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Numerical modeling of the wind load of a two-dimensional cable model in rain–wind-induced vibration

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HIGHLIGHTS

- An empirical formula of rain–wind-induced cable vibration (RWIV) is proposed.
- The parameters of the aerodynamic forces in RWIV are based on wind tunnel tests.
- The numerical results agree with the wind tunnel tests.
- Parametric analyses are investigated.

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ABSTRACT

Large amplitude rain–wind-induced vibration (RWIV) of stay cables has been widely reported in recent decades. As this large vibration might cause severe effects on stay cables and bridges, it has been become a worldwide concern in bridge and wind engineering. Extensive research has been conducted to investigate RWIV through field measurements, wind tunnel tests, numerical analysis, and the computational fluid dynamic method. In particular, to predict and avoid this large amplitude cable vibration, many numerical models based on the quasi-steady assumption have been proposed to numerically simulate the cable's responses. Recently, a new excitation mechanism has been proposed to explain RWIV through the interaction between the upper rivulet, boundary layer, and cable vibration, which indicated that the aerodynamic forces of the cable might also be related to the boundary layer state. In the present study, a new numerical model of the wind loads acting on a two-dimensional cable model during RWIV is established based on the boundary layer state. The established numerical model is then applied on a sectional model of stay cable which had been tested in a wind tunnel and the vibration responses are numerically calculated. The comparison between the calculated responses and the wind tunnel test results shows that this numerical model captured the main characteristics of RWIV. Finally, the parametric studies are conducted and the results show that the effective yaw angle, phase difference, cable diameter, damping ratio, and uniform coefficient have significant effects on the wind speed ranges or the vibration amplitude of the RWIV.

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1. Introduction

Rain–wind-induced vibration (RWIV) of stay cables has been widely reported as a complicated gas–liquid–solid coupled process with nonlinearity (Lemaitre et al., 2007, 2010; Robertson et al., 2010; Taylor and Robertson, 2011, 2015; Chen et al., 2013; Bi et al., 2013, 2014; Cheng et al., 2015; Wang et al., 2016; Jing et al., 2015, 2017). Extensive research has been conducted with the aim to reveal the excitation mechanism of RWIV (Hikami and Shiraishi, 1988; Matsumoto et al., 1992, 1995, 2003; Flamand, 1995; Cosentino et al., 2003a; Gu and Du, 2005; FHWA, 2007; Zuo et al., 2008; Zuo and Jones, 2010; Li et al., 2007, 2015a, b, 2010a, b; Jing et al., 2015, 2017; Du et al., 2013) and to establish a numerical model to numerically simulate the cable responses (Yamaguchi, 1990; Xu and Wang, 2001, 2003; Cosentino et al., 2003b; Seidel and Dinkler, 2006; Gu, 2009). Over the past two decades, many numerical models have been proposed by researchers.

Yamaguchi (1990) first established two mathematical models to simulate RWIV: the single degree of freedom (SDOF) model (Den Hartog mechanism) and the two degrees of freedom (TDOF) model, by means of quasi-steady galloping analysis. They concluded that the latter could explain large RWIV. Xu and Wang (2001, 2003) proposed an SDOF model to numerically analyze the response of an inclined and yawed cable, in which the upper rivulet was assumed to circumferentially oscillate with the same frequency as the cable and the amplitude ratio between the upper rivulet and cable vibrations was constant for a given wind speed. Both the effect of the mean wind velocity on the initial position of the upper rivulet and the effect of the oscillating rivulet on the cable were considered in their numerical model. Wilde and Witkowski (2003) derived a similar SDOF model and estimated the maximum amplitude of RWIV with their proposed mathematic model. Cao et al. (2003) then considered the uncertainly of the water rivulet's vibration and constructed a stochastic model for RWIV in which the movement of the upper rivulet was described using a simple stochastic process. The aerodynamic forces on the cable were still determined by the position of the upper rivulet.

Cosentino et al. (2003b) proposed a three-degrees-of-freedom model consisting of a two-dimensional motion of the cable and an oscillating upper rivulet in which the aerodynamic forces of the cable were determined by the boundary layer state. The boundary layer state was expressed by an empirical formula of the water rivulet's velocity. Seidel and Dinkler (2006) adopted their concept and established a numerical model considering the water rivulet as a movable disturbance that oscillated around the transition point of the flow at the same frequency as that of the cable vibration. The water rivulet's periodic disturbance induced the periodic transition of the flow from pre-critical to critical flow, resulting in the transfer of energy from the flow to the elastic structure.

Gu (2009) then established a TDOF model considering both the cable and upper rivulet oscillations. In his model, both the cable and water rivulet oscillations were calculated from the kinematic equations. The forces acting on the rivulet consisted of the inertial forces caused by the cable's motion and the rivulet motion itself, the rivulet's gravity, aerodynamic forces, and the friction force between the water rivulet and the cable surface. Both the aerodynamic forces of the cable and the upper rivulet were obtained through wind tunnel tests. Based on this numerical model, Wu et al. (2013) further considered the unsteady and hysteretic nonlinear features of the aerodynamic forces acting on the cable and the rivulet. Li et al. (2013) considered the interaction between the in-plane and out-of-plane vibrations of the cable and recently proposed eight aerodynamic derivatives to determine the unsteady self-excited aerodynamic forces on the cable and rivulet. They suggested that this was more accurate than the traditional quasi-steady aerodynamic forces (Li et al., 2016).

Generally, two types of numerical methods have been proposed: based on the quasi-steady assumption or based on the boundary layer state. Most of the proposed numerical methods were the former type, which can be even further categorized as two branches by the simulation of the upper rivulet's movement: one assumes that the upper rivulet movement is directly related to the cable vibration (Xu and Wang, 2001, 2003; Xu et al., 2006; Wilde and Witkowski, 2003; Cao et al., 2003; Li et al., 2015a, b) and the other calculates the upper rivulet's responses by solving the coupled kinematic equations (Gu, 2009; Wu et al., 2013; Li et al., 2013). However, for the quasi-steady models, the aerodynamic forces were measured using rigid and static water rivulet, which are different from the real situations of RWIV. Attempts to use the latter on the boundary layer state have been rare. Cosentino et al. (2003b) assumed that the upper rivulet modifies the flow regime into the one-bubble regime during cable's descending, which generates a downward lift force and produces a positive work to excite the cable vibration, and established a numerical model for RWIV. However, the reattachment of the boundary layer to the upper side produces upward aerodynamic forces rather than downward forces. Seidel and Dinkler (2006) assumed that, when a rivulet is located at the separation area, the flow transits from the pre-critical regime to the critical regime, as what happens in the Prandtl trip wire phenomenon. However, they did not differentiate the effects of the upper and lower rivulets or the upward and downward vibrations of the cable.

Recently, Jing et al. (2017) proposed a new excitation mechanism of RWIV through wind tunnel tests using the real water rivulet. They explained large amplitude RWIV using the different states of the boundary layer caused by the oscillation of the upper rivulet during the cable's ascending and descending, which indicated that the numerical model based on the boundary layer state is required. In the present study, a new numerical model of the wind loads acting on the two-dimensional cable model in RWIV is established based on the boundary layer state, according to the excitation mechanism proposed by Jing et al. (2017). Two sets of aerodynamic force coefficients are adopted to simulate the RWIV of a sectional model of stay cable using the proposed numerical model, and the calculated vibration amplitude are then compared with the experimental results. Parametric studies are conducted to investigate the influences of different factors on RWIV, including the wind speed, wind direction, structural damping ratio, phase difference, and the uniform coefficient.