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Flow-induced vibrations of two circular cylinders in tandem arrangement. Part 1: Characteristics of vibration

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ABSTRACT

This paper presents the results of an investigation on the flow-induced vibration characteristics of two circular cylinders in tandem arrangement, with $L/D = 0.1$–3.2 and reduced velocity $U_r = 1.5$–26, where L is the gap spacing between the cylinders and D is the cylinder diameter. The cylinder vibration was restricted to a plane normal to the incident flow. Three different experimental conditions were examined: (i) both cylinders were allowed to vibrate; (ii) the downstream cylinder only was allowed to vibrate with the upstream cylinder fixed; and (iii) the upstream cylinder only was allowed to vibrate with the downstream cylinder fixed. Five Regimes I–V were identified, depending on L/D, fluctuating lift forces and vibration characteristics of the cylinders. In Regimes I ($0.1 \le L/D < 0.2$) and IV ($2 \le L/D < 2.7$), the cylinder vibration is absent. In Regime II ($0.2 \le L/D < 0.6$), both cylinders vibrate violently for $U_r > 6$, including a divergent vibration of the upstream cylinder. In this regime, the vibration amplitude of the downstream cylinder is strongly dependent on whether the upstream cylinder is vibrating or fixed, whereas that of the upstream cylinder is weakly dependent on the downstream cylinder. In Regime III ($0.6 \le L/D < 2$), the convergent vibrations of the two cylinders occur at and around $U_r \approx 6.7$. In this regime, the upstream cylinder vibration is completely suppressed when the downstream cylinder is fixed, but the downstream cylinder vibration is almost independent on the upstream cylinder. Regime V corresponds to $L/D \ge 2.7$, where the two cylinders are separated sufficiently far, thus each vibrating like an isolated cylinder at and around $U_r \approx 6$. In this regime, the downstream cylinder vibration is strongly dependent on the upstream cylinder, but the upstream cylinder vibration is almost insensitive to the downstream cylinder condition.

1. Introduction

Many engineering structures are in arrays, such as groups of chimney stacks, tubes in heat exchangers, overhead power-line bundles, bridge piers, stays, masts, chemical reaction towers, off-shore platforms, adjacent skyscrapers, etc. A group of two cylinders are frequently used as a representative configuration of multiple structures. Most of the previous investigations have been performed on two rigid circular cylinders (Zdravkovich and Pridden, 1977; Zdravkovich, 1977; Gu, 1996; Gu and Sun, 1999; Sumner et al., 2000; Alam et al., 2003a, b, 2005; Alam and Sakamoto, 2005; Alam and Zhou, 2008). However, engineering structures are not always perfectly rigid and are rather frequently elastic. Zhou et al. (2001) studied the flow-induced vibrations on two side-by-side elastic cylinders. In their investigation, the structural vibration amplitude was very small, not exceeding 1% of the cylinder diameter. Similar studies concerning flow-induced aero-elastic vibration of structures in groups are not many.

Steady and fluctuating fluid forces acting on structures are mainly determined by flow around. The alternate shedding of vortices in the near wake leads to a fluctuating force on the structures. The non-linear coupling between the fluctuating force and the elastic structures may lead to structural vibration, acoustic noise, or resonance, and even trigger structural failure, which could cost millions of dollars. Thus, it is not surprising that extensive investigations have been conducted in the past to study the flow-induced response of multiple structures. A pair of two cylinders in the tandem arrangement could be chosen as the simplest case of a group of structures.

King and Johnes (1976) investigated the vibration characteristics of a cylinder placed downstream of another for spacing ratio $L/D = 3.5$–7. They observed the synchronization of the downstream cylinder vibration with that of the upstream cylinder. Ruscheweyh (1983) and Bokaian and Geoola (1984a, b) observed the vibration of a cylinder in the wake of another, and referred to the vibration as

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the wake-galloping. Cooper and Wardlaw (1971) unveiled that the wake-galloping vibration of the downstream cylinder occurred until $L/D = 20$. Lam and To (2003) conducted an investigation on the flow-induced vibration of the downstream cylinder, whose diameter was the half of the upstream cylinder diameter. Being larger, the upstream cylinder sheltered the downstream, which experienced no vibration. Laneville and Brika (1999, 1997) coupled two cylinders mechanically using thin wires and clarified relationship between the vibration displacement and phase of two cylinders. In spite of these, there are few studies concerning the flow-induced vibration of the downstream cylinder behind a fixed upstream cylinder (Tanida et al., 1973; Zdravkovich, 1974; Brika and Laneville, 1999). However, vibration of the upstream cylinder in front of a fixed downstream has not been investigated yet. Additional references concerning flow-induced vibrations of two cylinders, mostly on $L/D > 7$, can be found in Zdravkovich (1988). Studies pertaining to a systematic measurement of flow-induced vibrations at $L/D < 3.5$ are very scant.

Flow around two tandem circular rigid cylinders has been investigated from the subcritical Re to the supercritical (e.g., Okajima, 1979). In general this flow may be classified as three regimes based on L/D (Zdravkovich, 1987): (1) extended-body regime, where L/D is from 0 to 0.5 and the free shear layers separated from the upstream cylinder overshoot the downstream; (2) reattachment regime, where L/D is between 0.5 and 3, and the shear layers reattach on the downstream cylinder; and (3) co-shedding regime, where $L/D > 3$ and the shear layers roll up alternately, forming a vortex street in the gap between as well as behind the cylinders. Alam et al. (2003a) further divided the reattachment regime into two: regime of alternating reattachment of the shear layers ($L/D < 2$) and regime of steady reattachment of the shear layers ($L/D = 2$–3). The regime of alternating reattachment corresponds to a higher fluctuating lift force coefficient C_{Lf} specially on the downstream cylinder and the regime of steady reattachment corresponds to a lower C_{Lf} on both cylinders. It should be noted that the classification of the flow regimes for rigid cylinders is dependent on Reynolds number (Re) (Xu and Zhou, 2004). Naturally, the L/D ranges of the five regimes observed for flexible cylinders may differ at a very high Re.

