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Flow-induced vibration of three unevenly spaced in-line cylinders in cross-flow

Mahmoud Shaaban, Atef Mohany *

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, Oshawa, ON, Canada

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ABSTRACT

The flow over three cylinders arranged in-line with uneven spacing in cross-flow is numerically investigated at a Reynolds number of 200. The center-to-center distance between the upstream and the most downstream cylinder was kept constant at 4 diameters. The distance between the inline centers of the upstream and middle cylinders (x) was studied in the range of 1.05 to 2.95 diameters. The flow structure around the cylinders shows two distinctive patterns of vortex shedding, one of which occurs at $x = 1.60$ and 1.80 diameters, and causes significantly higher oscillating lift and mean drag forces with a lower value of Strouhal number. At these middle cylinder locations, the shear layer reattaches on the downstream cylinder and results in vortex formation in the gap between the middle and downstream cylinders. On the other hand, at all other locations of the middle cylinder the shear layer does not reattach on the downstream cylinder. Moreover, when the middle cylinder is located at $x = 1.60$ or 1.80 diameters, the vortex formation length is shorter and the vorticity in the downstream vortex street is higher than the case when the middle cylinder is located at all other locations. To understand the effect of these distinctive flow features on the flow-induced vibration response of the most downstream cylinder, the coupling between the flow field and the cylinder motion is numerically modeled. As the reduced velocity is increased, the oscillation amplitude of the downstream cylinder increases to its maximum at lock-in, then it starts to decrease similar to the case of a single cylinder. However, the oscillation amplitude reaches a higher value than that observed for the case of vortex-induced vibration of both a single cylinder and two tandem cylinders. Moreover, significant oscillation amplitude is pertained at high reduced velocities with dependency on the uneven spacing between the cylinders. The frequency of oscillations increases at different rates in three different ranges of reduced velocities, indicating different energy transfer mechanisms. Although the frequency of vibration is shifted away from the structure resonance frequency at high reduced velocities, the significant amplitude of oscillations is attributed to the interaction of two opposing mechanisms that occur when the cylinder is at different positions in the cycle. The wide range of reduced velocities at which the cylinder vibrates with a significant amplitude makes the configuration of three in-line cylinders a good candidate for flow energy harvesting.

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1. Introduction

A group of cylinders in cross-flow is an arrangement that recurs abundantly in many engineering applications. Structures of cylindrical cross sections can be found in buildings, heat exchangers in power plants, silos, underwater pipelines,

* Corresponding author.
E-mail address: atef.mohany@uoit.ca (A. Mohany).

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suspension and power cables, and many other applications in air, water, and multiphase flows. In some cases, the cylindrical structures are unevenly spaced, which is a distinct flow geometry that gives rise to flow patterns that are not thoroughly investigated. Fluid forces exerted on such configurations can cause failure or fretting wear, and therefore must be included in the design and operation considerations. For example, forces due to wind flow on structures such as tanks and silos can cause significant deflections and buckling (e.g. Portela and Godoy, 2005; Sosa and Godoy, 2005). Shedding of vortices around one or a group of cylinder-like structures can give rise to excessive noise (Mohany, 2006; Arafa and Mohany, 2015). In addition, flexible structures subject to flow are prone to vortex-induced vibration. Applications such as riser pipes in offshore oil fields, suspension cables in wind flow, highway light poles, data cables in underwater currents, and other applications can undergo vibrations of significant amplitudes which may endanger their operation (Weaver et al., 2000; Mohany et al., 2012; Hassan and Mohany, 2013).

An extensive review by Zdravkovich (1977) of the flow interference between two cylinders show that the flow field around a group of cylinders in close proximity subjected to cross-flow differs significantly from the case of isolated cylinders. Igarashi and Suzuki (1984) experimentally studied the characteristics of flow around three cylinders of equal diameters arranged inline with *even spacing*. They provided a detailed description of the flow patterns and fluid forces that occur in this arrangement, and reported bistable switching between the flow patterns. They described a complex combination of flow patterns around the cylinders. The observed patterns depend on the spacing between the cylinders and Reynolds number. However, it is unclear how the flow structure and the fluid forces acting on the cylinders would be affected if spacing between them was uneven. Zhang and Zhou (2001) investigated the effect of unequal cylinder spacing on the vortex streets behind three rigid side-by-side cylinders. They reported that slight inequalities in the spacing between the cylinders can lead to substantial changes in pressure distribution on cylinder surfaces, and therefore change lift and drag forces.

