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Aerodynamic mechanisms of galloping of an inclined square cylinder

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ABSTRACT

The aerodynamic mechanism of galloping of an inclined square cylinder was investigated using both experimental and numerical methods. Experimentally, pressure measurements on the inclined cylinder were taken in the wind tunnel. Numerically, a large eddy simulation was used to investigate the flow field around the cylinder. When the inclination is forward to the approaching wind, it significantly increases the curvature of the shear layer near the free end of the cylinder whereas decreases it near the base. Conversely, when the inclination is backward, it decreases the curvature near the free end while increases it near the base. The variation in the curvature has remarkably influenced the pressure distributions on the side faces and hence the transverse force coefficient, which governs the galloping behavior of the cylinder. The particular curvature of the shear layer in the forward inclination case is a consequence of an inverted V-shaped spanwise vorticity distribution, which is induced by an "extended tip vortex pair" with an inverted V-shaped streamwise vorticity distribution. However, in the backward inclination case, the shear layer curvature is attributable to a V-shaped spanwise vorticity distribution caused by an "extended base vortex pair" with a V-shaped streamwise vorticity distribution.

1. Introduction

Galloping is a well-known aeroelastic instability characterized by a large amplitude and low frequency motion in the direction normal to the oncoming flow. It has a potential to damage structures and has therefore been the topic of a number of studies. Majority of the relevant studies (Kwok and Melbourne, 1977, 1980; Novak, 1969; Parkinson and Smith, 1964; Parkinson and Sullivan, 1979) have concerned the galloping behavior of a slender structure whose principal axis is perpendicular to the oncoming flow.

The mechanism associated with galloping of rectangular or square section cylinders with their principal axis normal to the oncoming flow has been well documented (Nakamura and Hirata, 1994; Nakamura et al., 1991; Parkinson and Sullivan, 1979). A brief summary based on these studies is given here. At a high reduced wind speed, the shear layer that separates from a square cross section, or a rectangular cross section with a short afterbody, is free from the direct interference with the trailing edge. An initial downward cylinder motion causes the lower shear layer to move closer to the lower side and hence becomes more curved, whereas the upper shear layer moves further away from the upper side and therefore becomes less curved, as shown in Fig. 1. Consequently, a downward pressure force is induced and augment the cylinder's motion. Furthermore, Nakamura et al. (1991) attributed the absence of galloping at low reduced wind speeds to the interaction between the shear layer and the trailing edge. More specifically, as the wind speed is lowered, the wavelength of the wake wrinkling becomes progressively shorter, and hence the shear layer interacts with or even intermittently reattaches the trailing edge so that the shear layer is prevented from rolling up freely. The interaction or reattachment of the shear layer results in a relatively high pressure near the trailing edge. The high pressure compensates the significantly negative pressure in the upstream half of the side face and results in a negative slope of the "transverse force coefficient against wind incidence angle" curve at zero wind incidence angle. According to the Den Hartog's criterion (Den Hartog, 1985; Holmes, 2007), the negative slope implies that the cylinder is immune to galloping.

On the other hand, Matsumoto et al. (2010) have investigated the mechanism of dry galloping of an inclined cable. Dry galloping is considered to be caused by a mitigation of Karman vortex shedding. An axial flow, which is observed in the wake of the inclined cable without rivulet, plays a role similar to a splitter plate installed in the near wake. The splitter plate mitigates the Karman vortex shedding and hence interrupts the communication between two separated flows on the two sides. The interruption of the communication helps to maintain the pressure difference between both sides, which is able to induce the dry galloping. In summary, the axial flow induces the dry galloping of a cable. It

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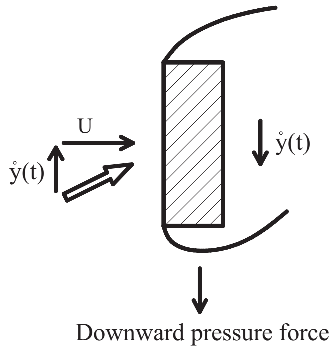

Fig. 1. Basic excitation mechanism of galloping (From Nakamura and Hirata (1994)).

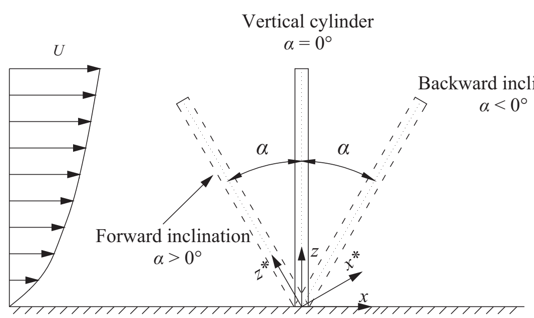

Fig. 2. Illustration of three different tested types of cylinders: forward inclined cylinder, vertical cylinder, and backward inclined cylinder. α is angle of inclination: a positive value represents forward inclination while a negative one denotes backward inclination.

