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Flow past tandem cylinders under forced vibration

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ABSTRACT

Flow past two cylinders in tandem arrangement under forced vibration has been studied experimentally employing the hydrogen bubble visualization technique. The Reynolds number, based on the cylinder diameter, is fixed at Re=250. In stationary state of the two cylinders with $P/D=2.0$, dual vortex shedding frequencies f_L (St=0.14) and f_H (St=0.18) are identified. f_L is associated with the shear layer reattachment behavior and f_H is related to the single bluff body behavior. Under a variety of forced vibrations of the two cylinders at a fixed vibration amplitude $A/D=0.25$, diverse and highly-repetitive vortex patterns are yielded. They are classified into two typical modes—a low-frequency mode and a high-frequency mode. The two modes are represented by two vortex patterns yielded from in-phase vibration of the two cylinders with $P/D=2.0$ and at vibration frequencies $f_e \approx f_L$ and $f_e \approx f_H$. The difference between the two modes is on the number of vortices formed per vibration cycle. For the low-frequency mode, the number is four; for the high-frequency model, it is two. In both modes, the vortex formation is phase-locked to the cylinder motion. For a specified mode with a fixed vortex number per cycle, the way the vortices evolve in the wake can be somewhat different by changing the vibration frequency, pitch ratio, as well as the vibration type. These affecting factors have been examined in this work, and the associated vortex patterns have been characterized and compared.

1. Introduction

Understanding flow past a group of bluff bodies is of great importance in many fields of engineering design. Examples include heat exchanger tubes, adjacent tall buildings, bundled transmission lines and piles of offshore platforms. Research on flow interaction with bluff bodies has had a particular concentration on flow around circular cylinders. The cylinders can be in a group of two, three, or more. With a group of two cylinders, they may be arranged in tandem, side-by-side, or staggered configurations. For the case of stationary cylinders, a large amount of research approaches have been made, involving qualitative flow visualization, particle image velocimetry, hot wire/film measurement, loading measurement, and numerical simulation. The resulted research findings have led to in-depth understanding on vortex dynamics, velocity fields, loading behavior, effects of Reynolds number, pitch ratio, and turbulent intensity. Most recently, Sumner (2010) has highlighted the progress in this area, covering more than 130 research papers.

Limiting to two stationary cylinders of equal diameter in tandem, the flow structure is sensitive to both Reynolds number Re and the pitch ratio P/D (P—center-to-center pitch and D—cylinder diameter). Igarashi (1981) identified eight typical flow patterns in the plane of $\{P/D, \mathrm{Re}\}$. Xu and Zhou (2004) further generalized the flow patterns into three regimes in the P/D

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domain only. These three regimes show single bluff body (SBB) behavior at small P/D, shear layer reattachment (SLR) behavior at intermediate P/D, and synchronized vortex shedding (SVS) behavior at large P/D. The specific ranges of P/D for each regime depend on Re. Data from Zdravkovich (1987) show these three ranges: $1 < P/D < 1.2$–1.8 for SBB, 1.2–$1.8 < P/D < 3.4$–3.8 for SLR, and $P/D > 3.4$–3.8 for SVS. Data from Zhou and Yiu (2006) are somewhat different: $1 < P/D < 2$ for SBB, $2 < P/D < 5$ for SLR, and $P/D > 5$ for SVS.

The frequency of vortex shedding behind the downstream cylinder in a two-stationary-cylinder system in tandem behaves differently in different regimes. Xu and Zhou (2004) gave the most extensive set of Strouhal number (St) data for a wide range of Reynolds number ($\mathrm{Re}=800$–4.2×10^4) and pitch ratio ($P/D=1$–15). For $\mathrm{Re}=80$ and $P/D=1$–12, Wang et al. (2010) provided another set of St. All the St data, in conjunction with flow patterns (e.g., Igarashi, 1981; Zdravkovich, 1987; Lin et al., 2002; Xu and Zhou, 2004), evidence the existence of bistable flow patterns at the SBB–SLR border and SLR–SVS border. Specifically, at the SBB–SLR border, where $P/D=1.2$–2.0 (depending on Re), there are two different wake patterns that are associated with two distinct vortex shedding frequencies. One pattern shows SBB behavior and the other SLR behavior; both are stable and changeover happens suddenly. Similar phenomenon occurs at the SLR–SVS border, where $P/D=3.4$–5.0 (depending on Re). Note that the abovementioned two borders are not sharply defined in the P/D domain even under a given Re. Typically mode exchanges occur in a small range of P/D rather than at a specific value of P/D, and hysteresis affects that largely. Tasaka et al. (2006) showed hysteretic mode exchange by increasing and decreasing Re. Wang et al. (2010) demonstrated the same phenomenon by increasing and decreasing P/D.

