Journal of Fluids and Structures 28 (2012) 103–114

Contents lists available at SciVerse ScienceDirect

Journal of Fluids and Structures

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

Tree-inspired piezoelectric energy harvesting

William B. Hobbs [a], David L. Hu [a,b,*]

[a] School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[b] School of Biology, Georgia Institute of Technology, Atlanta, GA 30332, USA

ARTICLE INFO

Article history:
Received 23 July 2010
Accepted 6 August 2011
Available online 22 September 2011

Keywords:
Vortex induced vibrations
Piezoelectric energy harvesting
Tandem cylinders

ABSTRACT

We design and test micro-watt energy-harvesters inspired by tree trunks swaying in the wind. A uniform flow vibrates a linear array of four cylinders affixed to piezoelectric energy transducers. Particular attention is paid to measuring the energy generated as a function of cylinder spacing, flow speed, and relative position of the cylinder within the array. Peak power is generated using cylinder center-to-center spacings of 3.3 diameters and flow speeds in which the vortex shedding frequency is 1.6 times the natural frequency of the cylinders. Using these flow speeds and spacings, the power generated by downstream cylinders can exceed that of leading cylinders by more than an order of magnitude. We visualize the flow in this system by studying the behavior of a dynamically matched flowing soap film with imbedded styrofoam disks. Our qualitative visualizations suggest that peak energy harvesting occurs under conditions in which vortices have fully detached from the leading cylinder.

1. Introduction

Energy harvesting is the process by which ambient energy is captured from external sources (thermal, wind, solar and hydrodynamic). One way to harvest energy is through the use of piezoelectricity, the ability of certain materials such as bone (Fukada and Yasuda, 1957), wood (Fukada, 1955) and ceramics to generate electric fields in response to mechanical strain. In this study, we investigate the feasibility of using biologically inspired kinetic sculptures to harvest energy by swaying in the wind. We examine primarily the use of ceramic piezoelectric transducers, but the principles we find may be applied to transducers composed of other materials.

While primarily used for sensing pressure, ceramic piezoelectric transducers have been recently implemented in several designs for fluid flow energy harvesting. They are envisioned for use in generating micro- and milli-watts for powering remote sensor networks and small-scale electronic devices. Some piezoelectrics replace electrical generators in conventional cam-driven rotating turbine designs (Priya et al., 2005). Other designs have been implemented to operate entirely differently from rotating designs. One example is the piezoelectric eel, an underwater sheet of piezoelectric polymer that oscillates in the wake of a bluff body (Taylor et al., 2001). The “oscillating blade” generator resembles a stalk of corn, in which a piezoelectric transducer connects a steel leaf spring to leaf-like ears (Schmidt, 1992).

Vortex-induced vibration is one of the primary mechanisms by which moving fluids cause objects to undergo oscillation, and is often capitalized upon in piezoelectric energy harvesting. The subject has a long history of experimental, theoretical and computational work, summarized in reviews by Bearman (1984), Williamson and Govardhan (2004), and

* Corresponding author at: School of Mechanical Engineering, Georgia Institute of Technology, 801 Ferst Drive, MRDC 1308, Atlanta, GA 30332-0405, USA. Tel.: +1 404 894 0573; fax: +1 404 894 8496.
E-mail address: hu@me.gatech.edu (D.L. Hu).

0889-9746/$ - see front matter
doi:10.1016/j.jfluidstructs.2011.08.005

Blevins (1990), and more recently in Bearman (2011) and Sumner (2010). For a single cylinder in uniform flow, the periodic shedding of vortices will generate lateral pressure asymmetries on the cylinder. If the cylinder is elastic, vibrations transverse to the flow direction will also occur (Tanida et al., 1973; Zhou et al., 1999). A second cylinder downstream from the first will also vibrate due to vortices shed upstream (Allen and Henning, 2003; Gaydon and Rockwell, 1999; Lin et al., 2002; Mittal and Kumar, 2001, 2004; Mizushima and Suehiro, 2005), and under certain circumstances with larger amplitudes than that of the first cylinder (Huera-Huarte and Bearman, 2011). To and Lam (2007) investigated the behavior of a flexible cylinder placed upstream of a large stationary cylinder. Three and four cylinders have been studied in various arrangements, but the effect of cylinder vibration on flow structure is less frequently taken into account. Several investigators have studied triangular arrays of fixed non-vibrating cylinders (e.g., Lam and Cheung, 1988; Tatsuno et al., 1998). An array of cylinders arranged traverse to the flow has been studied for the purpose of underwater energy harvesting of the ocean's currents (Bernitsas et al., 2008). However, the energy generation behind multiple elastic cylinders arranged in a line received little attention. This is precisely the configuration for an orchard of trees (de Langre, 2008; Dupont and Brunet, 2008), and in our energy-harvesting device.

