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Wake and suppression of flow-induced vibration of a circular cylinder

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A R T I C L E I N F O

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This experimental study examines the wake flow and the flow-induced vibration of an elastically supported circular cylinder (referred to as test cylinder, of diameter D), and then the suppression of the flow-induced vibration by a control cylinder (of diameter 0.5D) installed behind the circular test cylinder is investigated at Reynolds number $\mathrm{Re} = 1.4 \times 10^4$–$3.2 \times 10^4$ corresponding to the reduced velocity $U_r = 0.4$–22. The streamwise and lateral separations of the control cylinder from the test cylinder center are varied as 0.2D - 1.1D and 0 - 1.7D, respectively. The vortex trail encompassing the vortex generation to the disappearance in the wake of the test cylinder is identified by means of wake energy distributions obtained from power spectra of fluctuating streamwise velocities. Based on the energy distributions, the control cylinder positions are determined to suppress the flow-induced vibration. The process of vortex 'Generation → Growth → Disappearance' in the wake of a vibrating cylinder occurs closer to the cylinder compared to that of a non-vibrating cylinder. The lateral separation between the two rows of vortices for a vibrating cylinder is found to be smaller. The controlled vibration responses of the cylinder are classified into four patterns (I, II, III, and IV) depending on the control cylinder position. Patterns I and II, both self-limited amplitude vibrations, are characterized by the occurrence of vibrations at a smaller and a larger U_r, respectively, compared to the non-controlled counterpart. Pattern III represents an increasing vibration amplitude with an increase in U_r, resembling a galloping vibration. Pattern IV features vibration suppression resulting from the suppression of the Karman street in the wake. This regime is divided into two subregimes, IV-A and IV-B. While the interaction between the gap flow and freestream side shear layer of the test cylinder succeeds in the suppression of the Karman street in pattern IV-A, that between the gap shear layer and the control cylinder gives rise to the suppression of the Karman street in pattern IV-B.

1. Introduction

Circular cylindrical structures are commonly seen in our daily lives such as risers, bridge piers, pipelines, most of which stand against flowing fluids. The alternate vortex shedding from the structures may produce a large fluctuating pressure on the structures, causing structural vibrations, acoustic noise, and even resonance, which can trigger structural failure. Numerous failures in the practical applications of cylindrical structures in cross flow are illustrated in Chen (1987), Païdoussis (1993) and Blevins (1990). The cost associated with a typical engineering structural failure can easily reach the order of one million dollars and even billions of dollars. Naturally, there is a pressing need to study and to understand the fluid dynamics associated with multiple cylindrical structures in cross flow. Accordingly, many studies have delved into the interaction between flowing fluid and structures.

Flow-induced vibrations of two identical diameter cylinders in tandem, staggered and side-by-side arrangements are studied by Kim et al. (2009a), Alam and Kim (2009), and Kim and Alam (2015), respectively, where they found that flow-induced vibration characteristics of the cylinders are highly contingent on the cylinder arrangement and spacing between the cylinders. Kim and Alam (2015) for two side-by-side identical cylinders identified four vibration response patterns, namely (i) the two cylinders vibrating at a large amplitude in the same range of U_r at $0.1 \le T^* < 0.2$, (ii) no vibration generated for either cylinder at $0.2 \le T^* \le 0.9$, (iii) the two cylinders vibrating at different ranges of U_r at $0.9 < T^* < 2.1$, and (iv) each cylinder response resembling an isolated cylinder response at $2.1 \le T^* \le 3.2$, where T^* is the cylinder gap spacing ratio. Lam and To (2003) performed an experimental study where the downstream cylinder was flexible and half in diameter than the upstream cylinder. No vibration was observed. The cause of no vibration was attributed to the fact that the upstream cylinder of being larger diameter shelters the downstream cylinder. Tu et al. (2014) numerically studied

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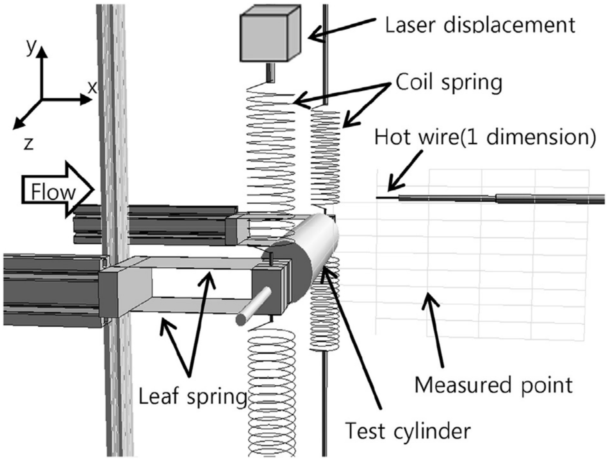

Fig. 1. Free-vibration experimental setup and coordinate system.

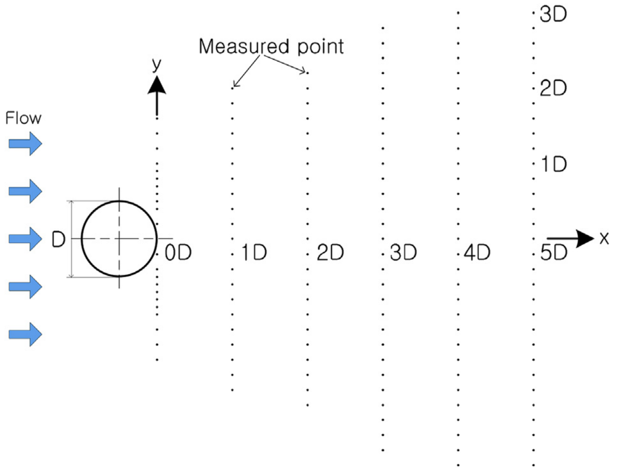

Fig. 2. Position of velocity measurements using a one-dimensional hot-wire probe.

