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Piezoelectric Vibration Energy Harvester Using Indirect Impact of Springless Proof Mass

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Abstract. This paper presents an impact-based piezoelectric vibration energy harvester using freely movable spherical proof mass and MFC (Macro Fiber Composite) beams as piezoelectric cantilevers. When external vibration is applied, a metal sphere moves freely along the channel and collides with both ends of the cavity, which induces the vibration of parallel-connected MFCs and generates electric power. A proof-of-concept device having the form-factor of a wristwatch has been designed and tested. Moreover, spherical proof mass made of different materials has been tested to analyze the relationship between output power, long-term reliability, and audible noise level during operation. Maximum peak-to-peak open circuit voltage of 41.2V and average power of 908.7 μ W have been obtained in response to a 3g vibration at 17Hz for device with parallel-connected MFC beams.

1. Introduction

Harvesting energy from low frequency vibrations such as human-body-induced motion has been drawing substantial research interest to eventually remove the need for battery replacement in some of the applications, such as implantable bio-sensors and wearable devices [1]. To overcome the major challenges in generating electric power, including low and random frequency of the vibrations, wide variety of non-resonant harvesters have been reported as alternative approaches. Frequency-up-converted electromagnetic transducers and piezoelectric generators using magnetic or impact-based systems are some of the examples [2, 3]. Although utilization in a specific wearable device application would require further research efforts, harvesters having the form-factor of a conventional wristwatch have also been reported, which utilized the asymmetric rotor to convert the external vibration into a rotational motion and generate power [4, 5]. Due to the straightforward operating principle and proven performance in the watch manufacturing industry, utilization of asymmetric rotor as a proof mass in energy harvesting device could potentially be a promising approach, but the improvement of output power and reduction of fabrication cost and complexity need to be accompanied.

Piezoelectric energy harvesters using impact-based power generation mechanisms have been widely researched due to simplicity of the system and effectiveness of energy conversion resulting from high energy density of the material. Despite the advantages, reliability issues in contact regions resulting from high amplitude excitation of proof mass pose major challenges. Previously, we have reported an indirect impact-based energy harvester to avoid the catastrophic failure of contacting surface due to high stress and deflection in conventional impact-based systems [6].

In this research, we present a low frequency vibration energy harvester using impact between single springless proof mass and aluminum housing of monolithic construction, which conveys the



vibration to two parallel-connected MFC beams for high output power generation while maintaining a small form-factor.

2. Harvester design

Schematic diagrams of the proposed vibration energy harvester are shown in figure 1. The harvester consists of a straight channel with spherical proof mass in the middle and two piezoelectric cantilevers attached on both sides of the channel. Piezoelectric cantilevers have been prepared by attaching copper blocks at top and bottom side of the free end of each MFC beams. Device housing, whose size was inspired by a conventional wristwatch, has been fabricated with aluminum, considering the ease of fabrication and high restitution coefficient. Previously, we have reported an indirect impact-based energy harvester with multiple proof mass and single piezoelectric cantilever in a circular geometry [7]. Despite some of the technological improvements from the earlier works, output power improvement was limited due to curved geometry. In this research, rectangular housing has been designed for higher power density and parallel-connected MFC beams have been used to improve the output power.

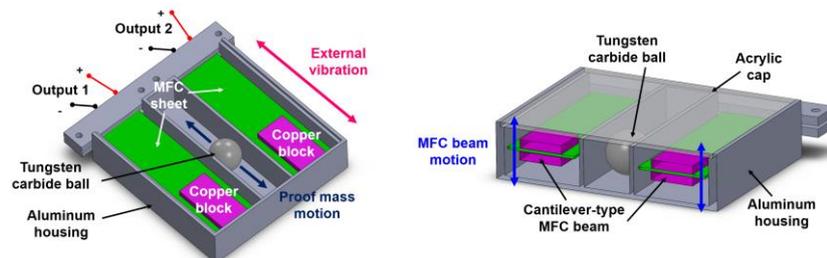


Figure 1. Schematics of the proposed piezoelectric energy harvester using tungsten carbide ball and MFC cantilevers: perspective view (left), cross-sectional view (right).

