Vortex induced vibrations of yawed bridge cables with asymmetrical surface roughness patterns

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SUMMARY
This paper presents the results of testing in a wind tunnel of bridge cable models with technological and climatic surface roughness at positive and negative inclination angles. The models were tested over a range of Reynolds numbers $Re = 1.2{\cdot}10^4 \div 1.2{\cdot}10^5$ and three yaw angles: 0 °; -30 °; +30 °. Models with ice accretions were additionally tested at three angles of attack on the ice edge: 0°, 90° and 180°. The Strouhal number and lock-in range were observed to vary with the relative position of the surface patterns and wind flow for the yawed configuration (positive and negative angles). For the ice accretion model, a dynamic response was also obtained for angles of wind attack which were not achieved in previous studies of this specific ice shape.

Keywords: vortex shedding, wind tunnel, bridge cable.

1. INTRODUCTION

The high load-bearing capacity with minimal material and weight of support cables presents low damping and a wide range of low frequency eigenmodes. These factors and the bluff shape makes cables susceptible to various Wind-Induced Vibrations (WIV). With the improvement of the instrumental base and monitoring methods the new data about complex and multimode Vortex Induced Vibrations (VIV) and Rain Wind Induced Vibrations (RWIV) cable vibrations in the shear flow profile of Atmospheric Boundary Layer (ABL), see (Flamand, 1995; Zuo et al., 2008; Zuo and Jones, 2010; Chen et al., 2011; Daniotti et. al., 2021, Kim et al., 2022, Hwang et al., 2025) were discovered. Research in real and CFD wind tunnels generate the bulk of the data and analytical results. In wind tunnel research, there is also a noticeable trend towards using and building new special equipment for large-scale testing of RWIV (D'Auteuil et al., 2020) VIV and dry state galloping (Jakobsen et al., 2012; McTavish et al., 2018; Jafari and Sarkar, 2019) and flexible models of inclined cables. The last type of setup allows to explore basic and high mode VIV (M. Matsumoto et al., 1998), as well as multimode VIV in shear flows under ABL modeling (Chen et al., 2015; Jafari and Sarkar 2020). The high length-to-diameter ratios allows the formation of the axial flow which play a significant role in the mechanism of dry galloping (Matsumoto et al., 2010) and interacting with Karman vortices leads to the high reduced velocity vortex-induced vibration (Matsumoto et al., 2001). From an engineering point of view, there is great interest in the use of cable surface modifications that may have advantages in controlling WIV (Bearman and Owen, 1998; Kleissl and Georgakis, 2011; Katsuchi et al., 2017; Nguyen et al., 2022). Rigid sectional models are easier to configure dynamic parameters, simulate turbulent flow conditions and measure aerodynamic force coefficients, surface pressure distributions, aeroelastic response and flow visualization (Kleissl and Georgakis., 2012; Christiansen et al., 2018; McTavish et al., 2020; Liu et al., 2021; Liu et al., 2024). Moreover, as (Matteoni and Georgakis, 2015) demonstrated, even relatively low technological or operational-induced roughness has a significant impact on both the static and aeroelastic behavior of cables. Therefore, increasing attention is being paid to studying the influence of ice deposits, which significantly alter cable aerodynamics. Experimental and numerical studies are creating a database of ice and snow accumulation patterns, climatic conditions, structural parameters and their effects (Gjelstrup et al., 2012; Demartino et al., 2015; Górski et al., 2021; Szilder et al., 2021, Peng et al., 2020; McTavish et al., 2021).

2. EXPERIMENTAL SETUP

2.1. Dynamic balance system

The experimental study was conducted on the basis of the YNU closed-circle wind tunnel. It has a cross-section of 1800 x 1800 mm and low initial turbulence. The existing dynamic balance for studying bridge deck vibrations was modified for cable models testing by changing the spring orientation to an X-shape and special add-on to allow changing the yaw angle and wind attack angles for asymmetric cross-sections of iced models. To ensure uniformity of wind flow and cutting off the wall boundary layer flat screens were installed inside the tunnel near parallel to the walls.

