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# Flow-induced vibrations of two cylinders of different natural frequencies

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ABSTRACT

The paper presents an experimental investigation on characteristics of flow-induced vibrations of two tandem cylinders of different natural frequencies. Both cylinders are allowed to vibrate in the cross-flow direction only. Six different natural frequency ratios $f_n^* (= f_{n,u}/f_{n,d}) = 0.6$, 0.8, 1.0, 1.2, 1.4 and 1.6 are considered, where $f_{n,u}$ and $f_{n,d}$ are the natural frequencies of the upstream and downstream cylinders, respectively. The spacing ratio $L/D$ (where $L$ is the spacing between the two cylinder centers and $D$ is the diameter) is considered as 1.5 and 2.0. Simultaneous measurements of vibration and frequency responses and vortex shedding frequencies are conducted using laser vibrometers and hotwires, respectively. The results indicate that in the galloping vibration regime there is a critical reduced velocity at which the amplitude of the downstream cylinder drastically jumps and that of the upstream cylinder may drop, depending on $f_n^*$. The jump/drop is connected to a lock-in of the vortex shedding with the fifth harmonics of $f_{n,d}$. The different natural frequencies of the cylinders may suppress both vortex-excited and galloping vibrations of the cylinders at different reduced velocity ranges. The vibration response and its connections with the frequency ratio are elucidated. How the different natural frequencies of the upstream and downstream cylinders affect the vortex shedding frequency in the wake is also illustrated.

## 1. Introduction

Combinations of multiple cylindrical structures appear widely in various engineering fields, such as risers, undersea pipelines, masts, groups of chimney stacks, transmission line bundles, chemical reaction towers, etc. Two tandem cylinders may be a representative model that can render us an insightful knowledge of the flow around multiple cylindrical structures. Two fixed, supported tandem cylinders have been prevailingly studied, concentrating on the flow structure (Lin et al., 2002; Jester and Kallinderis, 2003; Alam et al., 2005; Alam and Meyer, 2011; Alam and Meyer, 2013), fluid forces (Arie et al., 1983; Alam et al., 2003; Alam, 2016), Strouhal numbers (Igarashi, 1981; Alam, 2014), etc. See recent reviews by Sumner (2010) and Zhou and Alam (2016) for two fixed cylinders. Nevertheless, engineering structures are not always perfectly rigid but are elastic.

Flow-induced vibrations (FIV) of two elastic tandem cylinders have been extensively studied in the literature. When the two cylinders are free to vibrate in two-degree of freedoms, King and Johns (1976) performed experiments in a water tunnel for cylinder center-to-center spacing ratio $L/D = 1.25$–$7.0$ at a mass-damping ratio $m^*\zeta = 0.051$, where $D$ is the cylinder diameter, $m^*$ is the cylinder mass ratio, and $\zeta$ is the structural damping ratio. At $L/D = 2.5$, the upstream cylinder response shows a typical vortex excitation (VE) pattern. The maximum amplitude for the downstream cylinder occurs at a reduced velocity $U_r (= U_\infty/f_n D) = 7.7$ (where $U_\infty$ is the freestream velocity and $f_n$ is the natural frequency of the cylinder system), with the amplitude decreasing exponentially after the maximum. Vortex excited vibration or vortex excitation corresponds to the occurrence of vibration due to the resonance or lock-in where the vortex shedding frequency $f_v$ coincides with $f_n$. The vibration occurring at a higher or lower $f_v$ than $f_n$ is known as galloping. Huera-Huarte and Bearman (2011) conducted experiments on FIV of two tandem cylinders for $L/D = 2.0$–$4.0$ at $m^*\zeta = 0.043$. The upstream cylinder experiences a larger vortex-excited vibration than the downstream one for $L/D = 2.0$–$2.5$ at $U_r = 4$–$9$ where $f_v$ is close to $f_n$. At $L/D = 3.0$–$4.0$, the downstream cylinder exhibits galloping vibrations for $U_r > 9$. The phase lag between the cylinder displacements varies with $L/D$. In the VE regime ($3 < U_r < 9$), the phase lag increases monotonically from 0° to 180°. Brika and Laneville (1997) and Laneville and Brika (1999) examined the response of the downstream cylinder with the upstream cylinder stationary or vibrating for $L/D = 7$–$25$, $U_r = 4$–$25$ and $m^*\zeta = 0.00007$. When the upstream cylinder is free to oscillate, the downstream cylinder response is strongly dependent on $L/D$. The maximum vibration

