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2D numerical analysis on evolution of water film and cable vibration response subject to wind and rain

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ABSTRACT

Under wind and rain, cables of cable-stayed bridges may vibrate with large amplitude known as rain–wind induced vibration (RWIV). According to the previous researches, the formation and oscillation of water rivulets around cable plays an important role in RWIV. In this paper, 2D coupled equations of water film evolution and cable vibration are presented for the first time based on the combination of lubrication theory and vibration theory of single-mode system. To reveal the mechanism of RWIV, the mutual influences of water film evolution, lift and vibration of cable under different wind speeds are analysed by numerically solving the coupled equations. In accordance with the experimental results, the numerical results show that RWIV only occurs in special wind speed and the period of water film evolution is close to cable natural period, which makes cable vibrate with large amplitude. Under too low wind speed, the inconspicuous variation of water film morphology leads to small amplitude of lift and cable vibrating like free vibration. And when wind speed is too large, cable also vibrates with small amplitude as the water film morphology and lift change with little periodicity. These confirm the conclusion that the resonance between rivulets and cable may be one of the main reasons for RWIV.

1. Introduction

Rain–wind induced vibration (RWIV) is a large amplitude and low frequency vibration of cables of cable-stayed bridges and suspenders of arch bridges under wind and rain (Bosdogianni and Olivari, 1996). Since Hikami and Shiraishi (1988) found this phenomenon on the Meikonishi Bridge for the first time in 1984, researchers repeatedly observed the same phenomenon in the field (Costa et al., 1996; Ni et al., 2007; Zuo et al., 2008; Wang et al., 2003) and simulated RWIV through a series of wind tunnel tests (Cosentino et al., 2003; Flamand, 1995; Gu et al., 2002; Gu, 2009; Gu and Du, 2005; F.C. Li et al., 2010; Matsumoto et al., 1990, 1992; Xu et al., 2011). They found the basic characteristics of RWIV as follows: (1) upper and lower rivulets are formed on cable surface and oscillate with lower order modes; (2) RWIV only occurs in a certain range of wind speed under a little or moderate rainfall condition; (3) the vibration amplitude is related to the length, inclination direction, surface material of cable and the wind yaw angle.

RWIV is a very complex problem of coupling oscillation of gas, liquid and solid. Since Yamaguchi (1990) established a theoretical model based on wind tunnel tests, for revealing RWIV mechanism researchers created various theoretical models. It is the formation and oscillation of rivulets that has been viewed as the indispensable factor for RWIV by most researchers. According to different methods for simulating rivulets, these theoretical models can be divided into three types as follows:

(1) The rivulets are simulated as moving particles on the cable surface. And the aerodynamic coefficients of cable are substituted into the motion equations of cable and rivulets regarding them as known parameters, which are obtained by force or pressure tests of the cable section model with artificial rivulets in wind tunnel. Yamaguchi (1990) set up two-dimensional 2-DOF motion equations of cable with an upper rivulet by the quasi-steady galloping method based on the experiment of aerodynamic coefficients with an artificial rivulet. He found that when the fundamental frequency of upper rivulet oscillation coincides with the cable natural frequency, the coupled motions of rivulet and cable make aerodynamic damping negative, and then cause the large amplitude oscillation of stay cable. Peil and Nahrath (2003) established a 3-DOF model assuming that all aerodynamic

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pressures act on rivulets based on Yamaguchi's model. They described a conclusion that RWIV is caused by the motion of upper rivulet. A similar explanation was derived by Seidel and Dinkler (2006) through numerical solution for six coupled equations considering the movement of two rivulets on the cable surface as disturbance factors. S.Y. Li et al. (2009) derived the equations that govern three-dimensional continuous stay cable and three-dimensional continuous rivulet by assuming the interactions between the cable and the rivulet as the Coulomb and linear damping forces, and solved these partial differential equations with the numerical method to obtain the responses of the cable and the rivulet.

(2) The motion equation of rivulets is not established, and the forces of cable caused by rivulets motion are substituted into the cable motion equation considering them as known parameters based on the assumption of rivulets motion law. Xu and Wang (2003) presented a SDOF model based on Yamaguchi's theory. They simplified RWIV as a forced vibration with a load of rivulet movement by expressing the aerodynamic lift as a function of cable vertical speed, rivulet angle and angular velocity, while they did not consider the impact of cable movement on the amplitude and frequency of rivulet. Based on the assumption that the movement of rivulet is sinusoidal by experiences, S.Y. Li et al. (2007) developed an analytical model for RWIV of three-dimensional continuous stay cable with quasi-moving rivulet, and held that the cable may produce a large amplitude vibration when the rivulet oscillation frequency is similar to any order natural frequency of cable. Meanwhile, they found that the vibration mode of the cable is related to not only the rivulet oscillation frequency but also the formation position of rivulet on cable with the axial direction. Bi et al. (2010) explained the excitation mechanism of RWIV as the action of the centrifugal force of the water around the circumference of the cable surface using the resonance theory. H. Li et al. (2010) developed an ultrasonic transmission thickness measurement system for quantitative measurement of evolution and distribution of rivulets on stay cable surface subject to wind and rain, and then obtained aerodynamic forces of stay cable under RWIV by the hybrid approach that combines the experiment with computational fluid dynamics (CFD) based on the assumption that upper rivulet oscillates around the cable.

