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Flow-induced vibration of a circular cylinder surrounded by two, four and eight wake-control cylinders

M. Silva-Ortega [1], G.R.S. Assi *,[2]

Department of Naval Architecture & Ocean Engineering, EPUSP University of São Paulo, São Paulo, SP, Brazil

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ABSTRACT

The present work investigates the use of a polar array of 2, 4 and 8 wake-control cylinders as a means to suppress the vortex-induced vibration (VIV) of a larger circular cylinder. The diameter of the control cylinders and the gap between their walls have been varied in 27 different configurations. Experiments have been performed in water at Reynolds numbers between 5000 and 50,000. Cross-flow amplitude of displacement, frequency of vibration, mean drag and fluctuating lift coefficients are presented. While some configurations of control cylinders suppressed VIV, others produced a galloping-like response. 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%. 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 system appeared to be very sensitive to the parameters investigated; small variations in the size and position of the control cylinders produced unexpected responses.

1. Introduction

The vortex-shedding mechanism of a circular cylinder can be controlled, at least in theory, by the interference of small wake-control cylinders positioned around the circumference of the main body. Strykowski and Sreenivasan [18] and others have showed that this strategy is possible for low Reynolds numbers. Such control cylinders interact with the boundary layer and/or the separated shear layers, disrupting the formation of vortices that are convected downstream to form a vortex wake. As a consequence, the periodic hydrodynamic forces feeding back from the vortex-shedding mechanism are considerably reduced, if not completely suppressed. In theory, the mean drag acting on the body is also reduced if suppression of the vortex wake is achieved [3,1]. Therefore, the development of passive devices to control the wake of a bluff body has called the attention of not only the scientific community, but also of the industry. Applications may vary from reduction of vortex-generated noise in the field of aeroacoustics to the mitigation of hydrodynamic loads on floating platforms in the field of offshore engineering. The suppression of the flow-induced motion of offshore risers or of a monocolumn platform are good examples [15].

Placing a smaller control rod upstream of the main cylinder is also a well-established strategy for drag reduction [10]. But Strykowski and Sreenivasan [18] have proved that if the small control cylinder is placed within a defined region in the near-wake (downstream) of the main cylinder, coherent vortices could be effectively suppressed at a Reynolds number of $Re = 80$. Hwang and Choi [4] showed that the flow instability leading to the formation of a vortex street could be delayed by employing even smaller control cylinders at specific locations in the wake. Later, Kuo et al. [9] and Kuo and Chen [8] proved that, even if a vortex-wake is formed, the wake pattern could be altered by the presence of two control cylinders positioned in the near wake region.

Previous investigations positioning control cylinders in various arrangements around a bluff body have been performed through experiments and numerical simulations. Mittal [11] investigated the flow around a static cylinder with two wake-control cylinders positioned at $\pm 90^\circ$ in relation to the incoming flow at $Re = 10^2$ to 10^4. He found that vortex shedding could be suppressed only if the control cylinders (at that specific $\pm 90^\circ$ location) were rotating above a critical spinning ratio. Sakamoto and Haniu [16] also investigated the control of a vortex-wake by varying the position of a smaller cylinder around the main body. They observed that, for certain positions, the control cylinder could produce the useful

* Corresponding author.
E-mail address: g.assi@usp.br (G.R.S. Assi).
[1] Now at the Dept. Naval Architecture, Universidad Veracruzana, Mexico.
[2] Currently a Visiting Associate in Aerospace at GALCIT, California Institute of Technology, USA.

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effect of reducing the hydrodynamic forces experienced by the main body at $Re = 6.5 \times 10^4$.

Recently, Silva-Ortega [17] has shown that a polar array of 2, 4 and 8 control cylinders equally spaced around a static body could be developed into an effective device to suppress vortex shedding from a larger circular cylinder at $Re = 5000$ to $50,000$. Fundamental parameters (such as the number of control cylinders, their diameter and their distance from the main body) have been shown to play a significant role in the wake-control mechanism. As consequence, a reduction of hydrodynamic forces has been achieved.

1.1. Suppression of flow-induced vibration

In the present work, we move from controlling the wake of static bluff bodies to the field of hydroelasticity. This time we investigate the effectiveness of a polar array of control cylinders in suppressing the vortex-induced vibrations (VIV) of a circular cylinder that is free to respond to the excitation of the incoming flow. Our investigation is limited to vibrations in one degree of freedom in the cross-flow direction.