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amplitude and the synchronization region decrease with increasing $L/D$. Kim et al. (2009) at $m^*\zeta = 0.65$ performed wind tunnel experiments on two tandem cylinders both free to vibrate in the cross-flow direction for $L/D = 1.1$–$4.2$ and $U_r = 1.5$–$26$. They observed different responses at different $L/D$. No cylinder vibrates at $1.1 \le L/D < 1.2$ and $3.0 \le L/D < 3.7$. Both cylinders vibrate violently at $1.2 \le L/D < 1.6$ together with VE. At $1.6 \le L/D < 3.0$, VE is observed for both cylinders at $U_r$ smaller than that for a single isolated cylinder. At $L/D \ge 3.7$, each cylinder vibrates like an isolated cylinder. At $1.2 \le L/D < 1.6$ and $L/D \ge 3.7$, the downstream cylinder vibration has a small influence on the upstream cylinder vibration, but the influence of the upstream cylinder vibration on the downstream cylinder is very significant. The opposite relationship prevails at $1.6 \le L/D < 3.0$. Obviously, the mutual impacts of the initial conditions (vibrating or fixed) between the cylinders differ at different regimes. With $L/D$ varying from 1.2 to 6.0, vibration responses of the cylinders are systematically measured by Sun et al. (2015) for a larger range of $U_r$ (= 3.8–47.8). Based on the characteristics and galloping vibration generation mechanism, the vibration responses are classified into four regimes. Regime I ($L/D \le 1.5$) is characterized by both cylinders experiencing galloping vibrations and the downstream cylinder vibration amplitude smaller than the upstream cylinder. At Regime II ($1.5 < L/D < 2.5$), the galloping vibration is larger for the upstream cylinder than the downstream cylinder at smaller $U_r$, but the opposite prevails at larger $U_r$. At Regime III ($2.5 \le L/D \le 3.0$), the downstream cylinder vibration amplitude is larger than the upstream cylinder. Regime IV ($L/D > 3.0$) features small vibration for the downstream cylinder and no vibration for the upstream cylinder.

The past investigations were mostly concerned with two identical tandem cylinders which have the same natural frequency. However, the adjacent cylindrical structures may always not have the same natural frequency but may be of different frequencies. In addition, a flexible slender cylinder may have many natural frequencies associated with its structural modes, and the cylinder is usually excited at multiple modes. The number of dominant frequencies of the vibration response may augment with increasing $U_r$, vibration moving from one mode to another (Chaplin et al., 2005; Huera-Huarte et al., 2014). The amplitude of the response in each mode grows as $U_r$ is increased through its lock-in range until it discontinuously falls. It grows again as the next mode becomes dominant with the next lock-in appearing. The downstream cylinder essentially confronts a disturbed flow while the upstream cylinder undergoes the freestream flow (Huera-Huarte et al., 2016; Qin et al., 2017; Wang et al., 2018). As such, for two flexible tandem cylinders, different modes or natural frequencies may be excited, leading to different response frequencies. Consequently, a pair of cylinders of different natural frequencies is an important issue to be considered. To the best of the authors' knowledge, there is not a single systematic study of the flow-induced vibration of two cylinders (staggered, side-by-side or tandem) of different natural frequencies. Thus, a number of issues might arise. For instance, what is the effect of different natural frequencies of two elastic tandem cylinders on their vibration responses? While vibrations of two cylinders of an identical natural frequency are dependent on each other, can two cylinders vibrate at two different natural frequencies, respectively, given the two cylinders interacting each other? How do the different vibration frequencies influence the downstream vortex shedding frequency?

This work aims to experimentally investigate FIV responses of two tandem cylinders of different natural frequencies, where both cylinders are free to vibrate in the cross-flow direction. Two $L/D$ (= 1.5 and 2.0) are chosen from regimes I and II, respectively, based on the vibration regimes in Sun et al. (2015). Vibration responses of the cylinders are systematically measured for a large range of the incoming flow velocity $U_\infty = 0.6$–$16$ m/s, corresponding to $Re = 1.2 \times 10^3$–$3.2 \times 10^4$. Besides, simultaneous measurements of vortex shedding frequencies behind the downstream cylinder along with the vibration response are conducted to have a mutual discussion on the vibration response and shedding frequencies.

