real situations, the tapers building may be stiffer than the square buildings.

The displacement signals of both directions are recorded by two laser sensors at the sampling rate of 550 Hz. The sampling length is 16,384 for one sample record and the ensemble size is 10 in order to obtain a statistical result.

In the high-frequency force balance test, the three principal models are fixed to the balancer for both horizontal forces measuring under the same sampling conditions. Instantaneous wind velocity is recorded at the model height for further normalizations.

The interfering building model is acrylic and has the same size as the square prism model; unlike the principal building models, however, this interfering model is made rigid and un-flexible providing only the disturbed flow coming from upstream or downstream locations. The interference locations of interest are focused on those considered significant in the surrounding area (Fig. 4). Both the principal and interfering models are orientated with one face normal to the wind when both tests are carried out. Five location series including the upwind series, the oblique-upwind series, the side series, the oblique-downwind series and the downwind series are selected for observing different interference mechanisms.

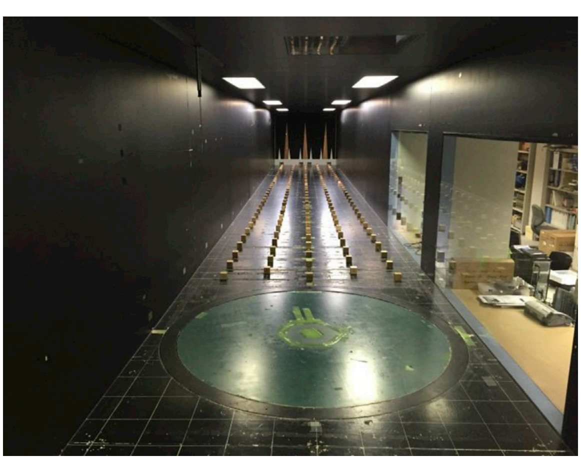

Photo 1. Wind tunnel at WERC, TPU.

3. Results and discussions

3.1. Interfered response characteristics

For convenient illustration hereafter, the RMS response, the standard deviation value of displacement, at rooftop is normalized to the averaged model width (0.07 m) for each sample record. The ensemble averaged RMS responses are then calculated. Among all the measurements, the averaged variation coefficients of ensemble averaged RMS responses are lower than 10% for along-wind and across-wind directions, which are both considered quite stable for the measurement accuracy. The reduced velocity is calculated as

$$U_r = \frac{\overline{U}_H}{f_0 B} \tag{2}$$

where $\overline{U}_H$ is the mean wind velocity at the model height. In this study, 20 locations of interfering model and 11 reduced velocities ($U_r = 2.5$, 3.9, 5.2, 6.8, 7.6, 8.4, 9.2, 10.0, 10.8, 11.6, and 12.4) together provide a total of 220 cases for the interfered response characteristics for each principal building. Among these cases, some at higher reduced velocities may contain distorted signals in few records. In such conditions, these distorted records are neglected while the rest of records are used for further analysis. The reason for such distorted signals can be explained by Fig. 5 (Lo et al., 2016). In those failed cases, the signal was distorted simply because the laser sensor misses the target of the gimbal. For instance in