J. Wind Eng. Ind. Aerodyn. 136 (2015) 89–100

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Effects of surface roughness and cross-sectional distortion on the wind-induced response of bridge cables in dry conditions

G. Matteoni [a,*], C.T. Georgakis [b]

[a] Arup, 13 Fitzroy Street, London W1T 4BQ, United Kingdom

[b] Department of Civil Engineering, Technical University of Denmark, Building 118, Brovej, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 8 February 2014
Received in revised form
12 October 2014
Accepted 2 November 2014
Available online 20 November 2014

Keywords:
Bridge cable
Surface roughness
Shape distortion
Dynamic
Inclined/yawed cable

ABSTRACT

Theoretical and experimental investigations to date have assumed that bridge stay cables can be modelled as ideal circular cylinders and that their aerodynamic coefficients are invariant with wind angle-of-attack. On the other hand it has been demonstrated that bridge cables are characterised by local alterations of their inherent surface roughness and shape. Small deviations from ideal circularity result in significant changes in the static drag and lift coefficients with Reynolds number. The present study focuses on the wind-induced response of a full-scale yawed bridge cable section model, for varying Reynolds numbers and wind angles-of-attack. Using passive-dynamic wind tunnel tests, it is shown that the in-plane aerodynamic damping of a bridge cable section, and the overall dynamic response, is strongly affected by changes in the wind angle-of-attack. Using the drag and lift coefficients, determined in static conditions for an identical cable model as the one used for passive-dynamic tests, the in-plane aerodynamic damping is evaluated by employing a one-degree-of-freedom (1 DOF) quasi-steady analytical model. Similarly, it is shown that regions of instability associated with the occurrence of negative aerodynamic damping are strongly dependent on the wind angle-of-attack.

1. Introduction

1.1. Overview of the dry inclined cable instability

The vibration of dry inclined cables, i.e. in the absence of rain or ice accretions, was first described by Japanese researchers (Matsumoto et al., 1989). It is characterised by the presence of divergent-type vibrations, i.e. dry inclined galloping, or by limited amplitude vibrations, i.e. the so-called vortex shedding at high reduced velocities (Matsumoto et al., 2010).

The cause of dry vibration is attributed by most authors to effects associated with the critical Reynolds number (Larose and Zan, 2001; Larose and Jakobsen, 2003; Cheng et al., 2008a). In this range, small imperfections in the cable geometry, such as the ovalisation of the HDPE tube covering the cables, or added surface roughness are sufficient to introduce important flow transitions, which can lead to cable vibrations, particularly if the inherent structural damping of the cable is very low (Larose and Zan, 2001). Moreover, for the specific case of dry inclined galloping, the secondary axial flow is considered to play a role. It is hypothesised that it acts as an *air curtain*, interrupting the fluid interaction between the cable's separated shear layers and generating an unsteady inner circulatory flow at either the lower leeward or the upper leeward side of the cable circular surface. This determines a region of significantly lower surface pressure which results in higher oscillatory aerodynamic forces and consequently violent vibrations (Matsumoto et al., 1990). On the other hand, the cause of high speed vortex shedding is attributed to the interaction between the conventional Karman vortex shedding and the axial vortex shedding, with the frequency of the latter being one-third of the former. This implies that the cylinder's response is amplified when the axial vortices shed once every three Karman vortices from either side of the cable's model (Matsumoto et al., 1999). Note that the findings by Matsumoto et al. (1990) and Matsumoto et al. (1999) on the 3D structure of the flow largely refer to the flow regions near the model ends.

Vibration of dry inclined cables has never been fully verified full-scale, and only a limited number of reports exist, for example Virlogeux, Irwin et al. (1999), Boujard (2007), Zuo and Jones (2010), and Matsumoto et al. (2010). On the other hand, it has been reproduced in wind tunnel experiments. By comparing results from different experimental campaigns, it is apparent that the characteristics of dry instability are strongly affected by the test conditions.

The first experimental investigation on the instability of inclined/yawed full-scale bridge cables in dry conditions was undertaken by Saito et al. (1994). Based on dynamic wind tunnel

* Corresponding author. Tel.: +44 207755 3119.
E-mail addresses: giulia.matteoni@arup.com (G. Matteoni), cg@byg.dtu.dk (C.T. Georgakis).

http://dx.doi.org/10.1016/j.jweia.2014.11.003
0167-6105/

tests performed on a cable model identical in mass as an actual bridge cable from the Higashi-Kobe Bridge in Japan, Saito et al. (1994) derived an instability criterion which suggests that dry inclined cable vibration can be excited at very low wind velocities corresponding to the subcritical Reynolds number range. The excitation cannot be suppressed even if the cable's Scrouton number or structural damping is significantly increased. The former is defined herewith as

$$S_c = \frac{m\zeta}{\rho D^2} \quad (1)$$

where ζ is the cable's structural damping ratio, m is the cable's mass per unit length, ρ is the air density and D is the cable's diameter. This implies that the majority of bridge cables of existing bridges might be prone to dry inclined instability. A second instability criterion for dry cable vibration was later derived by Honda et al. (1995). The criterion suggests that for wind velocities corresponding to the transition from the subcritical to the critical Reynolds number regime divergent motion starts. Experimental tests undertaken by Miyata et al. (1994) confirmed this finding. Honda et al. (1995) also observed that a significant increase in the structural damping (and thus in the Scrouton number) is not sufficient to suppress the instability.