## 2. Experimental setup

Experiments were performed in a low-speed, closed-circuit wind tunnel with a test section of 2.4 m in length, 0.6 m in width and 0.6 m in height. The two cylinders were mounted in tandem in the horizontal midplane of the test section. Fig. 1 shows a schematic of the experimental setup, definitions of symbols, and coordinates ($x'$, $y'$, $z'$) and ($x$, $y$, $z$) with the origins defined at the upstream- and downstream-cylinder centers at the midspan, respectively. Both cylinders were hollow, made of plexiglass, with the outer diameter $D = 30$ mm, inner diameter 27 mm, and length $l = 540$ mm. The mass ratio $m^* = m/m_f = 4m/(\pi\rho D^2 l)$ was 453,

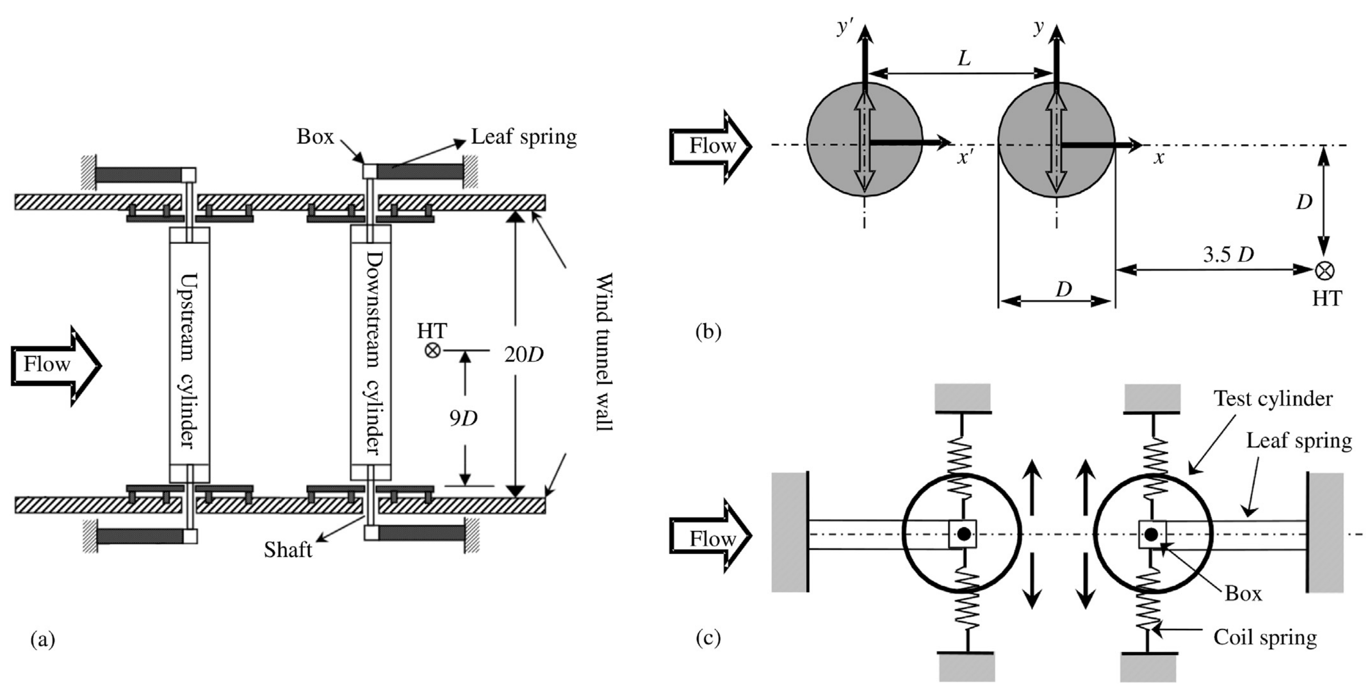


**Fig. 1.** (a) Experimental setup, (b) definition of symbols, (c) the cylinder support system.