(3) Lubrication theory is used to simulate the formation and oscillation of rivulets by assuming that there is continuous water film on the cable surface. Lemaitre et al. (2007) added wind as an exterior load that is expressed as pressure and friction coefficients $C_p(\theta)$ and $C_f(\theta)$ in the model presented by Reisfeld and Bankoff (1992) based on the lubrication theory to simulate the formation of rivulets and study the variation of water film around horizontal and static cable. Xu et al. (2011) modified motion equation of Lemaitre's model by assuming the dynamic characteristics of cable as known conditions of equation to consider the effect of cable movement on water film, and investigated the evolution of water film subject to gravity, wind pressure, friction and surface tension. On the other hand, to obtain the variation of water film around horizontal and static cable with time, Taylor and Robertson (2011) modified Lemaitre's model by the substitution of wind pressure and friction coefficients $C_p(\theta, t)$ and $C_f(\theta, t)$ which vary with time through numerical calculation for the fixed coefficients $C_p(\theta)$ and $C_f(\theta)$.

It can be seen that all above mentioned models based on lubrication theory are unilateral coupling of rivulets and cable, which can obtain the evolution of rivulets but not the vibration of cable. As RWIV is the two-way coupled interaction between rivulets and cable, it is necessary to establish a coupling model of gas, liquid and solid. In this paper, 2D coupled equations of water film evolution and cable vibration are established for the first time based on Xu's model and Taylor's model and combined with vibration theory of single-mode system in Section 2. In Section 3, a numerical solution method for obtaining wind pressure and friction coefficients ($C_p(\theta, t)$ and $C_f(\theta, t)$) with different water-film morphology is presented by CFD software—Fluent 6.3. And the numerical solution procedure of coupled equations is provided as well. Then the mechanism of RWIV is preliminarily revealed in Section 4 by discussing the relationships between rivulets, aerodynamic lift and vibration of cable with different wind speeds.

2. Model

2.1. Evolution equation of water film based on lubrication theory

As shown in Fig. 1(a), a stationary cable with a radius of α ($0^\circ \le \alpha \le 90^\circ$) is under the interaction of gravity and horizontal wind, while the wind is designated by speed U_0, yaw angle β ($0^\circ \le \beta \le 90^\circ$) and attack angle 0°.

The A–A cross-section of stay cable is taken as the study object shown in Fig. 1(b). According to the lubrication theory, there is a continuous thin water film of thickness $h(\theta, t)$, $(h > 0)$ in polar coordinates around the cable. Neglecting the gravity component along the cable, the gravity component perpendicular to the cable is given by

$$g_N = g\cos\alpha \tag{1}$$

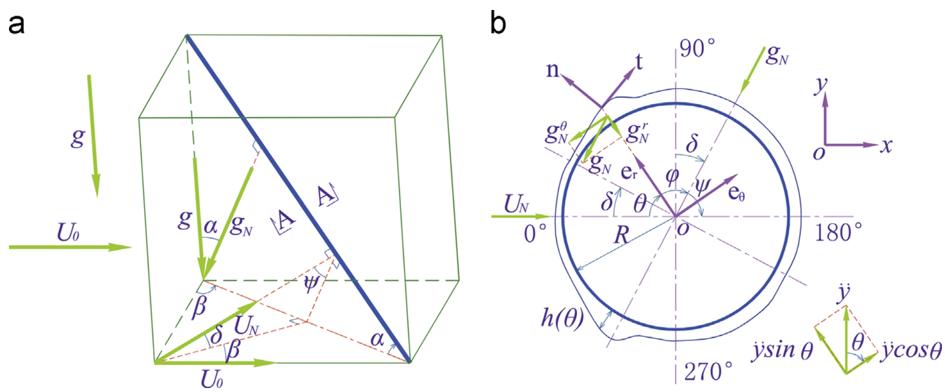

Fig. 1. Model of stay cable and water film. (a) Spatial position of stay cable and (b) Force of water film around stay cable.