Journal of Wind Engineering & Industrial Aerodynamics 168 (2017) 110–122

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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

Galloping of an elliptical cylinder at the critical Reynolds number and its quasi-steady prediction

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ARTICLE INFO

Keywords:
Wind tunnel test
Elliptical cylinder
Critical Reynolds number
Quasi-steady assumption
Galloping

ABSTRACT

Dry galloping of inclined cables has been shown to have a strong relation to the critical Reynolds number. This study considers the occurrence of galloping of an elliptical cylinder at the critical Reynolds number under normal wind and assesses the quasi-steady assumption made when predicting these vibrations. Static and dynamic wind tunnel tests are conducted to measure the wind pressure on a static cylinder and displacement of a three-degree-of-freedom vibrating cylinder. The static aerodynamic force on the cylinder exhibits reattachment, which lowers the drag coefficient and increases the lift coefficient at the critical Reynolds number. This phenomenon enables the across-wind galloping criterion to be satisfied by adversely changing the aerodynamic force with the angle of attack. Unsteady and steady-amplitude galloping is observed in dynamic tests in a certain range of Reynolds number and angle of attack. The observations indicate that the galloping is across-wind dominated and strongly dependent on the Reynolds number. Finally, quasi-steady predictions of galloping instability are compared with the observed galloping. The observed occurrences of galloping are largely within the predicted unstable range, but several other cases for which galloping was predicted do not exhibit large vibrations. This result implies that the quasi-steady assumption is not suitable for predicting the galloping of elliptical cylinders at the critical Reynolds number.

1. Introduction

A large vibration of an inclined cable, known as dry galloping, has attracted considerable interest and has been considered in a number of experimental and theoretical studies due to its complex aerodynamics (Cheng et al., 2008; Jakobsen et al., 2012; Macdonald and Larose, 2006, 2008a,b; Matsumoto et al., 2010; Nikitas and Macdonald, 2015; Raeesi et al., 2013). These vibrations occur in dry inclined cables without ice accretion and differ from both conventional across-wind galloping and wind-rain-induced vibrations. Three explanations for this phenomenon have been proposed since 2003. The first explanation is that the dry galloping is conventional across-wind galloping of an imperfect circular cylinder (Benidir et al., 2015; Matteoni and Georgakis, 2015) that satisfies the Den Hartog galloping criterion. The second explanation is that dry galloping is highly related to the mitigation of Karman vortex shedding and, also occurs for wind-rain-induced vibrations (Matsumoto et al., 2003, 2010). The third explanation is that dry galloping is related to some type of organization of the noise that arises from the critical Reynolds number (Nikitas and Macdonald, 2015; Nikitas et al., 2012). Although the mechanism of dry galloping remains unclear, The majority of researchers agree that the large amplitude vibrations are related to the critical Reynolds number, which has been shown to significantly influence the flow patterns, aerodynamic forces and galloping instabilities for cylinders with smooth cross-sections, such as circular cylinders (Zdravkovich, 1997b).

In the critical Reynolds number range, the boundary layer undergoes a flow transition, separation bubbles may form on one or both sides of the cylinder due to reattachment, and vortex shedding may disappear (Ma et al., 2015; Zdravkovich, 1997b). Furthermore, the flow in the critical Reynolds number range is sensitive to any disturbance, including cylinder motion or ambient flow conditions (Cao and Tamura, 2008; Rodríguez et al., 2013; Schewe, 1986). This sensitivity poses more uncertain factors on the dry galloping response and its excitation mechanism. The aeroelastic loading on a dry cable was analyzed based on dynamic wind pressure tests in a wind tunnel to obtain better understanding of the effect of the critical Reynolds number on galloping response. The results

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http://dx.doi.org/10.1016/j.jweia.2017.04.022
Received 23 August 2016; Received in revised form 23 April 2017; Accepted 26 April 2017

revealed an inherent flow pattern unsteadiness in the critical Reynolds number range and its interaction with the moving cylinder (Nikitas and Macdonald, 2015; Nikitas et al., 2012); however, more dynamic pressure tests are needed to draw clearer conclusions.

Dry galloping has typically been observed in wind tunnel tests on inclined cables in the critical Reynolds number range. Observations include the effects of the Reynolds number, an axial flow that may mitigate Karman vortex shedding and imperfection uncertainty that may result in aerodynamic force coefficients that satisfy the Den Hartog criterion. Since across-wind galloping was first proposed in 1932 by Den Hartog (Den-Hartog, 1932), it has been used to predict galloping instability and has been developed and applied in many studies (Ng et al., 2005; Nikitas and Macdonald, 2014; Païdoussis et al., 2011). Across-wind galloping is suitable for describing the Reynolds number-related galloping of electricity conductors at reduced velocities over 1000 (Macdonald et al., 2008) and corresponded reasonably well with the aerodynamic damping obtained from full-scale measurements on twin cable bridge stays. However, this criterion neglects the effect of the varying motion of structure on fluid around the structure and treats galloping as a quasi-steady process. There should be no Den Hartog galloping for a perfect circular cylinder because the criterion assumes that the change in aerodynamic force depends on changes in the relative angle of attack. However, results obtained from wind tunnel tests on circular cylinders has proven that the surface roughness and circularity defects have significantly affect both the mean aerodynamic forces and galloping instability. Benidir et al. (2015) found that the roughness and circularity defects cause boundary layer transitions to appear earlier or later and also cause the occurrence of jumps in the instantaneous lift between two or more quasi-stable states. Matteoni and Georgakis (2015) determined that dry cable instability is highly sensitive to microscopic geometrical imperfections of the cable model, which can trigger vibrations in the critical Reynolds number range with either positive or negative aerodynamic damping. These findings imply that geometrical imperfections or surface roughness may induce large vibrations in the critical Reynolds number range, but the mechanism is not as simple as the Den Hartog criterion.

