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An experimental investigation on vortex induced vibration of a flexible inclined cable under a shear flow

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ABSTRACT

In the present study, an experimental investigation was performed to characterize the vortex induced vibration (VIV) of a flexible cable in an oncoming shear flow. The VIV tests were conducted in a wind tunnel with a flexible cable model. It was found that, under different oncoming velocity profiles, the cable model behaved in single-mode and multi-mode VIVs. The displacement amplitudes of the single mode VIVs were found to be larger than those of multi-mode VIVs, and the cross-flow (CF) response was larger than that of in-line (IL) direction for either the single mode or multi-mode VIVs. For a single mode vibration, the largest CF response occurs in the 1st mode VIV, and the motion trajectory of the 1st mode VIV was found to be an inclined figure of eight shape, while other single mode VIVs behaved in ellipse or straight line trajectories. For multi-mode VIVs, no stable vibration trajectories were found to exist since the vibration frequency bands covered two or more vibration modes. The vortex-shedding frequencies in the wake behind the inclined cable were also characterized in the present study. The shedding frequencies of the wake vortices were found to coincide well with the vibration modes: for a single mode VIV, they were close to the dominant vibration mode; for a multi-mode VIV, they could also cover the appearing vibration modes.

1. Introduction

In recent years, more and more long-span bridges, such as suspension or cable-stayed bridges have been widely constructed worldwide due to their superior structural performance and elegant appearance. As we all know that, a uniform flow induces a single vortex shedding frequency, in contrast, non-uniform flows can potentially trigger responses with multiple narrow-band components since the vortex shedding frequency depends on the oncoming flow velocity and more than one modal frequency will be excited. All these long-span bridges are built in the atmospheric boundary layer where the velocity increases with the height. The key components of these long-span bridges, stayed cables, easily behave in multi-mode VIVs while in this non-uniform flow, i.e., the velocity profile in the atmospheric boundary layer (Main and Jones, 1999; Matsumoto et al., 2003; Zuo et al., 2008; Zuo and Jones, 2010; Chen et al., 2011, 2013). Zuo et al. (2008) and Zuo and Jones (2010) performed full-scale measurement investigations on the Fred Hartman Bridge in Houston (Texas, USA) and observed VIVs of cables with sixth and seventh modes or with fifth and sixth modes, respectively. Chen et al. (2011) observed the occurrence of higher multi-mode (nearly 20th) VIVs of the inclined cables in a cable-stayed bridge in China. Under a large velocity profile, when the velocity differences between the upper and lower ends of an

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inclined cable are large enough to excite two and more vibration modes, the inclined cables will behave in a multi-mode VIVs. Furthermore, Chen et al. (2013) indicated that the inclined cables with a length of 100 m would behave in mono-mode and multi-mode VIVs under different velocity profiles based on numerical simulations.

Being comparable to inclined cables, the VIVs of oceanic risers also happen more frequently. Both field and laboratory tests on long flexible risers in shear flows revealed the multiple frequencies of response (e.g., Lie and Kaasen, 2006; Trim et al., 2005; Vandiver et al., 2009). Lie and Kaasen (2006) carried out model analysis of measurement from a large-scale VIV testing model in linearly shear flow by using a riser model with a length of 90 m and diameter of 3 cm. Under a large velocity profile, the riser presented broad-banded response and no occurrences of single-mode (lock-in) were ever seen. Trim et al. (2005) performed the experimental investigation of VIV of long marine risers. It was found that the cross flow (CF) displacement is higher than the in line (IL) displacement for all velocities and the IL modes are approximately twice as much as that of the CF modes. At a low flow velocity, there was a relatively narrow band of dominant modes in all cases and the band broadens out at higher flow velocity, which is most evident for the CF response. Vandiver et al. (2009) conducted VIV experiments on a quite long (152.4 m) flexible cylinder in the ocean. The traveling wave VIV was dominant at high mode numbers with strong higher harmonic components and stable figures of eight trajectories.

