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Energy harvesting with a cymbal type piezoelectric transducer from low frequency compression

Jaakko Palosaari · Mikko Leinonen · Jari Hannu ·
Jari Juuti · Heli Jantunen

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Abstract In this paper a piezoelectric energy harvester based on a Cymbal type structure is presented. A piezoelectric disc ∅35 mm was confined between two convex steel discs ∅35 mm acting as a force amplifier delivering stress to the PZT and protecting the harvester. Optimization was performed and generated voltage and power of the harvester were measured as functions of resistive load and applied force. At 1.19 Hz compression frequency with 24.8 N force a Cymbal type harvester with 250 μm thick steel discs delivered an average power of 0.66 mW. Maximum power densities of 1.37 mW/cm^3 and 0.31 mW/cm^3 were measured for the piezo element and the whole component, respectively. The measured power levels reported in this article are able to satisfy the demands of some monitoring electronics or extend the battery life of a portable device.

Keywords Piezoelectric · Energy harvesting · Cymbal

1 Introduction

Recently the number of portable electrical devices, or devices embedded into surroundings, has increased and simultaneously the energy requirements of such devices have significantly decreased. However, the main maintenance problem still remains because batteries need to be replaced or recharged. In order to overcome this problem various energy harvesting techniques have been developed to transform different environmental energy sources into electrical energy suitable for devices [1–6].

Piezoelectric energy harvesting is found to be a feasible alternative when mechanical energy, such as vibration [7–9], is the dominant energy source compared to solar radiation or temperature gradients. Various potential piezoelectric materials and structures have been tested for energy harvesting applications because the target specifications and environmental conditions strongly dictate feasible material and design options [8–14]. One very challenging area is energy harvesting directly from human body, thus enabling charging of portable electronics. The human body releases energy to the environment in various ways, of which the major source is mechanical energy of the foot when walking or running. Mounting of the transducers into a shoe is one of the most attractive options for practical realisation to provide an user-friendly solution without external gear attached to the body [15–18].

Previously, Cymbal and Moonie type actuators have been widely studied and optimised for actuating purposes due to their ease of tailoring via dimension changes [19–25]. More recently, energy harvester designs and models of the Cymbal transducers have also been introduced. Studies have shown their feasibility for energy harvesting because of their high reliability and small deviation in long term usage [11, 26–28]. In this article we present a Cymbal type energy harvester component aimed for mounting in a shoe insole. The compressing force into the heel can be from one to three times of the body weight when walking or running [29]. This makes shoe insole the most attractive place for energy harvesting from human motion. The properties of the different assembled harvesters are characterised under various electrical and mechanical loads and their performance is discussed. The capabilities of the energy harvester are analysed and compared to existing solutions in energy harvesting [15, 27, 28].

J. Palosaari (✉) · M. Leinonen · J. Hannu · J. Juuti · H. Jantunen
Microelectronics and Materials Physics Laboratories,
University of Oulu,
P.O. Box 4500, 90014 Oulu, Finland
e-mail: naami@ee.oulu.fi

2 Experimental procedure

The structure of the piezoelectric Cymbal type energy harvester is presented in Fig. 1. The harvester consisted of a commercial PZT 5H disc (Morgan Electro Ceramics, ∅ 35 mm and thickness of 540 μm with silver electrodes thickness of 20 μm) two brass rings for electrical connection and two convex steel plates. Totally four different harvesters were manufactured using different steel plate thicknesses of 150, 200, 250 and 300 μm. Previous studies have stated the importance of design parameters for Cymbal actuators and energy harvesters where crucial parameters include cavity size between the piezo material and the steel plates. Also diameter and thickness of the steel and the piezo element play an important role in the optimisation of energy harvesting [19, 22, 26]. Our design deviated from a traditional Cymbal actuator by having evenly curved convex steel plates compared to the more angular shaped design used in traditional Cymbal actuators. However, the same crucial design parameters applied.

Poling of the PZT disc was carried out in 3.0 kV/mm electric field in silicone oil at 100 °C for 30 min. After poling, 150 μm thick brass contacts (outer ∅ 35 mm and inner ∅ 32 mm) were attached on the both sides of the piezo ceramic. Next, bent steel plates having a convex shape formed by a hydraulic press unit (Mega KMG-30A) and a specially designed mould were bonded onto the brass contacts. All the layers were bonded together with epoxy (Fig. 1(c)) using the width of the brass contacts (1.50 mm). Conductive silver paint was applied to ensure good electrical contact between the PZT and the brass.

