Engineering Structures 169 (2018) 188–200

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Wake-flow-induced vibrations of vertical hangers behind the tower of a long-span suspension bridge

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ARTICLE INFO

Keywords:
Tower wake flow
Vertical hangers
Vortex shedding
Forced vibration
Resonance

ABSTRACT

Violent vibrations have been reported in the vertical hangers of long-span suspension bridges, especially for those located in the vicinity of the towers. In the present study, an experimental investigation is performed to characterize the wake-flow-induced vibrations of vertical hangers behind the tower of a suspension bridge. The tower column and vertical cable models are determined by using a long-span suspension bridge with a geometrical scale ratio of 1:10. Regular vortex shedding from the tower column model is detected in the near wake with a Strouhal number (*St*) of 0.20, and the turbulence intensity of the wake flow behind the tower column model is found to be quite high. Arranged at different stations behind the tower column model, the vertical cables experience violent vibrations. The vibration frequencies of the vertical cables are synchronized with the vortex shedding from the upstream tower model within a certain velocity range, during which severe cable vibrations take place. When the incoming wind speed becomes high, the cable vibrations exhibit multimode characteristics. It is also found that the vertical cables arranged at the rear are subject to the combined interferences of the tower column model and the front cables. As a result, the vibration responses of the rear cables are more violent than those of the front cables.

1. Introduction

Cylindrical structures are commonly used in structural and bridge engineering. Examples of these structures are vertical hangers of suspension bridges, stay cables of cable-stayed bridges, and overhead power lines. Because of relatively low stiffness and damping ratios, cable structures are susceptible to wind-induced vibrations. Vortex-induced vibration (VIV) and rain-wind-induced vibration (RWIV) of stay cables were reported in previous studies [19,10]. The VIV of cylindrical structures is a subject that has attracted extensive attention. Apart from its relevance to practical engineering, it is also of great importance from the perspective of fundamental fluid dynamics. It is well known that flow around a circular cylinder is characterized by flow separation and alternating vortex shedding downstream in the near wake. When the fluid velocity increases, the shedding frequency approaches the natural frequency of a given oscillating cylinder, and then the two frequencies synchronize. This synchronization, which is generally referred to as lock-in [3], may occur and induce vibration of the cylinder. The VIV of a circular cylinder was comprehensively reviewed by Williamson and Govardhan [15], Sarpkaya [13], Gabbai and Benaroya [9], Bearman [2], and others.

For a circular cylinder immersed in the wake of another one, the wake interference from the upstream bluff body can result in completely different fluid and structural behaviours in comparison with an isolated cylinder. The body-wake interaction and aerodynamic interference between two closely separated circular cylinders have been intensively studied, as reviewed by Zdravkovich [16] and Sumner [14]. Zdravkovich [17] classified the flow past two tandem cylinders into three regimes: (I) the extended-body regime, when the cylinders are arranged so close that the shear layers rolled up from the upstream one shield the downstream one, and the gap flow between the cylinders is nearly stagnant; (II) the reattachment regime, where the shear layers are rolled up from the upstream cylinder, then reattach on the downstream one and finally result in an insignificant gap flow; (III) the co-shedding regime, where the shear layers separate alternately in the gap, and the gap flow becomes significant in this case.

Bokaian and Geoola [4] experimentally investigated the response of an elastically mounted circular cylinder immersed in the vicinity of an

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https://doi.org/10.1016/j.engstruct.2018.05.049
Received 16 August 2016; Received in revised form 13 April 2018; Accepted 14 May 2018
0141-0296/

identical and fixed one. Two kinds of instability were found in the dynamic tests, namely, vortex resonance and galloping. The galloping response occurred only when the downstream cylinder was well submerged in the near wake of the upstream one. The vortex shedding frequency was always found to lock to the oscillation frequency. In addition, the vibration characteristics were observed to remain unaffected although the turbulence intensity was changed. In addition, the galloping amplitudes were found to be sensitive to the aspect ratio of the cylinder models.

Brika and Laneville [5] investigated the dynamic behaviours of a long flexible cable in the wake of a stationary cylinder with a similar geometry. It was found that for tandem arranged cables, the dynamic response of the downstream cable was nonhysteretic, the synchronization onset was at higher reduced velocities, and the synchronization region was wider than that of an isolated cylinder. Hover and Triantafyllou [11] studied a cylinder placed 4.75 diameters behind a stationary cylinder of the same geometrical size. An in-line configuration was found to produce large-amplitude galloping responses, and an upward extension of the frequency lock-in range of the reduced velocity was observed. The frequency resonance onset was found at nearly the same reduced velocity for an isolated circular cylinder, whilst a large phase change of the lift force occurred at higher reduced velocities.

Assi et al. [1] experimentally investigated the mechanism of wake-induced vibrations (WIV) of a pair of tandem cylinders. A typical WIV response was found to be characterized by a build-up of amplitude persisting to high reduced velocities. This was different from the typical VIV response that often occurs in a limited resonance range. The researchers proposed that the WIV of the downstream cylinder was excited by the unsteady vortex-structure interactions between the downstream cylinder and the upstream wake: coherent vortices interfering with the downstream cylinder could induce fluctuations in the fluid force that were not synchronized with the cylinder motion. A phase lag between the cylinder motion and the fluid force was favourable and supported the positive energy transferred from the flow to the structure to maintain the vibrations. On the other hand, if the unsteady vortices were removed from the wake of the upstream cylinder, the WIV would hardly be generated.