Vortex shedding from a group of cylinders can lead to vibration in cylinders. The vibration, in turn, alters the flow structure around the cylinders dramatically. In the case of two cylinders in tandem, the study of vortex-induced vibration (VIV) can be very challenging due to the existence of a large number of affecting parameters. A limited number of approaches have been made in this area by Zdravkovich (1985), Assi et al. (2010), Huera-Huarte and Bearman (2011), and some others. To better study VIV of tandem cylinders, it is critically important to understand the VIV of an isolated cylinder and translate the approaches employed in isolated cylinders to tandem cylinders.

When an isolated cylinder performs transverse vibration in the free stream, vortex formation can be phase-locked to the cylinder motion in a certain range of the vibration frequency. This phenomenon is referred to as lock-in in the literature. Under forced vibration, at a low amplitude A (e.g., $A/D=0.25$) and in a frequency range around the frequency of vortex shedding from the stationary cylinder, two lock-in patterns have been identified. They are 2S mode (S for single vortex) and 2P mode (P for vortex pair). This result is in direct agreement with the one from free vibration, as summarized in the comprehensive review of Williamson and Govardhan (2004). Morse and Williamson (2009) further demonstrated that under carefully controlled conditions flow patterns generated by a cylinder in free vibration and a cylinder under forced vibration have a very close correspondence. This occurs only if energy transfer is from the flow to the cylinder in both cases. But under forced vibration, oftentimes energy transfer is from the cylinder to the flow. To identify the energy transfer direction under forced vibration, a large parameter space needs to be examined. An up-to-date review of recent studies on VIV of an isolated cylinder is provided by Wu et al. (2012).

Studies on forced vibration of an isolated cylinder are beneficial to better understand VIV of an isolated cylinder. The same approach can be extended to the study VIV of tandem cylinders. Beyond the scope of VIV study, the topic on forced vibration of tandem cylinders itself is of basic interest in flow–structure interaction. To the best of our knowledge, only one approach in this area has been made to date. Mahir and Rockwell (1996) employed forced vibration to study flow around tandem cylinders at a low Reynolds number $\mathrm{Re}=160$ and at two specified pitch ratio $P/D=2.5$ and 5. They identified the corresponding lock-in region in the plane of $\{A/D, f_e\}$ (f_e—excitation frequency) and characterized frequency responses in the wake.

In the present research, we focus on the characterization of flow patterns around two cylinders in tandem arrangement under forced vibration conditions via qualitative flow visualization. For this type of a flow–structure interaction, a large number of parameters can affect the flow. With particular interest in correlating flow behaviors between stationary and forced vibration cases, the present study concentrates on the detailed analysis of a small range of parameters: (i) the inflow is kept at a fixed low Reynolds number; (ii) the vibration is at a fixed low amplitude; and (iii) the pitch ratio varies in a small range around the SBB–SLR border only (defined in stationary state). This research is expected to enhance the fundamental understanding of the interaction between the flow and tandem cylinders under forced vibration.

2. Experimental method

Two circular cylinders of equal diameter in tandem arrangement have been experimentally explored in a recirculating-type, free-surface water channel at the University of Toronto Institute for Aerospace Studies under specified flow and vibration conditions. Some important parameters, such as the cylinder diameter D, center-to-center spacing or pitch P, vibration amplitude A, vibration or excitation frequency f_e, and the free-stream velocity U, are defined in Fig. 1.

The experimental setup is schematically illustrated in Fig. 2. The water channel provides continuous, uniform flow with less than 0.5% free-stream turbulence intensity along its test section. It has a cross section of 609 mm (width) by 762 mm (height). The water depth in the test section is 690 mm. The main test section is preceded by a set of honeycombs and screens, followed by a 6:1 contraction. A bottom plate was employed to raise the floor by 63.5 mm. The plate was 12.7 mm thick, and had a sharp leading edge of 23.6°. Two identical cylinders, made of stainless steel rods of diameter $D=6.35$ mm, were painted black and vertically fixed in the channel. Above the water surface, the two cylinders were mounted to two