Some years later, a series of wind tunnel tests were undertaken in collaboration between the University of Ottawa, Rowan Williams Davies and Irwin (RWDI), and the National Research Council Canada. The experimental campaign was part of a large study commissioned by the US Federal Highway Administration (FHWA). The main objective of the study was to verify the existence of dry inclined galloping and validate the severe instability criterion proposed by Saito et al. (1994). The test campaign consisted of three phases. In the first phase it was observed, based on passive-dynamic wind tunnel tests, that dry inclined cables can undergo two types of instability, i.e. a limited amplitude type, occurring over a narrow interval of wind velocities within the critical Reynolds number range, i.e. vortex shedding at high reduced velocity, and a divergent type, which is generated for all wind velocities above the critical one in the critical Reynolds number range, i.e. dry inclined galloping (Cheng et al., 2008a). Contrary to the previous test, the dry inclined galloping instability could be restricted by increasing the structural damping (or Scrouton number). Static wind tunnel tests undertaken in the second phase of the campaign served to clarify the origins of the dry inclined galloping instability. This was explained in a similar way as the conventional galloping of ice coated cables, i.e. in terms of the Den Hartog criterion (Cheng et al., 2008b). As a result of the experimental tests undertaken during phases 1 and 2, the FHWA proposed a new stability criterion for dry cable vibration (FHWA/HNTB, 2005). The criterion established a value of 10 as the minimum desired Scrouton number for *regular cable arrangements*. The criterion is less conservative than the one established by Saito et al. (1994) and is currently used by bridge designers. In the third phase, displacement and pressure measurements were performed on a cable section with identical characteristics as the one used in phase 1 (Jakobsen et al., 2012). Divergent response was observed for a limited range of Reynolds numbers corresponding to the end of the critical region, where the drag coefficient drops to a minimum and a steady lift appears. This is in contrast to conventional galloping which occurs at any wind speed above the critical one. It was further observed that, due to the effect of minor imperfections of the cable surface or slight lack of roundness, the lift coefficient is a function of the cable orientation about its axis. Slight increases in the surface roughness of the model, due to the localised accumulation of insects on the cable section, significantly affected the response of the cable. In connection with these latter findings, a recent investigation undertaken by Matteoni and Georgakis (2012) showed that bridge cables are characterised by a non-uniform distribution of surface roughness and shape. Based on static wind tunnel tests undertaken on full-scale bridge cable section models, it was demonstrated that the drag and lift coefficients of both cross-flow and inclined/yawed bridge cable models are strongly dependent on the degree of axial rotation of the cablemodel, i.e. on the wind angle-of-attack. Some of the findings were also achieved by Flamand and Boujard (2009). Assuming quasi-steady theory, Matteoni and Georgakis (2012) hypothesised that negative aerodynamic damping can be predicted, especially in the critical Reynolds number range, where the drag coefficient is reduced to its minimum, while the lift coefficient experiences significant variations with wind angle-of-attack. Nevertheless, no experimental evidence of this occurrence, based on passive-dynamic tests, has been yet demonstrated.

1.2. Objectives and findings of the present investigation

Further to the work of Matteoni and Georgakis (2012), the current work investigates the effects of surface roughness and cross-sectional distortion on the wind-induced response of bridge cables in dry conditions. In order to understand this dependency, passive-dynamic wind tunnel tests were undertaken on a section of a bridge cable inclined/yawed to the incoming wind. The in-plane aerodynamic damping and the peak-to-peak amplitude of the cable response were identified for varying Reynolds numbers and varying degrees of axial rotation of the HDPE tubing, i.e. for varying wind angles-of-attack. These parameters are of fundamental importance for understanding the characteristics of galloping vibrations of inclined cables. The mechanism of galloping was visually observed in full-scale or measured in wind tunnel experiments. Experimental observations showed that dry inclined galloping is characterised by major vibration components in the cable-wind plane, with smaller components in the out-of-plane direction (Cheng et al., 2008a).

Experimental observations of the investigation lead to the conclusion that dry instability of inclined/yawed bridge cables is very sensitive to microscopic geometrical imperfections of the cable model. The in-plane aerodynamic damping, as well as the peak to peak amplitude, changed significantly with Reynolds number for varying wind angles-of-attack. The unique alteration in the test setup when the cable is axially rotated, i.e. the surface roughness and shape of the model exposed to the oncoming wind, was sufficient enough to significantly alter the wind-induced response, and to trigger the cable instability over a broad range of Reynolds number.

The in-plane aerodynamic damping was additionally evaluated based on the static drag and lift coefficients obtained by Matteoni and Georgakis (2012) for a cable model oriented at the same cable-wind angle Φ as in the passive dynamic tests, for varying Reynolds numbers and wind angles-of-attack. This was done to compare the regions of dry instability based on the passive-dynamic and static tests. For this, a one-degree-of-freedom quasi-steady analytical model developed by Macdonald and Larose (2008) was implemented. It is not directly possible to compare the regions of instability based on the static and passive-dynamic tests. It should be noted that, due to a difference in the end conditions and in the relative roughness/shape distribution in the critical area of the cable, i.e. where flow separation is expected to occur, the flow regimes experienced by the static and passive-dynamic cable might not perfectly coincide. Nevertheless, both approaches demonstrate that the aerodynamic damping is strongly dependent on the wind angle-of-attack.

2. Materials and methods

2.1. Passive-dynamic wind tunnel tests

Passive-dynamic tunnel tests were performed at the new DTU/Force Climatic Wind Tunnel in Lyngby. The wind tunnel is a close