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Effects of oncoming flow conditions on the aerodynamic forces on a cantilevered square cylinder

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ABSTRACT

The aerodynamic forces on a cantilevered square cylinder with a height-to-width ratio (H/d) of 5 in a crossflow were experimentally investigated in a closed-loop low-speed wind tunnel. The freestream oncoming flow velocity (U_∞) ranged from 5 to 45 m/s, corresponding to Reynolds numbers, based on U_∞ and d, of 0.68×10^5 to 6.12×10^5. Two different oncoming flow conditions were tested. In case 1, the majority of the cylinder span was in the uniform flow, except the lower 1d which was immersed in a thin turbulent boundary layer; in case 2, the tested cylinder was completely immersed in a turbulent boundary layer. In both cases, the Reynolds number had a negligible effect on the aerodynamic forces of the cylinder. The predominant vortex shedding frequency was constant along the cylinder span, regardless of the thickness and nature of the boundary layer. In case 1, the lift fluctuated periodically with a large amplitude or did not exhibit obvious periodicity, which correspond to the anti-symmetric and symmetric vortex shedding modes, respectively. Proper orthogonal decomposition (POD) analysis showed that, in case 2, anti-symmetric vortex shedding tends to occur, instead of the symmetric mode, thus resulting in a larger fluctuating lift than that observed case 1.

1. Introduction

The flow around two-dimensional (2D) cylinders with circular and square cross-sections has long been the subject of fundamental and engineering investigations. This flow is characterized by periodic spanwise vortex shedding, which determines the aerodynamic forces on the cylinder. For a circular cylinder, the separation point of the shear layer oscillates on its curved surface during the vortex shedding process. It is sensitive to the effects of the Reynolds number (*Re*), turbulence intensity and surface roughness, especially near the critical Reynolds number regime (Farell and Blessmann, 1983). For the flow around a square cylinder, with one of its faces normal to the oncoming flow, the separation is fixed at its two leading edges (Vickery, 1966; Noda and Nakayama, 2003). However, Re still shows noticeable effects on the near wake and aerodynamic forces. For example, the near wake changes from 2D to 3D with a Re greater than 160 (Luo et al., 2003). This three-dimensionality was also observed by Okajima (1995) with a direct numerical simulation (DNS) at Re $=$ 1000. Moreover, strong dependence of both the time-averaged drag and vortex shedding frequency on Re over the range $100 < \text{Re} < 10^5$ was also observed (Okajima, 1995).

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A number of investigations have revealed the significant effects of turbulence intensity on the aerodynamic forces of a 2D square cylinder (e.g., Vickery, 1966; Lee, 1975; Tamura and Miyagi, 1999). Generally, an increase of the oncoming flow turbulence intensity significantly suppresses the fluctuation lift and reduces the drag by raising its base pressure (Vickery, 1966; Lee, 1975; Noda and Nakayama, 2003). Moreover, the addition of turbulence to the oncoming flow remarkably weakens the spanwise correlation of the fluctuation pressure on the cylinder side faces (Lee, 1975). Although the separation point is fixed at the leading edge, Lee (1975) suggested that the increased turbulence of the oncoming flow thickens the shear layer and deflects it to the body, which results in the downstream movement of the vortex formation region. Conversely, according to the experimental results of Vickery (1966), Lee (1975) and Noda and Nakayama (2003), the oncoming flow turbulence has a negligible effect on the vortex shedding frequency of a square cylinder.

In engineering applications, the cylinder-like structures are often finite in length and mounted on a flat wall, e.g., high-rise buildings, chimneys and submarine appendages. A number of investigations have revealed four major vortical components in the near wake of a cantilevered finite-length cylinder, i.e., tip vortex, spanwise vortex, based vortex and horseshoe vortex (Sumner et al., 2004; Donnert et al., 2007; Wang and Zhou, 2009; Sumner, 2013). The streamwise tip vortex and base vortex are accompanied by downwash and upwash flows, which make the near wake highly three-dimensional. The strength of the base vortex and associated upwash flow depend on the thickness of the boundary layer where the cantilevered cylinder is mounted (Wang et al., 2006). Specifically, a thicker boundary layer results in a stronger base vortex and upwash flow. The spanwise vortex largely depends on the cylinder aspect ratio H/d, where H is the cylinder height or length, and d is its characteristic width. Sakamoto and Arie (1983) measured the vortex shedding frequency and visualized the near wake of wall-mounted finite-length circular and square cylinders with different H/d. They suggested that Karman-type vortex shedding occurs for H/d larger than the critical value, while arch-type shedding occurs for smaller H/d. This critical H/d depends on the oncoming flow conditions, e.g., boundary layer thickness and the turbulence intensity of the oncoming flow. The horseshoe vortex is characterized by a rollup motion in front of the cylinder base, with both of its legs wrapping around the structure. Interestingly, in most experimental investigations on the near wake of a wall-mounted finite-length cylinder, the horseshoe vortex was not observed, e.g., Sumner et al. (2004), Bourgeois et al. (2011) and Kawai et al. (2012). This is because the dimensions of the horseshoe vortex are significantly smaller than those of the other three major components, i.e., the tip, base and spanwise vortices (Simpson, 2001; Lin et al., 2008). Moreover, the horseshoe vortex is restricted within the region very close to the wall (Hussein and Martinuzzi, 1996). The interactions of these major vortex components make the near wake of a cantilevered finite-length cylinder far more complicated than the 2D case.

