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Flow-mediated interaction between a vibrating cylinder and an elastically-mounted cylinder

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ABSTRACT

This study investigates the interaction between two cylinders of an identical diameter immersed in still fluid: the master cylinder is subject to forced vibration, while the adjacent slave cylinder is elastically-mounted and has only one-degree-of-freedom along the centreline of the two cylinders. The hydrodynamic interaction is simulated with an extensively-validated 2D Navier-Stokes solver that is based on the finite element method and the Arbitrary Lagrangian-Eulerian method. Extensive simulations are conducted, with a fixed Reynolds number of 100. The initial clearance distance, normalised by the cylinder diameter, ranges from 0.2 to 1.0. The mass ratio of the cylinder over the displaced fluid ranges from 1.5 to 2.5. The vibrating amplitude of the master cylinder, normalised by the cylinder diameter, varies from 0.025 to 0.1. Frequencies of the master's vibration, normalised by the slave's structural natural frequency, ranges from 0.05 to 2.4. When the frequency of the master cylinder reaches the immersed natural frequency of the slave cylinder, the slave cylinder's vibration observes resonance, and the phase difference between the two cylinders' movement experiences a 180° shift. In resonance, the slave-master phase difference is about 90°. The frequency of the vibration is found to significantly affect the flow features.

1. Introduction

Flow-mediated interactions can be found in various natural and engineering contexts. Objects moving in a fluid can interact with the neighbouring objects through the disturbed fluid between them. The subsequent motion of the neighbouring objects is of greater complexity than that of the objects subjected to a prescribed moving fluid. Flow mediated interaction is relevant to fish schooling (Liao, 2003; Gazzola et al., 2016), dolphin drafting (Weihs, 2004), swimming of micro-organisms (Gyrya et al., 2010; Ishikawa et al., 2006; Koch and Subramanian, 2011), the interference between risers (Bampalas and Graham, 2008), sperm-egg interaction (Riffell and Zimmer, 2007), formation of solid particle clusters (Voth et al., 2002), and dispersion of particle clouds (Metzger et al., 2007). These phenomena have been the subject of experimental and numerical investigations, aiming to identify the characteristics of the interactions. The findings of these studies have the potential to be exploited in engineering applications, e.g., vortex-induced vibration energy harvesters (Bernitsas et al., 2008) and self-propulsion devices (Van Rees et al., 2015).

Relevant to the flow mediated interactions between circular cylinders, numerous studies have been conducted over the past decades to investigate the fluid-structure interactions containing only a single oscillating cylinder. Despite the simple geometry, this problem involves a rich spectrum of physics and carries practical implications in ocean engineering and oil and gas industry, particularly for the risers of the deep sea oil drilling platforms.

For a circular cylinder immersed in a fluid oscillating sinusoidally, a scenario can be determined by two independent parameters, i.e. the Keulegan-Carpenter number and Reynolds number. The Keulegan-Carpenter number can be defined as $KC = U_m T/D$, where U_m is the amplitude of the oscillatory flow velocity, T the period of oscillatory flow, and D the diameter of the cylinder. The Reynolds number is defined as $Re_m = U_m D/\nu$, where ν is the fluid kinematic viscosity.

Williamson (1985) carried out experiments to examine how the forces upon an oscillating cylinder are related to the vortex shedding. He found that the number of vortex pairs shed from the cylinder per flow cycle increases with KC. Based on this pattern, five flow regimes were identified. Tatsuno and Bearman (1990) further investigated the flow features

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and found eight flow regimes based on flow visualization, i.e., regimes A^*, A, B, C, D, E, F, G. In most of these flow regimes, the three-dimensional (3D) flow was noticed. Only regimes A and A^* turned out to be two-dimensional (2D). In the present study, the vibration of both cylinders is well within Regime A^*, which is characterized by the 2D and symmetrical flows. Based on the regimes categorised by Tatsuno and Bearman (1990), Elston et al. (2006) identified two fundamentally different types of symmetry-breaking instability in the single-cylinder oscillation case. One is 2D instability and the other is 3D instability. Dütsch et al. (1998) conducted laser Doppler anemometry (LDA) measurements and numerical simulations of a laminar flow induced by the harmonic oscillation of a circular cylinder in otherwise still water, reporting reliable agreement between numerical and experimental results. By comparing with these experimental results, Lin et al. (2017) validated an in-house 2D Navier-Stokes model that is the basis of the present study.

Zhao and Cheng (2014) numerically studied the oscillatory flow past two circular cylinders. They found that, in the side-by-side arrangement with small gap ratios, the vortex shedding from the gap of the two cylinders dominates, resulting in the unique gap vortex shedding (GVS) regime, which cannot be found for a single cylinder case. In the tandem arrangement with a very small gap between the two cylinders, the flow regimes are similar to that of a single cylinder. A strong interaction between the vortex shedding flows from the two cylinders makes the flow notably irregular at large KC values in both side-by-side and tandem arrangements.