3. Fabrication

As shown in figure 2, a proof-of-concept harvester has been fabricated by attaching two MFC cantilevers ($26 \times 6.5 \times 0.3 \text{ mm}^3$ each) on one end of the channel which has 5mm-diameter tungsten carbide proof mass inside. To evaluate the relationship between output power, long-term reliability, and audible noise level of the device during operation, devices with various proof mass materials have been tested (figure 2(c)). Assembled device, which measures $27 \times 26.5 \times 6.5 \text{ mm}^3$, has been covered with an acrylic plate and tested using vibration exciter and pendulum test setup.

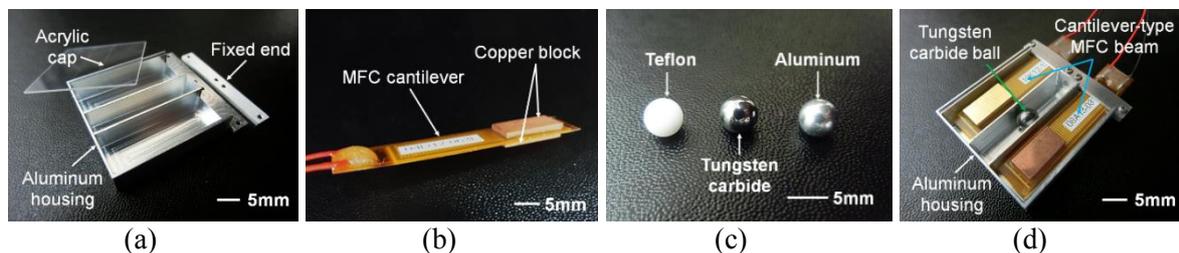


Figure 2. Assembled device: (a) Housing components, (b) MFC cantilever with copper blocks, (c) three different types of proof mass tested, (d) fabricated piezoelectric energy harvester.

4. Results and discussion

4.1. Vibration exciter test

To test the device performance at various input frequencies, output from the fabricated device has been measured while the device was shaken with vibration exciter. As shown in figure 3, sinusoidal

vibration has been applied in vertical direction. Input acceleration of 3g and input frequencies ranging from 10 to 20Hz with 1Hz step have been tested.

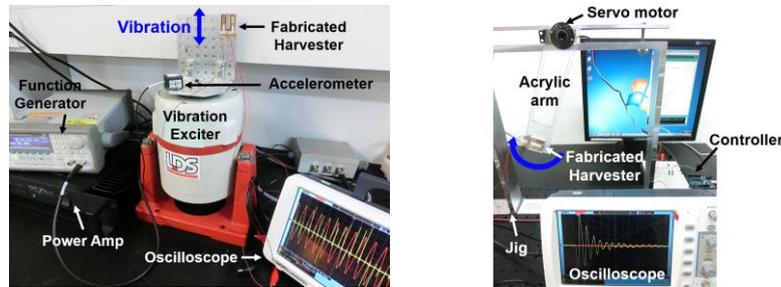


Figure 3. Experimental setup for the vibration exciter test (left) and pendulum test (right).

Output voltage waveforms of each MFC cantilevers have been compared to verify the symmetry (figure 4) and fabricated devices with single MFC and parallel-connected MFC cantilevers have been tested and compared. As shown in figure 5, peak-to-peak open circuit voltage of both devices show a similar trend at various input frequencies at 3g acceleration. Maximum open circuit voltage of 37.8V and 41.2V have been obtained for devices with single and parallel-connected MFCs, respectively.

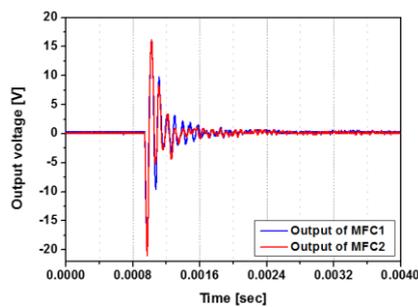


Figure 4. Open circuit voltage waveform of each MFC cantilevers (3g acceleration at 17Hz applied).

