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Hydrodynamic loads on a circular cylinder surrounded by two, four and eight wake-control cylinders

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ABSTRACT

The hydrodynamic loads of mean drag and fluctuating lift are presented for a circular cylinder fitted with 2, 4 and 8 wake-control cylinders positioned around its circumference. The device is fitted around the body to interact with the flow in the near wake and control vortex shedding. The efficiency regarding lift suppression and drag reduction has been investigated for nine different cases varying the diameter of the control cylinders and their relative gap from the wall. All cases have been compared with the hydrodynamic forces of a plain cylinder. The configuration with 4 control cylinders, gap ratio of $G/D = 0.05$ (G is the gap between the control cylinders and the main cylinder of diameter D) and diameter ratio of $d/D = 0.06$ (d is the diameter of the control cylinders) produced the lowest drag when compared to all other configurations: mean drag coefficient was 0.75, approximately 50% lower than that of a bare cylinder. Experiments have been conducted in a free-surface water channel at moderated Reynolds numbers between 5000 and 50,000.

1. Introduction

The periodic shedding of vortices downstream of a bluff body generates cyclic hydrodynamic loads that feed back on the body. Fluctuating lift will be at the frequency (f_s) in which vortices are shed in the wake, while drag will be at double that frequency ($2f_s$). With time, the cyclic loads may cause structural problems to the body, such as fatigue damage, a special concern for slender structures as riser pipes and submarine cables. Flexible structures with a bluff shape may be excited by this periodic load and respond with considerable oscillations. The motion of the structure interacts with the flow and develop into what is called vortex-induced vibrations (VIV).

Mitigating vortex shedding and VIV are important issues for many engineering applications, ranging from aeroacoustic problems in aviation to the vibration of a drilling riser in offshore exploration. Hence, the scientific community and the industry are constantly pursuing the development of new methods to control the wake and design novel VIV suppressors (devices attached to the body to mitigate the damaging effects of the vibration).

Wake-control mechanisms can be classified as passive or active systems (Choi et al., 2008), with the latter considering both open-loop and closed-loop control systems. Zdravkovich (1981) presents several passive-control devices, classifying them into three categories according to the way they affect the vortex-shedding mechanism: (i) Surface protrusions, which affect separation lines and/or separated shear layers: they involve helical strakes, wires, fins, studs, or spheres, among others. (ii) Shrouds, that affect the entrainment layers around the body. The perforated shroud and the axial rods are two examples. (iii) Near-wake stabilizers, that affect the switch of the confluence point. Fairings and splitter plates, which prevents communication between the opposing shear layers of the wake, are common examples. These passive methods require no external energy supply and they act primarily disrupting the formation and development of an organized wake of vortices.

Among the various solutions for passive vortex-shedding and VIV suppression, the helical strakes are one of the most commonly used in air and water flows (Bearman and Brankovic, 2004; Korkischko and Meneghini, 2010). But despite the proven efficiency of the strakes in reducing fluctuating lift, they increase the mean drag (Korkischko and Meneghini, 2011; Zdravkovich, 1981), which is undesirable in a great number of applications.

Placing a smaller control rod upstream of the main cylinder is a well-established strategy for drag reduction (Lee et al., 2004). Strykowski and Sreenivasan (1990) proved that if the small control cylinder is otherwise placed within a defined region in the near-wake (downstream) of the main cylinder, the wake could be effectively suppressed at a Reynolds number of $Re = 80$. Suppression of the vortex street is associated with

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damping the instability in the near-wake region. In their investigation, the ratio between the diameter of the control cylinder to the diameter of the main cylinder varied between $d/D = 1/3$ to $1/20$. They also showed that wake suppression is the most efficient when the small control cylinder is placed roughly around $1D$ downstream of the cylinder center and $1D$ to the side of the centerline of the wake for $d/D = 0.05$ to 0.07. Their experimental and numerical results also indicate that this region of effectiveness strongly depends on Re and d/D. For $Re = 80$ to 300, Kuo et al. (2007) showed detailed flow structures revealing the primary mechanism that led to significant lift and drag reduction without completely suppressing the shedding of a vortex street.

Zdravkovich (1981) presented results of an axial-rod shroud, following the concept that the shroud should break-up the flow into a large number of small vortices. Axial rods were fitted about the circular cylinder and several parameters were varied in order to find an optimum configuration for VIV suppression: the number of rods (varied between 4 and 218, defining the shroud porosity), the distance of the rods to the wall of the cylinder (gap) and their circumferential distribution. Tests were performed in a water channel and in a wind tunnel for $Re \approx 10^3$–10^5. The most interesting result, as far as suppression was concerned, was obtained for a porosity of 63% (39 rods) when the rods were positioned with a gap of $G/D \approx 0.25$ from the cylinder wall. But most surprisingly was the fact that the best suppression was achieve when the rods were not evenly distributed around the cylinder, but grouped close to the near wake, leaving an unshrouded portion (of about 90 degrees of the circumference) facing the free stream.

More recently, control of the wake of a cylinder with rotating control cylinders has been investigated experimentally (Korkischko and Meneghini, 2012) and numerically (Mittal, 2001; Silva-Ortega et al., 2014b). In a recent study, Silva-Ortega and Assi (2017) reported on VIV experiments performed with the same control cylinder discussed in the present work acting as VIV suppressors. They found that the best VIV suppressor was "composed of 8 control cylinders and mitigated 99% of the peak amplitude of vibration when compared to that of a plain cylinder; mean drag was increased by 12%". They also concluded that "a polar array of 4 control cylinders was the most efficient configuration to minimize the mean drag, but the system developed severe vibrations combining VIV and a galloping-like response".