The safety concerns in many applications that include flexible structures in fluid flow sparked remarkable research efforts to understand the phenomenon of flow-induced vibration. Significant attention has been focused towards the cases of a single and two cylinders. Anagnostopoulos and Bearman (1992) conducted an experimental investigation of the vortex-induced vibration of a single cylinder in a fully laminar regime at a Reynolds number up to 150 and at a high mass ratio m^* of 149, as defined in Eq. (6). They observed that the maximum oscillation amplitude of 0.6 diameters occurs near the lower limit of the lock-in region. Khalak and Williamson (1997) investigated the occurrence of vortex-induced vibration of a cylinder free to vibrate in one direction at low mass ratio and structural damping of $m^* = 2.4$ and $\zeta = 0.0059$, respectively. They observed significantly higher amplitudes of oscillation compared to previous studies at higher solid to displaced fluid mass ratio. Govardhan and Williamson (2006) investigated the effect of Reynolds number on the amplitude of oscillations of a single cylinder for a fixed mass ratio of m^*=10. They observed a constant maximum oscillation amplitude of 0.6 diameters in laminar flows. However, they reported that the maximum oscillation amplitude depends on log (Re) in turbulent flows. Hover and Triantafyllou (2001) experimentally investigated the flow-induced vibration of two tandem cylinders with only the downstream cylinder allowed to vibrate at $m^* = 3.0$ and $\zeta = 0.04$. They reported a wider lock-in range and a higher amplitude of oscillation than that of a single cylinder. More interestingly, they reported significantly higher amplitudes of oscillation at higher reduced velocities. Assi et al. (2010) experimentally investigated the mechanism of flow-induced vibrations for two tandem cylinders when the downstream cylinder is allowed to vibrate. They observed that the oscillations are characterized by a build-up of amplitude persisting to high reduced velocities, which is different than the limited resonance range of vortex-induced vibration of a single cylinder. Although the vortex-induced vibration of two tandem cylinders has been thoroughly investigated, it is not clear whether this knowledge can be extended to multiple inline cylinders in cross-flow. The case of vortex-induced vibration from three or more inline cylinders in cross-flow has never been investigated. Furthermore, the problem becomes more complicated when the cylinders have uneven spacing between them and the vibration response cannot be directly inferred from the case of two tandem cylinders.

Recent development in numerical techniques and computational power allowed for accurate simulation of flow-induced vibration of many configurations. Meneghini et al. (2001) simulated the two-dimensional flow around two circular cylinders in tandem and side-by-side arrangements at Re $= 200$. They showed that spacing between the cylinders in both arrangements has a significant effect on the wake pattern and Strouhal number. Tandem cylinders at gaps lower than 3 diameters shed vortices only from the downstream cylinders. Harichandan and Roy (2010) simulated the two-dimensional incompressible flow around several configurations of cylinders of the same diameter at Re = 100 and 200. For flow past three cylinders in tandem, they observed that the downstream cylinder which lies in the wake of the upstream cylinder experiences very large unsteady forces that can give rise to vortex-induced vibrations. The wake of the two upstream cylinders is significantly different from the wake of a single cylinder and is influenced by the cylinder spacing and can give rise to bistable flow patterns. The effect of such wake features on the flow-induced vibration is not fully understood.

Mittal and Kumar (2001) numerically studied the flow-induced vibrations of a pair of cylinders in tandem and staggered arrangements in the wake interference flow regime at Re $= 100$ and $m^* = 4.72$. They observed that the forces on the upstream cylinder are similar to those observed for a single cylinder, whereas the downstream cylinder experiences significant unsteady forces. For systems where displaced fluid mass is relatively close to the solid mass, Mittal and Kumar (2001) suggested that vortex-shedding frequency of the oscillating cylinder at lock-in does not exactly match the structural resonance frequency. They also observed that the maximum oscillation amplitude of the spring–mass system does not change significantly even if the mass of the oscillator is reduced by a factor of 100. Borazjani and Sotiropoulos (2009) examined the accuracy of two-dimensional simulation by performing several three-dimensional simulations. Their results at Re $= 100$ and 200 show that three-dimensional instabilities are not sufficiently strong to alter the dynamic response

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