



Power extraction using flow-induced vibration of a circular cylinder placed near another fixed cylinder



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ABSTRACT

We conducted an experiment in a towing tank to investigate the performance of an energy extraction system using the flow-induced vibration of a circular cylinder. This experiment tested three different cases involving the following arrangements of cylinder(s) of identical diameter: the upstream fixed–downstream movable arrangement (case F); the upstream movable–downstream fixed arrangement (case R); and a movable isolated cylinder (case I). In cases F and R, the separation distance (ratio of the distance between the centers of the two cylinders to their diameters) is fixed at 1.30. Measurement results show that while cases F and I generate vortex-induced vibration (VIV) resonance responses, case R yields wake-induced vibration (WIV) at reduced velocity over 9.0, which is significantly larger than that of the VIV response, leading to the induction of higher electronic power in a generator. Accordingly, primary energy conversion efficiency is higher in the case involving WIV.

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1. Introduction

Arrangements of multiple slender and long structures close to each other are used in many engineering applications such as pipe work in an energy plant, chimney stacks, and bridges. In a few of these structures, many of the cylinders used are directly exposed to fluid flows. It has been found that these cylinders vibrate considerably when the fluid flow velocity is within a certain range. Prolonged vibration can cause serious damage to structures or result in the development of fatigue in structural materials. Therefore, mechanical engineers and fluid–structure interaction researchers have expended considerable efforts on suppressing such vibration.

In a slender, long body subject to fluid flow, vibrations are caused by oscillatory fluid forces acting on the body. Placing the body in a fluid flow produces complex flow patterns downstream of the body. Such patterns comprise thin layers containing large velocity shear, deflected streams, wake regions, and vortices formed behind the body and then consecutively shed from the body, thereby exerting fluid force on the body. VIV ascribed to the fluid phenomenon has been studied extensively because it is a crucial design factor in terms of structural safety apart from being of much scientific interest.

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The fluid dynamic mechanism of the vibration of multiple slender and long bodies in proximity is to some extent similar to the mechanism of the VIV of a single body; however, these two types of vibration are generally regarded as different phenomena because the response of a body varies largely depending on its proximity to other bodies.

Several previous works on the response of two adjacent cylinders have clarified that the response has very large amplitudes for a wide range of flow velocities with a certain distances between two cylinders (separation distance), both in-line and transverse to the flow direction [1–10]. Vibration amplitude monotonically increases with flow velocity; this is in contrast to the amplitude of the VIV of a single cylinder, which is large within a limited range of flow velocities. Fluid dynamic explanations for very large amplitudes, which are unique to two cylinders, have been provided in previous works, a few of which note that if a vortex generated behind a body interferes with an adjacent body or with other vortices generated behind another body, vibratory responses of these bodies are more intense than the VIV response of an isolated body. In particular, a strong flow formed at the gap between the two cylinders, i.e. the gap flow plays an important role in enhancing the amplitude. On the basis of their understanding of such a response as a type of fluid dynamic instability, Bokaian and Geoola [3] refer to it as wake-induced galloping. Assi et al. [10] refer to it as WIV: we use this term in this paper to refer to the response of two cylinders, as presented below.

Our study attempts to develop a WIV-based renewable energy technology. The concept of extracting available energy through flow-induced vibration has been considered previously. Bernitsas et al. [11,12], Raghavan and Bernitsas [13], and Lee et al. [14,15] developed the VIV aquatic clean energy (VIVACE) converter, which consists of a spring, a generator, and a submerged cylinder. They experimentally investigated the influence of a few design parameters such as damping, mass ratio, and Reynolds number on the magnitude of generated electronic energy. Barrero-Gil et al. [16,17] theoretically addressed the properties of energy conversion through the galloping and VIV of a moving body by analyzing the equations of motion describing the galloping and VIV of a bluff body. Zhu et al. [18] developed a theoretical model for harvesting energy using oscillating flapping foils and identified parameter areas of large energy and high conversion efficiency.

We experimentally examined the output performance of the energy harvested from the vibratory motion of a circular cylinder mounted elastically close to a fixed cylinder, with the aim of extracting a greater amount of available power from WIV. To this end, the experimental apparatus used in our previous study [19] on energy conversion using VIV was recreated and installed in a towing tank in which we conducted power extraction measurements. The remainder of this paper is organized as follows. Section 2 describes the method of measurement and data processing. Section 3 details a method for estimating a power output, and Section 4 presents the obtained results. These results and a few proposed improvements are discussed in Section 5, and the conclusions of this study are presented in Section 6.

2. Experiment

2.1. Experimental equipment and data analysis

The experiment was conducted in a $(100 \times 8 \times 3.5) \text{ m}^3$ (length $\times$ breadth $\times$ depth) towing tank at Yokohama National University. We used two aluminum cylinders of identical diameter and span length (Table 1). These cylinders were towed with a carriage running along the length of the tank to reproduce a situation in which the cylinders are exposed to fluid flow (Figs. 1 and 2a). The first cylinder is movable, horizontally submerged, and supported elastically by coil springs, while the second is fixed adjacent to the first cylinder such that the two cylinders are in a tandem arrangement and the centerlines of the two cylinders are at the same height. The separation distance was fixed at $1.30D \text{ m}$ ($X/D=1.30$). Square acrylic plates were attached at both ends of the cylinders to avoid the influence of disturbances at cylinder ends on the measurements.

The motion of the movable cylinder includes horizontal excursions because the motion is rotational. However, the horizontal excursion length is on the order of $1.0 \times 10^{-5} \text{ m}$, which is considerably lower than the vertical excursion length; thus, the motion can be approximated as translational motion in the vertical direction. The cylinder motion is transmitted to a generator via the motion of rigid frames. The generator contains a ring-shaped coil made of an enameled wire, the oscillatory motion of which is driven by the cylinder motion and is accompanied by the insertion of a bar magnet into the coil, inducing an electric current in the enameled wire (Fig. 2b).

Towing velocity was measured using a rotary encoder. The displacement of the vibratory cylinder was measured using a laser displacement sensor (LM500, Keyence). Forces acting on the vibratory cylinder in the in-line and transverse directions were measured using strain gauges. Using strain amplifiers (AM10, Unipulse), bridge voltages were applied to the strain gauges for signal amplification. All digital signals generated by the abovementioned measurement equipment were recorded using a data logger (NR2000, Keyence). Before measurements in the towing tank, the strain gauges were loaded with standard weights for calibrating force–voltage conversion. Hydrodynamic forces were extracted by subtracting inertial forces from the measured forces because the strain gauges moving with the cylinder detect the inertial as well as the hydrodynamic forces.

2.2. Measurement conditions

The towing carriage was driven forward and backward to investigate the two following tandem arrangements: (1) the vibratory cylinder was at the rear and the fixed one was in the front (hereinafter, this case is referred to as case F, with the first letter of the term “front” identifying the position of the fixed cylinder), and (2) the vibratory cylinder was at the front

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