The objective of the present work is to investigate a method of suppressing the vortex wake of a circular cylinder employing a passive control strategy. A rigid section of a circular cylinder of diameter D is surrounded by a polar array of $N = 2$, 4 and 8 smaller control cylinders of diameter d, equally spaced about the circumference and separated by a gap G from the wall of the main cylinder. The ratios d/D and G/D are the control parameters of the experimental investigation. As seen above, previous results found in the literature indicate that there are many other significant parameters apart from the number and size of the control cylinders. Therefore, we have conducted an experimental investigation trying to probe the domain of only a few of those governing parameters.

The diameter of the control cylinders (d) was varied in three steps around the size of the smaller cylinders reported by Strykowski and Sreenivasan (1990). Since the vortex-formation length tends to be reduced by an increase in Re, the region of effective wake control presented by Strykowski and Sreenivasan (1990) for $Re = 80$ should be brought much closer to the base of the cylinder for our Re range. Inspired by the work of Zdravkovich (1981), the gap between the control cylinders and the wall of the main cylinder (G) was also varied in three steps. In the present parametric study neither the main cylinder nor the control cylinders were allowed to move or respond to the flow, so the efficiency of the wake-control method was evaluated by measuring the hydrodynamic loads acting on the body.

2. Experimental method

Experiments have been carried out in the recirculating water channel of NDF (Fluids and Dynamics Research Group) at the University of São Paulo, Brazil. The water channel has a free-surface test section which is 0.7 m wide, 0.9 m deep and 7.5 m long. Good quality flow can be achieved up to 1.0 m/s with turbulence intensity less than 3%. This laboratory has been especially designed for experiments with flow-induced vibrations. For further details the apparatus, validation and information on the facilities please refer to Assi et al. (2013, 2010a, 2010b).

A rigid section of a circular cylinder was made of a perspex tube of external diameter $D = 100$mm with a smooth surface. Two, four or eight identical control cylinders were made of perspex rods and supported by rings attached to the ends of the main cylinder. The distribution of the control cylinders about the main cylinder is presented in Fig. 1, in which the arrow indicates the direction of the incoming flow. The position of the N control cylinders was chosen so that they were equally spaced around the main cylinder, but keeping a symmetric distribution in relation to the streamwise axis, with no cylinder at the frontal stagnation point.

The axes of the control cylinders were parallel to the axis of the main cylinder, spanning the whole length of the model (immersed length of $L = 700$mm). Two extra supporting rings were installed at $L/3$ and $L2/3$ positions to hold the control cylinders in place and prevent them from vibrating by reducing their free span. The control cylinders did not present significant deflections nor vibrations due to their own VIV in the course of the experiments. The diameter of the control cylinders was varied in three steps of $d/D = 0.04$, 0.06 and 0.08. The gap measured between the wall of the control cylinders and the wall of the main cylinder could be set to $G/D = 0.05$, 0.10 and 0.15. The angular distribution of the control cylinders was kept constant for all cases while varying d/D and G/D. The models were the same employed by Silva-Ortega and Assi (2017).

Models were mounted on a especially built load cell (developed by Assi, 2009), rigidly attached to the frame of the test section to deduce the instantaneous and time-averaged hydrodynamic forces on the cylinder model. An illustration of the experimental setup is presented in Fig. 2. A summary of all the parameters investigated in the experiment is presented in Table 1, adding up to 27 different experimental configurations. In addition, preliminary tests have been performed with a bare cylinder (without control cylinders) to serve as a reference for comparison. The only flow variable changed during the course of the experiments was the flow velocity U, which alters the Reynolds number ($Re = UD/\nu$, based on the diameter D of the bare cylinder and the viscosity of water ν) between 5000 and 50,000.

3. Results

Measurements of lift and drag were made for each of the 27 configurations presented above. Results for a bare cylinder in the range $Re = 5,000$ to 50,000 are presented as a reference and for validation. This Re range falls in the subcritical regime in which transition to turbulence occurs in the separated shear layers and a considerable scatter of lift and drag is found in the literature (Zdravkovich, 1997). The mean drag coefficient ($\overline{C}_D$) and the RMS of the lift coefficient ($\widehat{C}_L$) are presented for a bare (or plain) cylinder in Fig. 3. In Fig. 3a, mean drag for the plain cylinder remains roughly around $\overline{C}_D \approx 1.4$, not too far but higher than the curve presented by Zdravkovich (1997), who summarized results from various sources.

It is worth highlighting that, in the present experiments, the top end of the cylinder pierced the free surface of the water, hence a small fraction of the drag is due to the generation of waves. The Froude number ($Fr = U/\sqrt{gD}$, where g is the acceleration of gravity) was rather small, varying between $Fr = 0.05$ and 0.5 for a constant ratio of Reynolds number to Froude number of $Re/Fr \approx 10^5$. Chaplin and Teigen (2003), who measured the wave-resistance drag on a bare cylinder piercing a free surface at $Re/Fr = 2.79 \times 10^5$, concluded that an increase in drag due to the formation of waves is only significant for Fr around 1 and should not

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