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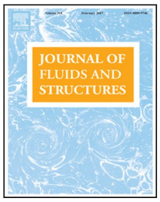

Flow-induced vibrations of two mechanically coupled pivoted circular cylinders: Characteristics of vibration

Hamid Arionfard, Yoshiki Nishi *

Department of Systems Design for Ocean-Space, Faculty of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya, Yokohama, Japan

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ABSTRACT

This paper presents the results of an experimental investigation on the vibration mechanisms of two connected circular cylinders that are free to rotate around a pivot in different arrangements including both cylinders on the downstream, both on the upstream and a cylinder on each side of the pivot point. The Reynolds number is varied during the test to find the maximum possible displacement amplitude for each configuration. Four main mechanisms of vibration are identified. The cylinders experience galloping if both located on the upstream of the pivot and the gap between them is zero. Vortex excitation (VE) is observed in two configurations and referred to as VE_{fSt} and VE_{fN}. VE_{fSt} occurs when both cylinders are located on the downstream of the pivot while the gap is zero. The frequency responses lock into the Strouhal frequency in this case. VE_{fN} occurs when the center of gravity (cg) is on the pivot and the gap ratio ($G = gap/cylinder\ diameter$) between the cylinders is $G > 3.9$. In this case, the frequency response locks into the natural frequency of the system. If one cylinder is located on the center of the rotation and the other cylinder is on the downstream, wake-induced vibration (WIV) takes place. While for $G < 1.4$ the response is a typical wake galloping, for $G > 1.4$ two vibration modes are recognizable as 'combined vortex resonance and galloping'. For all configurations with $G > 0$, gap-switching-induced vibration (GSIV) is observed especially for $1.9 < G < 2.4$. However, GSIV is the dominant mechanism of vibration if cg is on the pivot point. In cases where cg is not close to the pivot, the drag force may enhance the vibration if the Reynolds number is not large enough to suppress the motion.

1. Introduction

Arrays of cylinders are frequently seen in engineering structures, in different configurations and different Reynolds numbers. Typical examples include marine risers, offshore structures, a group of chimney stacks, heat exchanger tubes, bridge piers and cables, etc. While the simplest case of flow-induced vibration (FIV) is a single circular cylinder oscillating in cross-flow, flow structure around a cylinder undergoes substantial change when it is a member of a group of cylinders in close proximity.

Zdravkovich (1988) provided an extensive study on interference-induced oscillations in flow past two circular cylinders in various configurations and classified the flow regime to three categories of flow interference; If the cylinders are far apart, the flow around either of them is similar to that of an isolated cylinder. If the cylinders are close or the second cylinder is adjacent to or within the wake of the first cylinder, the interference between the two can be one of the three types: proximity

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* Corresponding author.
E-mail address: nishi-yoshiki-rg@ynu.ac.jp (Y. Nishi).

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interference, wake interference, and proximity and wake interference. The origin of oscillations are also classified as jet-switch, gap-flow-switch, wake-displacement and wake-galloping. The jet-switch mechanism happens when the fluid flow passes through two bluff bodies located side-by-side. Gap-flow-switch is observed in tandem and staggered configurations where the fluid flow passes through the gap between two bluff bodies in close proximity and generates an alternating pressure that tends to close the gap and keep the bluff bodies on the center line. The wake-displacement mechanism is similar to gap-flow-switch. However, the gap-flow-switch entirely disrupts the vortex shedding and distorts the near-wake of the upstream cylinder while wake-displacement only displaces the upstream wake. The wake-displacement mechanism is usually triggered by the vortex shedding excitation while the wake-galloping mechanism characterized by extremely large amplitudes, maintained by the variation of forces exerted on the cylinder by its displacement. It was also reported that the hysteretic effect of the gap-flow-switch maintained a large amplitude oscillation when the downstream cylinder was elastically mounted with only a transverse degree of freedom.