The sensitivity of the aerodynamic forces on circular cylinders to surface conditions in the critical Reynolds number range makes it difficult to use the quasi-steady assumption to predict galloping instability. The existence of axial flow on inclined cables makes it even more difficult to identify the effect of the Reynolds number. However, few studies have focused on cylinders with other smooth cross-sections such as elliptical cylinders. To reduce the problem to a clearer and more simple case, this study tests an elliptical cylinder under normal wind to determine the critical Reynolds number effect. The ellipse has similar aerodynamic characteristics as a circular cylinder, but it has a clear defined angle of attack rather than the symmetry of simply small geometrical imperfections or surface roughness. Additionally, the axial flow is likely to be negligible under normal wind. Assessing the possibility of galloping of an elliptical cylinder in the critical Reynolds number range and the ability of the quasi-steady assumption to predict the vibrations will provide better understanding of galloping at the critical Reynolds number.

In this study, an elliptical cylinder with a major-to-minor axis ratio of 1.5 is tested in a wind tunnel to determine the pressure distribution and its galloping response. The aerodynamic forces are measured using 320 pressure taps on four cross-sectional rings and four lines along the length of the cylinder. The characteristics of the aerodynamic forces on the cylinder in the critical Reynolds number range are described. Static aerodynamic forces are used to predict the galloping instability based on the quasi-steady assumption. Galloping is observed in dynamic tests. The validity of the quasi-steady assumption for predicting galloping at critical Reynolds numbers is determined by comparing the observed galloping with the predicted galloping.

2. Experimental setup

Tests were conducted in the STDU-1 wind tunnel at Shijiazhuang Tiedao University; the tunnel is a closed-circuit wind tunnel with a larger test section that is 4.38 m wide, 3 m high and 24 m long and a smaller section that is 2.2 m wide, 2 m high and 5 m long. The model and supporting system were placed in the larger test section, in which the velocity profile was uniform within ±0.5% and the turbulence intensity was approximately 0.5% at 20 m/s. The aerodynamic force coefficients were calculated from the integral of the pressure coefficients over the perimeter of the cross-section. C_P, C_D, C_L, and C_M are defined as the mean pressure coefficient, drag coefficient, lift coefficient and moment coefficient, respectively, and $C_{P\sigma}$ is the standard deviation of the pressure coefficient. The Reynolds number Re is defined as $Re = \rho DU/\mu$, where ρ, U and μ are the air density, mean oncoming wind velocity and dynamic viscosity of the air, respectively.

The elliptical cylinder model had a length L of 2900 mm, a minor axis D of 180 mm, and a major axis of 1.5D. The model was made of polyethylene pipe. Because the model and supporting system were in the wind tunnel, the end conditions may have a significant influence on the wind pressure distribution. Unfortunately, it is difficult to eliminate this effect completely. A fixed end plate is commonly used to reduce this impact, but this approach prevents possible axial flow for a skew cylinder (Yagi et al., 2009) (which is intended as a test in the next stage of our studies) and induces an additional aerodynamic force when it vibrates in dynamic tests. The end effects can also be reduced using a compensation model on both ends, but such a model cannot be used in dynamic tests because the compensation component will not have the same vibrations as the cylinder model. This study employed a fixed end plate with a hole in the center and an end cover at each end to maintain the same end conditions for both the static and dynamic tests for the both normal and skew cylinders. Each end plate has a length of 2280 mm and a circular hole at its center. An end cover with a shape of NACA2420 was connected to the endplate to reduce the effects of flow around the cylinder end and the supporting system on the aerodynamic forces and vibrations, as shown in Fig. 1 (a). In this arrangement, the supporting system and cylinder ends were enclosed by the end plates and covers, and the cylinder could move in the holes on the center of the end plates. The diameter of the hole can be enlarged from 200 mm to 800 mm. The hole needs to be large enough to meet the requirement of vibration and to be as small as possible to reduce its disturbance in flow condition at the ends. The diameter, which is a little larger than the requirement of the largest amplitude vibration in these tests, was set at 300 mm. An end bar was used at each end to fix the model for the static tests or hang springs for the dynamic tests.

Pressure measuring taps were arranged at four discrete cross-sections (termed Rings A, B, C and D) and four axial lines (termed L1, L2, L3 and L4). Ring C is in the middle of the cylinder, Ring B is 20 cm from Ring C, and Rings A and D are 85 cm from the ends of the cylinder, as shown in Fig. 1 (b). The four axial lines are located at both ends of the major and minor axes of the cross-section. Each ring has 50 taps around the circumference and each line has 30 taps uniformly distributed along the cylinder axis at spacing of 94 mm at one end and 87 mm at the other. The pressure tubes all measured 800 mm in length, and their effect on pressure distortion was corrected using the frequency-response function of each tube, which is estimated by the distributed friction model and verified by tests (Ma et al, 2013). The aerodynamic pressure was collected with pressure sensors (ESP-64Hd, Measurement Specialties (formerly PSI), Hampton, VA, USA) and a data acquisition system (DTC Initium, Measurement Specialties) with a recording length of 80 s and a sampling frequency of 331.60 Hz.

2.1. Static tests

Static pressure tests were performed to obtain the static aerodynamic forces on the cylinder. The wind speeds were 5 m/s and from 10 m/s to 20 m/s in 2 m/s intervals, which corresponds to a Reynolds number range from approximately 0.61×10^5 to 2.45×10^5 (based on the minor axis D) for the static tests. The angles of attack α were from wind parallel