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Numerical modelling for rain wind induced vibration of cables with longitudinal ribs

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ABSTRACT

Aerodynamic countermeasures are among the most effective ways to mitigate rain-wind induced vibrations. However, their vibration control mechanism is in many cases still unclear. This paper presents a numerical model for a cable section with an arbitrary 2D shape, able to geometrically describe aerodynamic countermeasures, excited by both wind and rain. Based on lubrication and vibration theory, 2D coupled equations for the water film evolution and for the across wind cable vibration are derived. Wind pressure and friction coefficients, for the different evolving water-film morphologies, are calculated by CFD software, while the instantaneous water film distribution and the vibration of the cable are calculated by numerically solving the derived coupled equations. For the case of rib additions to a nominally circular cable, the model shows that there is direct impact on the formation and dynamic characteristics of the critical for rain-wind induced vibrations upper rivulet. Particularly, depending on the rib number and position(s), the countermeasure can become effective or not by altering the lift acting upon the cable, and redistributing its frequency content associated with instability phenomena.

1. Introduction

On rainy and windy days, cable-stayed bridges, with cables inclined within a certain range of angles to the wind, may experience low frequency and large amplitude vibrations; this phenomenon is broadly described with the term rain-wind induced vibrations (RWIVs). Since the phenomenon was first properly framed by Hikami and Shiraishi in 1988 (Hikami and Shiraishi, 1988), RWIVs have been the focus of a considerable volume of research. Nowadays, RWIVs are considered a serious threat to the structural integrity of cable-stayed bridges because of the large stress amplitudes they impose on cables, and particularly their supports, with clear fatigue implications that could well result to failures and substantial economic losses due to traffic closures (Gu et al., 2007).

Researchers, through time, have proposed a series of effective countermeasures to mitigate rain-wind linked vibrations of cables. These are typically divided into three types, aerodynamic countermeasures (Gu et al., 2007; Li et al., 2010a,b; Kleissl and Georgakis, 2011; Li and Zhong, 2013), structural countermeasures (Wei and Yang, 2000; Caracoglia and Jones, 2005a,b, 2007; Bosch and Park, 2005; Caracoglia and Zuo, 2009; Ahmad et al., 2015; Zhou et al., 2015) and mechanical countermeasures (Krenk, 2000; Main and Jones, 2003; Chen, 2005; Casciati and Ubertini, 2008; Cheng et al., 2010; Boston et al., 2011; Fournier and Cheng, 2014; Egger et al., 2016; Raftoyiannis and Michaltsos, 2016). Because of the advantages of low cost and easy maintenance, aerodynamic countermeasures are currently popular in cable-stayed bridges all over the world; famous examples are the cases of the Sutong Bridge in China (Vo et al., 2016), the Normandy Bridge in France (Celeste et al., 2015), the Higashi Kobe Bridge in Japan (Vo et al., 2016) and many others. Aerodynamic countermeasures consist of cable additions like helixes, longitudinal grooves, protuberances and other similar flow spoilers. It has been broadly accepted that it is the appearance and oscillation of an upper, with respect to the flow, rivulet that drives the associated vibration phenomenon. As such, for an aerodynamic measure, the rationale to make it effective in its vibration mitigation role, is to alter the surface and