In contrast to the abundant research on the cylinders vibrating in a still fluid, the research on the flow mediated interaction between multiple immersed cylinders is relatively rare. Lamb (1932) investigated the interaction between two spheres submerged in inviscid fluid. One sphere is forced to oscillate along the centre-line, whereas the other nearby sphere of neutral buoyancy responds freely to the disturbed fluid. By theoretical analysis, Lamb (1932) found that the free sphere is “on the whole” attracted towards the oscillating sphere due to the imbalanced pressure force. By both analytical and numerical methods, Nair and Kanso (2007) investigated an identical configuration in greater detail, but for the case of two cylinders rather than two spheres. One cylinder is started impulsively and is forced to oscillate along the centre-line between two cylinders, whereas the second responds freely. Nair and Kanso (2007) found that, depending on the initial phase (i.e., initial velocity direction) of the oscillation, the free cylinder can be either repelled away or attracted towards the oscillating cylinder. They further suggested that this should also be true for the spheres considered by Lamb (1932), whose analysis only captured the attraction.

The flow mediated interaction between two cylinders was further studied by Gazzola et al. (2012), but the fluid was taken to be viscous rather than an inviscid. Gazzola et al. (2012) discovered the threshold Reynolds number, beyond which the slave or passive cylinder is repelled by the master or active cylinder, and under which it is attracted to the master cylinder. A secondary flow structure is discovered between the two cylinders. An increase in Reynolds number (i.e., a decrease in viscosity) slows down the dissipation of the secondary flow, which favours the repulsion of the slave cylinder by the master. They further discovered that the threshold Reynolds number is not affected by the initial phase of the master, i.e., the phase of the initial impulsive vibration of the master cylinder. This conclusion is different from that drawn in Nair and Kanso (2007) for the inviscid flow scenario, where the repulsion or attraction is found to be governed by the initial phase of the movement. The threshold Reynolds number decreases exponentially with the increase in the initial gap, whereas it is not substantially affected by the size difference between the two cylinders. Based on these observations, Gazzola et al. (2012) concluded that the flow features have a greater influence than the inertia of the slave cylinder. Therefore, in the present study, the diameters of the slave and the master cylinders are configured to be the same. Gazzola et al. (2012) also found that, given a very small vibration amplitude of the master cylinder, the level of repulsion or attraction is significantly reduced.

In summary, there has not been sufficient research on the flow mediated interaction between immersed objects and the existing limited research all considers the case where the slave object has the same density as the mediated fluid and is completely free to move under the unbalanced hydrodynamic force. However, in actual engineering applications, a vibrating structure is often of a different density from the fluid and is almost certainly elastically-mounted.

2. Problem setup and numerical method

In this study, two identical rigid cylinders are placed in otherwise still fluid, as seen in Fig. 1. At time zero, the master cylinder starts to vibrate harmonically to disturb the fluid, whereas the slave cylinder, which has 1 degree of freedom (1DOF) in the y direction, vibrates correspondingly under the action of the imbalanced hydrodynamic force. The two cylinders are initially separated by a gap of G. The non-dimensional analysis shows that it requires five non-dimensional parameters to define the problem, i.e. gap ratio (G/D), frequency of the master cylinder (A_1/D), amplitude of the master cylinder (A_1/D), the mass ratio of the slave cylinder ($m^* = m_c/m_{dis}$), and Reynolds number based on the maximum velocity of the master cylinder ($Re_m = 2\pi A_1 f_1 D/\nu$). Here, f_1 is the vibration frequency of the master cylinder, $f_n = (1/2\pi)^*\sqrt{k/m_c}$ is the structural natural frequency of the slave cylinder in vacuum, k is the stiffness of the spring, m_c the mass of the slave cylinder, m_{dis} the mass of the fluid displaced by the slave cylinder, and ν the kinematic viscosity.

Simulations are conducted for a range of combinations of parameters, but the Reynolds number is maintained constant as $Re_m = 100$. In summary, the master cylinder's frequency f_1/D ranges from 0.05 to 2.4; the amplitude of the master cylinder takes A_1/D of 0.025, 0.050, 0.075 or 0.1; the mass ratio m^* takes the value of 1.5, 1.7, 2.0, 2.2 or 2.5; the gap ratio G/D varies from 0.2 to 1.0 with an increment of 0.1. In total, 7448 combinations of parameters are examined.

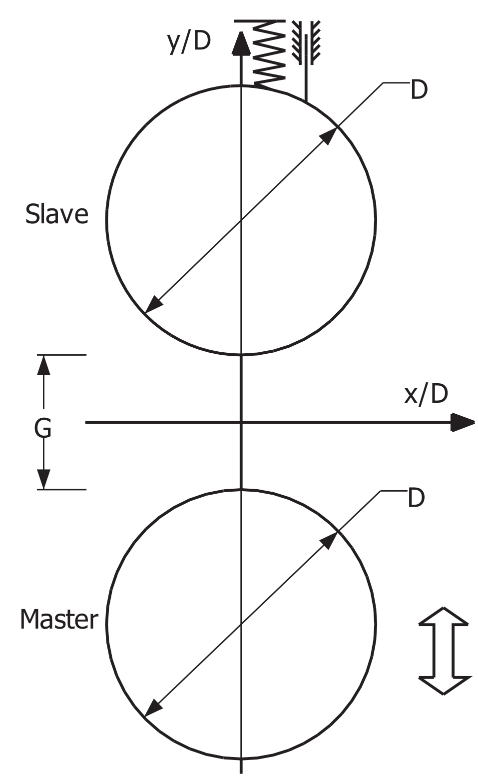

Figure 1. A sketch of interaction between two cylinders: While the master cylinder undergoes harmonic forced vibration, the slave cylinder is elastically mounted and vibrates passively along the y-axis.