2.2. Model design:

For the testing were produced 4 models diameter D = 0.11 m and different surface: 1) "smooth" cylinder, used as reference model; 2) model of cable with surface corresponding to the 1x61 wires construction; 3) model of cable with surface corresponding to the 1x91 wires construction; 4) model of cable with ice accretions obtained in laboratory. Helical cables of 1x61 and 1x91 design have lay length l_{lay}= $12 \cdot D$ and effective surface roughness $k_{eff} = d_{wire}/D_{cable} \cdot 100\%$= 5.6% and 4.6%, respectively. The length of models for 0 ° yaw angle were l = 1.67 m. The l/D ratio ≈ 15 high enough to achieve the 3 dimensional flow, see (Zuo and Jones, 2009). The shell of the models was 3D printed. A thin-walled aluminum tube was used as the supporting axle. At the ends of the printed shell were located 2 mm thick endplates with diameter 220 mm and uniform gap of 5 mm.

2.3. Test plan and measurement setup in the tunnel.

During the experimental design process, it was decided to test the effect of positive and negative yaw angles on the model response. In the case of asymmetry of the surface patterns along the axis of the models of spiral cables and cables with ice deposits, due to the difference in the angle of attack of the wind flow in relation to the surface roughness element, one should also expect different turbulence of the boundary layer, and as a consequence, a correlation of vortex shedding and the resulting forces. Three yaw angles γ were tested: 0 °; -30 °; +30 °. Models with ice accretions for each of the yaw angles were tested at three angles of attack on the ice edge α: 0°, 90° and 180°. All model configurations were equally mass tuned and balanced to a frequency 5 Hz. The model was suspended at a height of 900 mm from the floor – i.e. at the middle of the tunnel height. The flow velocity and initial turbulence were measured by a Pitot tube and a single-wire CTA sensor installed in front of the model at a distance 2920 mm. One CTA sensor was installed behind the model at a distance of 5D = 550 mm to measure the Strouhal frequency. The oscillation amplitude was measured by two orthogonal pairs of laser displacement sensors.

3. RESULTS AND DISCUSSION

Models were tested over a range $Re = 1.2 \cdot 10^4 \div 1.2 \cdot 10^5$, which corresponds to a stable subcritical VIV stage. Since the diameter ratio of the model is close to that of real cables (1:1.45 for iced and

2:1÷1:2 for helical and dry HDPE coated cables), the studied *Re* range corresponds to low natural modes (1÷5) depending on the diameter and mechanical tension (base frequency) of the real cable. In the measured range VIV with lock-in were observed for all models and angle configurations. No risk of galloping was detected for the tested models and configurations in the measured range. For the iced-cable model a dynamic VIV response was also obtained for $\alpha = 0°$, which were not achieved in previous studies due to problems with model balancing and coupling of vertical and torsional vibrations (Trush et al., 2025), and limitations of 1 degree of freedom for balance and low precision of shape reproduction due to the model production technology in (Trush et al., 2017). The Strouhal number and lock-in range were also observed to vary with the relative position of the surface patterns and wind flow for the yawed configuration (positive and negative angles). The highest amplitude of oscillations was observed for the iced-cable model at $\alpha = 0^o$ and 90^o and $\gamma = 0^o$. The lock-in range for models with all types of roughness at the yaw position shifted to higher velocity, i.e. a decrease in the Strouhal number was observed. At positive yaw angles (which corresponds to a sharper angle of attack of the wind flow to the surface roughness pattern), a greater shift and reduction in the lock-in range and a decrease in the Strouhal number were observed. This trend was observed for all types of surface roughness. These findings can be used to optimally select cable types and the placement/direction of surface modifications, as well as more accurately assess the risk of fatigue damage. Furthermore, a comparison of the current results with previous experiments also indicates the need for careful design of the experimental set.

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