Journal of Fluids and Structures 79 (2018) 39–49

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Large-amplitude flow-induced vibration of cylindrical pendulums

Junyoung Kim, Minho Song, Daegyoum Kim *

Department of Mechanical Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

A R T I C L E I N F O

Article history:
Received 2 July 2017
Received in revised form 2 December 2017
Accepted 30 January 2018

Keywords:
Flow-induced vibration
Pendulum
Vortex-induced vibration
Wake-induced galloping
Energy harvesting

A B S T R A C T

We experimentally investigated the self-excited vibration of a cylindrical pendulum in a uniform flow as a fundamental step in evaluating its feasibility for energy harvesting. In the pendulum configuration, a cylinder is fixed to rigid plates via a thin elastic sheet so that it can swing perpendicularly to the free stream and cause periodic deformation of the elastic sheet. The dynamics of the pendulum were examined by varying free-stream speed and several geometric parameters of the cylinder. In contrast to past studies of vortex-induced vibration, which mainly used reduced velocity to characterize the pendulum dynamics, our study introduced non-dimensional free-stream velocity, which is the relative magnitude of the restoring bending moment of the sheet to the hydrodynamic moment acting on the cylinder. We confirmed that all pendulums converted to an oscillatory mode at similar non-dimensional velocity and had almost identical amplitude and frequency responses at given non-dimensional velocity. The pendulum was able to oscillate with the amplitude much larger than its diameter in the limited range of the non-dimensional velocity. Mutual interactions between the two cylindrical pendulums closely arranged in tandem were also investigated, and the dependence of the amplitude response on center-to-center distance and the transition from vortex-induced vibration to wake galloping were observed.

1. Introduction

In recent years, with the remarkable growth of interest in renewable energy, many studies have been conducted on energy harvesting, in particular, using the flow-induced vibration of a flexible structure such as a flag or a beam (e.g. Allen and Smits, 2001; Akaydin et al., 2010; Giacomello and Porfiri, 2011; Akcabay and Young, 2012; Singh et al., 2012; Michelin and Doaré, 2013; Shoele and Mittal, 2016). Rotary turbines have been conventionally used to extract energy from a fluid flow. However, the rotary turbine systems are not suitable for low flow-speed environments and small-scale applications such as wireless communication in remote areas, and for these applications energy harvesting systems using flow-induced vibration have been considered as one of the alternatives. A fluid flow can induce periodic deformations in a flexible structure, and the strain energy of the deformed structure can be converted to electrical energy using a piezoelectric material (Wang et al., 2011; Akaydin et al., 2012; Hobbs and Hu, 2012; Gao et al., 2013).

On the other hand, the flow-induced vibration of cylindrical structures in a uniform flow has been one of the central topics in fluid–structure interactions. Understanding the phenomenon is critical to determining the performance of many engineering systems, such as the tubes in a heat exchanger, the risers of an offshore plant, energy harvesters, and bio-inspired flow sensors (Beem et al., 2013). The oscillation of an elastically-mounted rigid cylinder with uniform spanwise

* Corresponding author.
E-mail address: daegyoum@kaist.ac.kr (D. Kim).

https://doi.org/10.1016/j.jfluidstructs.2018.01.011
0889-9746/

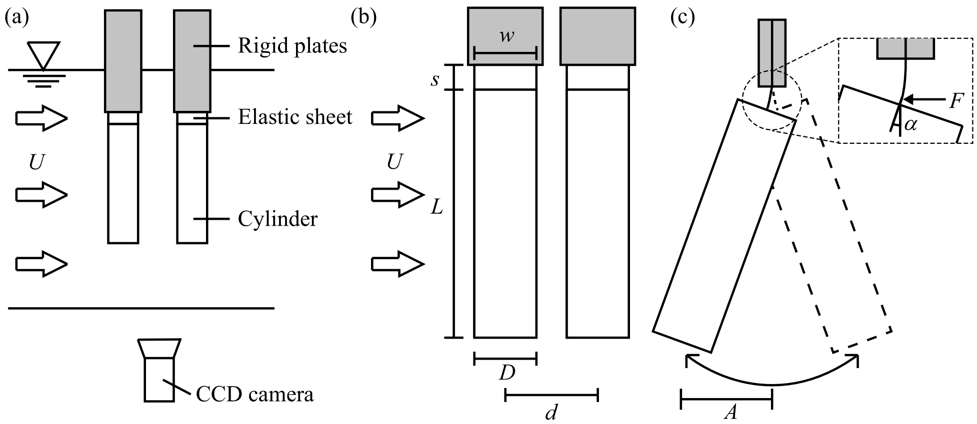

Fig. 1. (a) Experimental setup in a water tunnel for the single pendulum. (b) Schematic diagram of geometric parameters for the dual-pendulum case. (c) Swinging motion of the single pendulum from the front view.

