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Double-wall piezoelectric cylindrical energy harvester

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ABSTRACT

Cylindrical structures possess the advantage of responding multi-directional vibrations compared with cantilevers. In this paper a double-wall cylindrical energy harvesting device is proposed to scavenge multimode mechanical vibrations. Compared with the single-wall energy harvester, it is found from the finite element analysis that the double-wall device generates higher output voltage, and responds to a wider oscillating frequency range. These advantages have been validated by experiments, where the open circuit output voltage for eight resonating modes has been characterized. For further investigation, dynamic responses of the device at these eight resonating modes have been characterized under various excitations. It is seen from the experiment that as the driven voltage of the excitation source increases from 5 V to 16 V, the output voltage increases and the corresponding quality factors reduces.

1. Introduction

During the past decades, energy harvesters have been widely used in wireless sensor networks [1], mechanical structure health monitoring systems [2], and micro-air-vehicles powering units [3]. Energy harvesting can be achieved by transferring solar [4], thermal, and mechanical energy [5] into electricity. Since the mechanical vibration is commonly available, the vibrational energy harvesting devices have been intensively researched. Vibrational energy harvesters are normally categorized into three types in terms of transduction mechanism, which are electromagnetic [6], electrostatic [7], and piezoelectric [8]. This paper focuses on the piezoelectric vibrational energy harvesting devices. Several mechanical structures and operating mechanisms have been reported for piezoelectric vibrational energy harvesters. The rectangular cantilever is a general form of the energy harvesting device as it is easy to realize [9]. With the same volume of rectangular beam, Roundy et al. [10] devised a triangular trapezoidal beam achieving a better output performance. However, the cantilever devices are only effective in the first bending mode. In order to harvest multiple oscillating frequencies, Liu et al. [11] have fabricated an array of piezoelectric cantilevers with different lengths to respond more resonating frequencies. Schaufuss et al. [12] reported an approach by adjusting the position of the auxiliary mass to tune the external vibrating frequency. Liu et al. [13] proposed a double-mode energy harvester by placing an oscillator at the tip of the cantilever beam. Zhou et al. [14] achieved a novel energy harvester that enables harvesting energy from multimode resonance by introducing the multimode intermediate beam. Although the above developments have successfully improved the working efficiency, their configurations were complex and should be operated with the help of the auxiliary systems. In addition to the cantilever beam, Lee and Youn [15,16] introduced the concept of the multimodal energy harvesting skin to harvest the mechanical energy from multimode vibrations. Spiral-shape cantilever beam have been designed to harvest multiple resonant frequencies [17,18]. The piezoelectric cylindrical shell can be a potential structure to harvest multi-modal vibrations in real applications as it can be easily excited into both transverse and thickness shear vibrations [19,20]. Piezoelectric cylindrical shell has been widely used in ultrasonic motors [21], sensors [22], and resonators [23]. Models of tri-axial sensors and actuators made of a single piezoelectric cylindrical shell have been reported by Wakatsuki et al. [24]. Mazeika et al. proposed a new cylindrical piezoelectric actuator in which electrodes were segmented into several patches for verifying multimode responses [25]. Li and Tzou demonstrated a piezoelectric cylindrical vibrating energy harvester model to show the basic multi modal energy distribution in numerical methods [26]. This mechanism was later verified by their experimental study in a piezoelectric ring energy harvester in 2013 [27]. However, their models are all in simple support boundary conditions, which is different with our proposed clamped-free prototype. Furthermore, double cylindrical shells are reported in this paper for improving output electrical power and widening operation frequencies. The mechanical dynamic and vibration behaviors have been investigated in [28–30], it is a new approach to use it in energy

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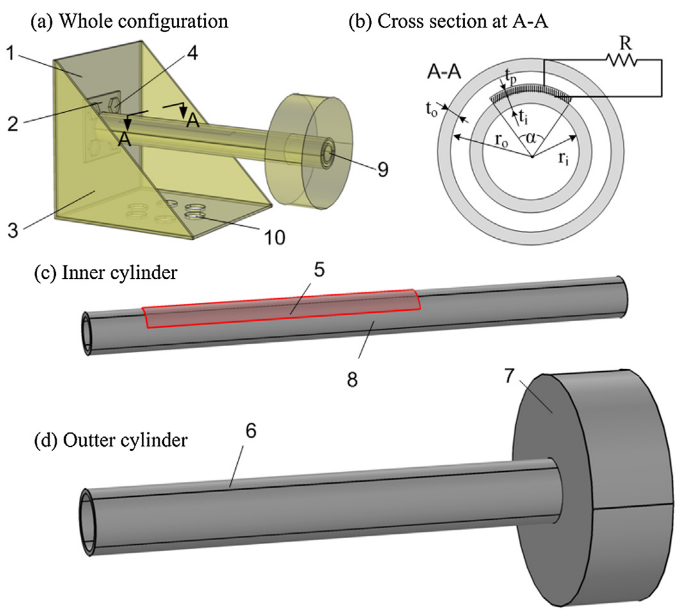

Fig. 1. (a) Schematic diagram of the double-wall cylindrical energy harvesting device, which includes: 1, L-shape fixture; 2, connecting plates used to connect outer cylinder with the fixture; 3, ribbed plates to enhance the stiffness of L-shape fixture; 4, screws to co-axially match the outer hollow cylinder with inner cylinder; 5, piezoelectric cylindrical patch; 6, outer hollow cylinder; 7, proof mass of outer cylinder; 8, inner hollow cylinder; 9, proof mass of inner cylinder; 10, screw holes to connect the assembled platform with vibrating shaker. (b) Cross-section at position A–A shown in Fig. 1(a), where R_i, R_o, α, t_i, t_p and t_o denote inner wall radius, outer wall radius, curved angle of piezoelectric layer, inner wall thickness, piezoelectric layer thickness, and outer wall thickness, (c) inner cylindrical shell and (d) outer cylindrical shell.

harvesting applications. The rest of this paper is structured as follows: schematic design of the double-wall cylindrical structure is shown in Section 2. Numerical analysis is conducted in Section 3. It follows by the description of experiment in Section 4. Finally, conclusions are drawn in Section 5.

