PIEZOELECTRIC AND ELECTROMAGNETIC HYBRID ENERGY HARVESTER USING TWO CANTILEVERS FOR FREQUENCY UP-CONVERSION

*Dae-Sung Kwon, Hee-Jin Ko, and Jongbaeg Kim**

School of Mechanical Engineering, Yonsei University, Korea

ABSTRACT

We developed frequency up-conversion hybrid energy harvester using two (internal and external) cantilevers. In order to increase harvesting power, the harvester utilizes piezoelectric and electromagnetic conversions simultaneously. By adopting frequency up-conversion method which is enabled by the bending of layered structures (substrate and two cantilevers) and separation between them, it can harvest electrical energy effectively from mechanical motion at extremely low frequency. The maximum power was measured to be 5.76 mW, which is the sum of the power generated by two different mechanisms.

INTRODUCTION

In recent years, the use of portable and wearable electronics has steadily increased. These electronic devices are usually powered by batteries. With technical advances, required power of the consumer electronics has been reduced. Harvesting energy from wasted ambient energy sources has become an attractive approach as alternative power source to be supplied to the electronics [1-3]. In particular, mechanical energy harvesters have attracted special interest because of the abundance of sources of the energy, such as vibration of machinery, wind, water waves, and human motions [4-7]. Despite the continuous development, the output power of the harvester still needs to be improved for the application to commercial electronic systems.

In order to increase the amount of harvested energy, one of the effective ways is to design a hybrid energy harvester. It is to harvest from energy sources on a single device using the combination of multiple energy conversion mechanisms – including piezoelectric, electromagnetic, electrostatic and triboelectric [8-10]. For harvesting mechanical energy, piezoelectric and electromagnetic conversions got much attention as they have high electromechanical coupling effect and no external voltage source requirement [11]. These conversion mechanisms are also advantageous for their insensitiveness to the change of ambient environment such as humidity [12].

Various studies on piezoelectric-electromagnetic hybrid energy harvester have been conducted about structural design, mathematical modeling, and electrical and mechanical damping optimization [13-15]. However, most of the harvester in these studies were driven at high resonant frequency to achieve high output power. In order to maximize the output power from both piezoelectric and electromagnetic conversions, large changes in the strain and the magnetic field is required within a unit time. While most of vibrational energy harvesters utilizing these conversion mechanisms can achieve maximum output power at its resonant frequency, the resonant frequency is usually very high compared to the frequencies of typical vibration sources [16]. Therefore, several frequency up-conversion mechanisms have been studied [17-19] and we developed frequency up-converting structure for piezoelectric energy harvester in the previous study [20].

In this paper, a flexible hybrid energy harvester that can be driven at low input frequencies is proposed to harness energy from ambient vibration or human body movements. To increase harvesting power, piezoelectric and electromagnetic conversion mechanisms are used simultaneously. In addition, it can harvest energy from extremely low frequency mechanical motion through the

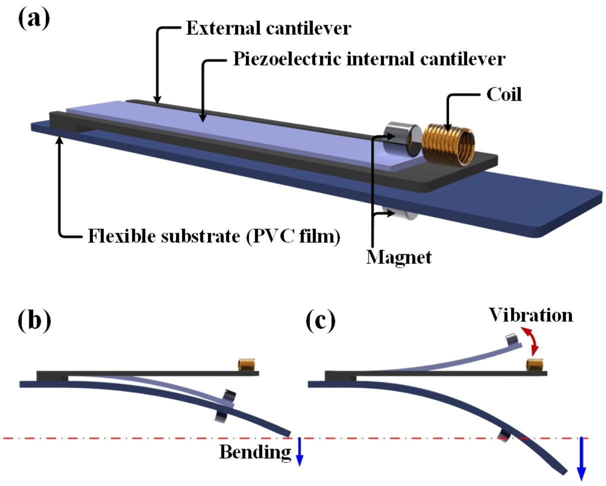

Figure 1: (a) Schematic diagram of the harvester. (b, c) Working principle of the harvester. When external bending is applied the substrate, the cantilever is released from the substrate and oscillates at its resonant frequency.

