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Computer vision-based recognition of rainwater rivulet morphology evolution during rain–wind-induced vibration of a 3D aeroelastic stay cable

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ABSTRACT

In this study, the morphology evolution of rainwater rivulets during the rain–wind-induced vibration (RWIV) of a three-dimensional (3D) aeroelastic stay cable model is identified using computer-vision technology. The formation and oscillation of rainwater rivulets on the cable surface are critical to the occurrence of the RWIV of the cable model. However, it is very difficult to obtain the water film and rainwater rivulets on the cable surface because no sensors can be installed on the cable surface. The computer vision technology can obtain information about the surface of an object. In this study, a wind tunnel test is performed to reproduce the RWIV along with rainwater rivulets and periodic oscillations along the cable circumference. To obtain the geometric and dynamic characteristics of the rainwater rivulets, a high-speed charge-coupled device (CCD) camera with a resolution of 1200 × 800 pixels and an acquisition frequency of 200 fps is employed to record the snapshots of the rivulet measurement regions. Then, an image recognition method based on comparison of color differences and least-square fitting techniques is employed to identify the rainwater rivulet morphology evolution on the cable surface. The rivulet width, film endpoints, and rivulet distribution characteristics in the spanwise direction are obtained; the oscillation frequency is subsequently calculated according to the rivulet time evolutions. Finally, the relationship between the oscillating characteristics of the rivulet and cable vibration is investigated; this relationship may help reveal the possible mechanics of the RWIV of stay cables.

1. Introduction

Inclined cables of cable-stayed bridges are prone to large-amplitude vibrations such as rain–wind-induced vibration (RWIV) under the simultaneous action of wind and rain. RWIV is a multiphase fluid structure instability phenomenon, and in the case of stay cables, this phenomenon occurs frequently in subcritical Reynolds number flow and may result in fatigue of the joints and reduction of the life of the cable. Many studies have explored the underlying mechanism of RWIV through field measurements (Hikami and Shiraishi, 1988; Fujino and Yoshida, 2002; Matsumoto et al., 2003a; Phelan et al., 2006; Ni et al., 2007; Zuo et al., 2008; Zuo and Jones, 2010), wind tunnel tests (Matsumoto et al., 1990, 1992, 1995, 1998, 2003b; Flamand, 1995; Gu et al., 2002; Gu and Du, 2005; Lemaitre et al., 2007; Zhan et al., 2008; Chen et al., 2013), and numerical simulations (Robertson et al., 2010; Taylor and Robertson, 2011; Bi et al., 2014; Cheng et al., 2015). Some researchers suggest that the RWIV is a new type of vibration accompanied and characterized by a significant phenomenon, namely, upper rivulet oscillation in the circumferential direction on the cable surface (Hikami and Shiraishi, 1988; Yamaguchi, 1990; Flamand, 1995; Matsumoto et al., 1995, 1998; Bosdogianni and Olivari, 1996; Gu and Du, 2005; Alam and Zhou, 2007; Lemaitre et al., 2007; Chen et al., 2013). The circumferentially vibrating upper rivulet located near the separation point is closely related to the mechanics of RWIV (Matsumoto et al., 1995, 2003a; Bosdogianni and Olivari, 1996; Wang et al., 2005; Alam and Zhou, 2007; Cheng et al., 2015). However, few wind tunnel experiments could describe the rainwater morphology evolution in detail because the multiphase measurement system employed in the wind tunnel tests requires more complex instruments and equipment, which cannot be easily implemented. Furthermore, quantitative information about the rainwater rivulet morphology, such as the position, thickness, and movement, cannot be obtained easily because of the limitations of the measurement system.

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Several wind tunnel experiments were carried out to implement measurements for obtaining information about the rainwater rivulet/water film (Kamei and Serizawa, 1998; Cosentino et al., 2003; Li et al., 2010, 2015; Zhang et al., 2015; Liu et al., 2017). A stay cable covered by a high-density polyethylene material was used in the wind tunnel (Cosentino et al., 2003). The pressure distribution around the cable surface was first measured; meanwhile, the thickness of the water film was measured by using the resistance wire distributed around the cable surface. Furthermore, to study the upper rivulet, an ultrasonic transmission thickness measurement system was employed to measure the time-dependent spatial distributions of rainwater around the surface of the stay cable when the RWIV phenomena were reproduced (Li et al., 2010). The location, geometry, and oscillation data of rainwater rivulets were recorded and analyzed. Additionally, the quantitative investigation of the upper rivulet oscillation indicated that the oscillation frequency of the upper rivulet, obtained by the wind tunnel experiment, approached the natural frequency of the segment model during RWIV. However, in these two experiments, the rainwater rivulet morphology distributions in the longitudinal direction were not measured; additionally, the differences in the surface material of the model and prototype were ignored. Digital image processing method was first employed to capture the rainwater morphology by using the digital video camera (Li et al., 2015); however, the cable segment model rather than the three-dimensional (3D) elastic model was employed in the testing, and the sampling rate of the digital camera was 25 fps. The rivulet morphology and movement features may be quite different on a deformed elastic stay cable. In addition, the cable segment model cannot reproduce a multiple-mode RWIV, which has been observed in many actual cable-stayed bridges. To the best of our knowledge, there are no other reports about rivulet morphology and movement features corresponding to the multiple-mode

