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Aerodynamic characteristics and excitation mechanisms of the galloping of an elliptical cylinder in the critical Reynolds number range

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ABSTRACT

The generation mechanisms of dry cable instabilities in the critical Reynolds number range are still unclear because of their complicated aerodynamic forces and a shortage of studies on the coupling process. Large amplitude vibrations of an elliptical cylinder in the critical Reynolds number range are reproduced in a wind tunnel, and displacements and wind pressure on the cylinder are recorded synchronously to illustrate the interactions between the cylinder motion and the aerodynamic forces in this study. Strong interactions are observed only when the flow starts reattaching at the rear of the cylinder in the early critical Reynolds number range, wherein the reattachment stops the Kármán vortex shedding and forms a separation bubble. Once the reattachment points move forward, large amplitude vibrations are not observed. The vibration is strongly related to the contribution of the pressure in the region of the separation bubble. The organization of aerodynamic forces along the length is also needed to cause the vibrations. The aerodynamic forces are not uniformly distributed along the cylinder in the critical Reynolds number range and they can either input or absorb energy during the vibrations.

1. Introduction

Large amplitude vibrations of dry circular cylinders in the critical Reynolds number range have been reproduced in wind tunnel experiments (Benidir et al., 2015; Jakobsen et al., 2012; Matsumoto et al., 2010; Matteoni and Georgakis, 2015; Nikitas and Macdonald, 2015; Nikitas et al., 2012). The mechanism of these vibrations, which are called dry galloping, is not yet clear due to the complexity of aerodynamic forces at critical Reynolds numbers. As it has been observed only on dry inclined cables in wind tunnels, the phenomenon could be attributed to a lack of circularity (Benidir et al., 2015; Flamand and Boujard, 2009; Matteoni and Georgakis, 2012, 2015), axial flow (Matsumoto et al., 2010) or the critical Reynolds number (Nikitas and Macdonald, 2015). The common understanding is that the critical Reynolds number definitely plays an important role for exciting the dry galloping.

In the critical Reynolds number range, flow around a circular cylinder exhibits a single bubble regime, whereby the transition occurs on one side of the cylinder and flow reattaches to cylinder on that side; and a two bubble regime, whereby the flow reattaches symmetrically on both sides (Benidir et al., 2015; Zdravkovich, 1997). The single bubble can produce a reattachment-type pressure distribution at high wind velocities, which may excite large vibrations; Meanwhile, Kármán vortex shedding is suppressed by the interruption of communication between the separation flows on both sides (Matsumoto et al., 2010). Studies have already shown that the flow in the critical Reynolds number range is sensitive to external disturbances or stimulations (Hoxey et al., 1998; Schewe, 1986; Zdravkovich, 1997). This sensitivity may be caused by the released separated flow from the control of the Kármán vortex (Matsumoto et al., 2010) and may allow an easier interaction between the fluid and the moving cylinder in the critical Reynolds number range. Unfortunately, it is difficult to distinguish the effects of reattachments induced by the occurrences of transitions in the boundary layer and those of the suppression of the Kármán vortex shedding since they occur together. Matsumoto et al. claimed the interaction could induce unsteady galloping whose response characteristics cannot be explained by quasi-steady theory, and the fluid-cylinder interaction of galloping in the critical Reynolds number range is worthy of further study. Nikitas and Macdonald have discussed the aerodynamic force characteristics of dry galloping, and their results show a periodic change in wind pressure on one side of the cylinder where the separation bubble is not fully formed, while the wind pressure hardly changed during the vibrations on the side with a stable separation bubble (Nikitas and Macdonald, 2015). This illustrates that the

