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Numerical simulation and analysis of the effects of water-film morphological changes on the aerodynamic lift of stay cables

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ABSTRACT

The cables in cable-stayed bridges can vibrate at large amplitudes during rain and windy conditions, a phenomenon known as rain-wind induced vibration (RWIV). Previous studies have demonstrated that the formation and oscillation of rivulets on stay cable surfaces play an important role in RWIV.This paper presents a new numerical method for simulating the evolution of rivulets on stay cable surfaces based on a combination of the gas–liquid two-phase theory and the volume of fluid method (VOF method), which allows for the straightforward determination of the cables' aerodynamic lift when RWIV occurs. To verify the accuracy of this method and analyze the effects of wind velocity on the water film and the aerodynamic lift around the cable, three cases with different loadings were investigated using the computational fluid dynamics (CFD) software CFX. To verify the method's accuracy, the aerodynamic lifts calculated from these cases were applied to the cable to obtain its vibrational response. In accordance with the experimental results, the numerical results demonstrated that an upper rivulet with a periodic oscillation was formed at a specific wind speed, causing the aerodynamic lift to change with a similar periodicity. The aerodynamic lift's frequency was approximately the cable's natural frequency, and induced large vibrations in the cable. No obvious upper rivulets were formed at sufficiently low wind speeds. The frequency of an aerodynamic lift that was significantly larger than the cable's natural frequency induced small vibrations in the cable. When the wind speed was sufficiently high, despite the eventual formation of a continuous upper rivulet, the frequencies of the upper rivulet's oscillation and the aerodynamic lift remained distinct from the natural frequency, and the cable continued to exhibit small-amplitude vibrations. These observations confirmed the conclusion that periodic variations in the water film morphology could lead to periodic changes in the aerodynamic lift that would induce RWIV.

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1. Introduction

Rain-wind induced vibration (RWIV) is a large-amplitude, low-frequency vibration in cable-stayed bridges and the suspenders in arch bridges under rain and windy conditions (Bosdogianni and Olivari, 1996). RWIV was initially observed by Hikami and Shiraishi (1988) on the Meikonishi Bridge in 1984, and has subsequently been reported worldwide (Geurts et al., 1998; Chen et al., 2003; Ni et al., 2007; Zuo et al., 2008).

To determine the mechanism underlying RWIVs, studies have been conducted using field measurements (Chen et al., 2003; Da Costa et al., 1996; Main and Jones, 1999; Ni et al., 2007; Zuo et al., 2008), wind tunnel tests with artificial rainfall (Cosentino et al., 2003; Gu and Du, 2005; Li et al., 2010a, 2010b; Matsumoto et al., 1990), and wind tunnel tests with artificial rivulets (Gu and Lu, 2001; Gu and Huang, 2008; Matsumoto et al., 1995; Du et al., 2013; Yamaguchi, 1990), and the results can be summarized as follows: (i) RWIV occurs over a certain range of wind speeds (5–20 m/s), and at low or moderate rainfall levels, (ii) upper and lower rivulets form on the cable surfaces and oscillate at lower order modes, and (iii) the amplitude of RWIV is related to the length, inclination direction, surface material of the cable and wind yaw angle.

Yamaguchi (1990) has developed two-dimensional, two-degree-of-freedom (2-DOF) equations of motion for cables with upper rivulets using a quasi-steady galloping method based on the experimental determination of aerodynamic coefficients with artificial rivulets. He has found that when the fundamental frequency of an upper rivulet's oscillation coincides with the natural frequency of the cable, the coupled motion of the rivulet and cable leads to negative aerodynamic damping and subsequent large-amplitude oscillations of the stay cable. Xu and Wang (2003) have presented a 1-DOF model based on Yamaguchi's theory, simplifying the RWIV as a forced vibration with a load from the rivulet's movement by expressing the aerodynamic lift as a function of the cable's vertical speed, rivulet angle and angular velocity. Wilde and Witkowski (2003) have considered the relationship between a rivulet's oscillation amplitude and wind speed using Xu and Wang's 1-DOF model. Assuming from experience that a rivulet undergoes sinusoidal motion, Gu et al. (2007) have developed an analytical model for the RWIV of three-dimensional, continuous stay cables with quasi-moving rivulets, and maintained that the cable may produce large-amplitude vibrations when the rivulet oscillation frequency is approximately any order of the cable's natural frequency. Bi et al. (2010) have explained the excitation mechanism of an RWIV as the action of the centrifugal force of the water surrounding the cable surface's circumference.

Lemaitre et al. (2007) have developed a two-dimensional model for a thin film surrounding a cylinder, subject to gravity and surface tension based on lubrication theory (Reisfeld and Bankoff, 1992). They have added wind as an exterior load in the model to simulate the formation of rivulets and study the variation of water film around horizontal and static cables. Xu et al. (2011) have modified the equations of motion in Lemaitre's model by assuming the dynamic characteristics of a cable as known conditions to consider the effect of the cable's movement on the water film. They have also investigated the evolution of a water film subjected to gravitational force, wind pressure, friction and surface tension, and determined the motion and morphological evolution of the rivulets when RWIV occurs. Taylor and Robertson (2011) have modified Lemaitre's model by including time-varying wind pressure and friction coefficients, $C_p(\theta,\ t)$ and $C_f(\theta,\ t)$, that have been determined using numerical calculations for the fixed coefficients $C_p(\theta)$ and $C_f(\theta)$ to obtain the variation in the water film surrounding horizontal and static cables over time. Bi et al. (2013) have presented novel two-dimensional coupled equations describing water-film evolution and cable vibration using lubrication theory for a single-mode system. Bi et al. (2014) have investigated the evolution of water film without considering cable's vibration by combining lubrication theory and computational fluid dynamics method.

CFD software has been increasingly applied to the study of RWIVs in recent years. Li et al. (2010a) quantitatively measured and analyzed the geometry and dynamic characteristics of rivulets around cables when RWIV occurs using an ultrasonic transmission thickness measurement system in a wind tunnel test and subsequently obtained the time history response of the cable's aerodynamic forces using a hybrid approach combining experiments and CFD numerical simulations. To simulate the formation of rivulets more accurately, this paper presents a numerical simulation approach to the evolution of the water film surrounding a cable by combining the gas–liquid two-phase theory and the volume-of-fluid (VOF) method for the first time. Using this method, the aerodynamic force of the cable when RWIV occurs can be obtained in a more straightforward manner than by using Lemaitre's model which is based on lubrication theory because the analytical formulas for the aerodynamic forces of the latter had not been derived until now. The formation process of rivulets on a cable is simulated using this approach, and the effects of gravity and air flow on the morphology of the rivulets are analyzed using the CFD software CFX. The procedure allows for the influence of rivulet formation on the flow fields of nearby cables and the cable's aerodynamic characteristics to be studied. The aerodynamic lift is substituted into the vibration equation of a single 1-DOF particle to obtain the cable's vibrational response and verify the accuracy of the results. Finally, this study attempts to make a preliminary determination of the mechanism underlying RWIV.

2. Theory and model

2.1. VOF method

The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and track the volume fraction of each throughout the domain.