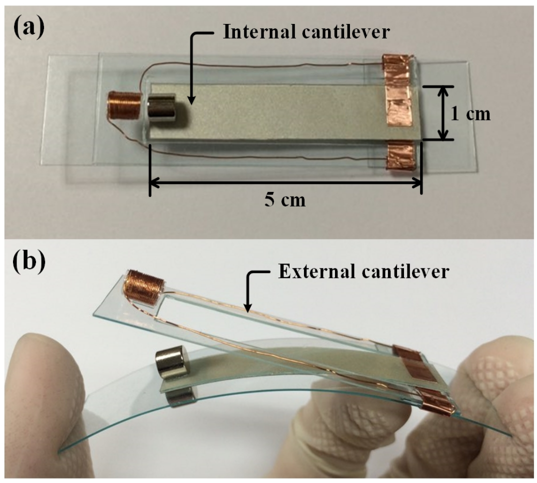

Figure 2: (a) Photograph of the fabricated harvester. (b) When the internal cantilever is deformed along with the substrate, the external cantilever remains in a flat state.

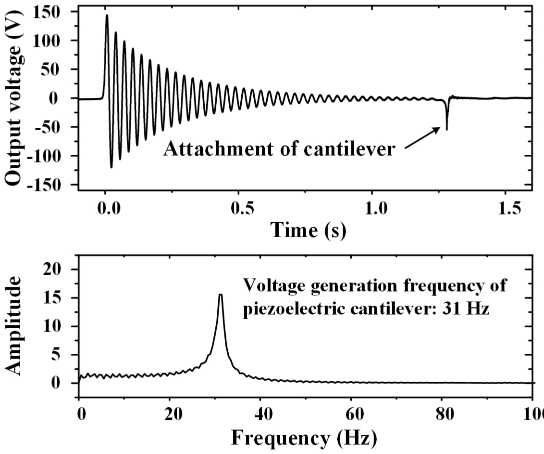

Figure 3: Open-circuit voltage from the piezoelectric harvesting in the time domain and frequency domain. An additional peak was formed owing to the reattachment of the two magnets.

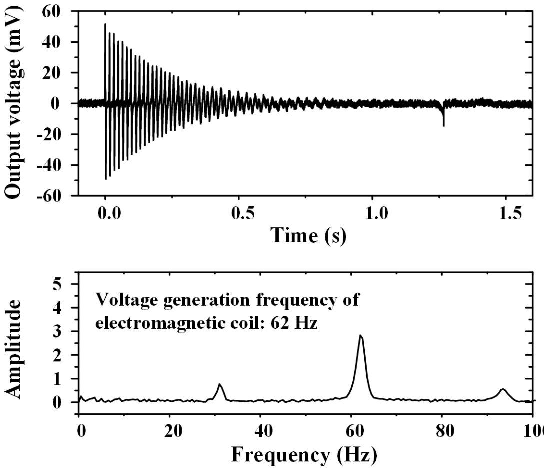

Figure 4: Open-circuit voltage of the electromagnetic conversion in the time domain and frequency domain. Voltage generation frequency of electromagnetic coil is twice of the frequency of piezoelectric cantilever.

frequency up-conversion method where the low frequency bending motion input to the harvester is stored as mechanical potential energy and it is released as high frequency vibration of the harvester structure.

DESIGN AND FABRICATION

Figure 1(a) shows the schematics of the hybrid energy harvester. The harvester is composed of two (internal and external) cantilevers on a flexible substrate. The piezoelectric internal cantilever is bound to the substrate by magnetic attraction force. Electromagnetic coil is mounted on one end of the external cantilever, while the other end is anchored to the substrate. The working principle of the harvester is depicted in figure 1(b) and (c). For external bending load applied to the harvester, the substrate and the internal cantilever deform together. When the bending radius of the cantilever becomes smaller than the threshold radius of curvature, it is released and oscillates at its resonant frequency. During this oscillation, the relative motion between the internal cantilever and the external cantilever occurs. Hence, it can harvest energy from the natural vibration of piezoelectric internal cantilever and the relative motion between a magnet and coil simultaneously. The threshold bending moment at which the magnet is released from the substrate is governed only by the radius of curvature and does not depend on the deformation rate or input bending frequency. Figure 2 shows photographs of the fabricated harvester. When external bending is applied to the substrate, the internal cantilever is deformed along with the substrate and the external cantilever remains in a flat state (figure 2(b)).

