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Vibration energy harvesting with a clamped piezoelectric circular diaphragm

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Abstract

With the rapid development of low power devices, the technology of energy harvesting has improved greatly. The performance of a PZT diaphragm energy harvester is demonstrated in this paper. Under an acceleration of 9.8 m/s^2, a pre-stress of 1.2 N applied on the harvester, a power of 12 mW was generated at the resonance frequency of the harvester (113 Hz) across a 33 k ohm resistor. It was found that the energy from the harvester increases while its resonance frequency decreases when the pre-stress increasing. The contacting part between the proof mass and the piezoelectric disc was found another key element, which would influence the performance of the harvester. With its simple structure, the diaphragm harvester may push energy harvesting devices towards practical applications.

Keywords: C. Piezoelectric properties; D. PZT; E. Functional applications; Energy harvesting

1. Introduction

With the booming of wireless sensor network (WSN) and micro-electromechanical system (MEMS) technology basing on the rapid development of low power devices, the research of energy harvesting has improved greatly. Piezoelectric materials have the potential to become an ideal sources of energy harvesting comparing with others (electromagnetic generation, electrostatic generation), because piezoelectric materials' natural of converting mechanical energy into electric power and the ease at which they can be integrated into a system [1]. There are many kinds of coupling modes, two of them are practical: the d_{31} mode and the d_{33} mode. In the d_{31} mode, a force is applied in the direction perpendicular to the poling direction. In the d_{33} mode, a force is applied in the same direction as the poling direction. In a former experiment by Baker et al. [2], the comparing between piezoelectric cantilever beam (d_{31} mode) and the piezoelectric stack (d_{33} mode) has shown that, the d_{31} mode has a lower coupling coefficient, k, than the d_{33} mode, but the d_{31} produced two orders of magnitude more power than d_{33} mode when subjected to the same force, because d_{33} mode has higher mechanical stiffness. In this article, we chose d_{31} mode to convert mechanical energy. The most common geometrical configuration of piezoelectric energy harvesting is the rectangular cantilever beam. The cantilever beam harvester has been well developed and proven to be easy to implement and effective for harvesting energy from ambient vibrations. There are many papers on piezoelectric cantilever beam including Roundy and Wright. They focused to discuss the modeling, design and optimization of piezoelectric generator based on a two-layer bending element. From their analytical model of the generator, designs of 1 cm^3 in size have demonstrated a power output of 375 μW from a vibration source of 2.5 m/s^2 at 120 Hz [3]. While there are a few reports for circular plate harvesters, the researchers from Pennsylvania State University reported a cymbal transducer having a ceramic disc with a diameter of 29 mm and 1 mm thickness. A power of 39 mW can be obtained across the load under a dynamic force of 7.8 N at 100 Hz [4]. Recent progress was performed by Hong Kong Polytechnic University. They manufactured a drum transducer with a dimension of $\Phi 20 \times 10$ mm^2. At 590 Hz a maximal output power of 11 mW can be obtained from its two piezoelectric discs across a resistive load of 50 k ohm [5]. The circular diaphragm structure is a common structure for sensors, such as pressure sensor. Usually, an external force applied on the pressure sensor always stands for a long time. If the sensor utilizes the outer mechanical energy effectively, the potential to make the sensor

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self powered is no doubt. Targeting this kind of application, this paper mainly studies the feasibility of taking PZT circular diaphragm as an energy harvester.

2. Experimental

The piezoelectric diaphragm harvester was fabricated from bonding a piezoelectric ceramic disk on a brass thin plate using epoxy (ThreeBond). A proof mass was adhered on the top of the piezoelectric plate to provide pre-stress with the same epoxy. The prototype is shown in Fig. 1, the diameter of the piezoelectric ceramic disc is 25 mm (R_2) and the brass plate is 30 mm (R_1). The thickness of both ceramic disc and brass plate is 0.2 mm. The polarity of the ceramic disc is along the thickness direction (*z*-axis). The electrical connections were sputtered respectively on the top of the ceramic disc and the button of the brass plate. Before measurement, a series proof mass with different quality were bonded on the top of the ceramic discs with different contacting areas in order to provide a series of pre-stress. Here, the value of the pre-stress equals to the quality of mass multiplies the acceleration of gravity. And plus, a parameter "*r*" is defined here which will determine the output charge of the harvester.

$$r = \frac{R_0}{R_2} \tag{1}$$

r equals to the ratio between the radius of the ceramic discs (R_2) and the radius of the contacting area of the proof mass (R_0).

