Journal of Fluids and Structures 34 (2012) 105–122

Contents lists available at SciVerse ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Local flow field of a surface-mounted finite circular cylinder

N. Rostamy, D. Sumner*, D.J. Bergstrom, J.D. Bugg

Department of Mechanical Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan, Canada S7N 5A9

ARTICLE INFO

Article history:
Received 15 August 2011
Accepted 12 April 2012
Available online 20 June 2012

Keywords:
Bluff body
Finite circular cylinder
Wake
Separated flow
Experimental fluid mechanics
Particle image velocimetry

ABSTRACT

The local flow field and near-wake region of a surface-mounted finite circular cylinder were studied experimentally in a low-speed wind tunnel using particle image velocimetry (PIV). The cylinder was mounted normal to a ground plane and was partially immersed in a flat-plate turbulent boundary layer. Four finite circular cylinders of aspect ratios AR=9, 7, 5 and 3 were tested at a Reynolds number of $Re_D=4.2\times10^4$. At the location of the cylinder, the boundary layer thickness relative to the cylinder diameter was $\delta/D=1.6$. PIV velocity field measurements were made in a vertical plane parallel to the mean flow direction on the flow centerline (the symmetry plane), within five diameters upstream and downstream of the cylinder, and also above the free end. Above the free end of the cylinder, flow separation from the leading edge leads to the formation of a mean recirculation zone on the free-end surface. The point of reattachment of the flow onto the free-end surface moves towards the trailing edge as the cylinder aspect ratio is decreased. Large regions of elevated turbulence intensity and Reynolds shear stress are found above the free end. In the near-wake region, the large recirculation zone contains a vortex immediately behind and below the free end; this vortex was found for all four aspect ratios. A second vortex is found behind the cylinder near the cylinder-wall junction; this vortex was not observed for the cylinder of AR=3, indicating a distinct wake structure for this cylinder.

1. Introduction

The flow around a bluff body at a sufficiently high Reynolds number is characterized by a large region of separated flow which leads to the formation of a sizeable wake downstream. The classical example of a two-dimensional bluff body is the "infinite" circular cylinder, which has been the subject of a number of review articles (e.g., Coutanceau and Defaye, 1991; Williamson, 1996) and monographs (e.g., Sumer and Fredsøe, 1997; Zdravkovich, 1997). For a wide range of Reynolds number, its flow field is characterized by the periodic, alternate formation and shedding of vortices from opposite sides of the circular cylinder and a regular pattern of vortices in its wake known as the von Kármán vortex street. Flow around an infinite cylinder has been studied extensively due to the common occurrence of cylinder-like structures in engineering applications and the potential for vortex-induced vibration.

Many of the cylinder-like structures encountered in engineering applications are better approximated as "finite" circular cylinders (e.g., Adaramola et al., 2006; Krajnović, 2011; Okamoto and Sunabashiri, 1992; Park and Lee, 2000; Sakamoto and Arie, 1983; Sumner et al., 2004; Tanaka and Murata, 1999; Wang et al., 2009). Surface-mounted finite-height circular cylinders are found in many engineering applications, such as buildings, cooling towers, fuel and gas storage tanks, bridge piers, and chimney stacks.

* Corresponding author. Tel.: +1 306 966 5537; fax: +1 306 966 5427.
E-mail address: david.sumner@usask.ca (D. Sumner).

0889-9746/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfluidstructs.2012.04.014

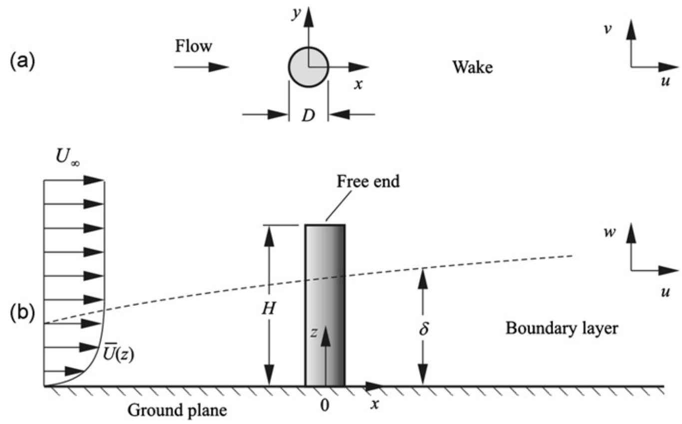

Fig. 1. A schematic representation of flow past a finite circular cylinder mounted normal to a ground plane and partially immersed in a flat-plate boundary layer: (a) top view and (b) side view.