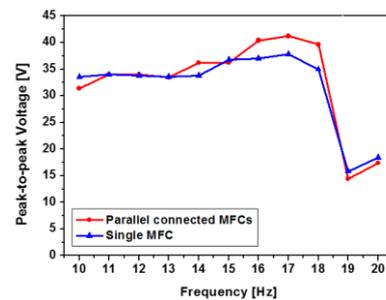
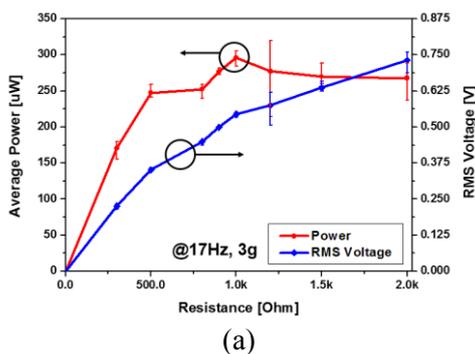
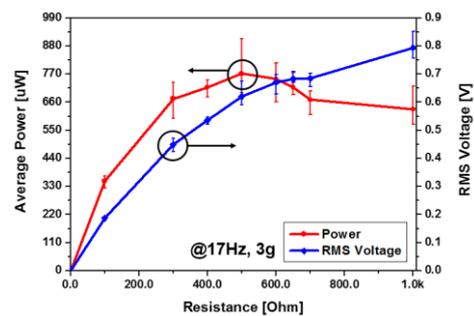


Figure 5. Peak-to-peak open circuit voltage vs. input frequency at 3g for devices with single MFC and parallel-connected MFCs.



(a)



(b)

Figure 6. RMS voltage and average power at various load resistance (3g acceleration at 17Hz applied): (a) device with single MFC cantilever, (b) device with parallel-connected MFC cantilevers.

Figure 6 shows the root-mean-square (RMS) voltage and average power delivered to external resistive load measured with devices having single MFC and parallel-connected MFCs. Input frequencies and accelerations for maximum open circuit voltages have been used in the experiment. At 3g acceleration at 17Hz, maximum output power of 320 μ W has been obtained at 1.2k Ω using the

device with single MFC. For the device with parallel-connected MFCs, maximum output power of $908.7\mu\text{W}$ has been achieved at 500Ω . Output power of the device with double MFCs was 284% higher than that of the device with single MFC, which can be ascribed to the lower impedance of the device with parallel-connected MFC cantilevers. Moreover, output voltage and power at low frequency vibrations have been improved significantly compared to previous results obtained with device having single MFC beam and metal spheres in two parallel channels [7].

4.2. Pendulum test

To evaluate the device under real-world operating conditions, pendulum test has also been carried out (figure 3). Assembled device with parallel-connected MFCs has been attached to a 20cm-long acrylic swing arm controlled by a servo motor. Output voltage and power have been measured at very low input frequencies ranging from 0.5 to 2.5Hz while varying the swing speed and angle. Open circuit voltage showed an increasing trend as the angular velocity and angle of swing were increased except at swing speed of $60^\circ/\text{sec}$ (figure 7(a)). Maximum open circuit voltage of 42V has been obtained at swing speed of $150^\circ/\text{sec}$ and total swing angle of 120° . RMS voltage and average power measured with 500Ω resistive load at various angular velocities are shown in figure 7(b). Increase of output power due to increased swing speed was more pronounced compared to that resulting from the increase of swing angle. Maximum output power reached $97.8\mu\text{W}$ at speed of $150^\circ/\text{sec}$ and swing angle of 60° , where the input frequency was twice that of the 120° swing condition. Although average power from pendulum test setup was much lower than that generated with vibration exciter, total amount of power generated at very low frequency vibration, mimicking that of the wrist motion, was relatively higher than expected.

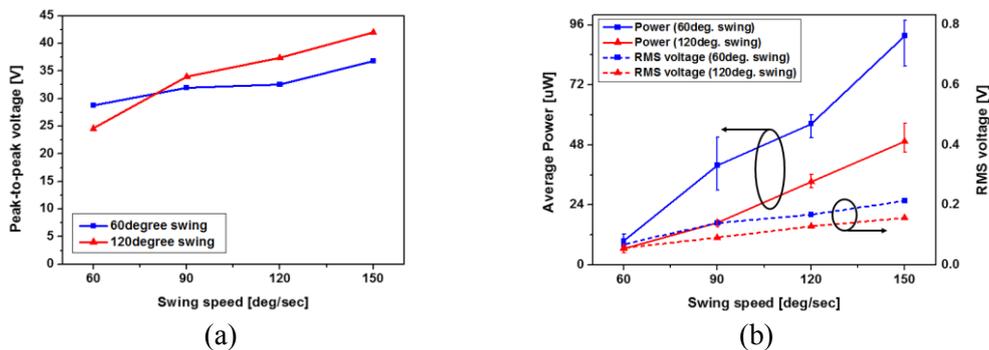


Figure 7. Pendulum test results: (a) peak-to-peak open circuit voltage at various swing speeds and angles, (b) RMS voltage and average power at various swing speeds and angles.