Compression of the steel plates stretched the PZT in the d31 direction the arrow indicates the direction of tension in Fig. 1(c). Stress cycles were applied with a computer controlled positioning drive system (Festo Ag & Co KG.) which is able to produce a compressive force of up to 800 N via a piston that moves with ±0.20 mm accuracy. A schematic of the measurement setup is shown in Fig. 2. Plastic cushions (1.4 mm thick, ∅ 2.50 mm) were placed on both sides of the harvester to direct the force to the middle point. A dynamic load cell (Omega Engineering, INC. DLC 101–100) was placed on the side opposite to the Festo drive system in order to measure the applied force simultaneously with the corresponding electrical measurements. A ball bearing directed the force evenly onto the load cell surface. The generated voltage was measured through a full wave rectifier circuit with a 1 μF capacitor storing the electrical energy from the harvester. A schematic of the electronics is shown in Fig. 3.

Measurements aimed to determine the optimal steel plate thickness for the maximum power levels from the Cymbal type energy harvester. Also the required force and matching impedance to achieve these power levels were measured. The matching impedance can be approximately given as

$$Z = \frac{1}{2\pi f \cdot C} \tag{1}$$

where f is the frequency and C is capacitance of the element [26]. The electric power available under the cyclic excitation is given by Eq. (2)

$$P = \frac{1}{2} C V^2 f \tag{2}$$

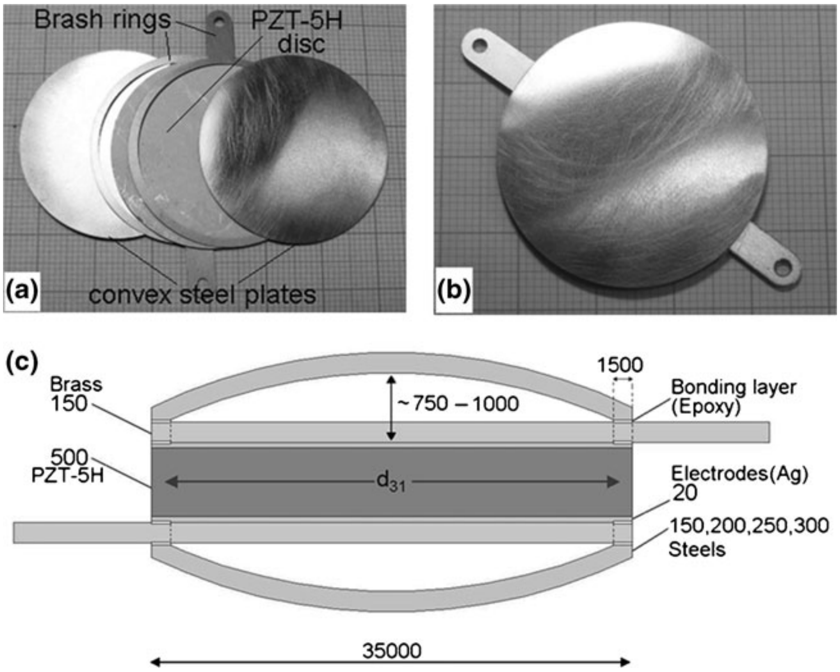

Fig. 1 Cymbal type harvester with (**a**) structure before assembly, (**b**) structure assembled and (**c**) cross section, with all dimensions at μm

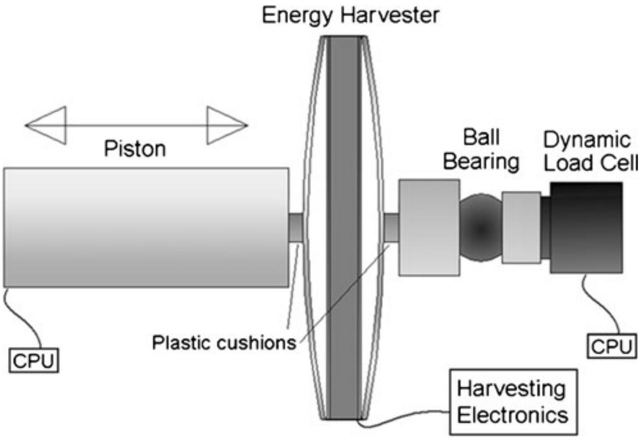

Fig. 2 Stress cycling setup

where V is the open circuit output voltage [26]. Ideal power into a resistive load can be calculated from