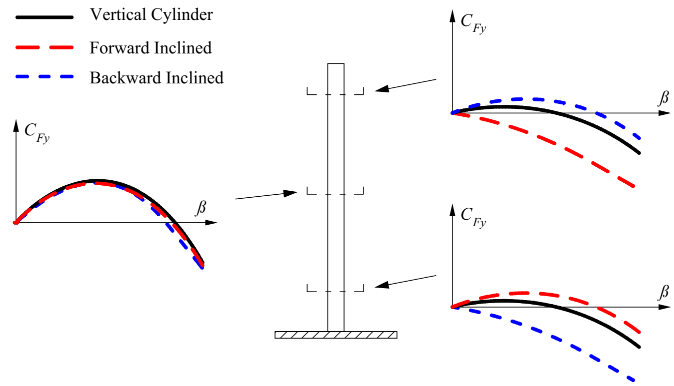

Fig. 3. Schematic illustration of variations in $C_{Fy}(z)$ for forward and backward inclinations at different heights.

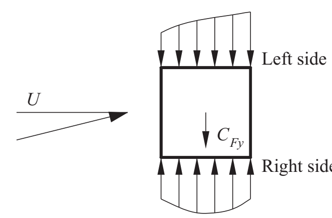

Fig. 4. Schematic illustration of a cross section of a square cylinder with pressure distributions on the side faces and the associated transverse force coefficient C_{Fy}.

should, however, be noted that aerodynamic characteristics between a circular cross-section and one with sharp corners are very different. Thus, the role of the axial flow may be different in the two scenarios.

The aforementioned studies have evaluated the galloping behavior or its mechanism of a cylinder with its principal axis perpendicular to the oncoming flow or of a circular cylinder inclined in the flow. However, some real structures with rectangular or square cross sections have been designed with an inclination deviating from the vertical direction. Examples are the pylon of the Alamillo Bridge and the Gate of Europe towers in Spain. In these cases, the oncoming flow impacts these structures obliquely. As it turns out, the inclination of the slender structure has a non-negligible effect on the galloping behavior.

To study the effect of inclination on the galloping oscillation of a slender square cylinder, Hu et al. (2015a) carried out a series of aeroelastic tests. Their investigation examined a cylinder in forward inclined (with respect to the upstream direction), vertical, and backward inclined (with respect to the downstream direction) orientations under action of wind flow with a zero-degree wind incidence angle. A schematic drawing to illustrate the inclination geometry is shown in Fig. 2. In the study, the quasi-steady theory proposed by Parkinson and Smith (1964) was applied to evaluate the effect of the inclination on galloping. The applicability of the theory to predict the galloping response of an inclined cylinder is also discussed. The aeroelastic test results showed that the galloping amplitude decreases substantially as the forward inclination angle increases. Furthermore, when the forward inclination angle is large enough (i.e. $\geq 10°$), galloping vanishes entirely. On the other hand, unlike the forward inclination cases, not all the backward inclination cases show a galloping oscillation with an amplitude smaller than that of the vertical case. At a small backward inclination angle (i.e. 5° and 10°), galloping amplitudes are significantly larger than that of a vertical cylinder, whereas at a large backward inclination angle (i.e. $\geq 20°$), lower amplitudes are exhibited. In fact, the cylinder at a backward inclination angle of 15° shows a galloping behavior comparable to a vertical cylinder.

Galloping behaviors of the cylinder with different inclinations have been explained by Hu et al. (2015a, 2015c) largely based on variations in transverse force coefficient C_{Fy}, which is a dominant parameter in the quasi-steady theory. Variations in local transverse force coefficients $C_{Fy}(z)$ for both forward and backward inclinations are sketched qualitatively in Fig. 3. The reduction in the galloping amplitude, or its absence, induced by forward inclination is attributable to a significant reduction in the local transverse force coefficient $C_{Fy}(z)$ near the free end of the cylinder, in spite of a slight increase near the base. However, that the cylinder with a backward inclination angle of 5° or 10° has larger galloping amplitudes than a vertical cylinder does, could be ascribed to an increase in $C_{Fy}(z)$ near the free end of the cylinder. On the other hand, the relatively lower transverse response observed at a backward inclination angle of 20° or 30° is caused by a decrease in $C_{Fy}(z)$ near the base. At a backward inclination angle of 15°, the fact that its galloping behavior is comparable to the vertical case stems from the offset of larger $C_{Fy}(z)$ near the free end and the smaller $C_{Fy}(z)$ at other heights of the cylinder.

Although the change in the galloping behavior caused by inclinations has been explained in terms of the variation in $C_{Fy}(z)$, its underlying mechanism remains unknown. Since C_{Fy} is the difference between the force coefficients on the two side faces, as shown in Fig. 4, its variation is highly dependent on the pressure distribution on both side faces. In the present study, pressure measurement in the wind tunnel and flow field visualization via large eddy simulation (LES) on a vertical cylinder and a series of inclined cylinders were performed to observe the variation in pressure distributions on the side faces, and to reveal the mechanism in terms of shear layer curvature and vortex structures in the near wake of the cylinder.