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Influence of aspect ratio on the mean flow field of a surface-mounted finite-height square prism

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ABSTRACT

The flow around surface-mounted, finite-height square prisms at a Reynolds number of $Re = 4.2 \times 10^4$ was investigated experimentally in a low-speed wind tunnel using particle image velocimetry. The thickness of the boundary layer on the ground plane relative to the width of the prism was $\delta/D = 1.5$. Four prism aspect ratios were tested, AR = 9, 7, 5, and 3, to study how the aspect ratio influences the flow field close to the prism. Upstream of the prism, lowering the aspect ratio from AR = 9 to AR = 3 causes the stagnation point on the upstream face to move closer to the free end, but there is no influence on the location and strength of the horseshoe vortex. Lowering the aspect ratio from AR = 9 to AR = 3 causes the cross-stream vortices in the upper and lower halves of the wake to move downstream and upstream, respectively; the latter vortex is absent for AR = 3, suggesting this prism sits below the critical aspect ratio. Above the free end of the prism, within the region of separated flow, lowering the aspect ratio from AR = 9 to AR = 3 shifts the location of the cross-stream vortex farther downstream. For the prism of AR = 3, reverse flow above the free end is stronger yet more unsteady compared to the more slender prisms, while the streamwise edge vortices are smaller and weaker.

1. Introduction

Surface-mounted, finite-height bluff bodies are commonly encountered in engineering applications, such as buildings, oil storage tanks, cooling towers, chimneys, electronic components on circuit boards, and isolated roughness elements in channels, where information on the flow field, surface pressure distributions, aerodynamic forces, flow-induced vibrations and sound, and convective heat transfer characteristics, are of particular interest. The flow around both finite cylinders (e.g., Kawamura et al., 1984; Sumner et al., 2004; Adaramola et al., 2006; Krajnović, 2011; Rostamy et al., 2012) and finite square or rectangular prisms (e.g., Wang and Zhou, 2009; Bourgeois et al., 2011, 2012; Sattari et al., 2012; El Hassan et al., 2015) is strongly three-dimensional, compared to the flow around more familiar “infinite” or two-dimensional cylinders and prisms.

For a wide range of Reynolds number, the flow field of an “infinite” or two-dimensional square prism oriented normal to the flow is characterized by flow separation from the upstream corners of the prism, the periodic, alternate formation and shedding of vortices from opposite sides of the prism, a regular pattern of vortices in its wake known as the von Kármán vortex street, and a high mean drag force coefficient. The effect of the prism’s orientation with respect to the freestream, i.e., where the incidence angle, α, is varied, has been of specific interest (e.g., Bearman and Trueman, 1972; Obasaju, 1983; Igarashi, 1984; Huang et al., 2010; Yen and Yang, 2011). Of note is the existence of a critical incidence angle, where the prism experiences its minimum mean drag force coefficient, maximum mean lift force coefficient magnitude, and maximum Strouhal number (i.e., maximum dimensionless vortex shedding frequency).

For the flow around a surface-mounted finite-height square prism, which is the subject of the present study, flow over the prism’s free end and flow around the prism-wall junction cause the local flow field and the wake to become strongly three-dimensional. Special features of the flow field include the horseshoe vortex which forms at the prism-wall junction, downwash along the centreline of the wake, two sets of time-mean streamwise counter-rotating vortex pairs, one in the upper half of the wake (far above the ground plane) originating from the free end (the tip vortices) and the other in the lower half of the wake near the ground plane (the base vortices), plus a mean recirculation zone above the free end. A schematic of the flow past a finite prism (of width D and height H), mounted normal to a ground plane and partially immersed in a flat-plate boundary layer (with thickness δ at the location of the prism), is shown in Fig. 1. In

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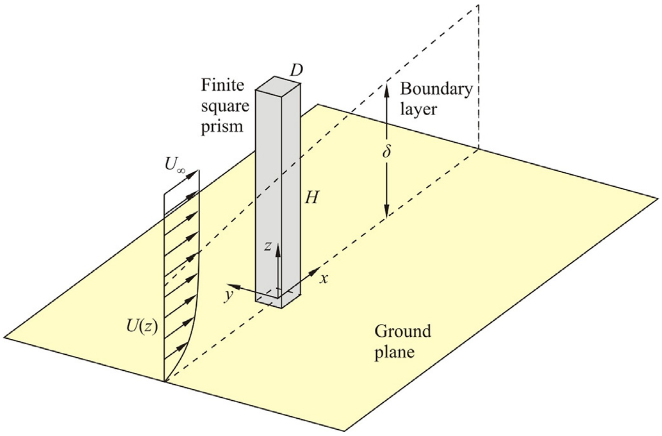

Fig. 1. Schematic of the flow around a surface-mounted, finite-height square prism.

this figure, the prism is oriented so that the leading face is normal to the approaching freestream, i.e., at an incidence angle of $\alpha = 0°$; the majority of the studies of finite prisms have focused on this orientation, including the present study. The main coordinate system is located at the junction of the prism and the ground plane, where x is the streamwise coordinate, y is the cross-stream coordinate, and z is the wall-normal coordinate; in addition, z' is the vertical coordinate for the position above the free-end surface. Notwithstanding the effect of incidence angle, α, the flow field of the finite square prism is strongly influenced by the prism's aspect ratio (or slenderness ratio), AR ($= H/D$), the Reynolds number, Re ($= DU_\infty/\nu$, where U_∞ is the freestream velocity and ν is the kinematic viscosity), and the relative thickness of the boundary layer on the ground plane, δ/D or δ/H (e.g., Wang et al., 2006; Hosseini et al., 2013; El Hassan et al., 2015). In the present study, the influence of aspect ratio is of specific interest.