The system of experiment and measurement is shown in Fig. 2. We programmed software to control the test system and realize real-time data acquisition. The shaker (YE5871) can apply a maximum of 50 N force with a wide frequency range from 50 to ~10,000 Hz. By using an arbitrary function generator (33220A, Agilent) and a power amplifier (YE5871A), the shaker was excited at various electric signals to produce a certain vibration condition for energy harvesters. In this study, we used the arbitrary function generator to generate a series of sinusoidal signals and amplified them, then input signals into the shaker to vibrate. The harvester was fixed on the fixture as Fig. 2 showed. The border of the brass plate was clamped by the fixture. The proof mass was bonded on the top of the ceramic plate and the button of the brass plate was empty. The fixture was attached to the shaker with a steel rod. An accelerometer (BW 14100) was used to monitor the acceleration of the device's vibration in order to ensure the experimental conditions the same.

The equivalent circuit of the harvester was modeled as a sinusoidal current source in parallel with its internal capacitance *Cp* (Fig. 3). The harvester generated an ac voltage, while a dc voltage was required if we want to use them. The electric circuit shown in Fig. 3 could make the transform successful. The full wave rectifying bridge circuit was made up with four signal Schotty diodes (1N5711) [5]. The filter capacitor was assumed to be large enough that the output voltage was essentially constant, in this experiment a capacitor of 100 μF was used [6]. We detected the voltage with the multimeter (Keithley 2000) and calculated the output power though the usual formulation:

$$p = \frac{V^2}{R} \tag{2}$$

The performance including the output voltage (*V*) and the output power (*P*) of the transducer were initially characterized

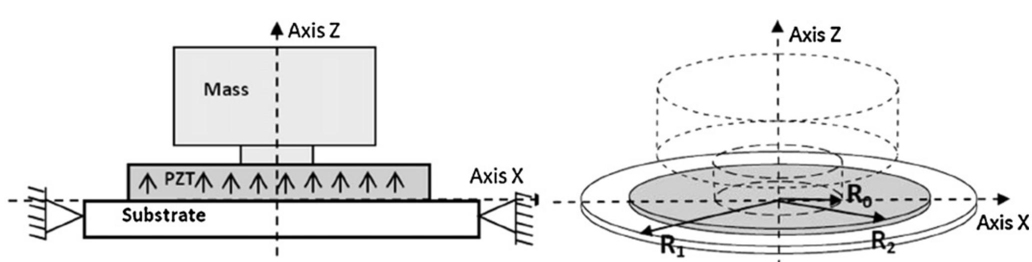

Fig. 1. Schematic diagram of PZT circular diaphragm harvester.

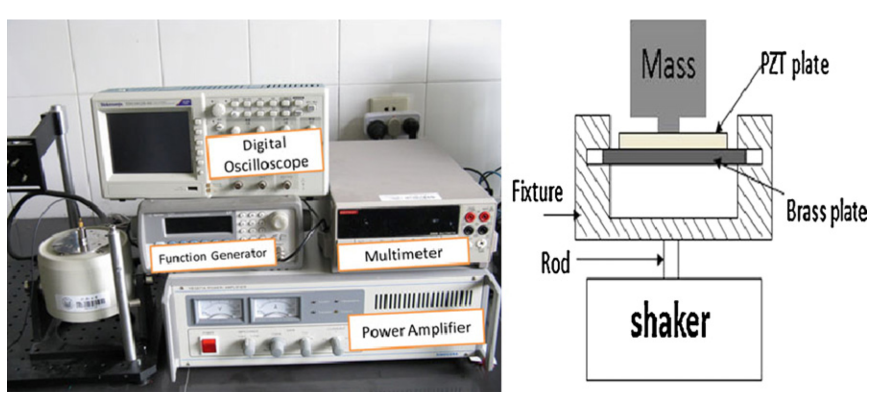

Fig. 2. Experimental system setup of energy harvesting with a piezoelectric diaphragm harvester.

