Journal of Fluids and Structures 82 (2018) 505–519

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Flow-induced vibration of two mechanically coupled pivoted circular cylinders: Vorticity dynamics

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ARTICLE INFO

Article history:
Received 4 December 2017
Received in revised form 14 June 2018
Accepted 31 July 2018

Keywords:
FIV
PIV
Gap flow
Pivoted cylinders
Mechanically coupled
Wake patterns

ABSTRACT

Herein, experiments were carried out with 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 while the other cylinder is at the pivot point. The gap between the two cylinders is varied from 0 to 4.9D (D being the diameter of the cylinder) and the center of gravity (cg) is varied from −2.5D to +2.5D from the pivot point. The hydrodynamic forces on the cylinders are measured with a load cell and the surrounding flow is measured simultaneously using particle image velocimetry (PIV). The Reynolds number is varied in the range of $500 < Re < 2.4 \times 10^4$ during the test to find the maximum possible displacement amplitude for each configuration. Then, an spectral analysis is performed on the measured velocity field to have information about the vortex shedding frequency of the unsteady flow in the gap region and cylinder wake. When the gap between the cylinders (g) is zero, the cylinders behave like a single bluff body (SBB) in cross-flow. However, depending on the arrangement, the wake patterns are different. If both cylinders are at the downstream side of the pivot, the cylinders act as a single body with an extended surface and alternating vortexes shed behind the cylinders in each cycle forming a single vortex street on the wake side (SBBV). Sliding both cylinders to the upstream side shifts the vibration mechanism to the single body galloping region (SBBG). The shear layer behind the two cylinders is stretched along the fluid flow and vortexes are formed at a greater distance downstream comparing to the SBBV.

Having one cylinder on the pivot changes the vibration to a typical wake induced vibration if the other cylinder is at the downstream. If the other cylinder is at the upstream, the vibration is similar to a single cylinder system but the cylinder on the pivot disturbs the wake and changes the stagnation point on the upstream cylinder.

When both cylinders are at an equal distance from the pivot point, three major flow fields are observed. For larger gaps (g >3.9D), there is no reattachment of the shear layers downstream and two synchronized vortex streets form behind the two cylinders. By decreasing the gap, the downstream cylinder starts to interact with the vortexes shed from the upstream cylinder. If 2.5D < g < 3.9D, the gap flow pattern is split-gap where the vortexes split inside the gap before reaching the downstream cylinder. As the gap decreases, vortex excitation (VE) is less effective and gap-switching induced vibration (GSIV) dominates the vibration mechanism. Reducing the gap to $G < 0.9$ turns the split-gap flow to an entire-gap flow pattern that forms a sharp velocity gradient inside the gap

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https://doi.org/10.1016/j.jfluidstructs.2018.07.016

region and increases the total lift force dramatically on the system which maintains a larger vibration amplitude.

1. Introduction

Interaction between fluid flow and arrays of cylindrical bodies is seen in multiple engineering applications including heat exchangers, support structures, marine risers, a group of chimney stacks, power cables, etc. Recently, this interaction is considered as a potential source for harvesting energy from the fluid flow. Accordingly, several mechanisms of fluid–structure interaction have been proposed in different configurations and different Reynolds numbers to maximize the efficiency of energy conversion. The vast majority of these studies have focused solely on transitional cross-flow oscillation where the drag force is either destructive or being wasted. However, it is possible 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. Such a system is studied numerically by Sung et al. (2015) as a "drag assisted converter" and tested experimentally by Arionfard and Nishi (2017). It was found that the drag force role depends on the location of the pivot point; If the cylinder is located on the upstream side of the pivot, the drag force resists the restoring moment while locating the cylinder on the upstream side of the pivot enhances the restoring moment. Therefore, the location of the cylinder related to pivot point dramatically effects the performance of a single rotationally vibrating cylinder. Recently, to overcome this problem and to improve the FIV performance of a single cylinder system in cross-flow, a double cylinder system is designed and studied by Arionfard and Nishi (2018). The vibration characteristics, resultant forces and configuration effect on the displacement respond is investigated and four main mechanisms of vibration were identified for a double cylinder system; Galloping happens if both cylinders are 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 upstream, the system behaves like a single cylinder system but by moving the other cylinder to 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'. A summary of vibration mechanisms associated with different configurations is shown in Fig. 1. To understand the vibration characteristics, investigating the flow field around the cylinders is inevitable. The flow field around two cylinders in tandem arrangement involves complex interactions between the shear layers, vortices and wakes (Borazjani and Sotiropoulos, 2009). This complexity further increases if the cylinders are mechanically coupled and oscillating rotationally around a pivot point.

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 a cylinder when it is mechanically coupled to another 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 cylinders are moving transitionally and the drag force has no effect on the vibration mechanism in their study since there is no rotation in the system.

The present paper is focused on the flow field and vorticity dynamics in different configurations of two rotationally moving cylinders. 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 an overall view over the vibration mechanisms followed by a discussion about the vorticity dynamic and the flow field analysis. Finally, we make conclusive remarks in Section 4.

2. Experimental setup and procedure

2.1. Water channel and test model

Experiments were performed in a recirculating free surface water channel with a test section of 30 cm wide by 30 cm deep and 1 meter long. The flow rate was controlled by using a centrifugal pump fitted with a variable speed controller, so the flow velocity in the test section could be adjusted to any value between 0.024 and 0.84 m s^{-1}. The channel floor and the two side walls of the test section were made of transparent acrylic to allow visual observation and particle image velocimetry (PIV) measurements.

A pair of cylinders with a diameter of D = 30 mm and length of 240 mm is used in the experiments resulting in a blockage ratio of 10%. However, on certain rotational displacements, the maximum projected area of both cylinders would result in a blockage ratio of around[1] 20%. According to Assi et al. (2010), although the maximum amplitude of oscillation decreases

1 The calculated blockage ratio for two cylinder has been corrected.