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Numerical study on the effect of shape modification to the flow around circular cylinders

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ABSTRACT

Shape modification has been one of the effective ways of manipulating the flow past bluff bodies. Aiming at exploration of the flow control mechanisms of shape modified circular cylinders, a series of numerical simulations are conducted at the Reynolds number of 5000. The modifications adopted in the current paper could be divided into two categories, the 2-dimensional cross-sectional modifications (polygonal and ridged) and 3-dimensional span-wise modifications (linear wavy, sinusoidal wavy and O-ringed). By exploiting the numerical data obtained from the Large Eddy Simulations, several aspects, including the wake flow properties, the aerodynamic forces, the flow instabilities and span-wise correlations are compared in detail. The two wavy cylinders are found to modify the flow wake significantly, leading to considerable reduction in aerodynamic forces. The polygonal and ridged cylinders, however, are of no such effect in aerodynamic force mitigation. The O-rings only have slight effect on the flow wake and the forces. As for the flow instabilities, the modifications adopted in this paper barely affects the Kármán vortex shedding frequency. The shear layer frequency, however, differs from case to case. Particularly, in the cases of the two wavy cylinders, disparity exists in the shear layer frequency at the node and saddle. This is explained by the boundary layer properties at separation. While recognizing the insufficiency in the span-wise length of the cylinders, the span-wise correlations of the aerodynamic forces are inspected. It is found that the lift forces of the 3-dimensional cylinders are generally less correlated than that of the 2-dimensional ones.

1. Introduction

Flow around circular cylindrical structures such as high rise buildings, bridge cables and overhead transmission lines is a common occurrence in various wind engineering applications. In most cases the elusive aerodynamic forces acting upon the cylinders induce undesired effects such as structural noise and fatigue. Especially in the case where the natural frequency meets the vortex shedding frequency, large amplitude vibrations could occur on the structures.

Owing to the engineering significance, flow control has been an active and patenting field of research for several decades. Previous investigations in this area have been fruitful in that not only a variety of methods have been proposed, but some of the basic flow control mechanisms explained. A comprehensive summary was presented in the annual review by Choi et al. (2008). Often, the control approaches could be categorized into active methods, which requires energy input, such as rotary (Poncet, 2002; Mittal and Kumar, 2003; He et al., 2000), blowing/suction (Fransson et al., 2004; Fujisawa et al., 2004), and distributed forcing (Kim and Choi, 2005), and passive control methods in which no external energy is supplied but modifications on the structure are required, such as surface roughness (Achenbach, 1971; Nakamura and Tomonari, 1982), dimples (Bearman and Harvey, 1993), grooves (Kimura and Tsutahara, 1991; Yamagishi and Oki, 2004, 2005), span-wise waviness Ahmed and Bays-Muchmore, 1992; Lam and Lin, 2009, helix (Zhou et al., 2011; Lee and Kim, 1997), and wake splitter plates (Hwang and Yang, 2007). In some researches, passive and active approaches are even combined (Bao and Tao, 2013; Udovidchik and Morrison, 2006).

Despite the abundance of these flow control approaches, only a few of them are applicable to the engineering applications. Particularly for the cable structures, active control approaches are excluded since the implementation of the energy supplement apparatuses is difficult. Direct wake modifications like splitter plates are also not suitable because this configuration could not

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attend to the flow coming from all directions. On the contrary, circular cylinders with shape modifications are easy to fabricate and install. Moreover, these methods are omni-directional so that they are effective irrespective of the direction of the incoming wind. In the following paragraphs, we present a selective retrospect on the documented flow control approaches or those which have the potential to be used for cable structures.

The aerodynamic means for controlling the flow wake and the aerodynamic forces by shape or surface modification could be classified into two major categories, based on their phenomenological mechanisms. The first is the boundary layer control. A laminar-to-turbulence transition takes place in the boundary layer at the critical Reynolds number and empowers it with larger momentum against the adverse pressure gradient. In this way the separation is delayed and the drag crisis is engendered. The idea of making the boundary layer turbulent has bred several flow control methods such as surface roughness, dimples, axial grooves and ridges, and polygon. The effect of surface roughness to the aerodynamic forces has been investigated by a number of researchers. Achenbach (1971) concluded from the wind tunnel experiments that the drag crisis could be made earlier by the introduction of surface roughness. However, this gain is accompanied with the unfavorable fact that the rougher the cylinder surface is, the smaller the reduction in the drag coefficients is through critical regime, and the higher the C_d is in the post-critical regime. Thus, the effectiveness of the surface-roughened cylinder is valid only in limited range of Reynolds numbers. Inspired by the dimpled golf balls (Bearman, 1976), Bearman and Harvey (1993) investigated the effect of dimples on the surface of a circular cylinder. It was found that with a similar value of k/D (D is the diameter of the cylinder and k is the sand height in the roughened cylinder or the depth of the dimples on the dimpled cylinder), the dimpled one induces a larger reduction in the drag than the sand-roughened cylinder, although, at a slightly higher *Re*. Besides, the drag coefficient in the trans-critical *Re* is substantially lower than that of the sand-roughened one. Kimura and Tsutahara (1991) explored the drag reduction effect of a single groove on a circular cylinder. It was found that the flow near the wall is energized by this groove and thusly travels slightly farther against the adverse pressure gradient before separation, leading to the favorable effect of drag mitigation. He further concluded that the position of the groove is important and the effect of the dimples on the golf balls is considered to be the same as that of the grooves. Apparently, since a single groove could not handle the complications in practical applications, a regular distribution of grooves is instead required. Such configurations have been considered by Yamagishi and Oki (2004), who investigated the shape effect of the grooves on a circular cylinder. Little disparity could be observed in the critical Reynolds number between the triangle-shaped and arc-shaped cylinders, but the latter is better at drag mitigation in the trans-critical regime. The same authors further studied the effect of the number of the grooves (Yamagishi and Oki, 2005) and came to the conclusion that increasing the number of the grooves would reduce the critical Reynolds number. In a similar fashion, ridges on the cylinder are also capable of drag mitigation. To reduce the wind load on the insulated wire, Matsumura et al. (2002) studied the cylinders with mountainous surfaces consisted of a number of ridges. It was revealed that, similar to the grooved ones, as the number of the ridges increases, both the wind speed at which the drag coefficient begins to drop and the wind speed at which the coefficient shows a minimum shift to the region of lower wind speed. Moreover, the minimum value of the drag coefficient decreases.

