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Unsteady pressure measurements on an oscillating slender prism using a forced vibration technique

Zeng-shun Chen [a], K.T. Tse [a,*], K.C.S. Kwok [b]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[b] School of Civil Engineering, The University of Sydney, Darlington, NSW, 2006, Australia

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ABSTRACT

The unsteady aerodynamic forces acting on a slender prism were investigated using a forced vibration technique. The prism was driven to oscillate by an actuator and the unsteady distributed pressures, under different wind velocities and oscillation amplitudes, were measured. The measurement was calibrated with respect to driving oscillation, aerodynamic force coefficient, as well as motion-induced force coefficient. Then, the generalized and local aerodynamic force coefficients and the motion-induced force coefficients of the prism, which are functions of reduced wind velocity and oscillation amplitude, were analyzed. It shows that the effects of structural motion on the coefficients are significant in the crosswind direction while the effects are slight in the along-wind direction. Furthermore, in the crosswind direction, the coefficients tend to increase with oscillation amplitudes at low wind speeds while they are at a quasi-steady state at high wind speeds. These characteristics were analyzed from the perspectives of generalized and pointwise spectra, force-response coherences and Strouhal numbers of the prism. The study advances the understanding of the effect of structural motion on three-dimensional prisms, which can be utilized to improve response predictions of the prisms.

1. Introduction

Architectural structures tend to be high and slender, and accurately obtaining the wind load of such structures is becoming more important than before. Generally, a high frequency base balance (HFBB) or a static synchronous multi-pressure sensing system (SMPSS) wind tunnel test is carried out to evaluate the wind load of structures. The HFBB test technique is an effective and expeditious way to obtain overall wind loads (i.e. base shear force and base over turning moment). Furthermore, only one test is needed to determine wind-induced responses for a series of structures with the same geometry. The SMPSS test is relatively complicate to the HFBB test, but it enables to measure the distributed wind forces at different levels of a structure and to reflect wind characteristics around a bluff body. However, both the HFBB and the SMPSS test techniques are static measurements and the effect of structural motion is therefore excluded. As is known, the effect is usually small, but when it is in-phase with wind velocity, the effect acts as aerodynamic damping and cannot be neglected. At low wind speeds, the motion-induced aerodynamic damping is positive, and neglecting its effect can lead to overestimation when predicting structural response; on the other hand, at high wind speeds, the motion-induced aerodynamic damping is negative, and neglecting its effect can result in underestimated prediction in structural response. Also, it has already been confirmed that the differences of wind loads measured by a static and a dynamic test are mainly ascribed to the effect of structural motion (Bearman and Obasaju, 1982; Cooper et al., 1997). Therefore, the unsteady wind loads of structures, which include the effect of structural motion should be acquired.

A forced vibration technique is usually utilized to accurately evaluate the unsteady wind load of a structure. Most studies have focused on the motion-induced forces of a two-dimensional section using a forced vibration technique. Bearman and Currie (1979); Bearman and Obasaju (1982) investigated the pressure-fluctuation of oscillating two-dimensional circular and square-sectional cylinders. Both the mean and fluctuating pressures of the cylinders at or away from the lock-in range were observed, and substantial differences between the two cylinders were discovered and analyzed. The studies found that, at high wind speeds, oscillating pressures are in close agreement with that measured from a static test suggesting that the cylinder is under quasi-steady state. Also, numerous measurements have immersed in unsteady aerodynamic forces of two-dimensional bridge deck sections. A forced vibration technique was mainly utilized for flutter derivative identification (Gu et al., 2000; Sarkar et al., 2009), aerodynamic force and damping

* Corresponding author.
E-mail addresses: zchenba@ust.hk (Z.-s. Chen), timkttse@ust.hk (K.T. Tse), kenny.kwok@sydney.edu.au (K.C.S. Kwok).

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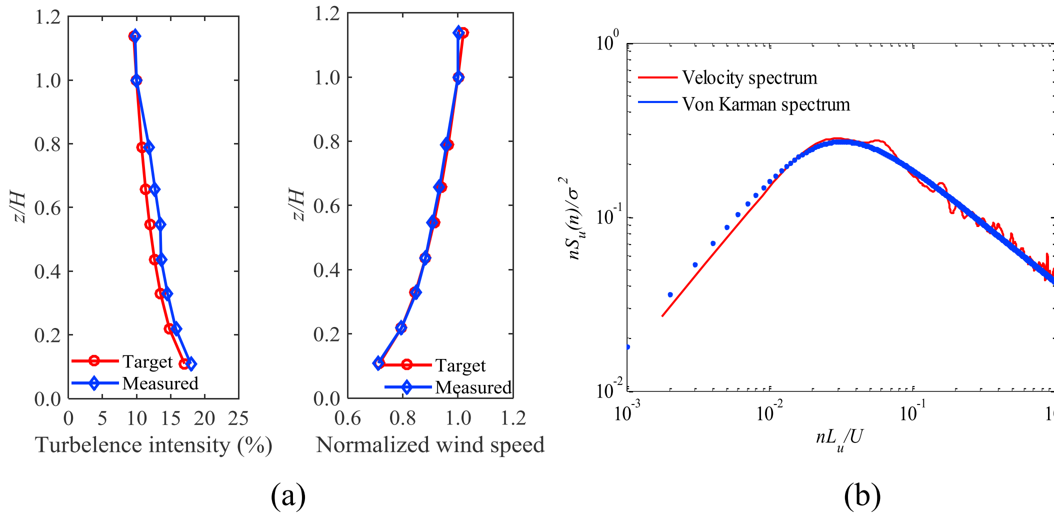