Due to the continuous efforts of numerous researchers, extensive knowledge on the vortex dynamics in the finite-length cylinder near wake has been accumulated in the last decade. Nevertheless, our understanding of the aerodynamic forces acting on a finite-length cylinder is still quite limited (Basu, 1986).

For a finite-length circular cylinder, most of the previous studies were concerned with the effects of H/d on the aerodynamic forces. Generally, the time-averaged drag coefficient ($\overline{C_d}$) and fluctuating lift coefficient ($C_l^{'}$) are smaller than the corresponding values for a 2D circular cylinder (Farivar, 1981; Fox and West, 1993a,b). Moreover, $\overline{C_d}$ decreases gradually with decreasing H/d (Sarode et al., 1981; Okamoto and Sunabashiri, 1992; Sumner et al., 2004; Wang et al., 2012). The reduction in $\overline{C_d}$ and $C_l^{'}$ of a finite-length circular cylinder may be attributed to the free-end effects, which attenuates the spanwise vortex shedding and raises the back pressure of the cylinder (Okamoto and Sunabashiri, 1992; Sumner et al., 2004). Due to the three-dimensional nature of the flow, the aerodynamic forces on a finite-length circular cylinder vary noticeably along its span, even if it is subjected to a uniform oncoming flow. In the subcritical regime, the local maximum drag coefficient $\overline{C_{d\_max}}$ occurs 0.5d below the free end of the cylinder with $1 < H/d < 6$, and is smaller than that of a 2D circular cylinder. In comparison, the local $\overline{C_{d\_max}}$ occurs near the free end and exceeds that of a 2D circular cylinder for $7 < H/d < 12.5$ (Okamoto and Yagita, 1973). For a finite-length circular cylinder with larger H/d, e.g., $20 < H/d < 30$, the local value of $\overline{C_d}$ is also noticeably smaller than that of a 2D circular cylinder over most of the span, indicating that the free-end effects are still significant (Fox and West, 1993a).

Similar to a 2D circular cylinder, Re has remarkable effects on the aerodynamics of a finite-length circular cylinder. Uematsu and Yamada (1995) measured the $\overline{C_d}$ of a cantilevered circular cylinder with $H/d = 5$ in both the subcritical and supercritical regimes. They found that the $\overline{C_d}$ in the supercritical regime is about 43% of the value in the subcritical regime. More recently, Wang et al. (2012) measured the $\overline{C_d}$ of a roughened finite-length circular cylinder with $H/d = 3$, 5 and 7. Their measurement results indicate that H/d has a negligible effect on the critical Re from subcritical to critical regimes. Moreover, the drag crisis becomes less obvious with decreasing H/d. Ayoub and Karamcheti (1982) measured the instantaneous surface pressure near the free end of a finite-length circular cylinder with $H/d = 11.96$, at Re $= 8.5 \times 10^4$, 1.8×10^5 and 7.7×10^5, belonging to the subcritical, critical and supercritical regimes, respectively. They suggested the vortex shedding near the free end is distinct from that on the main body of the cylinder. Particularly, the flow near the free end can be unstable and intermittent or subcritical when the main flow is supercritical. However, Wang et al. (2016) made a detailed measurement of the time-averaged pressure distribution on a finite-length circular cylinder with $H/d = 5$ with Re ranging from 0.68×10^5 to 6.21×10^5. Although most of the cylinder span was in the uniform oncoming flow, they found that the transition of the flow from subcritical to critical occurs at a smaller Re near the free end. That is, when the flow near the free end of the cylinder is in the critical or supercritical regimes, the flow at the lower half of the span may be still in the subcritical regime.

Far less attention has been paid to the aerodynamic forces of a finite-length square cylinder relative to those of a circular one. Sakamoto and Arie (1983) measured the vortex shedding frequency behind a finite-length square cylinder with $H/d = 0.5 - 8$, and observed a change in the variation of the Strouhal number (St) with aspect ratio at $H/d = 2.0$.