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Effects of ice accretion on the aerodynamics of bridge cables

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ABSTRACT

Undesirable wind induced vibrations of bridge cables can occur when atmospheric conditions are such to generate ice accretion. This paper contains the results of an extensive investigation of the effects of ice accretion due to in-cloud icing, on the aerodynamic characteristics of bridge hangers and stay cables. The aim of this paper is twofold; first, it was investigated the ice accretion process and the final shape of the ice accreted; then the aerodynamics of the ice accreted bridge cables was characterized, and related to the ice shape. Different climatic conditions, i.e. combinations of temperature, wind speed and yaw angle of accretion, were reproduced in a climatic wind tunnel, giving rise to different types of accretion. These were chosen such to generate the most common natural ice formations expected to produce bridge cable vibrations. A description of the geometric characteristics of the ice accretions is given in the paper. Only for the bridge hanger case, a short description of the evolution of the ice accretions is given. The aerodynamic force coefficients were then measured with varying yaw angle, angle of attack and wind speed, and are presented and discussed in the paper; these are found to be significantly affected by the characteristics of the ice accretion.

1. Introduction

Atmospheric icing is a general term for a number of processes where water either freezes in the atmosphere and sticks to objects exposed to the air, or freezes after getting in contact with cold surfaces. Ice accretion is a time-dependent modification of the shape of an object, occurring on a longer time scale compared with those of any possible structural dynamic behavior. Atmospheric icing occurs in different forms: (1) *hoar frost*, which is caused by condensation of vapor, (2) *in-cloud icing*, involving the freezing of supercooled water droplets in clouds or fog, and (3) *precipitation icing*, resulting from freezing rain, drizzle, wet snow or dry snow (Farzaneh, 2008). The study of ice and wet-snow accretion on structures exposed to the atmosphere is of interest to engineers and scientists since ice/snow loads, in some cases combined with wind actions, can induce structural failures (Poots, 1996).

The influence of ice on aerodynamics 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); less work is available in the area of bridge engineering. It should be highlighted that in the case of overhead power lines the typical diameter is generally smaller than in the case of bridge cables; the two conditions are not directly comparable, due to the different characteristics of the ice accretion, arising from the different thermodynamic behavior. In many cases, however, bridge cables have experienced problems connected to the ice formation. There are many possible types of wind-induced vibrations of cables, among which Kumarasena et al. (2007) indicate the galloping of cables with ice accumulations. The accumulation of ice on a cable in an ice or freezing rain storm can lead to change in shape of the cable, making it aerodynamically unstable. On the other hand, Kumarasena et al. (2007) state that they are not aware of this being a common problem on bridges. Tabatabai (2005) concluded that the effects of icing on galloping vibrations of stay cables need to be studied. Fujino et al. (2012), explaining the problem of galloping of iced cables, underlined that the theoretical analysis required reliable aerodynamic data for a range of realistic natural ice shapes formed under various climatic conditions of interest.

The methods used for the investigation of the physics of ice accretion on structures and of its implications on the aerodynamics are (1) continuous field measurements of ice load and wind-on-ice load, (2) simulations using icing wind tunnels and (3) use of mathematical and computational icing models (Poots, 1996).

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Full-scale monitoring campaigns indicated that ice accretion from light precipitation at moderate low temperatures (i.e. between 0° and $-5\,°C$) may lead to large amplitude vibrations of bridge cables under wind action. Large oscillations of long cables can cause premature fatigue failures at the anchor points. These oscillations can also trigger the phenomenon of ice shedding. In particular, three types of cable ice shedding, or ice mass reduction, have been identified: ice melting, ice sublimation, and mechanical ice breaking (Druez et al., 1995), the latter being influenced by the cable vibration. Falling ice becomes a safety issue for motorists and pedestrians crossing bridges, which need to be closed until the ice is gone. Gimsing and Georgakis (2011) report a series of closures occurred to bridges. For example, between 2004 and 2007, the Storebælt Bridge was closed an average of 14.3 h a year, 12 of which were due to falling ice and snow. The Øresund Bridge had to be closed six times between 2000 and 2010 due to ice and snow. Many other bridges throughout the Northern Hemisphere have had similar closures, including the Uddevalla Bridge in Sweden, the Severn Bridge in the UK, the Zakim Bunker Hill Bridge in the USA and the Hukacho Bridge in Japan. On the 19th of December 2012 the Port Mann Bridge in Canada was closed between 1:30 pm and 6 pm. Before the closure, the vehicle insurance entity in British Columbia reported 60 separate claims of ice-damage. In addition, the closure of a bridge on a major route can produce severe consequences on industry, commerce and society as a whole.

