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Study on the role of rivulet in rain–wind-induced cable vibration through wind tunnel testing

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ABSTRACT

Rain–wind-induced vibration (RWIV) of stay cables has become a concern in bridge engineering over the past decades. The excitation mechanism of RWIV remains unclear. Many researchers believe that the upper rivulet is crucial to RWIV. However, experimental study on rivulet is challenging and limited. The current study designs and tests a cable model of 160 mm in diameter in an open jet wind tunnel. The upper rivulet movement and cable vibration are simultaneously measured. The importance of the upper rivulet in RWIV is directly demonstrated by alternately controlling the upper and lower rivulets. The characteristics of the upper rivulet movement and the effects of this movement on RWIV are investigated in detail. The experiment shows that the rivulet–cable system is coupled, which causes the cable and upper rivulet to vibrate at different amplitudes under the same wind speed. The upper rivulet harmonic movement changes the wind loading on the cable, causing the harmonic vibration of the cable, which in turn exerts a harmonic inertia force on the rivulet. A large vibration of the coupled system then develops.

1. Introduction

Stay cables are important constituent parts of cable-stayed bridges. Given their inherent characteristics of low damping and great flexibility, these cables are prone to large vibrations caused by external excitations, such as wind, rain, vehicles, and anchorage motion (Xia and Fujino, 2006). Large cable vibration has been observed in several cable-stayed bridges, such as Dongting Lake Bridge (Ni et al., 2007), Meikonishi Bridge (Hikami and Shiraishi, 1988), Ajigawa Bridge (Ohshima and Nanjo, 1987), Faroe Bridge and Tenpohzan Bridge (Matsumoto et al., 1989), Koehlbrant Bridge (Saito et al., 1994), and two bridges in Shanghai and Nanjing, China (Gu and Du, 2005), during the simultaneous occurrence of rain and wind. Such occurrence is called rain–wind-induced vibration (RWIV).

Extensive research has been conducted to investigate RWIV through field measurements, wind tunnel tests, and theoretical analyses. Ni et al. (2007) conducted continuous field measurements on the Dongting Lake cable-stayed bridge and observed that large RWIV occurs at 6–14 m/s wind speed and between 10° and 50° wind direction (relative yaw angle). Main and Jones (1999) performed long-term field measurements on the Fred Hartman Bridge in Houston and the Veteran's Memorial Bridge in Port Arthur. They found that most high-amplitude responses were velocity-restricted and occurred in

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the presence of moderate rain and in narrow range of wind direction. Zuo et al. (2008) compared the vortex-induced vibration and RWIV in three-dimensional environment from field measurements and observed multiple modes of RWIV. Later, Zuo and Jones (2010) observed that RWIVs could occur under very turbulent wind and very heavy rainfall, and, large vibrations of dry cables occurred under high reduced velocity. They concluded that RWIV and dry cable vibration might be due to a kind of vortex shedding, different from the classical Karman vortex shedding.

Hikami and Shiraishi (1988) reproduced RWIV in a wind tunnel and investigated the effects of wind speed and direction, rain intensity, and vibration frequency. They concluded that the formation of the upper rivulet made the cable aerodynamic unstable. Matsumoto et al. (1992, 1995, 2003, 2005) conducted a series of wind tunnel tests and addressed the importance of the axial flow in RWIV. They classified RWIV into three types: the galloping type related to a negative slope of the lift force caused by the upper water rivulet or axial flow, the vortex-shedding type with a long period, and the mixed type. Flamand (1995) reproduced RWIV in a wind tunnel with an inclined angle of 25°. RWIV occurred at the wind speed ranging from 7 m/s to 13 m/s and a yaw angle between 25° and 50°. Gu and Du (2005) investigated the effects of inclination angle, yaw angle, frequency, and cable damping on the characteristics of RWIV through wind tunnel tests. They pointed out that the upper rivulet movement on the cable was the prerequisite of RWIV. Xu et al. (2006) measured the drag and lift coefficients of inclined circular cylinders with artificial rivulet and investigated the effects of artificial rivulet shape and size. They observed that the drag and lift coefficients varied with the position of the artificial rivulet and concluded that the RWIV might be excited by the negative slopes in the lift coefficient curve. Du et al. (2013) measured the wind pressures and aerodynamic forces acting on both inclined cylinder and artificial upper rivulet in a wind tunnel. They observed that the aerodynamic forces acting on the cylinder and the rivulet varied with the upper rivulet's position and concluded that this might be the excitation mechanism of the RWIV.