The wake of two tandem cylinders in each regime has been investigated in detail in Zhou and Yiu (2006). It is the vortex-induced vibration of the two cylinders that needs attention. As the flow-induced vibration of a cylinder is linked with C_{Lf}, it is important to know how C_{Lf} of the two tandem-rigid cylinders depends on L/D. Fig. 1 shows the C_{Lf} distribution of two rigid

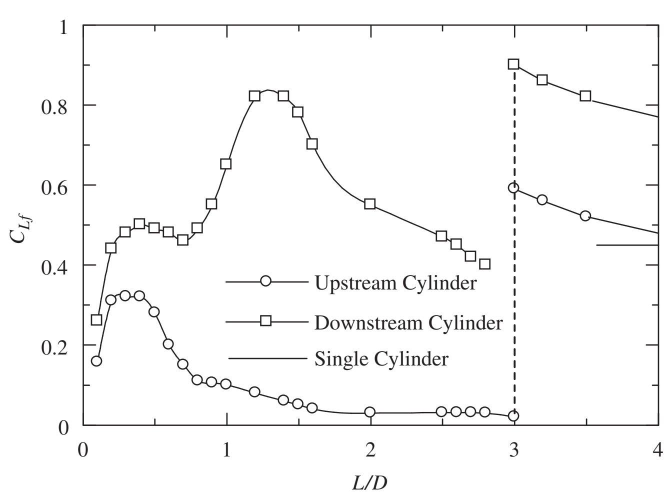

Fig. 1. Fluctuating lift coefficient C_{Lf} of two cylinders in tandem arrangement with changing L/D (Alam et al., 2003a).

cylinders in the tandem arrangement for $L/D = 0.1$–4.0 including the reattachment ($L/D < 3.0$) and co-shedding flow ($L/D > 3.0$) regimes. $L/D = 3.0$, where C_{Lf} jumps from a lower magnitude to a higher one, is the critical spacing or sometimes referred to as the transition spacing of the two flow regimes (e.g., Alam et al., 2003a). A higher C_{Lf} of the upstream cylinder is observed at $L/D = 3.0$ for the co-shedding flow and that of the downstream cylinder is at $L/D = 1.4$ and 3.0 for alternating reattachment and co-shedding flow, respectively (see Alam et al., 2003a for details). C_{Lf} varies rapidly with L/D due to interference between the cylinders. Given two elastic cylinders, it is of fundamental interest to understand: (i) how the flow-induced vibration varies with L/D and (ii) the difference in the vibration characteristics between elastic and rigid cylinders.

This work aims to investigate experimentally flow-induced vibration characteristics on two tandem closely separated cylinders ($L/D = 0.1$–3.2), covering: (i) flow-induced structural response, (ii) artificial perturbation effect, and (iii) interference between their vibrations. Furthermore, a forced vibration test was performed in water channel to reproduce the vibration amplitude of the free vibration at given reduced velocity in order to clarify the generation mechanism of the flow-induced vibrations.

2. Experimental details

The free-vibration tests were carried out in a closed-circuit rectangular wind tunnel with a test section of 0.35 m wide, 1.2 m high and 3 m long. Two circular cylinders, each 66 mm diameter, were spanned in the horizontal 0.35 m dimension of the tunnel. The cylinders to be as light as possible were made of polyurethane and covered with a 0.2 mm aluminum plate. The shaft supporting the cylinder was from aluminum pipe of 10 mm in diameter and secured at both ends with support assemblies outside the wind tunnel (Fig. 2). Each support assembly of the test cylinder consisted of two leaf springs of 0.3 mm thick (phosphor bronze) and two coil springs, allowing the cylinder to vibrate only in the vertical direction (cross-flow). The vibration displacement of the cylinder was measured by a laser displacement meter. Flow velocity was measured using a propeller-type velocity meter. The vortex shedding frequency was determined from a spectrum analysis of fluctuating velocity measured using a hot wire placed at $3D$ downstream and $1.5D$ lateral from the center of the downstream cylinder. The reduced velocity U_r [$= U_\infty/(f_c D)$, where U_∞ is the free-stream velocity and f_c is the natural frequency of a installed cylinder] was varied from 1.5 to 26, but the reduced mass-damping factor Cn [$= 2m\delta/(\rho D^2)$, where m is the cylinder mass of unit length, δ is the logarithmic decrement, and ρ is the density of fluid] was kept at around 6.36. U_∞ was varied from 1 to 17 m/s, corresponding to $Re = 4365$–74 200. When the cylinders do not vibrate naturally, a perturbation (initial artificial oscillation) on the cylinder was produced by fingers, and its effect on the cylinder vibrations was observed. The interference between a vibrating cylinder and the other was examined by fixing a cylinder with the other allowed to vibrate.

Flow visualization was carried out in a water channel with a 2-m-long test section of 0.30 m in width and 0.4 m in depth to observe the flow structure around the vibrating cylinders. The cylinders were forced to vibrate through a vibration system, as shown in Fig. 3. The system consists of a motor, crankshaft and X axis stage. Rotation of motor generates reciprocating motion of two acrylic boards and hence that of the cylinders in the cross-flow direction. The vibration amplitude and phase between the cylinders could be varied by a proper adjustment in the X axis stage. U_r may be adjusted by changing the cylinder vibration frequency. The flow structure was visualized using the hydrogen