Some authors have tried to investigate numerically the problem of ice accretion (Poots, 1996; Launiainen, 1986; Lozowski et al., 1983; Makkonen, 1984, 2000). For transmission line engineering applications, Farzaneh (2008) reported a numerical study of the effects of ice accretion on vortex-induced vibrations. Fu et al. (2006) developed a two-dimensional model for the prediction of the ice accretion process on a stationary transmission line. The shapes calculated under dry and wet icing conditions well compared with those obtained in experimental tests, but the surface roughness was not well predicted. This made the results inadequate for aerodynamic simulations (Achenbach, 1971), and led many authors to investigate the phenomenon experimentally. In cross flow conditions, Koss et al. (2012) investigated experimentally the shape of the ice accretion on circular cables with diameters of 0.0381 m and 0.089 m in vertical and horizontal configurations, respectively; the climatic conditions tested were among those in which large amplitude vibration of iced bridge cables had been observed. Gjelstrup et al. (2012) performed static and dynamic wind tunnel tests on vertical cables, using simulated ice accretion reproduced using a rapid prototyping technique. An added complexity of the aerodynamics occurs when considering a cylinder that is yawed and inclined. Less researchers have addressed the problem of ice accreted cylinders in inclined flow. Kollár and Farzaneh (2010) performed experiments on a cylinder having a diameter of 0.038 m and a length of 0.92 m in an icing wind tunnel considering two meteorological conditions: in-cloud icing and freezing rain icing. The diameter chosen is typical of overhead power lines. They varied the angles of the cylinder with respect to the oncoming flow. They concluded that the ice mass accreted on a unit length of the cylinder depends on the orientation of the cable with respect to the flow. They measured the mass, the shape and the longitudinal profile of ice accretion, but no aerodynamic force measurements were taken.

The necessity of a deeper understanding of the aerodynamic behavior of iced bridge cables, led in 2008 to the construction of a special climatic wind tunnel (CWT) allowing tests simulating *low-altitude atmospheric icing* on full-scale section models under different climatic conditions (Georgakis et al., 2009). During the last years, many efforts have been devoted to the development of the system for the simulation of the climatic condition of the in-cloud ice accretion on bridge cables. First results on ice accretion and static load coefficients for an horizontal cable have been published by Koss and Matteoni (2011). After the first attempts, an innovative spray bar creating the conditions for low-altitude atmospheric in-cloud icing of one-dimensional objects (i.e. bridge cables) has been constructed. The results from icing tests described in this work were obtained using this innovative spray bar, and are focused on vertical hangers and on inclined stay cables; they are part of an extensive research project aimed at the understanding of the effects of ice accretion on the bridge cables. The first results of this research relative to the horizontal case have been published by Koss and Lund (2013) and Koss et al. (2013). In particular, in Koss et al. (2013) the influence of the ice accretion on the aerodynamic forces on horizontal cables with surface modifications. The preliminary results for the vertical and inclined cases have been published in Demartino et al. (2013a) and Demartino et al. (2013b), respectively.

The current work investigates the effects of ice accretion due to in-cloud icing on the aerodynamics of a vertical and inclined cylinder having a diameter of 160 mm and made of high density polyethylene (HDPE) like a typical configuration of bridge hangers or stay cables. The aim of this paper is twofold; first, it investigated the ice accretion process and the final shape of the ice accreted, then the aerodynamics of the ice accreted bridge cables was characterized and related to the ice shape. Different climatic conditions, i.e. combinations of temperature, wind speed and yaw angle of accretion, were reproduced in the climatic wind tunnel, giving rise to different types of accretion. These were chosen as such to generate the most common natural ice formations expected to produce bridge cable vibrations. A description of the geometric characteristics of the ice accretions is given in the paper. Only for the bridge hanger case, a short description of the evolution of the ice accretions is given. Ice accretion can lead to instability phenomena. As the wind direction and the atmospheric conditions are variable in time, ice accretion can be generated in one particular condition whilst instability can occur in a different one; accordingly aerodynamic force coefficients were measured with varying angle of attack or yaw angle at different wind speeds. In the stay cable case, a variation of the relative angle of attack takes place during the cable motion, accordingly in one CC the aerodynamic force coefficients were measured also with varying the angle of attack and the yaw angle. The results demonstrate how the ice accretion on bridge cables can strongly affects the mean aerodynamic coefficients of bridge cables differently depending on the climatic condition. Demartino and Ricciardelli (2015) investigated the aerodynamic stability of ice-accreted bridge cables using quasi-steady sectional models taken from the literature by applying wind tunnel experimental data reported in this paper.

2. Wind tunnel tests

To investigate the aerodynamic behavior of ice-accreted cables, a particular set-up was designed, reproducing the conditions of in-cloud icing. The set-up consists of a spray bar system and a cable section model placed in the climatic wind tunnel as shown in Fig. 1. The spray bar system was placed in the settling chamber downstream of the honeycomb grid, and the cable section model was placed vertically in the center of the test section. In the following, the climatic wind tunnel, the spray system, the cable section model and the test procedure and measurements are described. Details of the experimental setup and of its calibration can be found in Demartino (2014).

2.1. Climatic wind tunnel

The tests were performed at the DTU/Force Technology collaborative climatic wind tunnel (CWT) in Lyngby, Denmark. The wind