Moreover, Mathelin and de Langre (2005) and Violette et al. (2007) investigated VIVs of long risers under ocean shear flows by using a wake oscillator model. The risers showed multi-mode or mono-mode responses under different shear flows. Their results provided a precious estimation of the vibration amplitudes along the risers. As the span of the bridge increases, the wind profile between two ends of a stayed cable becomes remarkable with the length of the cable increasing dramatically. The wind speed is normally increasing with height; the cable may experience higher shedding frequency at the higher end and such flow profile may excite more than one natural frequency of the cable. Therefore, it is essential to investigate the VIV of an inclined cable under different wind velocity profiles. Computational fluid dynamics (CFD) numerical simulations were also used to study the VIV characteristics of long flexible cylinders. By means of direct numerical simulations, Newman and Karniadakis (1997) and Evangelinos and Karniadakis (1999) studied flow-induced vibrations of a flexible cable at $Re=100$ and $Re=1000$, respectively. The wake patterns were investigated in detail by combining the influence of the nature of the vibration (standing or traveling wave) on the flow structure development. However, the results were obtained in a uniform flow. Lucor et al. (2006) performed VIV studies of long flexible cylinders with aspect ratios larger than 500 in linear and exponential shear flows. Compared with each other, the bandwidth of large oscillation in an exponential shear flow was greater than that in a linear shear flow. Bourguet et al. (2011) investigated VIVs of a long flexible cylinder in a shear flow with an aspect ratio of 200 and at three different Reynolds numbers from 110 to 1100. As a multi-mode VIV, traveling waves were the main part of the flow structure between the two ends of the long cylinder and the standing wave was predominant near the ends, its contribution increasing with Reynolds number. The synchronization region which covered at least 30% of the cylinder length was often lying within the high-velocity zone. They also obtained that the in-line and cross-flow vibrations had a frequency ratio approximately equal to two. However, Huera-Huarte and Bearman (2009) conducted a test for showing the dynamic response of a vertical long flexible cylinder vibrating at low mode numbers. The results indicated that the dominant frequency of the in-line vibrations is the same with that of cross-flow vibrations due to the reason that the IL response frequency cannot lock on the 2nd mode even with added.

In the present paper, the VIVs of an inclined flexible cable model with a length of 6.08 m under different wind velocity profiles were performed to investigate the characteristics of the vibrations and the wake frequencies of the cable model. The structure of this paper is arranged as follows. In Section 2, the experimental setup for reproduction of VIV of the cable model is finished. In Sections 3 and 4, the characteristics of the VIV of the cable model are studied, including the characteristics of the cable vibrations and vortex shedding frequencies varying along the axial direction of the cable in the wake, followed by a section of conclusions derived from the present study.

2. Experiment setup

The experiments were performed in the Joint Laboratory of Wind Tunnel and Wave Flume located at Harbin Institute of Technology (in China) as shown in Fig. 1. The wind tunnel is a closed loop tunnel with two test sections. The dimension of the smaller test section is 4.0 m (width) × 3.0 m (height) with a length of 25 m, and that of the larger one is 6.0 m (width) × 3.6 m (height) with a length of 50 m. The wave trough is located under the larger section and separated by movable floors. The maximum wind speeds can be up to 50 m/s and 30 m/s for the small and large test sections, respectively.

2.1. Flexible cable model

The flexible cable model had a length L of 6.08 m, and the diameter D of cable is 0.042 m. The aspect ratio of cable in this study was about 144.7. The weight of the cable model was 0.467 kg/m. The experimental configurations were shown in Fig. 1(a), the lower and upper ends were 0.45 and 3.05 m above the floor of the wind tunnel, and the inclined angle of the flexible cable was 25.3° and the yaw angle was set as 0° in the testing.

The cable model was axially tensioned by two end plates with a tension of 850 N: the upper end fixed on the upper plate and the lower end fixed on the lower plate. Two ends of the cable model cannot move in the axial, CF and IL directions. The cross-section of the cable model is shown in Fig. 1(b) where the cable model had a 7.5 mm diameter steel stand core with multi-layer foam tapes attached to it. This skeleton structure was covered with a flexible PVC skin, providing an

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