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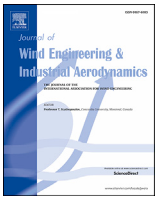

Aerodynamic damping of inclined slender prisms

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ABSTRACT

The aerodynamic damping of forward and backward inclined prisms has been identified through a series of forced vibration wind tunnel tests. The test results show that the amplitude of vibration and reduced wind velocity both have a significant effect on the aerodynamic damping of the inclined prisms, especially at reduced wind speeds where von Karman vortex lock-in occurs. The effect of forward and backward inclination on the characteristics of aerodynamic damping in inclined prisms is dissimilar to a vertical prism, and the characteristics have been discussed in terms of the unsteady aerodynamic force and Strouhal number in this study. This study not only advances our understanding on aerodynamic damping of inclined prisms, but also provides values that can be used to estimate aerodynamics and aeroelasticities of inclined prisms.

1. Introduction

Structural oscillations in a crosswind direction, including lateral buffeting, vortex-induced vibration (VIV), galloping, and the combination of VIV and galloping which is known as low wind speed galloping (Mannini et al., 2014, 2015), depend on flow features and local flow characteristics around a structure such as flow separation, flow reattachment, and wake formation. All these oscillations are affected by structural and aerodynamic damping; the former of which is complex because of uncertainty (Kareem and Gurley, 1996) while the latter can be determined by measured responses (Gao and Zhu, 2015). Aerodynamic damping is a crucial parameter for galloping, VIV-galloping, and flutter; if left undamped, these oscillations may strengthen ultimately leading to the collapse of a structure. For example, the Tacoma Narrows Bridge (Billah and Scanlan, 1991), traffic signal structures (Hamilton III et al., 2000; Pulipaka et al., 1998) and towers of transmission lines (Jiang et al., 2004), collapsed due to minus aerodynamic damping. Moreover, the lack of understanding on aerodynamic damping can lead to either an overestimation or underestimation of wind-induced responses of a structure, depending on whether the aerodynamic damping is positive or negative. Especially for slender structures that are sensitive to wind, it is important to be able to evaluate the aerodynamic damping of structures accurately.

Aerodynamic damping is often estimated by the classical quasi-steady theory, which is recognized as a function of reduced wind speed. However, the quasi-static approximation of aerodynamic damping is linear with respect to reduced wind speed and the amplitude-dependent variation is not presented (Chen, 2014; Cooper et al., 1997). Moreover, it was reported that the quasi-steady theory is not suitable for predicting low wind speed galloping (VIV-galloping) (Mannini et al., 2015) and galloping of inclined prisms (Hu et al., 2015c). The quasi-steady theory fails because it does not consider the 'unsteady effect' (related to the memory of the fluid regarding what happened at previous time instants). This can be attributed to galloping force used in the quasi-steady theory being estimated by a polynomial that is determined from a static wind tunnel test. In other words, since the 'unsteady effect' is not considered, it leads to considerable differences in the predicted aerodynamics and aeroelasticity of structures (Gao and Zhu, 2016).

A forced vibration test technique that includes the effect of structural motion on the observed aerodynamic force is often employed to improve the accuracy in estimating the aerodynamic damping of a structure. Vickery and Steckley (1993) investigated the aerodynamic damping of vertical prisms using a novel forced vibration system. The effect of amplitude of vibration, reduced wind speed, turbulence intensity and aspect ratio (height-to-width ratio) on aerodynamic damping was studied. According to the study, Watanabe et al. (1997) proposed an empirical function for evaluating the aerodynamic damping of slender prisms. The accuracy of this function was later verified (Quan et al., 2005). Chen (2013) has modeled the nonlinear aerodynamic damping of tall buildings using a second-order polynomial function based on Vickery and Steckley's wind tunnel data, and presented a framework for estimating the

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crosswind induced responses of slender prisms. Matsumoto (1996) investigated the characteristics of the aerodynamic damping of 2-D rectangular prisms with various side ratios using a forced vibration system. Cooper et al. (1997) and Fediw et al. (1995) performed a forced vibration wind tunnel test to measure the unsteady aerodynamic forces acting on a tapered prism to study the characteristics of aerodynamic damping. Apart from the forced-vibration-based studies, researchers employed mathematical models or techniques to identify the aerodynamic damping of structures, such as advanced data-driven models (Aquino and Tamura, 2013; Spence and Kareem, 2013) and the random decrement technique (Marukawa et al., 1996; Quan et al., 2005; Tamura and Suganuma, 1996). Kareem and Gurley (1996) summarized several types of damping sources and mathematical models of damping in structures, with an emphasis on the treatment of inherent uncertainty in damping prediction and estimation for practical applications. These studies have advanced our understanding on aerodynamic damping of structures and improved the accuracy in predicting wind-excited responses.

In light of the fact that (1) many structures have been built with an inclination, such as the bridge towers of the Alamillo Bridge in Spain, Kumdang Bridge in Korea, Hong Shan Bridge in China, the Capital Gate in the United Arab Emirates, the Two Towers of Bologna in Italy and bridge cables, and (2) vertical structures built on mountain slopes subject to pitching wind flows blowing along the mountain slope (Fig. 1), it is necessary to study the aerodynamics and aeroelasticity of inclined prismatic structures. Hu et al. (2016; 2015c) have comprehensively studied the aerodynamic forces and galloping of backward and forward inclined prisms. The maximum galloping response was found at a backward inclination of 5°, and the quasi-steady theory was not suitable for predicting the onset wind speeds of galloping of inclined prisms. Many other researchers (Cheng et al., 2008a, 2008b; Piccardo et al., 2011) have investigated galloping of two-dimensional inclined cylinders.