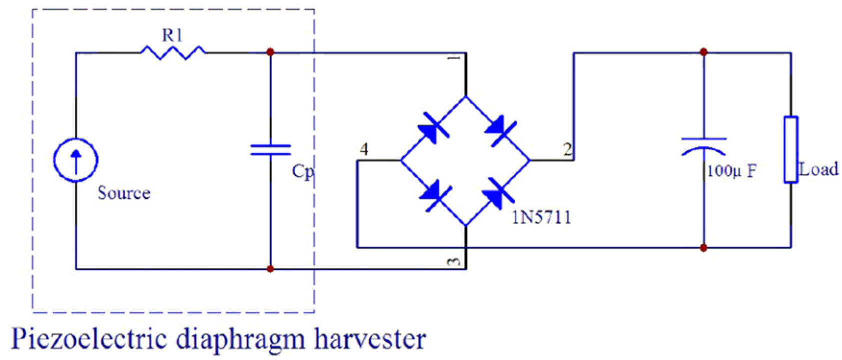

Fig. 3. Schematic diagram of energy harvesting circuit.

with the circuit directly across the resistive loads (R) without any amplification.

3. Results and discussion

Fig. 4 shows the results of the harvester output voltage and power with various resistive. It was measured with a fixed pre-stress condition of 1.20 N, under an acceleration level of 9.8 m/s^2. The radius ratio between proof mass contacting area and ceramic disc is 0.36, which means the previously defined parameter "r" is 0.36. Fig. 4(a) illustrates that the output voltage raise as the impedance of the resistor increases. When the resistance is 102 k ohm the maximum voltage approaches 33 V. Fig. 4(b) shows that a maximum output power of about 12 mW generated with resistive load 33 k ohm. There is the maximum power output when the impedance of the resistor is matched the equivalent impedance of the harvester [4]. It means the impedance of 33 k ohm matches the equivalent impedance of the harvester. Both Fig. 4(a) and (b) shows the lowest resonance frequency of the harvester is about of 113 Hz which is equal to the natural frequency [7]. When the vibration frequency increases near 113 Hz, the output power increases significantly, nevertheless, it decreases sharply when the load resistance is further increased.

Fig. 5(a) and (b) demonstrates the maximum of the output voltage and the output power improves as the pre-stress increases, meantime, the resonance frequency of the harvester is moved to lower frequency from 310 Hz to 110 Hz. It was measured at various pre-stress conditions. The parameter "r" is 0.36. The impedance resistances are all 33 k ohm. It was seem that increasing the pre-stress can improve the performance of the harvester at relatively low frequency [8]. However, the pre-stress cannot be increased indefinitely due to the mechanical limitation of the harvester, especially the fracture of the ceramic PZT [9]. Actually, when the pre-stress increases from 0 N to 0.8 N, the change of the output power is significant. But, when the pre-stress is over 1.0 N, the output power does not increase evidently.

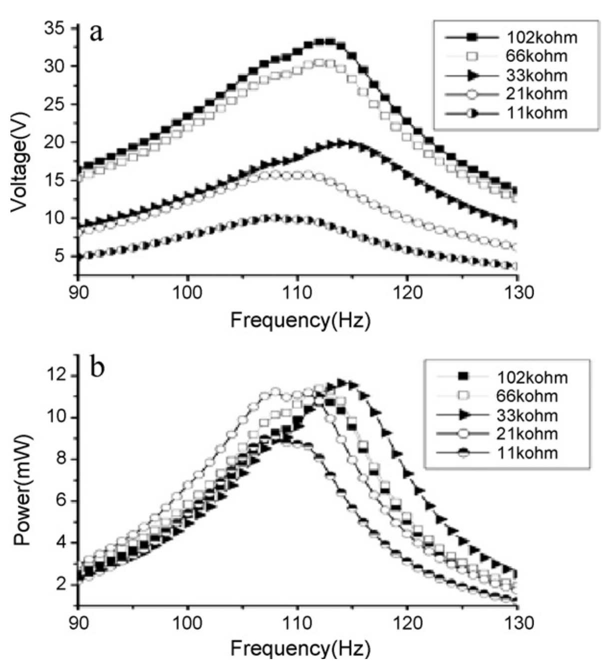

Fig. 4. Output voltage (a) and power (b) of a piezoelectric diaphragm harvester as a function of frequency with various resistive loads after rectification.

