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Experimental and theoretical investigation of an impact vibration harvester with triboelectric transduction

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ABSTRACT

There has been remarkable interest in triboelectric mechanisms because of their high efficiency, wide availability, and low-cost generation of sustainable power. Using impact vibrations, we introduce piece-wise stiffness to the system to enlarge frequency bandwidth. The triboelectric layers consist of Aluminum, which also serves as an electrode, and Polydimethylsiloxane (PDMS) with micro semi-cylindrical patterns. At the bottom of the PDMS layer, there is another Al electrode. The layers are sandwiched between the center mass of a clamped-clamped beam and its base. The center mass enhances the impact force on the triboelectric layers subjected to external vibrations. Upon impact, alternating current, caused by the contact electrification and electrostatic induction, flows between the Al electrodes. Because of the impact, the equivalent stiffness of the structure increases and as a result, the frequency bandwidth gets wider. The output voltage and power reach as large as 5.5 V, 15 μW, respectively at 0.8 g vibrational amplitude. In addition, we report how the surface charge density increases with the excitation levels. The analysis delineates the interactions between impact vibrations and triboelectric transductions. The ability of the system to achieve wider bandwidth paves the way for efficient triboelectric vibrational energy harvesters.

1. Introduction

Ambient mechanical vibration is an energy source and because of increasing energy demand, it is the subject of many studies for powering wireless sensors and other electronics in the micro-to milli-watts range. Transduction mechanisms for vibration energy conversion are based on the piezoelectric [1–4], pyroelectric [5,6], and triboelectric effects [7–15]. Triboelectric conversion occurs when two different materials with opposite tendencies to lose and gain electrons undergo periodic contact and release [16–21]. Triboelectric mechanisms can be used in different types of sensors such as pressure sensors [22], magnetic sensors [23], chemical sensors [24,25], and motion sensors [26,27]. The cyclical process drives electric charges to the surfaces of the two triboelectric materials. The quantity of the generated electric charges depends on the surface charge density. The charge density is a function of chemical properties of the materials and the micro-surface patterns that define the area of contact [28]. Micro patterns increase the contact surfaces and enhance the conversion efficiency [29,30].

One major drawback for different vibrational energy harvesters is narrow bandwidth, which severely limits the performance of the harvesters considering the wide bandwidth of ambient vibrations. To broaden the bandwidth, different sources of nonlinearities are proposed, such as magnetic [2,4,31–35], and mechanical [36–40] forces. Other approaches include mixed frequency

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excitation [41], multiple cantilevers that have close natural frequencies [42] and internal resonance [43].

An alternative approach to increase the frequency bandwidth has been to use impact vibration energy harvesting [7,29,44–46]. However, most research has been focused on empirical studies of the impact vibration harvesters. One exception is the work by Mahmoud and Abdel-Rahman [40] on modeling the impact vibration energy harvester with electrostatic transduction. As triboelectric transducers are more efficient than electrostatic ones, we expected the combination of impact energy harvesters with the triboelectric mechanism would have higher conversion efficiency. Other advantages of triboelectric transduction include simple fabrication, excellent reliability, and low cost.

For this article, we created an impact vibration energy harvester with triboelectric transducers to achieve high energy density and large bandwidth. The impact vibration is utilized because of its compatibility with the inherent contact and separation characteristic of the triboelectric layers, which makes it a unique attribute to scavenge the energy from ambient. However, there is a lack of knowledge on the interaction of system dynamics and the triboelectric effect despite much research on the triboelectric materials. We addressed this deficiency by presenting a mathematical model that predicted the harvester dynamics as well as its output with very good accuracy. We conducted a thorough study on the effect of impact to delineate the coupled nature of impact and triboelectric energy conversion. Using the impact vibration, we achieved larger bandwidth compared to linear triboelectric resonators previously reported, and the increase improves the efficiency of vibration energy harvesting.

The outline of the paper is as follows. The design and fabrication of a polydimethylsiloxane (PDMS) based triboelectric generator (TEG) is described in Section 2. The working steps and the theoretical model for a single-degree-of-freedom system are developed in Section 3. The experimental set-up and frequency response results are discussed in Section 4. We report on the optimal resistance that results in the largest power. The theoretical results were in good agreement with the experimental results. In addition, we examined the surface charge density as a function of the vibrational amplitude and studied the effect of the gap on the output. Finally, the conclusion follows in Section 5.

2. Device structure and fabrication

The energy harvester contains a clamped-clamped polymer beam with a center mass, see Fig. 1. The energy conversion occurs from the separation and contact of the triboelectric layers in the middle of the structure under the mass. The triboelectric layers consist of a top aluminum layer with a semi-cylindrical pattern and a bottom PDMS layer with the reverse pattern on the other Al layer. Once the base of the device vibrates, the center mass impacts the lower layer and the triboelectric charges are generated on the contact surfaces, which induce electrostatic charges on the bottom Al layer. If wires connect the two Al layers, there will be an alternating current [24]. For more explanation on the principle of operation read Section 3. The dimensions of the energy harvester are given in Table 1.

To have a large contact surface, the micro-patterns on the surface of PDMS and Al layer are matched. This is done by making the lower PDMS layer by using the upper Al layer as a mold. The upper electrode is made of Al by Progressive Tools [47] with dimensions of (5.2 cm × 3.7 cm × 0.25 cm) and contains semi-cylindrical grooves as wide as 267 μm, see Fig. 2a. The molds are cleaned with distilled water and acetone using an ultrasonic technique. Then, a PDMS mixture of 10 : 1 ratio of silicon elastomer base to curing agent is made and spread on a clean piece of glass on top of a heater. After that, the molds are placed over the PDMS mixture and pressed slowly at an angle to reduce the air bubbles in the final PDMS layer. The mixture is then baked at 80°C for an hour. After baking, the aluminum mold is peeled off yielding a 500 μm thick PDMS layer with the reverse pattern as shown in Fig. 2b. A thin Al sheet with the similar size of the aluminum mold is spin-coated with a thin layer of PDMS; baked at

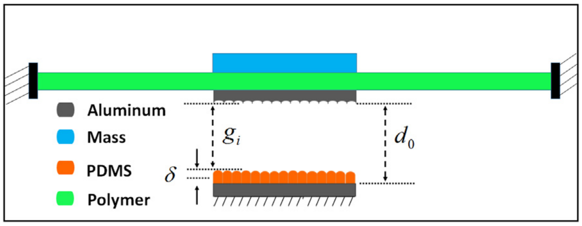

Fig. 1. Schematic for the triboelectric energy harvester.

Table 1
Geometrical parameters of the harvester.

Geometrical parameters	Value
Beam dimensions (l × w × h)	(10 × 3.7 × 0.1) cm
Center mass dimensions (l × w × h)	(5.2 × 3.8 × 0.7) cm
Mold dimensions (l × w × h)	(5.2 × 3.7 × 0.25) cm
Center mass and Mold density	2700 kg/m^3
Polymer beam density	1220 kg/m^3