The harvester was fabricated using polymer film for the flexibility of the device itself. The substrate and the two cantilevers of the harvester were fabricated using a flexible polyvinyl chloride (PVC) film, and the piezoelectric polyvinylidene fluoride (PVDF) film was bonded to the backside of internal cantilever; two neodymium magnets bound the substrate and the internal cantilever together. The length, width, and the total thickness of the internal cantilever were 50 mm, 10 mm, and 510 µm (400 µm-thick PVC film plus 110 µm-thick PVDF film), respectively.

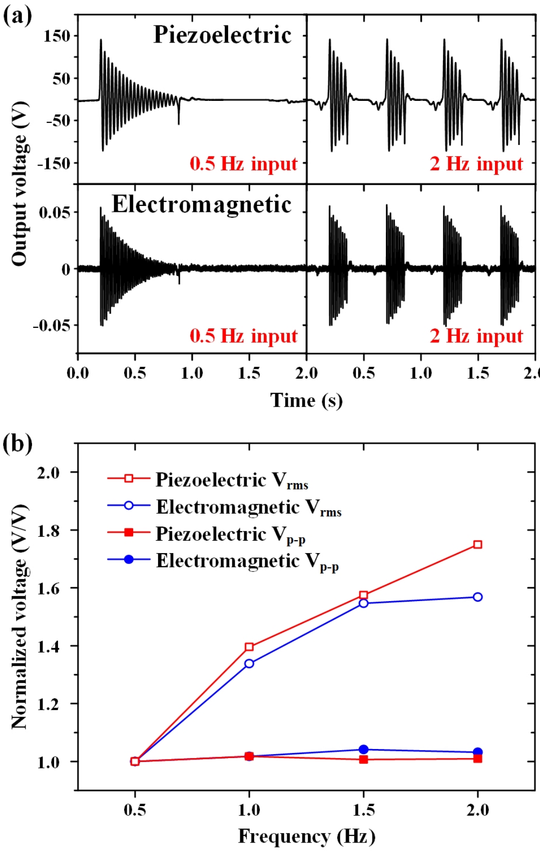

Figure 5: (a) Output voltage response of the harvester with varying input frequency. (b) When the input frequency increases, the RMS voltage of the harvester increases, while the peak-to-peak voltage of the harvester remains almost constant.

RESULTS AND DISCUSSION

Figure 3 shows the open-circuit voltage from the piezoelectric harvesting. Measured peak-to-peak voltage was 263 V and voltage generation frequency was 31 Hz which is the natural frequency of vibrating cantilever. When the bent substrate of the harvester returned to the

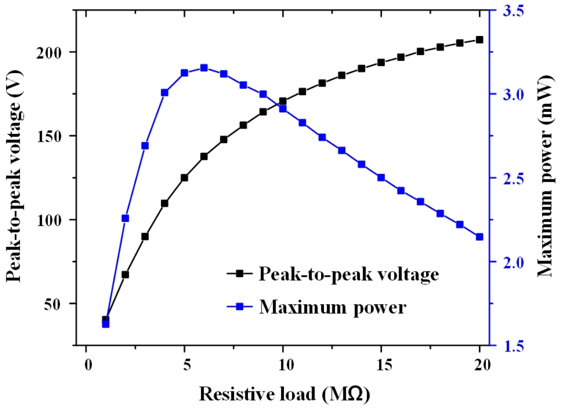

Figure 6: Output voltage and power from piezoelectric harvesting at various resistive loads. The maximum power is 3.16 mW for a resistive load of 6 MΩ.