In this study, we present the design of a new piezoelectric device that uses tree-like swaying to harvest wind energy. The power output of our design is on the order of micro-watts, which on the same order of magnitude as other piezoelectric energy devices. This level of power is adequate for powering ultra-low power micro-controllers with sensing, recording, and wireless communication capabilities. In Section 2, we overview our device design and use this physical picture to conduct a dimensional analysis of our design in Section 3. In Section 4, we describe the methods used to collect energy data from our device and to dynamically match our system to a flowing soap film used for flow visualization. In Section 5, we present our experimental results, focusing on characterizing peak energy generation of our device over a range of device spacings and flow speeds. In Section 6, we discuss the efficiency of our device and provide guidelines for setting up the device for maximum power generation. In Section 7, we discuss the implications of our work and suggest directions for future research.

2. Device design considerations

A photograph of our device is shown in Fig. 1. The device consists of cylinders affixed to the ground via piezoelectric disks. The disk orientation permits cylinder tilting only in the cross-flow direction only, as shown in Fig. 2. In our early tests, we found that more degrees of freedom were unnecessary. For example, two degrees of freedom resulted in 95% of the vibration occurring in the transverse direction, in agreement with the results of Jauvtis and Williamson (2004).

Previous approaches for studying elastic cylinders have focused on increasing the amplitude of oscillation by optimizing the reduced damping as shown in the so-called "Griffin plots" (Khalak and Williamson, 1999). We stress that their analysis does

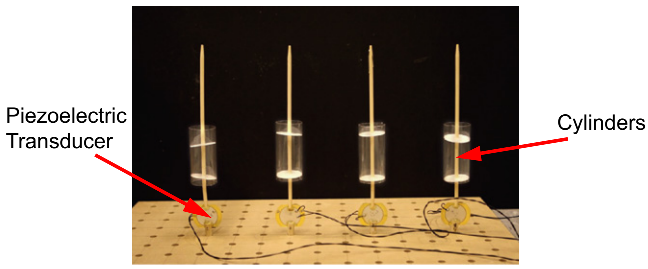

Fig. 1. Photograph of four piezoelectric devices in series.

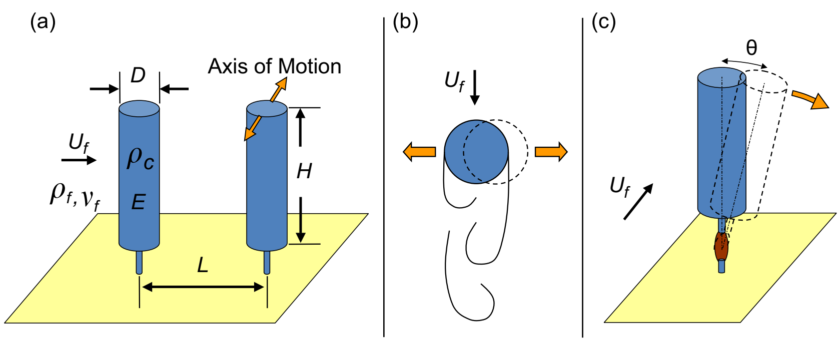

Fig. 2. Schematic diagrams illustrating the arrangement of energy-harvesting cylinders. (a) Side view of the cylinders, along with variables characterizing the properties of the flow and the cylinder. (b)–(c) Top and front views. Yellow arrows indicate the direction of cylinder vibration, which is transverse to the incoming flow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)