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shape of the cable in order to inhibit the appearance and block the oscillation of any upper rivulets. Many experimental researches and numerical simulations have been conducted to fully characterize the mitigation mechanism for different aerodynamic countermeasures. Fournier and Cheng (2014) analyzed the vibration control effect of longitudinal ribs and helixes, and concluded that the function of them was to reduce the correlation between rivulets and the wind flow. Wind tunnel experiments by Gu et al. (2007) established that only helixes with certain diameter, height and twining direction characteristics could restrain RWIVs effectively. Li and Lin (2005) introduced the equivalent damping ratio, as in aerodynamic damping, to quantitatively evaluate the effects of aerodynamic countermeasures in RWIV resisting performance, presenting also through wind tunnel experiments that such damping contributions are more substantial for the case of longitudinal ribs and helixes than for that of elliptical rings. An extensive wind-tunnel test campaign by Kleissl and Georgakis (2011), considering many different novel shape options, showed that shrouds had a stabilizing effect when added to a circular cylinder, while at the same time they could significantly also reduce vortex-induced oscillating lift forces; morphologies like that of a wavy, longitudinally, cylinder and a hexagonally faceted cylinder were shown to be unstable, at least for the specific geometric details selected. Li and Zhong (2014) investigated the effects of parameters of helical lines on RWIV control employing initially wind tunnel tests and numerically analyzing the end result of variations in terms of the mean drag coefficient, the fluctuating lift coefficient, the vortex shedding frequency, and the correlation coefficient along the cable axis.

Clearly, the majority of researchers that study rain-wind aerodynamic countermeasures, do so by mainly using wind tunnel experiments, which are extremely difficult to accurately reproduce the evolution of the water film around a tested cable. However, combining with full-scale observations, it is effectively captured that it is always the formation of rivulets that drive any dynamic instability mechanism (Verwiebe and Ruscheweyh, 1998; Peil and Nahrath, 2003; Gu and Du, 2005). Having said that, the detailed complex interactions between the external coupled rain-wind flow, the evolution of the water film and the vibration of the cable is not always unique, and there is no consensus on best selection of aerodynamic countermeasures. This makes any relevant design process rather heuristic and sometimes uncertain for engineers that need to take decisions on a one-to-one basis, supported by explicit tests. Therefore, it seems necessary to complement the field with more theoretical researches that could support developing numerical simulation tools able to capture the vibration control actions of aerodynamic countermeasures and to rationalize design.

In this paper, a new model based on lubrication theory (Lemaitre et al., 2006, 2007), is presented in Section 2 to describe the evolution of the water film around a rain-wind exposed stay cable with an arbitrary 2D cross-sectional shape. Namely, 2D coupled equations governing the across wind motion of the cable and its water film development are derived. As means of validation, numerical results for the case of a nominally circular section cable are compared against wind tunnel dynamic test data in Section 3. In Section 4, the results of water film evolution and vibration for a stay cable equipped with different setups of longitudinal ribs are presented and analyzed in order to elucidate the vibration control mechanism of rib-like aerodynamic countermeasures.

2. Coupled water evolution – vibration model

This part initially presents the kinematics of a thin water film that covers the surface of an inclined cable with an arbitrary cross-sectional shape. Subsequently, 2D coupled equations for the water film evolution and the cable vibration are established by combining lubrication theory and vibration theory for single-degree-of-freedom motion (Bi et al., 2013, 2014a,b). The proposed extension over past similar approaches, allows particularly the equations of water film evolution to capture more generic morphologies of cables as is the case of aerodynamic countermeasures.

2.1. Evolution equation for the water film

As shown in Fig. 1(a), under the action of gravity g and horizontal wind U_0, a generically inclined cable covered by a water film of thickness $h(\theta, t)$ is assumed. The inclination angle α ($0^\circ \le \alpha \le 90^\circ$) and yaw angle β ($0^\circ \le \beta \le 90^\circ$) fully capture the geometry of the problem. Namely, the two also define the angle between the gravity normal $\mathbf{g_N}$ and the wind-cable normal velocity $\mathbf{U_N}$ vectors; this is noted as $\delta + \pi/2$, where $\delta = \arctan(\sin\alpha \cdot \tan\beta)$; see e.g. Bi et al., 2013.

The A-A cross-section of the stay cable, shown in Fig. 1(b), is taken as the object of this study. The distance $s(\theta)$ between the nominal centre and the surface of the cable is not a constant with R being the designation for the minimum value of $s(\theta)$. The gravity component along the cable and any other influence of axial flow is neglected.

