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Unsteady flow past a finite square cylinder mounted on a wall at low Reynolds number

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ABSTRACT

The flow past a finite length square cylinder resembles flow across a short protrusion or a pin fin in a flow device. Direct numerical simulation (DNS) past a finite length square cylinder has been performed at a Reynolds number of 250. The flow field has been explored by solving three-dimensional unsteady Navier–Stokes equations using second order spatial and temporal discretizations. Four different cylinder height-to-width or aspect ratios (2, 3, 4 and 5) have been used to quantify its effect on the flow field and integral parameters. The cylinder aspect ratio is found to have significant effect on the instantaneous as well as time-averaged flow characteristics. The evolution of various flow structures associated with finite length cylinder such as wakes, tip vortices, base vortices and horse-shoe vortices are discussed. The non-dimensional frequency or Strouhal number and drag coefficient is found to increase with increase in cylinder aspect ratio.

1. Introduction

Unsteady flow around the finite size bluff bodies is a topic of great practical importance. High-rise buildings, chimneys and tube banks in heat exchangers are some of the examples where such flow at high Reynolds number occurs. Recently, the dispersion of pollution has intensified the need to understand wake dynamics behind a stack. However, the low Reynolds number flow past a finite cylinder has its applications in electronic chip cooling and mini compact heat exchangers.

The conditions on either ends of the cylinder affect the vortex shedding pattern and consequently alter the integral parameters. A finite cylinder placed vertically on a plate leads to two different end effects namely, free-end and plate-body junction. Both of these end conditions result in additional flow complexity along with the regular vortex shedding past a bluff body as shown in Fig. 1 [1]. In addition to Reynolds number, the free-stream turbulence, the height-to-diameter ratio, h/d and the boundary layer thickness of the incoming flow are seen to influence the flow behind the cylinder as mentioned in Kawamura et al. [2].

A survey of literature indicates a substantial amount of data accumulated by past researchers on flow past infinite or two-dimensional cylinder while the number of research works on finite length cylinder is limited. The literature on this class of flow reveals studies both at low as well as high Reynolds numbers. A numerical study of internal flow past a finite circular cylinder having an aspect ratio (AR) of 10 has been carried out by Liu et al. [3]. They reported the formation of the tip vortex at the free-end and necklace or horse-shoe vortex at the plate-body junction for a range of Reynolds number (100–200). The dependency of flow structures on the various end conditions of finite circular cylinder has been reported experimentally at low Reynolds number by Slaouti and Gerrard [4]. The important finding of the study is the three-dimensional structures of the wake that depends strongly on the end constructions of the cylinder. In an another study by Gerich and Eckelmann [5], the effect of end conditions on the flow structures at low Reynolds number has also been demonstrated and it was observed that the frequency of vortex shedding near either ends of the cylinder is somewhat less than that at the center where regular vortex shedding persists. For the configuration under study, the critical Reynolds number range is seen to be extended from 150 to 250. Sau et al. [6] have carried out a three-dimensional numerical study in a channel with a built-in finite square cylinder for a series of Reynolds number (225, 300 and 500), which demonstrated the unsteady vortex–vortex and vortex–surface interaction using flow topology and critical point theory.

The turbulent flow past a finite circular cylinder has been studied experimentally using hot-film anemometer by Farivar [7]. The pressure and frequency measurements indicate a suppressed two-dimensional region on the lower part of the cylinder and the existence of three distinct vortex rows with different frequencies along the length of the cylinder. Another experimental study using a hot-wire anemometer has been demonstrated by Ayoub and Karamcheti [8] for the tip region of a circular cylinder. It has been observed that the wake has a cellular structure and the flow is unstable and

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Nomenclature

Ar	local face area of the cylinder
d	width of the square cylinder
C_D	local drag coefficient, $D/(1/2\rho u_\infty^2 \text{Ar})$
$\langle C_D \rangle$	over-all drag coefficient (both space and time-averaged)
D	local drag force on the cylinder, $\wp_1(dxdz) - \wp_2(dxdz)$
f	vortex shedding frequency
D	transverse dimension of the flow domain
H	longitudinal dimension of the flow domain
h	height of the cylinder
L	length in the axial direction, $L_u + L_d$
p	static pressure (non-dimensional)
$\wp$	combined pressure and frictional stress distribution on the surface of the cylinder
Re	Reynolds number, $u_\infty d/\nu$
S	Strouhal number, fd/u_∞
t	time (non-dimensional)
u, v, w	streamwise and transverse velocity components (non-dimensional)
x, y, z	streamwise and transverse coordinates (non-dimensional)

Greek symbols

ν	kinematic viscosity
ρ	density
ω_i	instantaneous vorticity vector, $\varepsilon_{ijk}\partial u_k/\partial x_j$

Subscripts

∞	uniform
1, 2	forward and rear faces of the cylinder

intermittent in the tip region. A wind tunnel experiment for flow past finite circular as well as rectangular cylinder placed in a turbulent boundary layer has been conducted by Sakamoto and Arie [9]. The aspect ratio of circular cylinders is varied between 0.5 and 8.0. Their results reveal that with the decrease in aspect ratio, the vortex shedding behind each of the cylinder is found to change from Kármán-type to arch-type vortex.