Xu and Wang (2003) and Wang and Xu (2003) proposed one- and two-degree-of-freedom (DOF) models that consider the effect of moving upper rivulet on rain–wind loading to simulate RWIV. Cosentino et al. (2003b) proposed a three-DOF model that consists of a two-dimensional motion of the cable cross-section and an oscillating rivulet. These models could successfully capture the velocity-restricted and amplitude-restricted characteristics of RWIV.

Through the abovementioned studies, the onset conditions of RWIV, such as wind speed and direction and rainfall intensity, have been investigated. RWIV characteristics, including large and restricted amplitude and low dominant frequency, have been widely reported. Nevertheless, the precise excitation mechanism of RWIV is still unclear and some conclusions even controversial. In summary, researchers have attributed the cable instability to following factors: (1) presence of the water rivulet on the cable surface (Ni et al., 2007; Hikami and Shiraishi, 1988; Gu and Du, 2005; Flamand, 1995; Xu et al., 2006; Du et al., 2013; Xu and Wang, 2003; Wang and Xu, 2003; Li et al., 2010b; Chen et al., 2013; Gu and Huang, 2008), (2) the axial flow formed along the inclined cable (Matsumoto et al., 1992, 1995, 2003, 2005), (3) swirling flow travels along the inclined circular cylinder (Yeo and Jones, 2008, 2012), and (4) the Reynolds number effect (Seidel and Dinkler, 2006). Numerous researchers believe that the upper rivulet is the most important factor in RWIV, and various studies have been conducted to investigate its role in RWIV. For example, Hikami and Shiraishi (1988) and Ni et al. (2007) observed that the large vibration disappeared when rain stopped during their field testing. Flamand (1995) indicated that the location and movement of the upper rivulet were the main factor in large cable vibration. Gu and Huang (2008) used artificial rivulets to investigate the effect of rivulet motion on cable vibration theoretically and experimentally. Xu et al. (2006) and Du et al. (2013) studied the effect of the upper rivulet position on the aerodynamic coefficients of inclined cylinders based on the quasi-steady assumption. Li et al. (2010a) and Chen et al. (2013) observed that the upper rivulet significantly affected the aerodynamic coefficients of an inclined cable through a hybrid numerical and experimental approach.

However, most of the above studies used artificial rivulets and very few employed real water rivulets. Directly measuring rivulets is very difficult on site or in wind tunnels because the rivulet is extremely small, thin, sensitive to wind flow, and uncontrollable (Cosentino et al., 2003a; Li et al., 2010a). In the current study, a stay cable with real water rivulets was tested in a wind tunnel. A digital video camera was installed to record rivulet movement during the test. The digital image processing method was applied to extract the time history of the rivulet movement. Cable vibration was measured by laser distance sensors. The upper and lower rivulets were alternately switched on/off to study their roles in RWIV. The characteristics of rivulet oscillation and the relationship between cable vibration and rivulet oscillation are extensively analyzed to assist in understanding the mechanism of RWIV.

2. Wind tunnel test

A cable model was tested in an open jet wind tunnel, which measured 1.34 m wide and 1.54 m high. The cable model was made of high-density polyethylene (HDPE) coated steel tube and was elaborated in the same way as the real stay-cables. The cable was 160 mm in diameter and 2.7 m in length with a 2 m-long test segment in the middle and transition segments at both ends (Fig. 1). The mass of the entire cable model was measured as 66.0 kg. The cable was suspended by springs at both ends in the transverse direction and by a steel wire in the longitudinal direction as shown in Fig. 1(b). The springs were mounted on a firm steel frame, which was fixed on the ground. The springs were away from the test segment and thus didn't affect the wind condition of the cable, enabling the cable to vibrate freely in the horizontal and vertical directions. The test segment was placed at the outlet of the wind tunnel. The cable model was installed with an inclination angle α of 32°