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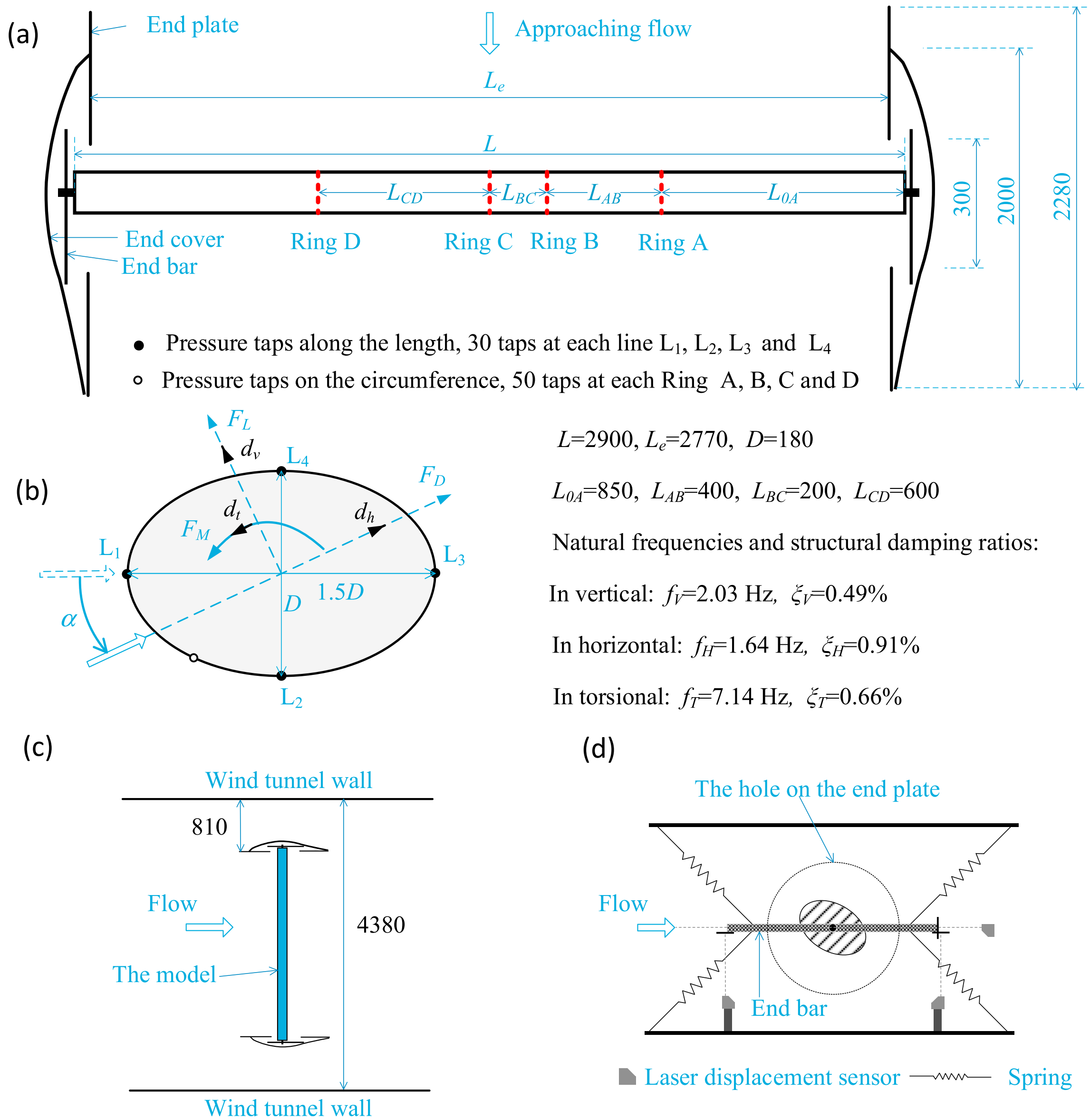

Fig. 1. Schematics of the wind tunnel arrangement and the model with the main parameters indicated: (a) model and end conditions, (b) cross-section and pressure tap arrangement, (c) model in wind tunnel, (d) support system at the end.

reattachment on the side with the separation bubble contributes little to the large vibrations and implies that the reattachment may not be a necessary condition for the vibrations, which makes the situation even more complex. Their results also show that the aerodynamic forces on different pressure rings spread along the cylinder have distinctly different contributions to the excitations. Noting the sensitivity of the aerodynamic forces in the critical Reynolds number range; and that, in reality, any tested model and approaching flow are not perfectly uniform, the aerodynamic force distribution along the cylinder axis is also worth considering. Thus, the analysis of the variations of aerodynamic forces on a vibrating cylinder in the critical Reynolds number range could be very helpful for understanding the mechanism of dry galloping and identifying the effects of reattachment and the suppression of vortex shedding.

Reattachment and separation bubbles also occur on cylinders with other curved cross-sections, such as elliptical and semi-elliptical sections, at Reynolds numbers, which is of concern to civil engineers (Alonso et al., 2010; Ma et al., 2015). These shapes share similar features in the critical Reynolds number range to a circular cylinder, but they have a clear definition of the angle of attack, which could be important when considering the lack of circularity. For a circular cylinder, the single separation bubble regime is exhibited only in a narrow Reynolds number range before regular vortex shedding reappears when separation bubbles form on both sides. For an unsymmetrical shape, the wide Reynolds number range in which flow reattaches to only one side of the cylinder can provide a better chance of identifying the effects of reattachment and the suppression of vortex shedding.

In this paper, a cylinder with an elliptical cross-section and a major to minor axis ratio of 1.5 is tested in a wind tunnel. The wind pressure on the cylinder is measured in both static and dynamic tests. The displacements of and wind pressures on the cylinder are recorded synchronously during the dynamic tests to obtain the variations in the aerodynamic forces and vibrations. By analysing the responses of and aerodynamic forces on the cylinder for large amplitude galloping in the critical Reynolds number range, the present work aims to reveal the process of the fluid-cylinder interactions and effects of the distribution of the spanwise aerodynamic forces on the vibrations.

2. Experimental setup and procedure

A series of static and dynamic tests were carried out using the same