2. Schematic design of the device

Schematic configuration of the double-wall piezoelectric cylindrical energy harvester is shown as Fig. 1(a). This device mainly consists of two steel cylindrical shells and a fixture. The fixture was machined into an L-shape so that the inertial masses move perpendicularly to the longitudinal axis of the cylinder to induce transverse motions. In order to enhance the fixture stiffness, two triangular ribbed plates were also welded along the L-shape plate edges. One end of the inner cylinder (Fig. 1(c)) was welded to the fixture directly, and the other end was attached with a proof mass. To make sure the outer cylinder gets through the inner shell, the proof mass was placed inside of the inner cylinder. Similarly, one end of the outer cylinder (Fig. 1(d)) was welded through a square connecting plate with screw holes and the other end was attached with a proof mass. The outer cylindrical shell was assembled co-axially with the inner wall. The whole assembled structure is excited with a vibrating source. Fig. 1(b) shows the cross-section of the double-wall cylindrical device. The symbols R_i, R_o, α, t_i, t_p and t_o represent the inner wall radius, outer wall radius, curved angle of piezoelectric layer, inner wall thickness, piezoelectric layer thickness, and outer wall thickness. The values for them are 3 mm, 5 mm, 75.4°, 0.8 mm, 0.11 mm and 0.8 mm, respectively. Fig. 1(c) and (d) show the detailed structures of both the inner and outer cylindrical shells. Lengths of the inner cylindrical shell, piezoelectric layer and outer cylindrical shell are 101 mm, 50 mm, and 100 mm. The radius and length of the inner proof mass are 3 mm and 15 mm. The inner radius, outer radius, and length of outer proof mass are 5.8 mm, 20.8 mm, and 15 mm. The piezoelectric layer is placed 10 mm away from the fixed end to leave enough space for the electric wire. Based on the direct piezoelectric effect, the vibration of the structure will induce charges on the surface of the piezoelectric layer. Simulation of the structure is conducted in the following section.

3. FEM simulations of cylindrical energy harvesting device

FEM (finite element method) simulations of the proposed cylindrical device are conducted using the software package ANSYS 12.0. In the numerical simulation, the piezoelectric layer is modeled by element Solid226. The external load resistor is included in the simulation using element type Circu94. Solid186 is used to model remaining mechanical structures. Dimensions of the model are set according to the design dimensions of the device. As for the material properties, we choose the PVDF for the piezoelectric material and mild steel for cylindrical substrate and remaining mechanical structures. The density, Poisson ratio, and Young's modulus of mild steel are 7860 kg/m^3, 0.3 and, 210 GPa, respectively. As the curved piezoelectric layer is polarized in the radius direction, and cylindrical coordinate system in ANSYS is set as (r, θ, z) in default, the stiffness matrix c^E_{ANSYS}, the piezoelectric coupling matrix e_{ANSYS}, and the dielectric coefficient matrix ε_{ANSYS} are detailed in Eq. (1). Values for the elasticity stiffness, the piezoelectric stress coefficients, and the dielectric coefficients of PVDF material are designated as $c_{11} = c_{22} = c_{33} = 3.933 Gpa$, $c_{12} = c_{21} = c_{13} = c_{31} = c_{23} = c_{32} = 1.6075 Gpa$, $c_{44} = c_{55} = c_{66} = 1.1628 Gpa$, $e_{13} = e_{23} = 0.0744$ C/m^2, $e_{33} = -0.0558$ C/m^2, $\varepsilon_{11} = \varepsilon_{22} = \varepsilon_{33} = 12$.

$$c^E_{ANSYS} = \begin{bmatrix} c_{33} & c_{32} & c_{31} & 0 & 0 & 0 \\ c_{23} & c_{22} & c_{21} & 0 & 0 & 0 \\ c_{13} & c_{12} & c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{55} \end{bmatrix}$$
$$e_{ANSYS} = \begin{bmatrix} e_{33} & 0 & 0 \\ e_{23} & 0 & 0 \\ e_{13} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \varepsilon_{ANSYS} = \begin{bmatrix} \varepsilon_{33} & & \\ & \varepsilon_{22} & \\ & & \varepsilon_{11} \end{bmatrix} \quad (1)$$

Electrodes across the surfaces of PVDF films are modeled as coupled elements. From the experimental observation, as the driving frequency is over 1254 Hz, both the output voltage and power become much smaller. Hence in the modal analysis, the range of the simulation conducted is set within 0–1200 Hz. Calculated resonant frequencies of the first 7 modes of a single cylindrical shell device are 156.336 Hz, 173.121 Hz, 362.856 Hz, 403.665 Hz, 896.086 Hz, 913.901 Hz, and 1160 Hz. The corresponding mode shapes of the piezoelectric layer are shown as Fig. 2, in which the first mode is the torsional mode, and second and sixth modes are pure bending modes in vertical direction. As for the third and fourth modes, bending and torsional modes exist simultaneously, while the torsional motion dominates in the third mode and the bending motion dominates in the fourth mode. In Fig. 2(e), both the vertical and lateral bending modes can be observed in the fifth mode. For the seventh mode, only extension motion along the length direction can be obtained. As for the double-wall cylindrical structure, there are 10 modes that can be obtained and the resonant frequencies are calculated to be 57.475 Hz, 63.768 Hz, 253.726 Hz,