4.3. Performance analysis

As shown in figure 8, fabricated device has been connected to a simple storage circuit with diode rectifier and capacitor. For device with parallel-connected MFCs, 277seconds of vibration at $3g$ acceleration at 17Hz was sufficient to fully charge the $1,000\mu\text{F}$ capacitor and stored energy was $1,549\mu\text{J}$, which was high enough to turn on the LED in storage circuit.

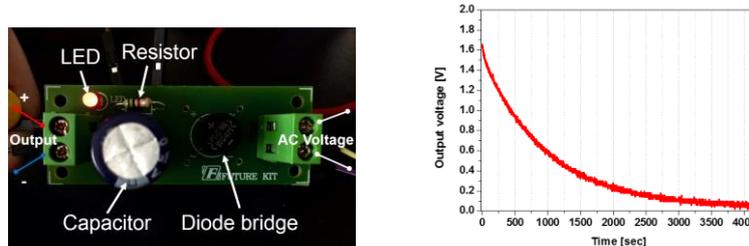


Figure 8. Energy storage test results: circuit with diode rectifier, capacitor and LED (left), discharge waveform (right).

As the output power, long-term reliability, and audible noise level of the device are closely related to the impact between proof mass and channel end, performance of the devices with various proof mass materials have been compared. Cyclic test has been performed with 3g acceleration at 17Hz. As shown in figure 9(a), noticeable drop of output power has been observed with device having tungsten carbide proof mass. However, devices with aluminum and Teflon proof mass showed no sign of power degradation up to 489,600cycles at the cost of reduced initial output power. Measured noise level from device with tungsten carbide and Teflon proof mass were 112dB and 41dB, respectively (figure 9(b)). Aluminum or Teflon proof mass can be an option in terms of enhanced long-term reliability and noise level with trade-off in output power. Device performance can be further improved by appropriate choice of spherical proof mass and housing materials, and optimized device geometry. Further improvement of output characteristics is expected by additional dynamic analysis and optimization of the device geometry at both ends of the cavity. Moreover, position and size of the proof mass attached to the MFC cantilever require optimization to maximize the efficiency of the energy conversion.

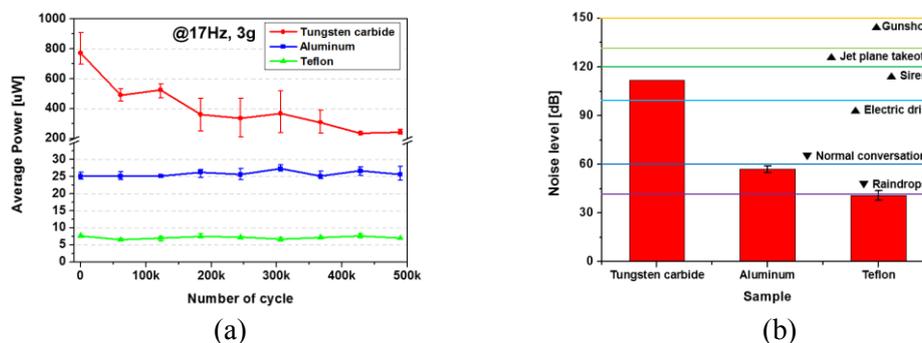


Figure 9. Effect of the spherical proof mass material (device with parallel-connected MFC beams tested): (a) output power variation, (b) audible noise measurement result.

5. Conclusion

We have demonstrated an indirect impact based piezoelectric vibration energy harvester using freely movable spherical proof mass and parallel-connected MFC beams as piezoelectric cantilevers. A proof-of-concept device having the form-factor of a conventional wristwatch has been designed, fabricated and tested successfully in various operating conditions. Maximum peak-to-peak open circuit voltage of 41.2V and average power of 908.7μW have been obtained at 3g acceleration at 17Hz in vibration exciter test. Effect of proof mass material in long-term reliability and audible noise level of the fabricated device have been verified by cyclic testing and noise measurement. Although fabricated device requires further optimization, we have successfully verified the concept of an indirect impact-based piezoelectric energy harvesting device for potential wearable device applications.

6. Acknowledgement

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