So far, the surface/shape modifications mentioned above are mostly applied on the cross-sections to achieve a retreated separation of the boundary layer. The second category of modifications, as opposed to the first, is usually performed in the axial direction. One of the benefits in doing this is to force the 3-dimensionlization of the flow separation. The research group led by Bearman has been active in this field for several years. Bearman and Owen (1998) investigated the effect of sinusoidal waviness installed at the stagnation face of a rectangular cylinder. Substantial drag reduction was achieved, accompanied by significant attenuation of the Kármán vortex behind the bluff body. El-Gammal et al. (2007) then introduced this idea of span-wise sinusoidal perturbation method (SPPM) to control the vortex-induced vibrations in a plate girder bridge. In the subsequent work, Owen et al. (2001) studied a circular cross-sectional body with a sinuous axis and a circular cylinder with hemispherical bumps attached. Again significant drag reduction was obtained for these two configurations. An elegant flow visualization of the sinuous axis cylinder was also provided by the same group (Owen et al., 2000). Another kind of circular wavy cylinder, which is configured by keeping the axis straight and varying the local diameter, has also been investigated intensively. Ahmed and Bays-Muchmore (1992) experimentally examined this shape as early as the year of 1992. After him, the research team led by Lam from Hong Kong Polytechnic University conducted a series of systematic investigations focusing on the flow physics and the shape optimization of the sinusoidal wavy cylinders, with Reynolds number spanning from 100 to 50,000 (Lam and Lin, 2009; Lam et al., 2004, 2004; Lam and Lin, 2007, 2008). Some other researchers (Xu et al., 2010; Lee and Nguyen, 2007; Kleissl and Georgakis, 2010) also contributed to enhance the understanding of this particular shape. Based on these literature, the most salient features of this shape are summarized as follows. (i) The wavy surface leads to the formation of a 3-dimensional shear layer, which is more stable than the 2-dimensional one; (ii) the vortex formation length is elongated by this more stable shear layer, resulting in reduced drag force; (iii) the vortex shedding is attenuated, leading to mitigated lift force. The attachment of O-rings onto the cylinder surface has also been reported efficacious in reducing the aerodynamic forces. Different from the wavy cylinders, in which the gain of force mitigation could be attained even at low Reynolds number flows, in both works by Lim and Lee (2004) and Nakamura and Igarashi (2008), the effectiveness of the O-rings was only reported in relatively higher Reynolds numbers of around 10^4. Moreover, if the grooves were engraved in the longitudinal direction, the desired effect of aerodynamic force reduction could also be achieved, as was revealed by Lim and Lee (2002). One common observation between the O-ringed cylinders and the longitudinally grooved cylinder is the elongated vortex formation regions, which was considered by Zdravkovich (1981) as the governing factor for high effectiveness of flow control. It appears that axial modifications of these kinds are also able to alter the wake flow in a beneficial way, however, the profound cause of which is less clear.

If a third category must be added to accommodate the industrially favorable morphology of the cylinder with helical strakes (Zdravkovich, 1981; Vandiver et al., 2006; Zhou et al., 2011), then we would call it a combination of the previous two, since modifications are performed both in the cross-section and the spanwise direction. However, while these strakes do serve well as countermeasures for vortex induced vibration, a by-product is the large drag force that arises from them. Protrusions in smaller size, such as wires, fillets, strips, as well as the engraved grooves, could also be arranged in a helical fashion, although with uneven performance in flow control. Lee and Kim (1997) studied the flow wake structure of a circular cylinder wrapped with 3 helical wires and reported the suppression of Kármán vortex along with elongated vortex formation region. From these observations it could be inferred that the aerodynamic forces were reduced. However,