VIV is a fluid-structure interaction phenomenon that occurs when the frequency of vortex shedding resonates with one of the natural frequencies of an elastic bluff body. Please refer to Williamson and Govardhan [19] for a comprehensive review of the phenomenon. In principle, if a device is able to suppress the formation of coherent vortices, VIV is eliminated at its root and vibrations do not develop. Now, it is one thing to disrupt or control the wake of a bluff body when the body is static, but it is another to control the wake of a body that is free to respond to the flow. Sometimes an efficient device for the control of vortex-shedding is not as efficient in suppressing VIV. Various examples of VIV suppressors are found in the literature, for example, in the review by Zdravkovich [22].

Korkischko and Meneghini [7] have performed VIV experiments with a circular cylinder free to oscillate in the cross-flow direction and fitted with two wake-control cylinders in the range of $Re = 7500$. They found that the two non-rotating control cylinders positioned at $\pm 90^\circ$ were not effective in suppressing VIV of the main body. In fact, they only reduced the peak amplitude of response by 17%, when compared to that of a plain cylinder. However, when they applied enough rotation to the small cylinders, the vortex wake was stabilized and VIV was suppressed.

Zhu et al. [23] performed numerical simulations of the flow at $Re = 2000$ and showed that the two-degree-of-freedom vibration of an elastic cylinder could be reduced by 89% when two control cylinders were positioned at $\pm 135^\circ$ from the frontal stagnation point of the cylinder. Again, when the two control cylinders were forced to rotate, an ever better suppression was obtained. Similar results were obtained by Muddada and Patnaik [13], who performed two-dimensional numerical simulations of the flow around a cylinder fitted with two control cylinders located at $\pm 120^\circ$ in the range of $Re = 100$–300.

Wu et al. [21] tested the VIV suppression of a long flexible cable with a circular cross section fitted with four flexible control rods positioned parallel to the axis of the cylinder. At $Re \approx 10^3$, they observed that the dynamic response of the cable was substantially altered by the hydrodynamic interaction of the flow-control rods. In their experimental arrangement, the distribution of the control rods was such that there was always one rod aligned with the incoming flow. In another study, Wu et al. [20] investigated the effect of rotating the array of control rods around the main cylinder.

1.2. Objective

In the present study, we start with the polar arrays of 2, 4 and 8 control cylinders proposed by Silva-Ortega [17] to reduce the hydrodynamic loads on a static cylinder and employ them as a means to suppress the cross-flow VIV of a larger elastic circular cylinder. The dynamic response due to VIV, as well has the hydrodynamic loads acting on the cylinder, are presented for a wide range of flow speeds.

We will conclude that the VIV of a circular cylinder can be mitigated by specific arrangements of wake-control cylinders in the range of Reynolds number between 5000 and 50,000. On the other hand, a few arrangements may cause the system to develop severe vibrations associated with a galloping-like excitation, showing that the dynamic response of the system is very sensitive to small variations in the geometrical parameters.

2. Experimental setup

Experiments have been carried out in the Circulating Water Channel of NDF (Fluids and Dynamics Research Group) at the University of São Paulo, Brazil. The water channel has an open 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%. For further details on the apparatus, other VIV experiments employing the elastic rig and information on the facilities please refer to Silva-Ortega [17] or Assi et al. [2].

A rigid section of a smooth circular cylinder was made of a perspex tube of external diameter $D = 100$ mm. Two, four or eight identical wake-control cylinders of diameter d_c 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 are 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.

It is worth noting that our cylinder fitted with 2 control cylinder is similar to other arrangements found in the literature ([7,11] for example). Our arrangement with 4 control cylinder is not similar to that of Wu et al. [21], since they always kept one control cylinder facing the incoming flow. We are not aware of other works that have employed an array of $N = 8$ wake-control cylinders.

The axes of the control cylinders were parallel to the axis of the main cylinder, spanning the whole immersed length of the model ($L = 700$ 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.

Inspired by the experimental results of Korkischko and Meneghini [7] and based on the parametric variation of Silva-Ortega [17], the diameter of the control cylinders was varied in three steps of $d_c/D = 0.04$, 0.06 and 0.08. The gap measured between the wall of the control cylinders and the wall of the main cylinder was set to $G/D = 0.05$, 0.10 and 0.15. A total of 27 geometric variations employing the wake-control cylinder have been tested, in addition to the case of a plain cylinder (without control cylinders) that served a reference.

Models were mounted on a especially built load cell attached to a sliding frame and supported by air bearings. A pair of coil springs provided the restoration force to the system, which was free to oscillate only in the cross-flow direction, as shown in Fig. 2. An optical sensor measured the displacement (y) of the cylinder, keeping structural mass and damping to a minimum. The product between the mass ratio (m^*, calculated as the ratio between the total oscillating mass and the mass of displaced water) and the damping ratio (ζ, measured as a percentage of the critical damping) was $m^*\zeta = 0.066$. The natural frequency of the system (f_0) as well