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Flow characteristics of two in-phase oscillating cylinders in side-by-side arrangement

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ABSTRACT

Numerical simulations of flow past two side-by-side arranged cylinders with the same diameters of *D*, forced to oscillate transversely in a uniform cross-flow, are presented for a fixed Reynolds number of 100. The two-dimensional incompressible Navier–Stokes equations in Arbitrary-Lagrangian–Eulerian formulation are solved by Characteristic-Based-Split finite element method using MINI triangular element. The simulations are performed for four center-to-center cylinder spacings, *s*, ranging from 1.2*D* to 4.0*D*, corresponding to four kinds of wake pattern for the stationary two cylinders. The cylinders are oscillated in in-phase mode and their harmonic motions are restricted to relatively smaller amplitude with wide range of frequencies. The numerical results show that there exist five different flow response states, according to the different characteristics shown by the power spectra of lift forces, phase portraits of lift force against cylinder motion, time histories of energy transferring and flow fields visualized in vorticity contours. The force characteristics are also investigated in terms of time-averaged and root-mean-square quantities, and show that the roles of the gap spacing, flow response state and excitation frequency are different for different aerodynamic force quantities.

1. Introduction

The problem of flow around oscillating cylinder is of great interest due to its relevance to vortex-induced vibration, which has been a major issue for the design of riser tubes employed in offshore-drilling and production to bring oil from the seabed to the surface. Regarding the fundamental physics of the flow field, the coupling of the unsteady wake to the motion of cylinders, gives rise to a number of interesting behaviors, such as vortex lock-on, wake mode transitions, hysteresis and bifurcation and many more, with the underlying mechanism of enormous vorticity dynamics. For these reasons, a number of experimental and numerical studies are focused on the subject of flow and moving body interaction.

In a pioneering work on the subject of forced oscillation studies, Bishop and Hassan [1] found that as an oscillating frequency approaches to the vortex shedding frequency of a stationary cylinder, there is a sharp increase in the magnitude of the lift force and a distinct jump in the phase between the cylinder displacement and the lift force. Such changes in the fluid forcing have also been found by subsequent controlled oscillation studies, including Mercier [3], and Sarpkaya [6] and Gopalkrishnan [7]. In Bishop and Hassan [1], a hysteresis effect (see Fig. 13 in their article) was shown depending on whether the oscillation frequency is increased or decreased in continuous fashion. Carberry et al. [10] made an observation of a hysteretic transition of drag force, similar with that found in Bishop and Hassan [1], by varying oscillation frequency in a stepwise fashion with the wake returning to the stationary cylinder state between each test case.

The coalescence of cross-flow oscillation and vortex-shedding frequencies, which occurs at the frequency ratio around unity ($f_e/f_o \approx 1$, f_e and f_o are, respectively, the excitation frequency and natural shedding frequency for a stationary cylinder), is the most well known feature of the flow past oscillating cylinder, and is referred to as lock-on or synchronization. Stansby [11] experimentally investigated the forced oscillations of a circular cylinder, and showed that the lock-on boundaries expanded with the increasing oscillation amplitude. The frequency lock-on was also observed by Koopman [2] in the oscillating cylinder flows at low Reynolds number.

The vortex-mode in the near wake of a cylinder subjected to prescribed oscillation was studied both by experimental visualization methods and numerical calculations [4,12–14]. Williamson and Roshko [12] described a number of vortex shedding modes at Re = 300–1000. There were three different shedding modes, according to the number of vortex-couple pairs (‘P’) or single

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vortices ('S') shed into the wake per oscillating cycle: (i) 2P mode; (ii) 2S mode; and (iii) P + S mode. The wake patterns similar to 2S, 2P and P + S modes have also been observed in the experiments of Ongoren and Rockwell [5]. The asymmetric mode of P + S was observed in the earlier experiments of Griffin and Ramberg [15] at Re = 190. Leontini et al. [13] carried out two-dimensional simulations of the flow past a circular cylinder forced to oscillate at low Reynolds number. They produced two detailed maps of the wake modes in the frequency-amplitude space. They reported that the wake modes observed in the synchronized regime were dimensionality dependent. This was also supported by the evidence from the two dimensional calculations of Blackburn and Henderson [8]. More recently, Morse and Williamson [14] additionally identified a distinct mode of vortex shedding in the region, where 2S and 2P overlap. This newly observed shedding mode was characterized such that two pairs of vortices were shed per cycle of oscillation, but the secondary vortex was much weaker, and labeled by the authors as '$2P_o$' mode.

The relation between the vortex patterns and the statistical characteristic is another interesting issue. Lu and Dalton [16] found numerically that the base pressure dropped sharply when the vortex switched from one side of the cylinder to the other. Carberry et al. [9] carried out experimental investigation on the wake states of an oscillating cylinder. They showed that the lift force transition from a low amplitude out-phase to a high amplitude in-phase was associated with a change in the sign of the initial vortex and the mode of vortex shedding. Blackburn and Henderson [8] suggested from the numerical analysis that the phase-switching behavior was attributed to a competition between two vorticity generation mechanisms: at low-frequency of oscillation, the tangential pressure gradient governs the production of vorticity on the surface; while for high-frequency oscillation, the surface-tangential component of the cylinder acceleration plays a key role in the vorticity production mechanism.

