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Multi-modal vortex- and rain–wind- induced vibrations of an inclined flexible cable

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ABSTRACT

We reproduce multi-modal vortex-induced vibrations (VIVs) and multi-modal rain–wind-induced vibrations (RWIVs) of an inclined and yawed cable in wind tunnel tests. The flexible cable model has low mass and low damping. First, the cable model is kept dry and exposed to uniform airflow; it experiences first-, second- and third-mode VIVs with the increase of wind speed. The structural responses of VIVs are analysed and the frequency lock-in phenomenon is observed for different modes of VIVs of the flexible cable. In addition to VIVs of the dry cable, RWIVs are excited by guiding water rivulets on the cable surface from a water tube. The first-, second- and third-mode RWIVs of the flexible cable are observed and identified at a much higher range of incoming wind speeds than that of the VIVs. To further explore the origin of the multi-modal behaviours of RWIVs, the upper rivulet is guided and restricted to form locally along the cable. Experimental results reveal that the higher- and multiple-mode RWIVs can be excited by a local rivulet, even under a lower wind speed. Finally, RWIVs are compared to VIVs to uncover their underlying similarities and relationships.

1. Introduction

Because of their inherent flexibility, low damping and relatively low mass, long stay cables of cable-stayed bridges are sensitive to wind-induced vibrations. Vortex-induced vibrations (VIVs) and rain–wind-induced vibrations (RWIVs) have been issues of great concern to the bridge engineering community, because the large-amplitude vibrations may lead to fatigue and durability problems. For example, cable–deck connections may suffer from failure, owing to the breakdown of protections against corrosion [1,2].

When subjected to wind, stay cables are characterised by flow separation and alternating vortex shedding into the wake. Periodic vortex shedding can result in large unsteady cross-flow forces acting on the cable [3]. If the shedding frequency approaches an order of the modal frequency of the flexible cable, a cable-wake resonance develops. This fluid-structure synchronization, often referred to as ‘lock-in’, may induce significant cross-flow vibrations of the cables. In bridge engineering, multi-modal VIVs on stay cables are often associated with the non-uniformity of the incoming flow, because bridges are

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usually constructed in the atmospheric boundary layer [4]. Chen et al. [5] conducted a numerical study, suggesting that a 100-m inclined cable would experience multi-modal VIVs under different velocity profiles. Chen et al. [6] experimentally investigated a flexible cable subject to sheared incoming flow. Results revealed that the cable model experienced single- and multi-modal VIVs under different incoming velocity profiles, and the vortex shedding frequencies from the cable synchronised well with the cable's modal frequencies.

Hikami and Shiraishi [7] found that the amplitude of wind-induced vibrations of stay cables could be greatly amplified if they are simultaneously subject to light-to-moderate rain conditions. Owing to great vibration amplitudes, RWIVs have become a major concern for bridge engineers over the past three decades. Vigorous efforts have been made to explore the excitation mechanism of severe cable vibrations under rain and wind conditions. Various research philosophies and approaches, including theoretical modelling [8–10], field observation [11–13], computational fluid dynamics [14,15] and wind tunnel tests [16–23] have been employed to obtain a better understanding of the behaviours and excitation mechanisms of RWIVs.

This type of severe cable vibration, jointly induced by rain and wind, is characterised by much lower frequencies and much larger amplitudes than conventional VIVs. It is generally recognised that RWIVs often occur for wind-speed ranges of 8 to 15 m/s, in the frequency range of 1–3 Hz and with yaw angles 20–60°, as concluded by Flamand [16]. Additionally, the upper rivulet on the leeward side of the cable surface and its circumferential oscillation play a crucial role in the excitation of RWIVs. Several wind tunnel tests [16–23] have been conducted to gain insights into the excitation mechanism of RWIVs; they considerably improved our understanding of this phenomenon. However, during previous wind tunnel tests, rigid and segmental models were usually employed because of the limitation of the test sections. Thus far, the multi-modal behaviours of RWIVs on a stay cable have never been reproduced or investigated in a wind tunnel test. An alternative approach to studying multi-modal RWIVs is field monitoring. Ni et al. [11] measured the response characteristics and excitation mechanisms of stay cables experiencing RWIVs on the Dongting Lake Bridge, P. R. China. Field monitoring was realised by employing accelerometers, anemometers and rain gauges. The dominant frequency of RWIVs corresponded to the third mode frequency of the cable, and the first five modes were found to participate. Zuo et al. [12] developed a long-term full-scale monitoring system on the Fred Hartman Bridge, United States, to investigate the characteristics of stay-cable vibrations. They attempted to interpret both VIVs and RWIVs in the context of the three-dimensional nature of the environment. By investigating the similarities and differences between VIVs and RWIVs, they argued that RWIVs might be a vortex-induced type of excitation that is different from conventional vortex shedding. This exhibited similarities to the research findings of Matsumoto et al. [24], in which RWIV was explained as a type of VIV at a high reduced velocity. It was shown by experiments that the upper rivulet on the cable surface and the incoming turbulence played crucial roles in the mechanism of the VIV at a high reduced velocity. Zuo and Jones [13] reported a type of large-amplitude vibration of dry cables at a high reduced velocity. They proposed that the large-amplitude cable vibrations, with or without rainfall, might originate from the same type of vortex-shedding mechanism that is different from the von Kármán vortex shedding. Moreover, such a mechanism would be promoted and enhanced by the upper rivulet.

In the present study, we reproduce multi-modal VIVs and multi-modal RWIVs by employing an inclined flexible cable model in a wind tunnel test. The VIVs are reproduced under a smooth incoming airflow, and the RWIVs are excited under the joint action of a smooth incoming flow and a guided upper rivulet.

This paper is organised as follows. Details of the flexible cable model and the experimental setup are given in Section 2. Experiment results, including multi-modal VIVs and multi-modal RWIVs, excited by either increasing wind speed or local rivulets of the flexible cable, are presented and analysed in Section 3. Conclusions are drawn in Section 4.

2. Experimental setup

2.1. Introduction to the laboratory facilities

Our experimental study was performed in the larger test section of the Joint Laboratory of Wind Tunnel and Wave Flume (WTWF), Harbin Institute of Technology, PR China. The closed-loop wind tunnel laboratory has two test sections, a larger one and a smaller one, as sketched in Fig. 1(a). The dimension of the larger test section is 6.0 m (width) × 3.6 m (height) with a length of 50 m, whereas that of the smaller one is 4.0 m (width) × 3.0 m (height) × 25 m (length). A wave flume, as deep as 26 m, lies beneath the larger test section. The wave flume is separated from the larger test section by movable and perforated floors, as noted in Fig. 1(a) and (c). The perforated floor allows an immediate water drainage into the wave flume. Therefore, the larger section of the WTWF laboratory was suitable for performing our experimental study of RWIVs.

2.2. Flexible cable model and experimental setup

To excite multi-modal vibrations, the flexible cable model needs to be sufficiently long, within the limitations of the larger test section of WTWF. A cable having a total length, L, of 8.31 m and an outer diameter, D, of 98.36 mm was manufactured to reproduce multi-modal VIVs and RWIVs for our experiment. The flexible cable model realises low mass and low damping ratios on a 12-mm diameter steel wire rope inside with multiple layers of foam taps wrapped around it, as illustrated in Fig. 1(b). These are the key factors influencing the occurrence of VIVs and, particularly, RWIVs. A polyolefin heat-shrink tube