Flow around a surface-mounted cube, i.e., a finite square prism with AR = 1, has received considerable attention in the literature owing to its special geometrical shape, particularly at an incidence angle of $\alpha = 0°$ From the channel flow experiments of Meinders et al. (1999), the flow field is characterized by a horseshoe vortex on the ground plane upstream of the cube, an arch vortex structure in the near wake region, and a periodic signal attributed to vortex shedding in the wake (e.g., Okamoto and Uemura, 1991). In addition, vertically oriented vortical structures, or corner vortices, are found on either side of the cube, and flow separating from the vertically oriented leading edges reattaches onto the side faces; this reattachment is also seen in the numerical simulations of Yakhot et al. (2006). Above the free end, flow separates from the sharp horizontal leading edge of the free-end surface, and a bound vortex (called the top vortex T, by Yakhot et al., 2006) is contained within the region of separated flow; no vortex shedding is associated with this separated shear layer. When the thickness of the boundary layer on the ground plane is significantly lower than the height of the cube, this separated flow reattaches onto the free end; however, when the boundary layer is close to or thicker than the height of the cube, flow reattachment on the upper surface does not occur (Castro and Robins, 1977). Yakhot et al. (2006) show the existence of small counter-clockwise (CCW) vortices (M and N vortices) upstream and downstream of cube at its junction with the ground plane; a similar secondary vortex on the upstream face of the cube was seen in the experiments of Nakamura et al. (2001). The numerical simulations by Hwang and Yang (2004) show the formation and shedding of "hairpin" vortices from the upper surface and "lateral" vortices from the side surfaces, which are similar to the arch vortex structure seen in other studies.

For higher aspect ratios, where AR > 1, several recent experimental studies by Wang and Zhou (2009), Bourgeois et al. (2011, 2012), Sattari et al. (2012), Hosseini et al. (2013), Wang et al. (2014a), and El Hassan et al. (2015), and numerical studies by Einian et al. (2010, 2011), Saha (2013), Saeedi et al. (2014), Wang et al. (2014b), and Saeedi and Wang (2016), have provided new physical insight into the complexity of the near-wake vortex dynamics and vortex shedding, for finite prisms of AR = 2 to 11, with the near wake of the prism characterized by periodic, alternate formation of full-loop or half-loop vortex structures, depending on AR and δ/D. Of the studies mentioned above, and summarized in Table 1, only the experiments of Wang and Zhou (2009), which covered a wide range of aspect ratios from AR = 3 to 11, and the numerical simulations of Saha (2013), which covered lower aspect ratios from AR = 2 to 5, have considered in extensive detail the influence of changing the prism's aspect ratio. The present study aims to address some of these gaps in the literature, by considering how AR influences a number of regions within the mean flow field, in particular the flow above the free end.

Other studies of higher-aspect ratio finite prisms have examined how AR, δ/D, and α act to influence the aerodynamic forces and vortex shedding frequencies (e.g., Sarode et al., 1981; Sakamoto and Arie, 1983; Sakamoto and Oiwake, 1984; Sakamoto, 1985; McClean and Sumner, 2014; Ogunremi and Sumner, 2015); the studies listed here have covered aspect ratios from AR = 0.5 to 11. Very few of these studies, however, have reported any accompanying measurements or visualization of the flow field in an attempt to explain, physically, the behaviour of the flow and the measured data. In the present study, force and vortex shedding frequency measurements were not made, but data from two similar studies are referenced (McClean and Sumner, 2014; Ogunremi and Sumner, 2015).

Many studies of finite square prisms have shown that the effect of aspect ratio extends to the basic structure and behaviour of the wake, with two different wake structures depending on the whether the prism is above or below a critical aspect ratio. For prisms smaller than the critical aspect ratio, the wake structure has often been associated with symmetric "arch vortex shedding" (as described above for the flow around a surface-mounted cube) whereas for prisms greater than the critical aspect ratio, the wake structure is said to exhibit the familiar anti-symmetric Kármán vortex shedding. More recent studies of finite-prism wakes, which refer to full-loop and half-loop vortex structures, and quadrupole and dipole wake structures, as characterizing the near-wake vortex dynamics (e.g., Bourgeois et al., 2011, 2012; Sattari et al., 2012; Hosseini et al., 2013; El Hassan et al., 2015) seem to be still consistent with the notion of a critical aspect ratio. The critical aspect ratio is not precisely defined in the literature but is based mainly on observations of the dominant wake flow pattern and/or noting changes to the behaviour of experimental data. The flow around a finite cylinder is similarly dependent on a critical aspect ratio (e.g., Kawamura et al., 1984; Sumner et al., 2004; Rostamy et al., 2012; Sumner et al., 2015). For many studies in the literature, the value of the critical aspect ratio for finite cylinders and square prisms lies between AR = 3–5. In the present study, additional information is provided that supports the existence of a critical aspect ratio, based on several flow features in addition to the basic wake structure.

Boundary layer thickness effects on the forces and vortex shedding frequencies have been studied by Sakamoto and Arie (1983), Sakamoto and Oiwake (1984), and Sakamoto (1985), for prisms of smaller aspect ratios, from AR = 1 to 5. Okuda and Taniike (1993), Hosseini et al. (2013), and El Hassan et al. (2015) have considered how boundary layer thickness affects the wake structure. In the present study, however, a fixed boundary layer thickness and a fixed prism width are used.