However, some different observations on the relationship between the phase switching and the shedding mode were also made in available literatures. In Ongoren and Rockwell [4], the change in the vortex-shedding phase was not associated with a change in shedding mode, remaining the 2S mode on both sides of the phase switch. Den Hartog's experimental visualizations [17] did not record any evidence for a change in shedding mode with the occurrence of phase switching. Leontini et al. [13] showed that the transition from 2S to P + S shedding was not correlated to the energy transfer between the fluid and cylinder. Further, their results indicated that a swing in phase between lift and displacement does not necessarily result in a transition of the vortex shedding pattern.

Previous literatures have greatly enhanced our understanding of vortex-induced vibration phenomena for vibrating bodies. However, instead of an isolated cylinder, we are more frequently encountered with multiple cylinders oscillated in response to flow induced forces. For this reason, extensive studies have also been conducted on the flow behavior for multiple cylinders. The two cylinders with variant arrangements was considered to be a justifiable simplification of them (see Zdravkovich [18], Sumner et al. [19] and Sumner [52]). Williamson [20] experimentally studied the vortex shedding characteristics of a pair of circular cylinders. It was found that vortex-shedding synchronization occurred either in phase or in anti-phase when the gap size was beyond the critical distance. Within the critical distance, the vortex shed in an asymmetric form. It was observed further that in this asymmetric regime, there were certain harmonic modes of vortex shedding, whereby the shedding frequency on one side of the wake is a multiple of that on the other side. Kim and Durbin [21] experimentally investigated the unsteady wake of a pair of circular cylinders separated in a cross-flow direction by less than one cylinder diameter. They reported that the wakes flop randomly between two asymmetric modes, and the time scale for the flopping was several orders of magnitude longer than that of vortex-shedding. Sumner et al. [19] experimentally studied the flow field for two circular cylinders in a side-by-side configuration. They identified three basic flow patterns: (i) single bluff body vortex shedding at small s/D; (ii) biased flow with synchronized vortex shedding at intermediate s/D; and (iii) symmetric flow with synchronized vortex shedding at large s/D. Zhou et al. [22] performed an experimental work on the turbulent wake of two side-by-side slightly heated cylinders. It was found that the flow structure, heat and momentum transport were dependent on the gap spacing between the cylinders. Xu et al. [23] experimentally investigated the wake structure of two cylinders and found that with the increasing of Reynolds number, the wake structure changed from one single vortex street to two streets with one narrow and one wide for the same gap spacing. Furthermore, the critical Reynolds number, at which the wake structure transition occurred, increased with the decreasing gap spacing. Kang [24] investigated two-dimensional flow over two cylinders in side-by-side arrangement, and showed the existence of six kinds of wake patterns over the considered spacing ranges, including anti-phase synchronized, in-phase synchronized, flip-flopping, deflected, single bluff-body and steady wake patterns. The flow characteristics were found to be significantly dependent both on Reynolds number and gap spacing, with the effect of latter was greater than that of the former.

Albeit the wake interference from stationary cylinders was investigated widely in recent years, there are only a few studies available on the oscillations of multi-cylinders. An experimental research on the wake behind a pair of cylinders subjected to forced oscillation was carried out by Mahir and Rockwell [25]. Their results showed that the extent of the lock-on region was depended on the gap size. If the gap was sufficiently large, there was a lock-on response of near-wake vortex formation; whereas for the sufficiently small gap, the lock-on response was not attained at all. It was also observed that the phase angle between cylinder oscillations had distinct effects on the extent of lock-on region as well as the patterns of wake vortices. Recently, a numerical study on the flow around two forced oscillating cylinders in side-by-side arrangement was conducted by Lee et al. [26]. The two cylinders were oscillated out of phase with each other. They showed that most of the wake patterns of two oscillating cylinders can be explained by the mechanism underlying in the behavior of two stationary cylinders, a single oscillating cylinder and their combinations; and agreed with classifications of flow over two stationary cylinders.

A more complex flow could arise for the OSCILLATING two cylinders, when compared to the stationary counterpart. Evidently, besides the parameters of amplitude and frequency, the variation of gap spacing and the phase angle in the oscillations can also lead to a rich flow behavior in their wake region. As found in Kang [24], gap spacing is a significantly important factor for characteristics of the flow around two cylinders. However, so far, no experiments are aimed at the exploration of the spacing effect on the flow of oscillating multi-cylinder system. In Mahir and Rockwell [25], the considered gap spacing was corresponded to only one type of wake pattern of Kang [24]. Lee et al. [26] restricted on the cylinders in an anti-phase periodic oscillation. Thus further investigation is still necessary to give further understanding of the flow response under complicated scenario with different gap spacings and phase angles.

The present work aims to numerically investigate the characteristics of flow over two in-phase oscillating cylinders in a side-by-side configuration. We focused on the effect of gap spacing and excitation frequency, and more particularly to identify various types of flow state in response to these controlled parameters. The flow response identification is mainly based on the frequency response behavior, phase portrait of lift coefficient versus cylinder