Fig. 1. The characteristics of wind profiles: (a) the target and simulated wind flow; (b) the normalized spectrum of longitudinal velocity.

determination (Chen and Kareem, 2002), as well as spanwise wind force correlation analysis (Ehsan et al., 1990; Li et al., 2016). The above studies aimed to investigate the effect of structural motion, which can help improve response predictions of structures. However, many structures in the real world are three-dimensional (3-D), i.e. bridge towers, buildings, etc., and the effect of motion on 3-D structures are different from that on 2-D structures due to the effect of geometric configuration.

Few studies have focused on unsteady aerodynamic forces of 3-D prisms. Steckley (1989), Steckley et al. (1990) and Vickery and Steckley (1993) evaluated the motion-induced wind forces of prisms from a forced vibration base force measurement. Based on the wind forces, the motion-induced aerodynamic damping and stiffness of the prisms were determined and analyzed. Then, the response predictions were improved by considering the obtained aerodynamic damping and stiffness. Afterwards, Watanabe et al. (1997) gave the empirical expressions of the aerodynamic damping, which was derived from Steckley's data. Following the expressions, Chen (2013) investigated the nonlinear aerodynamic damping and crosswind response of prisms. The above analyses were mainly based on unsteady base force measurements, and distributed unsteady wind forces could not be considered. To solve this problem, Cooper et al. (1997) and Katagiri et al. (2001, 2002) observed and analyzed the distributed unsteady aerodynamic forces of a tapered and a rectangular (side ratio = 2) buildings. These studies have greatly improved our understanding on the motion-induced aerodynamic forces, and enhanced the accuracy of wind-induced response predictions of flexible structures. However, it should be emphasized that studies concerning the motion-induced wind forces with 3-D models are still limited and some results may not well present the effect of structural motion on observed unsteady aerodynamic forces due to uncertainties in their measurements. More importantly, unsteady distributed pressures acting on a 3-D slender square prism have not been investigated yet.

This study aims to investigate the distributed unsteady aerodynamic force of a slender square prism using a forced vibration technique. In section 2, wind tunnel tests of the prism were performed. In the tests, the model was driven to oscillate under different oscillating amplitudes, and the distributed unsteady pressure and responses were measured simultaneously. In section 3, aerodynamic parameters were defined. In section 4, the forced vibration test was validated with respect to driving oscillation, aerodynamic force coefficient and motion-induced force coefficient. After that, the unsteady force coefficient and the motion-induced force coefficient (i.e. aerodynamic damping and stiffness terms) of the prism, under different oscillation amplitudes and wind velocities, were determined and analyzed. In the last section, further discussions of the force were given from the aspects of unsteady pressure spectrum, force-response coherence and the Strouhal number (the lock-in and away from the lock-in ranges). This fundamental study can help understand the effect of structural motion, which can be utilized to evaluate the aerodynamic damping of structures and improve the response predictions of the structures.

2. Experimental setups

2.1. Wind flow field

A forced vibration test was carried out in the high-speed section of the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology with dimensions 29.2 m (length) × 3 m (width) × 2 m (height). The terrain category II defined in the AS/NZS 1170.2:2002 was simulated in the wind tunnel by adjusting roughness elements and spires in the upstream of the test section. The mean wind speed and flow turbulence intensity were measured using a hot-wire anemometer. Comparisons between the target and measured wind profiles, as well as the normalized spectrum of longitudinal velocity component at the top of the test model were presented in Fig. 1. From Fig. 1, the measured turbulence intensity I_u and the mean wind speed along the height of the model are in close agreement with the targets. The trend of the velocity spectrum is close to the von Karman spectrum. This suggests the selected wind profile was well simulated and can be utilized for wind tunnel test.

2.2. Forced vibration technique

The dimensions of the test model in the present study were 50.8 mm (D) × 50.8 mm (D) × 915 mm (H) with an aspect ratio being around 18:1; where D denotes the width and depth of the model and H is the height of the model. Correspondingly, the blockage ratio of the test model was 0.78%, which is much smaller than the critical value of 5% (Holmes, 2015). The prism was driven to oscillate sinusoidally in the crosswind direction using a forced vibration system which consists of an actuator, a signal generator and a power amplifier (Fig. 2). The oscillating frequency f was set to 7.8 Hz which is the same with that in an aeroelastic test (Hu et al., 2015c). The root-mean-square (RMS) response ratio of the prism σ_y/D ranged from 6% to 20%; where σ_y is the RMS tip oscillating amplitude of the test model. The response was measured using a laser displacement sensor (LDS) installed at the bottom of the test rig (Fig. 2). Before the test, the relationship of the tip and the bottom oscillations was calibrated so as to determine the tip oscillations through the bottom observed data. During the test, only normal flow incidence on the prism was considered and the reduced wind speed V_R ($V_R = U/fD$, U is the