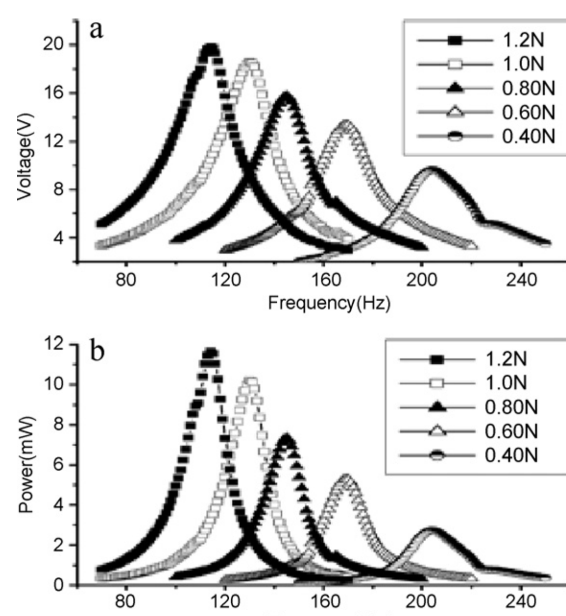

Fig. 5. Output voltage (a) and power (b) of a piezoelectric diaphragm harvester as a function of frequency with various pre-stress after rectification.

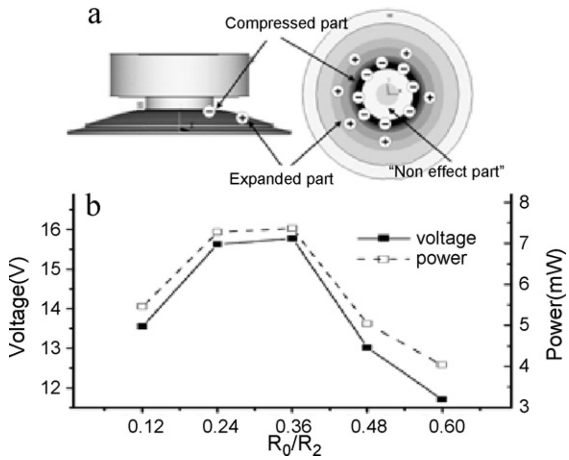

Fig. 6. (a) Simulation of deflection and strain of the circular diaphragm energy harvester (b) peak voltage and power versus ‘‘*r*’’.

A series of harvesters are tested with the same pre-stress 0.80 N but different ‘‘*r*’’. The diameter of the contacting area respectively is 3 mm, 6 mm, 9 mm, 12 mm, 15 mm. The value of ‘‘*r*’’ is as the following 0.12, 0.24, 0.36, 0.48, 0.60. It is clear that, from Fig. 6(b), we can see that there exists relative higher output when the ‘‘*r*’’ equals to 0.36 and 0.48. As is well known strain is one of the essential elements which will influence the output charge of piezoelectric material. There is substantial strain generated if the harvester bends like this as Fig. 6(a) shows (The device is simulated with software of numerical simulation, ANSYS 11.0. The deformed shape has been amplified as the left one shows, the right one is the schematic diagram of strain distribution). Some of the piezoelectric material outputs in positive charge (expanded regions) and some negative (compressed regions). The two kinds of charge will cancel out each other [10]. In the situation that the proof mass bonding with piezoelectric material in ideal condition, the deformation of the bonding part of the piezoelectric diaphragm is limit as the right one of Fig. 6(a) shows, which means the bonding part of piezoelectric material can hardly generate strain, then no charge, neither positive nor negative, so we defined this part as ‘‘non effect part’’. The output charge which the multimeter detected equals to the absolute value of positive part and negative part of the whole disc. Here, as Fig. 6(a) shows, we assume the center part generates negative charge yet the outer part generates positive charge in the same moment. With the bonding part enlarging, the ‘‘non effect part’’ widens, so the negative charge reduces and the absolute value of output charge increases, so the power increases. If the area of ‘‘non effect part’’ increases to some extent, both of the compressed and expanded part decreases, and both of them even generate few positive charges, so at this time the absolute value of output positive and negative charges decrease, then the output charges decrease. To conclude, an optimal contacting area exists between the mass and piezoelectric diaphragm.

4. Conclusions

We started from several angles to approach the target of optimizing a circular piezoelectric diaphragm harvester. We studied the phenomena that output energy raised and the resonance frequency decreased by increasing the quality of mass, while we found the contacting part between the mass and the piezoelectric disc affects the output charge. A pre-stress of 1.2 N at 113 Hz on the harvester with a dimension of $\Phi 30 \times 0.4\ \mathrm{mm}^2$ resulted in an electrical power generation of 12 mW across an 33 k ohm resistor. It shows the potential feasibility that the circular diaphragm energy harvester can provide enough power for wireless sensors and some MEMS system.

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