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Galloping of forward and backward inclined slender square cylinders

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ABSTRACT

This study investigated the galloping behavior of a slender square-section cylinder inclined from the vertical direction by a series of angles. Both aeroelastic tests and pressure measurements were performed on the cylinder with forward inclinations (inclined to the upwind direction), a vertical attitude and backward inclinations (inclined to the downwind direction). Results from the aeroelastic tests show that the galloping amplitude of the cylinder decreases substantially with increasing the forward inclination angle. Unlike the forward inclination case, not all the backward inclined cylinders oscillate at an amplitude smaller than the vertical cylinder does. The galloping amplitude of the cylinder with a small backward inclination angle is significantly larger than that of the vertical cylinder, whereas the cylinder with a large backward inclination angle exhibits a lower amplitude. Comparing aeroelastic galloping amplitudes with those predicted by the quasi-steady theory shows that the quasi-steady theory is applicable to predict the variation trend of the galloping behavior induced by both forward and backward inclinations, although it is unable to give accurate predictions on galloping amplitudes of all the inclined cylinders.

1. Introduction

Galloping of slender cylinders could lead to serious structural damages because it induces large-amplitude oscillations. Thus, it has been the topic of a number of previous studies. Since the conclusions of these previous studies constitute the core of our understanding on this classical crosswind vibration, they are briefly reviewed in the following text.

From a theoretical perspective, Parkinson, one of the pioneers in the field, has conducted a series of studies (Parkinson and Brooks, 1961; Parkinson and Smith, 1964) to construct the quasi-steady theory, which has been recognized as the foundation for analytically estimating the aerodynamic force acting on structures during galloping. The quasi-steady theory assumes that the aerodynamic force acting on the structure, at each motion-induced wind incidence angle, is identical to the aerodynamic force measured at the same wind incidence angle in a static wind tunnel test. The quasi-steady theory was initially established for predicting the galloping behavior of two-dimensional (2D) structures. The structures in reality are, however, three-dimensional (3D) and the 3D effect cannot be ignored for most of the structures. Since the structural dynamics and aerodynamics of 3D structures are different from 2D structures, the application of the original quasi-steady theory is limited. Consequently, endeavors have been made (Mukhopadhyay and Dugundji, 1976; Novak, 1969, 1972; Parkinson and Sullivan, 1979) to extend the quasi-steady theory, which aims to investigate the galloping behavior of 3D structures. Meanwhile, aeroelastic tests performed in these studies proved that the quasi-steady theory is capable of predicting the galloping response of 3D structures.

Factors determining the onset or the amplitude of galloping have been studied extensively as well. The section shape of a bluff body has been found to play a deterministic role in the onset of galloping (Parkinson, 1989). For example, some shapes without an afterbody (the part of the cross-section downstream of the separation points), such as a D-section prism with the circular surface facing the flow, cannot gallop in any flow condition (Païdoussis et al., 2010; Parkinson, 1974). For some shapes, galloping may occur in a turbulent flow but not in a smooth flow, and by contrast, some other shapes may gallop in a smooth flow but not in a turbulent flow (Blevins, 1990). Furthermore, the afterbody length, related to the section shape, significantly influences the galloping behavior of the bluff body (Parkinson, 1989), due to the interactions of separated shear layers with the sides of the bluff body.

As mentioned above, galloping varies under a smooth flow and a turbulent flow. Hence, the turbulence intensity could have a significant effect on galloping. Some studies (Laneville and Parkinson, 1971; Novak and Davenport, 1970) reported that the galloping amplitude decreases with increasing the turbulence intensity. However, Kwok

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and Melbourne (1980) found that there is a considerable galloping amplitude for a slender square tower immersed in a turbulent boundary layer flow, whereas no galloping is observed in a uniformly smooth flow until the wind incidence angle reaches about 9°. In addition to the above mentioned parameters, the influence of the Reynolds number, which is commonly used to characterize the flow regime, on galloping has also been revealed (Barrero-Gil et al., 2009; Joly et al., 2012).

It should be pointed out that the majority of previous studies were devoted to study the galloping behavior of structures with their principal axes perpendicular to the oncoming flow, for example a vertical structure subject to a boundary layer flow. However, some slender structures in reality, such as the pylons of the Alamillo Bridge in Spain (Fig. 1), the Kumdang Bridge in Korea and the Hong Shan Bridge in China, are inclined. Predictably, the inclination of the slender structure has non-negligible impacts on its galloping oscillation. Skarecky (1975) pointed out that the stable galloping amplitude for a circular cylinder could be reached at higher velocities in a yawed flow (the flow is not perpendicular to the cylinder axis) than in a non-yawed flow, and that the galloping amplitude reduced with the yaw angle (from the plane normal to the cylinder). Similarly, Piccardo et al. (2011) investigated the influence of yaw angles on the galloping instability of a 2D square-section cylinder and demonstrated that the critical condition for galloping to occur is modulated by the yaw effect. It is worth mentioning that both studies only concerned galloping of a 2D inclined cylinder with either circular or square cross sections without considering the 3D effect.

