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Flow around circular cylinders with very low aspect ratio

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ABSTARCT

Experiments on the flow around stationary circular cylinders with very low aspect ratio piercing the water free surface were carried out in a recirculating water channel. Eight different aspect ratios were tested, namely $L/D=$ 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, 1.5 and 2.0; no end-plates were employed. Forces were measured using a six degree-of-freedom load cell and the Strouhal number was inferred through the transverse force fluctuation frequency. The range of Reynolds number covered $10\,000<\mathrm{Re}<50\,000$. PIV measurements were performed in some aspect ratio cases, namely $L/D=$ 0.3, 0.5, 1.0 and 2.0 for Reynolds number equal to 43 000. The results showed a decrease in drag force coefficients with decreasing aspect ratio, as well as a decrease in Strouhal number with decreasing aspect ratio. The PIV measurements and the PSD of forces showed different behavior for cylinders with $L/D\leq0.5$, in which cases the free-end effects were predominant. Even without von Kármán street main characteristics around the majority length of the cylinder, in the range of $0.2<L/D\leq0.5$, the vortex shedding around it is capable of producing alternating forces in the transverse direction. Therefore, alternating forces were not observed in the transverse direction for cylinders with $L/D\leq0.2$.

1. Introduction

The flow field around stationary low aspect ratio cylinders, $L/D<6$, where L is the immersed length of the cylinder and D is the diameter, is much less understood than the classical case of infinite length cylinder, in which the flow can be assumed as two-dimensional in most cases. Most publications on this subject refer to flow around surface-mounted low aspect ratio cylinders, in that the three-dimensional structures formed behind the cylinder significantly change the wake downstream and consequently modify the forces and pressure field on the cylinder. The paper by Sumner (2013) is a comprehensive review of the theme.

Downstream of the low aspect ratio cylinder, the wake is characterized by a pair of counter-rotating streamwise vortices originating from the free end and denominated tip-vortices, as first seen in Okamoto and Yagita (1973) and Kawamura et al. (1984). Additionally, Roh and Park (2003) showed that the tip vortices originate in the upstream region of the free end. On the other hand, the model presented by Lee (1997) for a very low aspect ratio cylinder showed “arch-type vortex” formation in the near-wake region. In this model, flow separating from the circumferential leading edge of the free-end surface does not reattach but becomes contiguous with the arch-type vortex forming behind the cylinder.

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Nomenclature

ρ	water density
ω_y	mean transversal vorticity
ω_z	mean vertical vorticity
D	cylinder diameter
$C_x\,(t)$	non-dimensional streamwise force
$\overline{C_x}$	averaged mean non-dimensional streamwise force
$C_{x\ rms}$	non-dimensional streamwise force fluctuation
$C_y(t)$	non-dimensional transverse force
$C_{y\ rms}$	non-dimensional transverse force fluctuation
D	cylinder diameter
Fr_D	Froude number based on cylinder diameter
Fr_L	Froude number based on submersed cylinder length
f_s	vortex shedding frequency
$F_x(t)$	streamwise force
$F_y(t)$	transverse force
g	gravity acceleration
H	water level of the water channel
L	submersed cylinder length
L/D	aspect ratio
Re	Reynolds number
St	Strouhal number
U	incident flow velocity
U_x	mean streamwise velocity
U'_x	streamwise velocity fluctuation
U'_y	transverse velocity fluctuation
U'_z	vertical velocity fluctuation
W	water channel width
x	streamwise direction
y	transverse direction
z	vertical direction

Actually, another couple of counter-rotating streamwise vortices generated over the free end of a cylinder with $L/D=5$ were visualized by Park and Lee (2000) through a particle tracer technique and light sheet; these structures are detached from the separation region at the circumferential leading edge of the free end, one for each side of the wake, and they are counter-rotating with respect to the tip-vortices. These two couples of vortexes were visualized using the PIV – particle image velocimetry technique and can be found in Sumner et al. (2004), Adaramola et al. (2006) and Rostamy et al. (2012), for cylinders ranging from $3<L/D<9$; and Pattenden et al. (2005), for cylinder with $L/D=1$. More recently, Palau-Salvador et al. (2010) presented a comparison between experimental and numerical results (LES – large eddy simulations) for cylinders with $L/D=2.5$ and 5.

Some recent papers on the subject of the free-end flow by Roh and Park (2003), Pattenden et al. (2005) and Hain et al. (2008) showed a flow topology consisting of two pairs of counter-rotating streamwise vortices for cylinder with $1\le L/D\le 4.25$. The streamwise vorticity is thus important to low aspect ratio cylinders, and may be the source of the alternating forces since the low aspect ratio cylinders do not present von Kárman street, i.e., alternating vortex shedding. The numerical results by Rosetti et al. (2013), for a cylinder with $L/D=2$, showed the presence of two pair of vortices formed at the free end that fold around the trailing edge of the cylinder and are up-washed by the flow meeting the arch-type vortices. Those works emphasize the increasing importance of the free-end flow with reducing aspect ratio.

An interesting way to look at the flow around very low aspect ratio cylinders is looking at the flow around a hemispherical mounted-surface, e.g. in Taniguchi et al. (1982), Savory (1986) and Tamai et al. (1987). In this way, the recirculation region, or separation bubbles, behind the very low aspect ratio cylinder acts to alter the shape around it to become similar to a hemispheric. This favors the formation of the arch-type vortex (see Lee, 1997). In the hemispheric case, arched tubes formed behind the hemisphere, several of the tubes coalesced and shedding; this behavior is responsible for an alternating force in the transverse direction. Analogous behavior can be attributed to very low aspect ratio cylinders if the same model proposed by Lee (1997) is used. The works on VIV of spheres can also help to understand the VIV of low aspect ratio cylinders (see Govardhan and Williamson, 1997, 2005; Jauvtis et al., 2001; Schouveiler and Provansal, 2002), since the main source of the forces in the transverse direction is due to the interaction of the trailing vortices with streamwise vorticity.

In the offshore scenario, the low aspect ratio cylinders have attracted attention due to the increasing size of the circular platforms, such as spar and monocolumn. The current incidence around these types of platforms promotes the phenomenon of VIM – vortex-induced motion. VIM causes vortex-shedding around the platforms and, consequently, motion amplitudes of the order of the characteristic length of the body subject to VIM in the horizontal plane. Another important VIM characteristic is the low aspect ratio of these systems, i.e. $L/D<6$. Spar platforms ranging from $1.5<L/D<6$ (see examples in van Dijk et al., 2003; Roddier et al., 2009); monocolumn platforms ranging from $0.2<L/D<0.5$ (see examples in Cueva et al., 2006; Gonçalves et al., 2010); and aspect ratio of semi-submersible columns ranging from $0.4<L/D<3$ (see examples in Waals et al., 2007; Gonçalves et al., 2012a). The aspect ratio of these systems confirms the importance of better understanding the flow around finite height cylinders. More details about the VIM in offshore platforms can be found in detail in Fujarra et al. (2012). On the other hand, fundamental works about VIV of low aspect ratio cylinders are few in the literature, among which Someya et al. (2010), Gonçalves et al. (2012b, 2013), Rahman and Thiagarajan (2013) and Zhao and Cheng (2014) can be highlighted.

In the offshore scenario described previously, the cylindrical structures pierce the free surface. The flow around surface-mounted cylinders and cylinders piercing free surface are different due to the boundary conditions. In the first one, the cylinder can be immersed in the boundary layer formed at the surface bottom, and also the bottom can be considered a

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