According to the lubrication theory, the equation of water film is derived by the Navier-Stokes equations written as

$$\begin{cases} \rho \dfrac{D\mathbf{u}}{Dt} = \rho(\mathbf{g_N} - \ddot{\mathbf{y}}) - \nabla p + \mu \Delta \mathbf{u} \\ \qquad \nabla \cdot \mathbf{u} = 0 \end{cases} \tag{1}$$

The velocity vector field $\mathbf{u}$, water density ρ, pressure p and dynamic viscosity μ of the water film are as denoted by Lemaitre et al. (2007). The vector of velocity is decomposed into $\mathbf{u} = u_r\mathbf{e_r} + u_\theta\mathbf{e_\theta}$, and in the same way we proceed for $\mathbf{g_N} = g_N^r\mathbf{e_r} + g_N^\theta\mathbf{e_\theta}$ and $\ddot{\mathbf{y}} = \ddot{y}^r\mathbf{e_r} + \ddot{y}^\theta\mathbf{e_\theta}$, where $\ddot{\mathbf{y}}$ is the vector of acceleration of the cable in the across wind direction. $(\mathbf{e_r}, \mathbf{e_\theta})$ stands for the pair of unit vectors in the polar coordinate system, with the water film being bounded between the $s(\theta) = r$ and the $s(\theta) + h(\theta, t) = r$ curves (i.e. instantaneous water thickness and radius variable designated by $h(\theta, t)$ and $r$respectively). In polar coordinates the Navier-Stokes equations take the form

$$\rho\left(\partial_t u_r + u_r\partial_r u_r + \frac{u_\theta}{r}\partial_\theta u_r - \frac{u_\theta^2}{r}\right) = \rho\left(g_N^r - \ddot{y}^r\right) - \partial_r p + \mu\left(\Delta u_r - \frac{2}{r^2}\partial_\theta u_\theta - \frac{u_r}{r^2}\right) \tag{2}$$

$$\rho\left(\partial_t u_\theta + u_r\partial_r u_\theta + \frac{u_\theta}{r}\partial_\theta u_r - \frac{u_r u_\theta}{r}\right) = \rho\left(g_N^\theta - \ddot{y}^\theta\right) - \frac{1}{r}\partial_\theta p + \mu\left(\Delta u_r + \frac{2}{r^2}\partial_\theta u_r - \frac{u_\theta}{r^2}\right) \tag{3}$$

$$\frac{1}{r}\partial_r(ru_r) + \frac{1}{r}\partial_\theta u_\theta = 0 \tag{4}$$

Dimensionless variables are defined as

$$U = \tfrac{R}{\nu}u_r,\ V = \tfrac{R}{\nu}u_\theta,\ P = \tfrac{h_0^3}{\rho\nu^2 R}p,\ G = \tfrac{h_0^3}{3\nu^2}g_N,$$

$$\ddot{Y} = \frac{h_0^3}{3\nu^2}\ddot{y},\ \varepsilon = \frac{h_0}{R},\ \xi = \frac{r-R}{h_0} \tag{5}$$

where h_0 is the initial thickness of water film around the cable, and ν is the kinematic viscosity of the water film.

Employing these, Eqs. (2)–(4) are written in their equivalent non-dimensional form as

$$\begin{aligned} &\varepsilon^3\left[\partial_T U + U\partial_\xi U + \frac{V}{1+\varepsilon\xi}\partial_\theta U - \frac{V^2}{\varepsilon(1+\varepsilon\xi)}\right] \\ &= -3\varepsilon\left[G\sin(\theta-\delta) - \ddot{Y}\sin\theta\right] - \partial_\xi P + \varepsilon^2\partial_\xi\left\{\frac{\partial_\xi[(1+\varepsilon\xi)V]}{1+\varepsilon\xi}\right\} \\ &+ \frac{\varepsilon^4}{(1+\varepsilon\xi)^2}\partial_\theta^2 U - \frac{2\varepsilon^3}{(1+\varepsilon\xi)^2}\partial_\theta V \end{aligned} \tag{6}$$