An experimental study has been considered by Sakamoto and Oiwake [10] to investigate the effect of aspect ratio and the boundary layer thickness on the fluctuating force. It has been observed that the fluctuating lift has stronger dependency on the aspect ratio while the fluctuating drag force shows a lower magnitude compared to lift force. The flow structures past a finite circular cylinder placed in a turbulent boundary layer has been investigated experimentally using both hot-wire anemometry and flow visualization technique by Park and Lee [11]. They observed that the flow in the tip region is dominated by complicated flow structure and the shedding frequency is lower compared to that in an infinite cylinder. Wang et al. [1] has demonstrated experimentally the effects of the boundary layer profile on the turbulent flow past a finite length cylinder. Their finding reveals that the initial boundary layer thickness has a significant effect on the near-wake of the cylinder. An experimental study of high Reynolds number turbulent flow past a finite circular cylinder placed on a ground plate has been carried out by Okamoto and Sunabashiri [12]. The flow pattern is found to

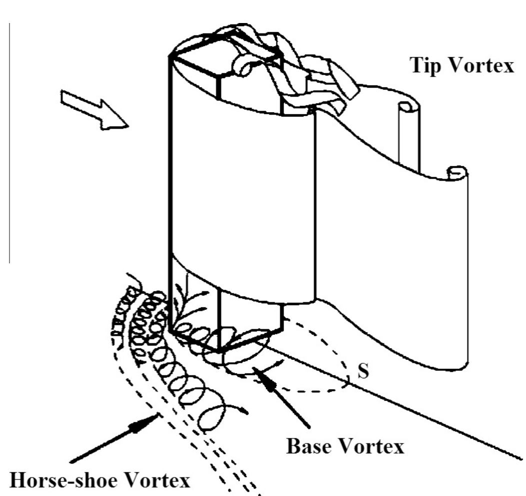

Fig. 1. Schematic of flow past a finite cylinder [1].

change from symmetric arch-type vortex shedding to anti-symmetric Kármán-type vortex shedding as the aspect ratio increases. Recently, Wang and Zhou [13] reported an experimental study of near-wake of a finite-length square cylinder, with one end mounted on a flat plate while the other end free for Reynolds number of 221 and 9300. It was observed that two types of primary vortex structures also called arch type vortices. One of the arch type vortices reveals anti-symmetric shedding pattern similar to the Kármán vortices while the other shows symmetric shedding. These two types of shedding appear intermittently depending on the aspect ratio of cylinder. Sin and So [14] carried out measurements of the unsteady forces on the finite cylinder placed in turbulent crossflow. Their results reveal strong effect of separation on the flow structures as well as steady and unsteady forces at a location very close to the tip.

A large eddy simulation (LES) technique has been used to simulate the turbulent flow past a finite circular cylinder having an aspect ratio of 2.5 by Fröhlich and Rodi [15]. Their calculations show that the short height cylinder does not produce any Kármán type vortices as the shear layers from side edges and the top edge of the cylinder interact closely. Their average results exhibit an arch-type vortex behind the cylinder as observed in the flow around a wall-mounted cube. A three-dimensional numerical study of laminar flow past a truncated square cylinder placed inside a rectangular duct for Reynolds range of 10–400 are carried out by Dousset and Pothérat [16]. This study is in contrast to others where the external flow of finite cylinder is considered. The formation mechanism of hairpin vortices generated in the wake of the cylinder has been discussed. They also summarized the various flow structures developed at different Reynolds numbers for a fixed aspect ratio of 4.0. The turbulent flow past a finite circular cylinder having an aspect ratio of 6 mounted on thin boundary layer has been numerically simulated using LES by Krajnović [17]. The details of flow structures near the tip region and near-wake have been discussed elaborately and confirmed many previous findings. Bourgeois et al. [18] studied experimentally the turbulent phase-averaged flow structures past a finite square cylinder (AR = 4) placed on a thin boundary layer. Coherent and incoherent flow fields and effect of incoherent turbulence on the characteristics of turbulent wake were both documented in that study. In a recent study by the same authors [19], the topological model of the vortex structures and its effect on fluctuating energy in the wake has been discussed.

The above discussion shows that the flow structures are quite complex for a finite cylinder compared to that of a two-dimensional cylinder. Both tip vortex and horse-shoe vortex systems