$$P = \frac{V^2}{R} \tag{3}$$

where R is the electrical load resistance. First the voltage output was measured across the full wave rectifier and 1 μF capacitor, as a result of a single compression due to the force applied via the piston. Based on these results each harvester was then compressed with an optimal force at 1.19 Hz frequency which is close to that of normal human walking pace [15]. Voltage gain with and without a resistive load was measured from the continuous cyclic stresses and the generated power was calculated from the results. The efficiency of the electronics was also estimated by comparing the actual power levels generated with the rectifier to the ideal power measured directly into an electrical load. Additionally the effect of frequency on the power output was observed with three different frequencies of stress cycles, with the same amount of force used in each case. Power curves were calculated from these results for the harvester assembled from 150 μm steel plates.

3 Results and discussion

Steel plates were pushed together from the centre of the Cymbal harvester via plastic cushions. Compression of the convex plates caused strain to the piezo-element producing a positive voltage. Release of the force in turn resulted in a negative voltage which was converted to positive by the full wave rectifier. In Fig. 4 the measured voltage output stored in the capacitor from a single compression (no release) is shown as a function of force. Voltages were measured with the electronic circuit shown in Fig. 3 without the load RL from all of the four harvesters. Results showed a moderately linear increase of the voltage as a function of force. After the linear regime the voltage saturated. This was probably caused by the convex steel plates reaching near to the piezo surface and starting to buckle. The steel plates never touched the piezo surface, therefore the energy from the compression was wasted on the deformation of the steel plates, hence reducing the force leverage towards the piezo element.

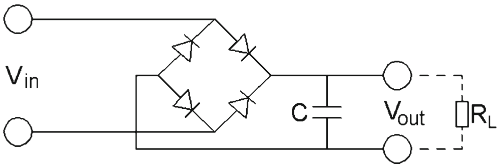

Fig. 3 Harvester electronics with full wave rectifier, 1 μF capacitor and a resistive load

As the thickness of the steel plates was increased the point of saturation was naturally reached with a greater force. Conversely, the thinner the steel plate the more sensitive to pressure was the harvester and higher voltages were produced with smaller forces. The force corresponding to the point just before the total saturation of the voltage gain was used for the continuous stress measurements, due to the optimal force/energy gain at this point. The design with the 250 μm steel plates proved to be the most efficient for transferring tensile stress to piezo material and delivered close to 7 V from a single compression with 30 N.

The force corresponding to the point just before the total saturation of the voltage gain (Fig. 4) was used for the continuous stress measurements. Figure 5 shows the voltages stored across the capacitor as a function of time during continuous 1.19 Hz compression. No load was applied at this stage. The voltage increased with each compression and release of the piston but was simultaneously decreased due to the loading effect of the 10 MΩ probe used for the measurement. The first peak in voltage level corresponds

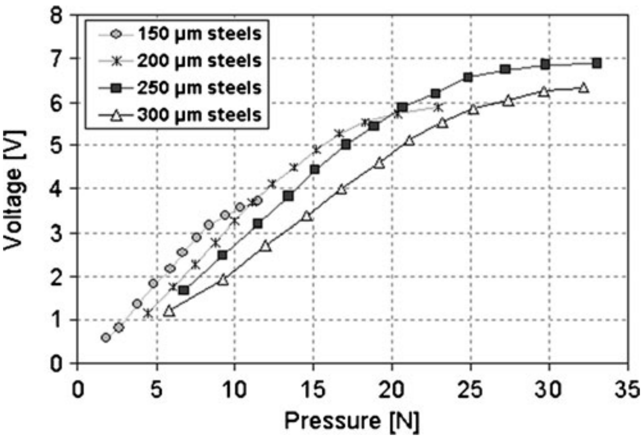

Fig. 4 Voltage from a single compression as a function of applied force with different steel thicknesses