In the present study, a bundle of vertical hangers of a suspension bridge suffer from wake interference from the upstream tower, and the wake-flow-forced buffeting responses are experimentally investigated. This paper is organized as follows. The engineering background and problem are described in Section 2, the model configuration and experimental details are given in Section 3, the wake flow characteristics behind the tower column are presented in Section 4, the dynamic responses of vertical cables subject to tower wake flow are presented in Section 5, and some discussions and concluding remarks follow in Section 6.

2. Background and problem description

The long-span suspension bridge investigated in the present study joins Zhoushan Archipelago to Ningbo, Zhejiang Province, P.R. China, as illustrated in Fig. 1. With a main span of 1650 m, this is the longest bridge in China and the second longest suspension bridge in the world (after Akashi Kaikyō bridge, main span of 1991 m, Japan). The towers rise to a height of 236.5 m above the sea. They support the main cables from which the twin box girders are suspended through hundreds of vertical hangers. Each bundle of hangers is composed of four separate steel wire ropes, as shown in Fig. 2. Instead of an isolated vertical hanger, a bundle of separated hangers is usually adopted in suspension bridges. Examples include Akashi Kaikyō bridge in Japan and the Golden Gate bridge in the U.S.

The length of the longest vertical hangers of the long-span suspension bridge, which are located in the vicinity of the bridge tower, is about 169.7 m. Because of relatively low stiffness and damping ratios, these long and flexible vertical hangers of the long-span suspension bridge are sensitive to wind and may suffer from wind-induced vibrations. Violent vibrations of the vertical hangers have been observed. In situ monitoring data and video records reveal that characteristics of the violent vibrations occurring in the vertical hangers of the suspension bridge can be summarized as follows: (1) violent vibrations of the vertical hangers are frequently observed in a wind speed range of 14–18 m/s; (2) in the vicinity of the bridge tower, vibrations of the vertical hangers are particularly violent, i.e. the longest vertical hangers; and (3) frequent collisions between vertical hangers are witnessed and recorded. It is noteworthy that the violent vibrations of vertical hangers have also been reported at Akashi-Kaikyō bridge [7,12,8]. It is observed that the excessive vibrations of the downstream ropes were excited by the upstream ropes, indicating the occurrence of wake-induced flutter. Significant vibrations were recorded especially during typhoons, and the high-damping rubber dampers installed to suppress vortex-induced vibrations of these ropes were found to be damaged. To improve their aerodynamic characteristics, the vertical hanger ropes were wrapped with helical wires of 10 mm in diameter [7].

Violent oscillations of the vertical hangers and their collisions raised concerns regarding safety and durability in the bridge engineering community. Some possible excitation mechanisms were proposed to explain the violent oscillations of the vertical hangers, especially for those in the vicinity of the bridge tower. Conventional vortex-induced excitation as a possible mechanism responsible for the violent oscillations was excluded for the simple reason that the onset velocity of the lock-in range is quite low. The natural frequency of the hangers in the vicinity of the tower is about 0.45–0.52 Hz (dependent on the length), and their diameter is 0.088 m. The hangers are observed to vibrate mainly with first-mode frequency. If the cylindrical structures' Strouhal number (*St*) is assumed to be 0.2, then the onset velocity of the vortex-induced vibration is estimated to be 0.2 m/s. When the bridge is subject to crosswinds, wake galloping responses of the two rear vertical hangers are likely to take place owing to the aerodynamic interference of the front hangers. However, wake galloping cannot fully explain the violent oscillations since the spacing between the front and rear vertical hangers is about nine times the hanger diameters, at which the upstream interference is believed to be not that substantial. Zhang and Ge [18] suggested that all vertical hangers were hung from the main cables, and that the buffeting responses of the main cables would therefore be an excitation mechanism of the vibration of the vertical hangers. The researchers proposed a 'main-cable buffeting induced resonance' to explain the violent oscillations of the vertical hangers observed in the suspension bridge. Some would argue that it is still unclear whether the main-cable buffeting could excite such violent vibrations in the vertical hangers.

Previously proposed mechanisms, including the wake galloping response and main-cable buffeting-induced resonance, cannot fully explain this phenomenon. However, the excitation mechanism of the vertical hangers and the role of the bridge tower have not been thoroughly clarified. Further investigations are therefore needed. As mentioned above, violent oscillations of the vertical hangers are observed in the vicinity of the bridge tower, so the interference effects of the tower wake cannot be neglected when the direction of the incoming wind is parallel or oblique to the bridge axis. Under this circumstance, the neighbouring vertical hangers are immersed in the wake of a bridge tower column and cannot be exempted from body-wake interference. In the present study, the interference effects of the bridge tower column on the vertical hangers are experimentally investigated. An excitation mechanism, i.e. tower wake flow forced vibrations, is proposed to explain the violent oscillations of the vertical hangers when the incoming wind attacks along the direction of the bridge axis.

3. Experimental details

An experiment was conducted in the larger test section of the Joint