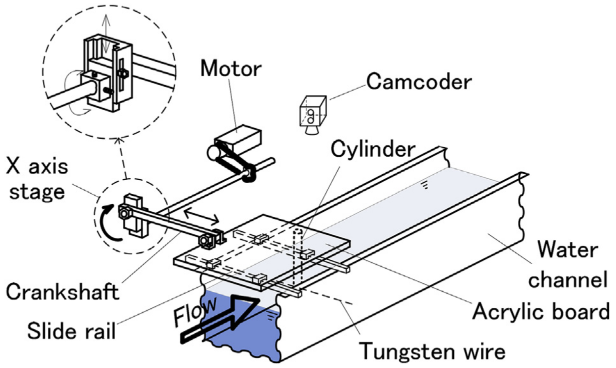

Fig. 3. Visualization test equipment using water channel.

flow-induced vibrations of an elastically mounted circular cylinder subjected to a planar shear flow with the single- (only cross-flow direction) and two-degree of freedoms (both in-line and cross-flow directions) in the laminar flow (Re = 150). The effects of shear rate ($k = 0.0$–0.1), reduced velocity ($U_r = 3.0$–12.0) and natural frequency ratio ($r = 1.0$–2.0) on the characteristics of vortex-induced vibration (VIV) responses were studied. Chen et al. (2013) investigated the VIV of a circular cylinder under a suction flow, reporting an optimal suction flow

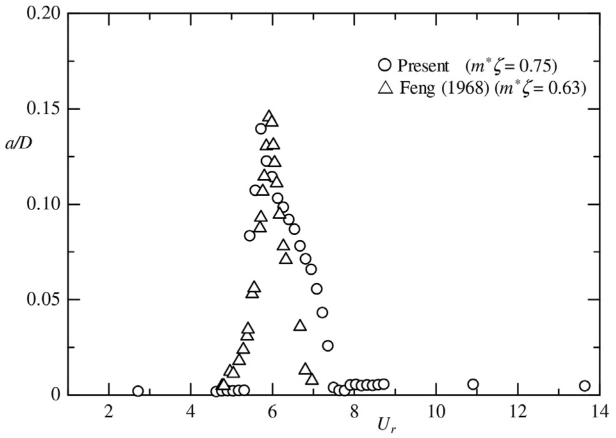

Fig. 4. Flow-induced vibration response of the test cylinder (no control): dependence of amplitude ratio a/D on reduced velocity U_r.

rate at which VIV was completely suppressed. The rotary oscillation control can be implemented to suppress the response amplitude of VIV by locking the vortex shedding frequency at the forcing frequency. Using a traveling wave wall method, Xu et al. (2014) focused on the suppression of the VIV of an elastically supported circular cylinder with a two-degree of freedom at a low Re = 200.

To investigate the feasibility for the flow control around a cylinder, Strykowski and Sreenivasan (1990) used a control cylinder of the diameter ranging from 0.05D to 0.33D and observed that a placement of a smaller cylinder in the near wake of the cylinder can alter the vortex shedding. The temporal growth rate of disturbances was weakened and drag was reduced. Zhao et al. (2007) performed a similar numerical investigation using a control cylinder of diameter 0.5D. Sakamoto et al. (1991) examined the suppression of the fluid forces by adding a control cylinder in a shear layer of a square cylinder. The reduction was, however, more for the fluctuating forces than for the time-mean forces, 95% for fluctuating lift, 75% for fluctuating drag, and only 30% for time-mean drag. Wu et al. (2012) conducted experiments with a focus on vibration suppression of a deepwater riser by using four control cylinders, each of diameter of 0.25D. The vibration was suppressed for certain configurations. The mechanism of vibration suppression, however, remained unclear. Igarashi and Terachi (2002) examined the wake of a flat plate adding a control cylinder of diameter (0.04–0.4)D and found a larger reduction in drag for a larger diameter control cylinder.

Wu et al. (2014) numerically investigated VIV characteristics of a cylinder controlled by a hinged flat plate. The addition of the hinged plate efficiently suppressed the VIV of and force fluctuations on the cylinder. An active control method for suppressing VIV response of an elastically mounted cylinder by forcing rotary oscillation was presented by Du and Sun (2015). Kim et al. (2009b) used tripwires to suppress VIV and galloping vibrations of a single and two tandem cylinders. Tripping wire positions α measured from the leading stagnation line of the cylinder were changed from $\alpha = \pm 20°$ to $\pm 60°$ to determine the optimum range of α for suppressing structural vibrations. The vibrations on both cylinders were completely suppressed for $\alpha = 20°$–$30°$. Lu et al. (2014) in a laminar flow investigated the effect of rod-to-cylinder spacing ratio, rod and cylinder diameter ratio, Re, and angle of attack on the main circular cylinder. It was observed that the range of the spacing ratio where significant force suppression is achieved becomes narrower as the Re increases in the laminar regime but was insensitive to the diameter ratio.

Among the studies delving into the topics associated with circular cylinders, the studies that examined the suppression of vibration and fluid forces provide some basic techniques to prevent failure or to extend the service life of cylindrical structures. This study aims (i) to identify the behavior of vortex flow created by a free-vibrating circular cylinder and to investigate some aspects, like the vortex generation, growth, decay,