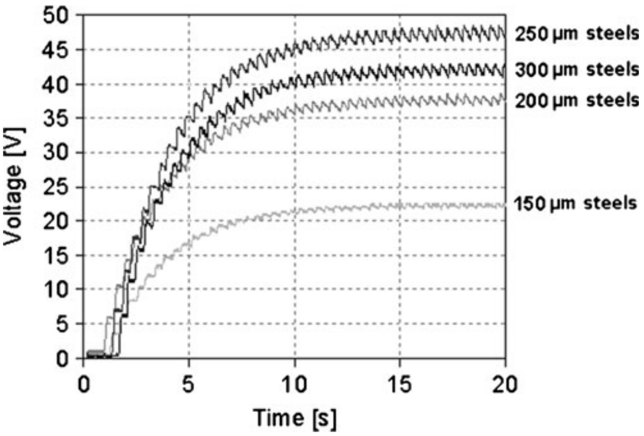

Fig. 5 Voltage stored in capacitor with 1.19 Hz compression frequency. Force applied to each Cymbal structures: 10.1 N to 150 µm, 17.0 N to 200 µm, 24.8 N to 250 µm and 27.1 N to 300 µm

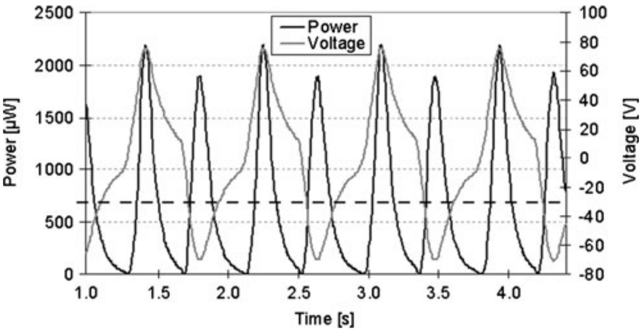

Fig. 7 Voltage and ideal power gain measured from Cymbal type harvester with 250 µm thick steel plates. Compression parameters: 1.19 Hz and 24.8 N

well with the measurement results in Fig. 4. Constant discharging caused the voltage to saturate at a certain level. With 24.8 N excitation the harvester with 250 µm thick steel plates obtained the highest performance i.e. a mean voltage of 47.4 V after 20 s.

Output power (Fig. 6) of the harvesters was measured in an electrical load resistance which was connected across the capacitor of the harvester electronics (Fig. 3). All the harvesters were stressed at the same 1.19 Hz frequency and with the force before voltage saturation (Fig. 4). Cymbal type harvester with 250 µm steel plates gave the maximum power of 0.27 mW with 24.8 N compressions having an optimal load at 3.6 MΩ. This corresponds to a power density of 0.56 mW/cm^3 for the piezo element and 0.13 mW/cm^3 for the whole component.

The voltage gain was next measured directly across an electrical load and the ideal power was calculated. Without the rectifier or the capacitor a matching impedance of 2.6 M Ω was obtained using Eq. 1. Using the same actuation parameters as before, the voltage varied over −72 V to +82 V and the peak power calculated from Eq. 3 was 2.20 mW. An average power of 0.66 mW (dashed line in Fig. 7) was measured for the harvester. The power (0.27 mW) measured with the harvester electronics was 41 % of this value. Computed ideal power densities as above gave 1.37 mW/cm^3 for the piezo element and 0.31 mW/cm^3 for the whole component.

Figure 8 shows the generated power with the harvester electronics at 0.35 Hz, 1.19 Hz and 1.65 Hz compression frequencies. All three compressions were applied using the same force of 6.0 N. Results show that the excitation frequency and impedance matching are very crucial to energy harvesting. With 1.65 Hz compared to 0.35 Hz the maximum power was about five times greater, from 39.1 µW to 8.3 µW respectively corresponding closely to increased frequency. However, the difference was even greater when measured with smaller electrical loads, as the frequency not only increased the available energy but also decreased the matching impedance. For example, powers measured in a 100 kΩ load were 0.16 µW, 3.17 µW and 5.83 µW for each of the three frequencies. These power and matching impedance

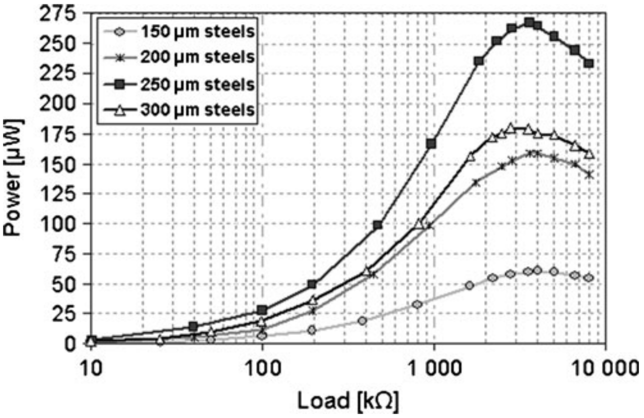

Fig. 6 Power generation with 1.19 Hz compression rate. Force applied to Cymbal structures: 10.1 N, 17.0 N, 24.8 N, 27.1 N with steel thickness respectively: 150 µm, 200 µm, 250 µm, 300 µm