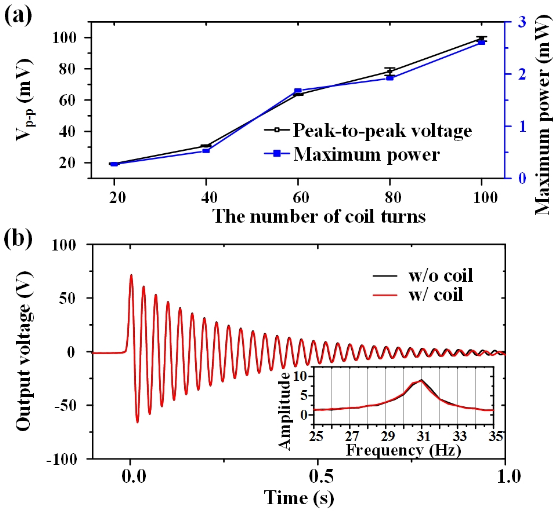

Figure 7: (a) Changes in peak-to-peak voltage and maximum power of the electromagnetic coil according to the number of coil turns. (b) Piezoelectric output voltages for two different cases: with and without coil.

original flat shape, an additional peak was formed owing to the reattachment of the two magnets. Figure 4 shows the open-circuit voltage of the electromagnetic conversion with 100 coil turns. Measured peak-to-peak voltage was 106 mV and voltage generation frequency was 62 Hz. This is exactly a double of the cantilever's natural frequency, because each of approach and recession of the magnet to and from the coil will make voltage peak.

Figure 5 shows the output voltage responses for varying input frequency. Figure 5(a) compares the waveform of the output voltage for input frequencies of 0.5 and 2 Hz. The harvester was able to efficiently harvest energy at a very low input frequency of 0.5 Hz. When the input frequency was increased, the substrate returned to the initial flat state before the cantilever vibration decayed completely, and the cantilever was reattached to the substrate stopping the vibration. Figure 5(b) shows the output voltages for four different input frequencies in the range of 0.5 Hz to 2 Hz. To reveal relative increment of the output for higher input frequency, the y-axis values are shown as the voltage outputs divided by the output at 0.5 Hz input frequency. When the input frequency increases, the RMS voltage of the harvester increases, while the peak-to-peak voltage of the harvester remains almost constant. The RMS voltage, however, does not increase linearly with respect to the input frequency increment due to the fast reattachment of the cantilever before the vibration completely decayed at higher input frequency.

Figure 6 shows the optimal load of piezoelectric cantilever for maximum power generation. The maximum power from piezoelectric harvesting was 3.16 mW for a resistive load of 6 MΩ. Figure 7(a) shows the changes in peak-to-peak voltage of the electromagnetic coil according to the number of coil turns. When the number of coil turns increases, the output voltage and power also increase. The maximum power from electromagnetic coil was 2.60 mW with 100 coil turns. Figure 7(b) compares the piezoelectric output voltages for two different cases: with and without coil. With coil, the voltage generation frequency is slightly lower due to magnetic damping, but the difference in output power is minimal. As a result, the maximum output power of the hybrid energy harvester is 5.76 mW, which is the sum of power generated by two different mechanisms.

CONCLUSIONS

In this paper, we proposed frequency up-conversion hybrid energy harvester that converts deformation of the device itself into vibration of the device. The harvester was fabricated in layered structures of flexible polymer films and can harvest energy by bending of the layered structures and separation between them. To increase the harvested power, the harvester simultaneously utilizes piezoelectric and electromagnetic conversions. The peak-to-peak power was 3.16 mW by piezoelectric conversion and 2.60 mW by electrostatic conversion. Because the proposed harvester operates via the accumulation of strain energy, it is possible to harvest energy from extremely low input frequencies without decreasing the output voltage.

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CONTACT

*J. Kim, tel: +82-2-2123-2812; kimjb@yonsei.ac.kr