Understandably, the flow-structure interaction is significantly different between 3D and 2D structures, because the flow fields around them are different. For a 3D cylinder, tip vortices are shed from the free end and base vortices are generated near the base of the cylinder. Only the middle span, which locates far away from the free end and the base, preserves the well-known Von Karman vortices (Uffinger et al., 2013; Wang and Zhou, 2009). In other words, the main form of vortex shedding behind a 2D cylinder is mainly observed in the flow around the middle span of a 3D cylinder. Furthermore, if a 3D cylinder is inclined, it is reasonable to expect that vortices shedding from the inclined cylinder exhibit more obvious three-dimensionality, i.e., variations along the span of the cylinder. The three-dimensionality of the vortices would lead to a 3D wake, and hence a 3D distribution of aerodynamic forces acting on the cylinder. As a result, the galloping behavior of an inclined cylinder is different from that of a vertical one. However, to the author's knowledge, the galloping behavior of an inclined square-section cylinder has never been systematically investigated, although this type of cylinder has been found in the form of inclined pylons, architectural sculptures and even iconic tall buildings.

Fig. 1. The Alamillo Bridge in Spain.

The objective of the present study is to investigate the impacts of inclinations on the galloping behavior of a square-section cylinder by using the transverse responses obtained from aeroelastic tests and the predictions made based on the quasi-steady theory. As regards aeroelastic tests, the aeroelastic model of a slender cylinder was manufactured to obtain its transverse amplitudes directly in a wind tunnel. Pressure measurements on a static cylinder with dimensions identical to the aeroelastic model were conducted to acquire transverse force coefficients in relation to the wind incidence angle for the prediction based on the quasi-steady theory. Both aeroelastic tests and pressure measurements were performed on the cylinder with forward inclinations (inclined to the upwind direction), a vertical attitude, and backward inclinations (inclined to the downwind direction).

The paper is organized as follows: after the introduction in Section 1, Section 2 describes the wind tunnel tests of both the aeroelastic tests and the pressure measurements. Section 3 presents experimentally-obtained and theoretically-predicted galloping amplitudes, and Section 4 discusses the applicability of the quasi-steady theory on predicting the galloping behavior of the inclined cylinders and analyzes the mechanisms through which the inclination influences the galloping behavior. The concluding remarks are given in Section 5. Finally, the theoretical galloping onset wind speed and the amplitude, which are derived based on the quasi-steady theory, are given in Appendices.

2. Experimental setup

2.1. Wind tunnel facility and flow field

Aeroelastic tests and pressure measurements were carried out in the high-speed section ($3 \times 2\ m^2$) of the CLP Power Wind/Wave Tunnel Facility at the Hong Kong University of Science and Technology. The tests were performed under a turbulent flow generated by using roughness elements and spires in the upstream of the test section. Instantaneous wind speeds were measured to determine the mean wind speed and turbulence intensity profiles before the actual tests by using a hot-wire anemometer installed at different heights in the cross-section where the model was positioned. The target mean wind speed and turbulence intensity profiles were calculated according to the specifications corresponding to the open terrain (Category 2) in the AS/NZS 1170.2:2002 (Standards Australia/Standards New Zealand, 2002). Comparisons (shown in Fig. 2) of the measured mean wind speed and turbulence intensity profiles with the target profiles indicate the reliability of the test condition. The mean wind speed was normalized by the corresponding value at the vertical cylinder height. Additionally, the longitudinal integral scale of turbulence at the height was approximately 0.48 m, corresponding to a full-scale length of 120 m.

2.2. Aeroelastic tests

To investigate the influence of the inclinations on galloping oscillations of slender cylinders, a series of aeroelastic tests were carried out on a square-section cylinder inclined from the vertical direction by a range of angles to acquire the galloping amplitudes directly. The prototype of the tested model was a slender square-section tower whose aspect ratio (height/width) is 18. More specifically, the dimensions of the prototype were 12.7 m × 12.7 m × 228.6 m. Because the length scale adopted was 1:250, the scaled model was made by a square aluminum hollow cylinder with width D=5.08 cm (2 in.) and height H=91.44 cm (36 in.). Consequently, the blockage ratio of the model in the wind tunnel