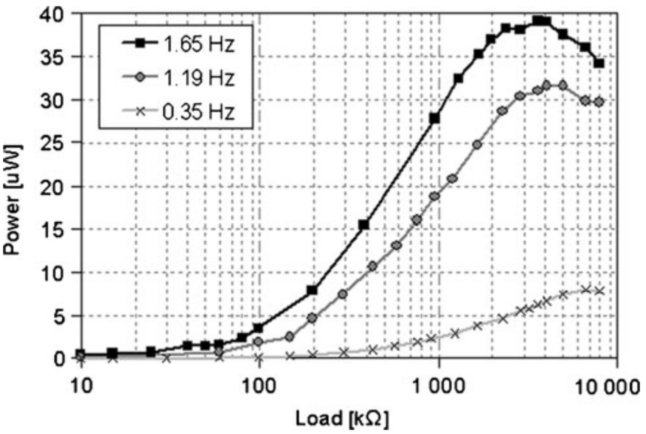

Fig. 8 Generated power as a function of load from the Cymbal type harvester with 150 µm steels with different frequencies

relations with frequency can be seen from Eqs. 1 and 2. Power generated by piezoelectric Cymbal type harvesters is thus proportional to the piezo/steel thickness ratio, the frequency and the amount of compression force.

When comparison is made with power levels given in other reports from the same type of energy harvesters it should be noted what frequency, applied force and electronics were used. A power of 26.0 mW was reported from a rectifier for a Cymbal energy harvester under 100 Hz and 7.8 N. This corresponds to 39.4 mW/cm^3 for the soft piezo material used and 20.0 mW/cm^3 for the whole component [27]. In another article, an ideal power of 14 mW was harvested straight from a matching impedance at resonance frequency from a rectangular shaped Cymbal transducer made from a single crystal wafer. The paper reports 188.0 mW/cm^3 for the single crystal wafer and 60.8 mW/cm^3 for the whole component when actuated with 500 Hz and 0.55 N [28].

Power harvesting from shoes occurs at very low frequencies close to 1 Hz [15]. An ideal power of 8.4 mW was harvested straight over a matching impedance from a dimorph, made from two commercial thunder TH-6R actuators and a middle plate. The power efficiency was ~4.4 mW/cm^3 for the piezo material and ~0.44 mW/cm^3 for the whole component. This was achieved from the heel of a shoe by the force of human body weight at walking frequency [15]. This power efficiency for the whole component is close to that which we have measured (0.31 mW/cm^3) from the Cymbal type energy harvester, but our harvester operated with a much smaller force thus having less effect towards user.

4 Conclusions

At 1.19 Hz compression frequency and with 24.8 N applied force the Cymbal type harvester with 250 μm thick steel plates generated the highest energy level. The average ideal power measured straight from the electrical load was 0.66 mW for the harvester which was equal to a power density of 1.37 mW/cm^3 for the piezo element and 0.31 mW/cm^3 for the whole component. The measured power of 0.27 mW with the harvester electronics driving a load is closer to a practical hands-on application. Our design deviates from a traditional Cymbal actuator by having evenly curved convex steel plates. However, the same crucial design parameters of cavity size, diameter and thickness of the steel plates still apply. Harvester can be mounted inside a cylinder shape holster where a flexible top and bottom covers are connected via plastic cushions to the harvester. This way the compressing force from the feet is always directed vertically to the harvester improving durability.

High stiffness and impedance of the piezo material, especially at low frequencies, makes the application the design challenging. The matching impedance could be reduced with thinner piezo material or with several harvesters connected in parallel. This would also enable multiplication of the generated energy as there is capacity for forces of several hundreds of newtons in the case of human walking. Increasing the area and decreasing the thickness of the piezo material would increase the capacitance of the component and therefore reduce the matching impedance. This would in turn enhance the power output and lower the component force demands. The results suggest also that the compression frequency of the harvester has a significant impact on the power levels available. Measured power levels in this article would already satisfy the demands of some monitoring electronics or extend the battery life of a portable device. This opens a possibility for various applications where power grid access is unavailable, such as several day hiking expeditions or military missions.

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