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Aerodynamic stability of ice-accreted bridge cables

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A B S T R A C T

The prediction of galloping instability is usually based on a quasi-steady approach, in which instantaneous wind forces are derived from the aerodynamic force coefficients obtained in static wind tunnel tests. Several galloping models exist, that differ for the degrees of freedom and for the geometric and aerodynamic characteristics considered. The aim of this paper is twofold: first, it compares the background hypotheses of the different galloping models, and the results they produce. This is done though an application to ice-accreted bridge cables, the analysis of the stability of which is the second aim of the paper. Wind tunnel data obtained by the authors for bridge hangers and stay cables are used in the calculations. As to the comparison among the different models, not existing a benchmark, the research is not aimed at judging the quality of each of them, but rather at pointing out the differences they bring and at discussing their most appropriate application.

1. Introduction

Bridge hangers and stay cables are flexible structural elements, with very low damping and therefore prone to vibrations (de Sá Caetano, 2007). These are mainly caused by traffic and by wind, with the latter becoming dominant as bridge spans increase. Wind induced vibrations can occur under three different surface states of the cable, i.e. dry, wet and ice-accreted. In particular, ice accumulation during iced or freezing rainstorms can lead to modifications in the shape of the cable, making it aerodynamically unstable. Full-scale monitoring campaigns indicated that ice accretion from light precipitation at moderate low temperatures (between 0 °C and −5 °C) may lead to large amplitude vibrations of bridge cables under wind action (Koss et al., 2013). The influence of ice on aerodynamics and stability has been studied mainly in the fields of electrical distribution (Farzaneh, 2008), of aviation (Lynch and Khodadoust, 2001) and of wind power (Makkonen et al., 2001). Presently, in the area of bridge engineering, very little knowledge exists of the characteristics of such vibrations and of the associated excitation of the ice-accreted cable, due to the lack of field and wind tunnel data.

On the other hand, several quasi-steady models are available in the literature for predicting cable aerodynamic instabilities, each of which retaining or neglecting the different aspects of the dynamic and aerodynamic behavior. Acampora et al. (2014) compared the damping matrices identified from the full-scale measurements with those coming from the application of quasi-steady theory to wind tunnel data; they concluded that the quasi-steady theory gives a reasonable description of the cable behavior. A pioneering work on the evaluation of aerodynamic stability of iced bridge

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hanger was performed by Gjelstrup et al. (2012); however the data coming from tests on artificial ice accretion reproduced with a rapid-prototyping (3-D printing) technique do not guarantee an accurate reconstruction of the aerodynamic behavior. Recently, Nikitas and Macdonald (2013) evaluated the differences between the results arising from the application of 1-DoF and 2-DoFs galloping criteria using literature aerodynamic data for a variety of cross sections. However, the aerodynamic data used for the ice accreted condition (Jones, 1992) apply only to electrical conductors. In this paper, the instability of ice-accreted bridge cables is investigated by applying wind tunnel experimental data obtained by the authors to quasi-steady sectional aerodynamic stability models taken from the literature. The first aim is that of a comparison among the background hypotheses and the results provided by each model. The second aim is that of analyzing the conditions of potential aerodynamic instability of ice-accreted bridge cables. Force coefficients were obtained through a series of static wind tunnel tests on a full-scale vertical and inclined bridge cable section model, under typical climatic conditions for in-cloud icing (Demartino et al., 2014; Demartino, 2014). As to the comparison among the different models, not existing a benchmark, the research is not aimed at judging the quality of each of them, but rather at pointing out the differences they bring.

2. Galloping stability models

2.1. Historical overview

In the 1930s, galloping of ice-accreted conductors has been a design and operating issue. Davison (1930) ascribed the occurrence of galloping during freezing rain storms to a change in the aerodynamic lift force, occurring when the wind blows across an iced conductor. Two years later, Den Hartog (1932) presented a first mathematical description of the galloping mechanism, together with a criterion for assessing the susceptibility to across-wind galloping of a cylinder in cross-flow; this accounts only for the dependence of the aerodynamic coefficients on the angle of attack. Cheng et al. (2008) investigated the applicability of Den Hartog criterion, giving an explanation of its driving mechanism, and compared its predictions with experimental observations. Davenport (1962) proposed an expression for the aerodynamic damping in both across- and along-wind directions, of a cylinder in cross flow. Two decades later, the instability criterion today widely referred to as *drag crisis* was proposed by Martin et al. (1981). In the same year, Nigol and Buchan (1981) investigated torsional galloping, and observed that when the center of mass does not coincide with the center of rotation (inertial coupling), as for eccentrically iced conductors, instability can occur, and they derived the critical condition. The instability of an inclined cylinder was investigated by Macdonald and Larose (2006), who derived a general expression for the quasi-steady aerodynamic damping of a yawed and inclined cylinder; their approach accounts for the dependence of the aerodynamic coefficients on the angle of attack, on the wind-cable angle and on the Reynolds number.

In the 1970s, the coupling between DoFs was investigated. Until then, galloping analyses had been based on the assumption that vibrations occur in one DoF, and it became clear that for many structures this is a restrictive assumption. Blevins and Iwan (1975) presented a coupled across-wind and torsional 2-DoF galloping model for cylinders in cross flow; the model allows for a detuning between the two DoFs. In the 1990s, Yu et al. (1992) improved the model of Blevins and Iwan (1975), by incorporating inertial coupling and Jones (1992) derived a model for the across- and along-wind 2-DoF galloping. Both models, however, are bound to cross flow conditions and to perfect tuning of the DoFs. Luongo and Piccardo (2005) improved the model of Jones (1992) by considering the case of detuned DoFs. They used a perturbation approach to find an approximated analytical solution for the eigenvalue problem, which coincides with the exact solution for tuned DoFs, and which gives a very good approximation for detuned DoFs. The first 2-DoF galloping model for cylinders in inclined flow is that of Carassale et al. (2004), applying to detuned across- and along-wind vibration; the model accounts for the dependency of the aerodynamic coefficients on the angle of attack and on the wind-cable angle. Macdonald and Larose (2008a,b) improved the model of Carassale et al. (2004) by including the dependency of the aerodynamic coefficients on the Reynolds number.

The first attempts to consider a 3-DoF behavior were made by Yu et al. (1993a,b), who developed a model to describe the galloping of multi-span electrical transmission lines, having an asymmetric ice accretion. The model considers a cylinder in cross flow and accounts for inertial coupling and for the dependency of the aerodynamic coefficients on the angle of attack. Wang and Lilien (1998) improved the model by including the dependency of the aerodynamic coefficients on the Reynolds number. The case of an inclined flow was investigated by Gjelstrup and Georgakis (2011), who derived a 3-DoF model, accounting for the dependency of the aerodynamic coefficients on the angle of attack, on the wind-cable angle and on the Reynolds number, and for the inertial coupling.

The main characteristics of the models described above are summarized in Table 1.

2.2. General framework for galloping stability models

A cylinder of arbitrary cross section (Fig. 1) is considered, exposed to a uniform flow $\mathbf{U} = [U\ 0\ 0]^{\mathrm{T}}$, in the global reference system (X, Y, Z). The attitude of the cylinder to the flow is described through the *inclination*, Θ, i.e. the angle between the cylinder axis z and its projection on the horizontal plane, and the *yaw*, β, i.e. the angle between $\mathbf{U}$ and the projection of the cylinder axis on the horizontal plane. These two angles can be condensed in a single parameter, the *wind-cable angle*, Φ. In this context $\mathbf{U}$ is decomposed into two components: one perpendicular to the cylinder axis, named *normal flow*, U_N, and