A schematic of a the flow around a surface-mounted finite circular cylinder is shown in Fig. 1, for a cylinder of diameter, D, and height, H, where x is the streamwise coordinate, y is the cross-stream coordinate, z is the wall-normal coordinate, u is the streamwise velocity component, v is the cross-stream velocity component, and w is the wall-normal velocity component. Here, the cylinder is mounted normal to a ground plane and is partially immersed in a flat-plate boundary layer, where $\overline{U}(z)$ is the incoming mean flow velocity profile, U_∞ is the freestream velocity outside the boundary layer on the ground plane, and δ is the thickness of the boundary layer. Flow over the circular cylinder's free end and flow around the cylinder-wall junction cause the local flow field and the cylinder's wake to become strongly three dimensional. In addition to the familiar Kármán vortex shedding from the sides of the cylinder, the horseshoe vortex forming upstream at the cylinder-wall junction, and two sets of streamwise counter-rotating vortex pairs within the wake, one near the free end (the tip vortices) and the other near the ground plane (the base vortices), highlight the increased complexity of the fluid behavior in the wake.

Apart from the Reynolds number, $\mathrm{Re}_D = U_\infty D/\nu$ (whereν is the kinematic viscosity), the wake of the finite circular cylinder is strongly influenced by several other parameters, including the cylinder aspect ratio (or slenderness ratio) $\mathrm{AR} = H/D$, the approach velocity profile on the ground plane, $\overline{U}(z)/U_\infty$, and the relative thickness of the boundary layer on the ground plane, i.e., the ratios δ/D or δ/H. Many studies in the literature (e.g., Adaramola et al., 2006; Okamoto and Yagita, 1973; Sakamoto and Arie, 1983; Sumner et al., 2004) have shown the existence of a critical aspect ratio below which the cylinder has a distinct wake structure (variously referred to as symmetric "arch vortex shedding", depending on the study, which is distinct from the more familiar antisymmetric Kármán vortex shedding). The critical aspect ratio ranges from AR=1 to 7 depending on the study, and is sensitive to the thickness of the boundary layer on the ground plane.

Because of the complexity of the flow field around the finite circular cylinder, and the many influencing parameters, further study is needed to obtain a complete physical understanding of the wake behavior, especially very close to the cylinder (i.e., the local flow field or the near-wake region) where the flow is strongly three-dimensional and recirculating. In the present study, the time-averaged near-wake region and the local flow field in a vertical plane parallel to the mean flow direction on the flow centerline (i.e., in the symmetry plane) of a surface-mounted finite circular cylinder were investigated in a low-speed wind tunnel using particle image velocimetry (PIV). The aim of the study was to gain an improved physical description of the flow field close to the cylinder. As such, most of the measurements were made within five diameters (5D) upstream and downstream of the cylinder, with a special focus in the flow around the free end and immediately behind the cylinder where the flow recirculates. Of particular interest was the effect of aspect ratio, and four cylinder aspect ratios were examined: AR=9, 7, 5, and 3. These aspect ratios, and the experimental approach followed in the present study, are similar to Sumner et al. (2004) and Adaramola et al. (2006), where the critical aspect ratio was between AR=5 and 3.

2. Literature review

The three-dimensional local flow field of a surface-mounted finite circular cylinder is much less well understood than the classical case of the infinite cylinder. This can in part be attributed to the challenges it poses for visualization, measurement, and modeling, owing to the complex fluid behavior immediately upstream and downstream of the cylinder, and around the free-end and cylinder-wall junction.

Upstream of the finite cylinder, an adverse pressure gradient is created which causes the approaching boundary layer on the ground plane to undergo three-dimensional separation, and the familiar horseshoe (or necklace) vortex is formed.