Bokaian and Geoola (1984) also studied a case where the upstream cylinder is fixed and the downstream one is free to vibrate in the cross-flow direction for different spacing ratios and Reynolds numbers. It was found that depending on the spacing ratio, the downstream cylinder exhibited vortex excitation, galloping, or a combined VE and galloping, or separated VE and galloping. They also reported that there is a hydrodynamic restoring force in the gap between the cylinders that is acting to return the cylinder to the original position.

Although excitation mechanisms are addressed in many studies, little is known about restoring mechanism of the gap-flow-switching vibration (GSIV). Borazjani and Sotiropoulos (2009) reported that a significant portion of the incoming flow is able to pass through the gap between the two cylinders and the gap-flow mechanism starts to dominate the vortex excitation dynamics. The gap flow switching induces pressure gradients between the cylinders that results in a large oscillatory force in phase with the vortex shedding and lead to the experimentally observed larger vibration amplitudes.

Recently, to improve the energy conversion efficiency of FIV of a single circular cylinder in cross flow, a "drag assisted converter" is studied numerically by Sung et al. (2015) and tested experimentally by Arionfard and Nishi (2017). The main idea is to take advantage of the drag force by pivoting the cylinder eccentrically. While the lift force induced by vortexes starts the vibration, the drag force assists the motion depending on the pivot location and the Reynolds number.

In contrast to gap flow force, the drag force resists the restoring force in a single rotationally vibrating cylinder. Our interest is to investigate the interaction of both GSIV and drag-assist force in one system. In order to have a drag-assisted vibration, it is necessary to have a rotationally oscillating cylinder. On the other hand, the most basic method of generating a GSIV is by having two circular cylinders in proximity range. Therefore, by combining these two configurations we proposed two mechanically coupled cylinders that are free to vibrate rotationally around a pivot point.

Needless to say, it is necessary to understand the vibration mechanism and vorticity dynamics in such a system, especially from the point of view of energy generation, where enhancement is the key to improve the energy conversion efficiency. Moreover, based on the idea of harnessing the energy of FIV, coupling group of energy converters as an energy farm is inevitable. Due to the physical connection between the cylinders in such a system, the vibration mechanism may be galloping, vortex excitation (VE), WIV, GSIV or a combination of them.

To the author's best knowledge, very few publications can be found on flow around mechanically coupled cylinders. Brika and Laneville (1997) for example, reported a substantial change of the flow around the cylinder when it is mechanically coupled to a cylinder in close proximity. Even in its practical use in suspension bridges and transmission line bundles, the mechanical coupling between the cylinders is rarely considered in laboratory tests. King and Johns (1976), Maeda et al. (1997) and Cui et al. (2014) are among those few who have examined this effect. While the first two researches investigate two elastic cylinders and side by side configuration, Maeda et al. (1997) research is probably closest research to our proposed configuration. However, the drag force has no effect on the transitional vibration mechanism in their study since there is no rotation in the system.

Although the resultant forces, power and efficiency of a single pivoted cylinder is investigated in our previous study (Arionfard and Nishi, 2017), extensive research on the vibration mechanism and vorticity dynamics is necessary to understand the interaction of the flow with a group of rotationally moving cylinders. Given two mechanically coupled cylinders, it is of fundamental interest to understand: (i) how the flow-induced vibration varies with the gap between the two cylinders and the center of gravity location (ii) the resultant forces on the cylinders in different configurations and (iii) The vortex pattern characteristics in different configurations.

The present paper is focused on the first two questions while the last question is covered in a separate study. The outline of this paper is organized as follows. The experimental setup and measurement methods used in this study are explained in Section 2. The results are presented in Section 3 including a discussion about the vibration mechanisms associated to each configuration separately, followed by an overall view of all studied cases. Finally, we make conclusive remarks in Section 4.

2. Experimental setup and measurement methods

2.1. Water channel and test model

Model tests were conducted in a recirculating free surface water channel. The channel length is 1 meter with a test section dimensions of 0.3 m wide by 0.3 m deep. The channel floor and the two side walls of the test section were made of transparent acrylic to allow visual observations and particle image velocimetry (PIV) measurements. The flow rate was