Although researchers have made efforts to study the aerodynamic forces and aeroelastic performance of inclined prisms, to the authors' best knowledge, aerodynamic damping of inclined prisms has not been investigated. The objective of this study is to identify aerodynamic damping in both forward and backward inclined prisms with an emphasis on understanding its characteristics. This objective is achieved by performing a series of forced vibration wind tunnel tests through which the unsteady wind force and forced vibration of the inclined prisms are simultaneously measured. The aerodynamic damping of the inclined prisms is expressed as a function of amplitude of oscillation and reduced wind velocity. It is identified according to the unsteady crosswind force measured from the forced vibration test. The characteristics of the aerodynamic damping of the prisms are discussed in terms of the unsteady crosswind force and Strouhal number. The effects of forward and backward inclination on the characteristics of the aerodynamic damping are also illustrated. The present study has not only advanced our understanding on the characteristics of the aerodynamic damping of inclined prisms, but also provided values that can be utilized for estimating the aeroelasticity (i.e. VIV, galloping, VIV-galloping, etc.).

Following section 1, section 2 highlights a mathematical model for identifying the aerodynamic damping of structures, which is a function of the amplitude of vibration and reduced wind speed. Section 3 illustrates experimental the setup of the forced vibration test on the forward and backward inclined prisms. Section 4 presents the generalized and local aerodynamic damping of the inclined prisms. Section 5 discusses the experimental results in terms of the unsteady crosswind force and the Strouhal number. Section 6 summarizes the main findings of this study.

2. Aerodynamic damping model

The governing equation of motion of a prism is expressed in terms of the first mode shape in the crosswind direction as

$$M_s\left(\ddot{y}+2\zeta_s\omega_s\dot{y}+\omega_s^2 y\right)=P(t) \tag{1}$$

$$M_s=\int_0^H m(z)\phi^2(z)dz \tag{2}$$

$$P(t)=\int_0^H P(z,t)\phi(z)dz \tag{3}$$

where M_s, ω_s, and ζ_s are the generalized mass, model frequency, and damping ratio; y is the generalized crosswind induced response; $m(z)$ is the mass per unit height at elevation z above the ground. $\phi(z)$ is the mode shape and $\phi(z)=\frac{z}{H}$ in the crosswind direction. $P(t)$ is the generalized crosswind force that consists of the components of aerodynamic and motion-induced (self-excited) force, and is expressed as

$$P(t)=\int_0^H \frac{1}{2}\rho U^2 D[C_L(z,t)+C_M(z,y,t)]\phi(z)dz \tag{4}$$

where ρ denotes density of the air; U is the wind velocity at the top of the prism; D and H are the width and height of the prism; $C_L(z,t)$ and $C_M(z,y,t)$ are the local aerodynamic force coefficient and motion-induced force coefficient at height z above the ground.

Generalized forces are often determined either using a high frequency force balance (HFFB) technique through measuring base forces, or a synchronous multi-pressure sensing system (SMPSS) technique through integrating spatial-temporal varying wind forces per unit height. The present study uses the SMPSS technique.

The motion-induced force coefficient can be determined using a forced vibration wind tunnel test, where a test model is forced to vibrate harmonically and the normalized non-dimensional tip amplitude is expressed as $y(t)=\hat{y}\cos(2\pi ft)$, where $\hat{y}$ denotes the maximum tip

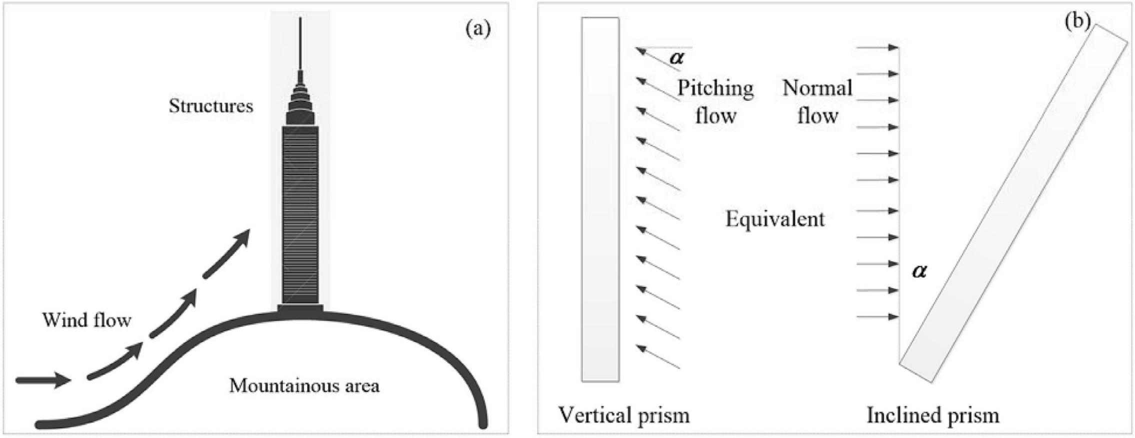

Fig. 1. A vertical prism subjecting to pitching wind flow and an inclined prism subjecting to horizontal wind flow (α denotes inclination).