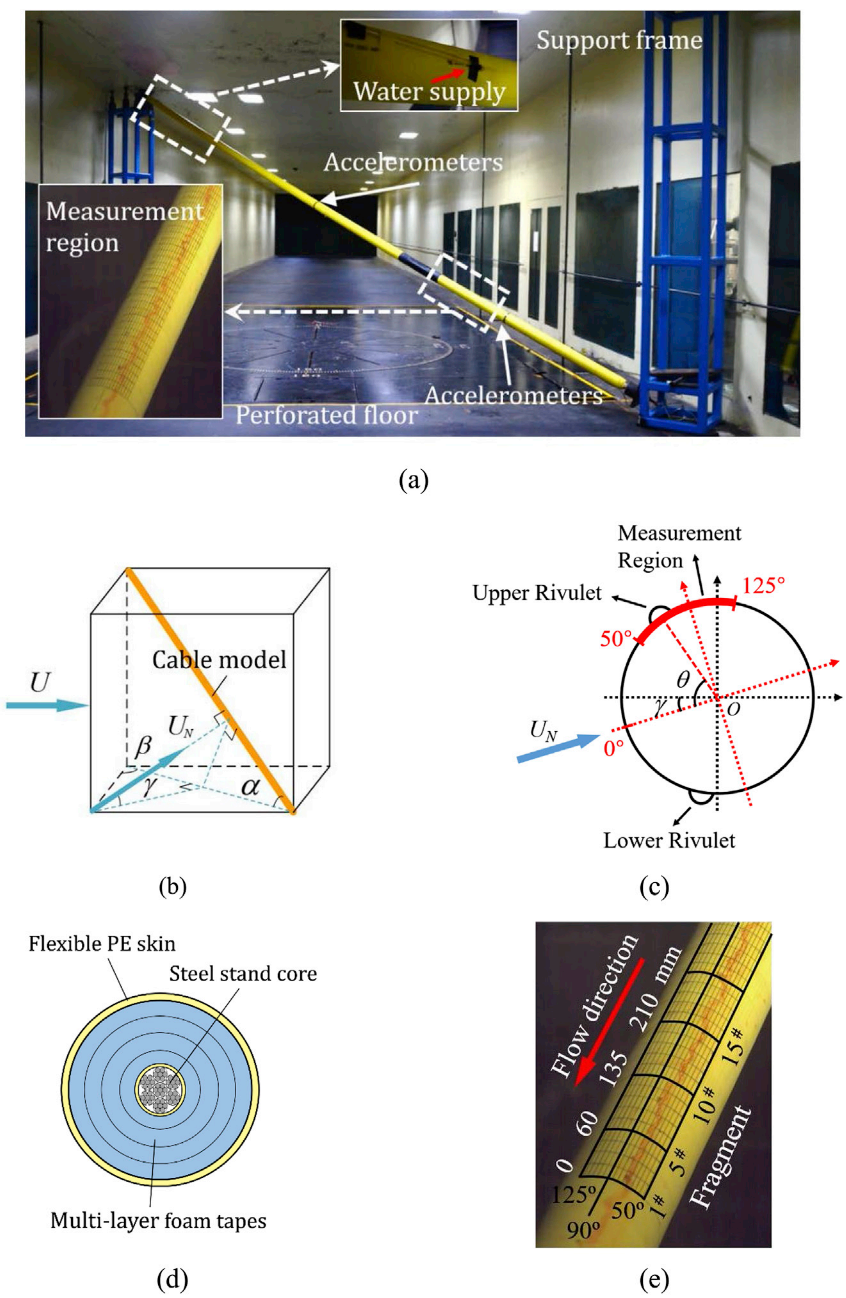

Fig. 1. Experiment setup of RWIV of the flexible cable model: (a) snapshot of the flexible cable model and wind tunnel (b) schematic diagram of the inclination angle α, wind yaw angle β and relative attack angle γ of the cable model (c) schematic diagram of circumferential coordinate system (d) cross-section of the cable model and (e) coordinates of the measurement region.