amplitude has been actively studied in this regard (see Williamson and Govardhan (2004) and references therein). In this case, the cylinder has two distinct dynamic responses of the oscillating amplitude depending on a mass–damping parameter, $m^*\zeta$, where m^* is the mass ratio and ζ is the damping ratio. The mass ratio is the mass of an oscillating structure divided by the displaced fluid mass, and the damping ratio is defined as the ratio of a damping coefficient to a critical damping coefficient. Govardhan and Williamson (2000) confirmed that the amplitude of the cylinder exhibited two branches, an initial branch and a lower branch, for high mass–damping parameter values. They found that the amplitude increased with the reduced velocity in the initial branch, but decreased in the lower branch. The cylinder showed a jump in amplitude and frequency between the initial and lower branches. Also, in the cases with a low mass–damping parameter, along with the initial and lower branches, it displayed an additional branch named upper branch, which was distinctly larger in amplitude.

Expending the research on a cylinder with uniform amplitude, the mutual interaction of a pair of cylinders in tandem was actively explored for the combination of one fixed upstream cylinder and one free downstream cylinder oscillating in a transverse direction (Assi et al., 2006; Qin et al., 2017) or two free cylinders (Borazjani and Sotiropoulos, 2009; Prasanth and Mittal, 2009; Yu et al., 2016; Griffith et al., 2017). These configurations display dynamic patterns that are different from a single cylinder, depending on the center-to-center distance. The interaction of multiple cylinders elastically mounted was also investigated experimentally to evaluate the performance of a laboratory-scale energy harvesting system, the Vortex Induced Vibration for Aquatic Clean Energy (VIVACE) (Kim et al., 2013b).

Compared to the cylinder with uniform spanwise amplitude (i.e. the heaving motion of the two-dimensional cylinder), there have been few reports about the cylindrical structure which has a linear spanwise variation in amplitude (i.e. the swinging motion of a pendulum with respect to a fixed point). See Flemming and Williamson (2005) for various types of amplitude distribution. Flemming and Williamson (2005) investigated a pivoted cylinder vibrating in two degrees of freedom in a fluid flow. Like the cylinder with uniform spanwise amplitude, the pivoted cylinder showed initial, lower and occasionally upper branches based on the inertia-damping parameter, $I^*\zeta$. I^* is the inertial ratio where the moment of inertia of the cylinder is divided by that of the displaced fluid. Another study on a pivoted cylinder model with very low aspect ratio ($L/D = 0.3$–2.0) and small mass ratio ($m^* = 1.00$–4.36) showed that the mass ratio and the aspect ratio affected the amplitude of the cylinder in a transverse direction (Gonçalves et al., 2013). Even though many studies on the dynamics of a pair of cylinders with uniform amplitude have been conducted, a pair of cylinders with linear spanwise amplitude have not been investigated.

In this study, we investigate the dynamics of a cylindrical pendulum permitted to oscillate only in the transverse direction under a uniform stream. The cylindrical pendulum in this work is a cylindrical structure whose top is connected to fixed plates via a thin elastic sheet. The elastic sheet is clamped at both ends and can be bent side to side by the oscillation of the cylinder (Fig. 1). This cylindrical pendulum oscillates in one degree of freedom whereas the pivoted cylinder mentioned above mainly oscillates in two degrees of freedom. The bending rigidity of the elastic sheet can be varied to investigate the effect of sheet bending rigidity on the response of the pendulum, simply by changing its geometric parameters, such as height, width, and thickness. In practice, the elastic sheet can be replaced with a piezoelectric sheet to convert the deformation energy into electrical energy, and our pendulum configuration can thus be applied for energy harvesting. Although a similar model was studied in the perspective of electrical power generation using a wind tunnel (Abdelkefi et al., 2013), the characteristics of the responses for both single and dual cylindrical pendulums oscillating in a uniform free stream have not been investigated to the best of our knowledge.

In this work, first we examine the vibrating patterns of a single cylindrical pendulum and find a dimensionless parameter to characterize its response to a fluid flow by varying free-stream velocity and geometric parameters such as the length