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Development of Enhanced Piezoelectric Energy Harvester Induced by Human Motion

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Abstract— **In this study, a high frequency piezoelectric energy harvester converted from the human low vibrated motion energy was newly developed. This hybrid energy harvester consists of the unimorph piezoelectric cantilever and a couple of permanent magnets. One magnet was attached at the end of cantilever, and the counterpart magnet was set at the end of the pendulum. The mechanical energy provided through the human walking motion, which is a typical ubiquitous presence of vibration, is converted to the electric energy via the piezoelectric cantilever vibration system. At first, we studied the energy convert mechanism and the performance of our energy harvester, where the resonance free vibration of unimorph cantilever with one permanent magnet under a rather high frequency was induced by the artificial low frequency vibration. The counterpart magnet attached on the pendulum. Next, we equipped the counterpart permanent magnet pendulum, which was fluctuated under a very low frequency by the human walking, and the piezoelectric cantilever, which had the permanent magnet at the end. The low-to-high frequency convert "hybrid system" can be characterized as an enhanced energy harvest one. We examined and obtained maximum values of voltage and power in this system, as 1.2V and 1.2 μW. Those results show the possibility to apply for the energy harvester in the portable and implantable Bio-MEMS devices.**

I. Introduction

Recently, studies on the body area network (BAN), which integrated short-range wireless network equipments, such as the medical and health care devices, have been carried out to develop the ubiquitous care system. Long-term health monitoring can be achieved by BAN [1,2], which will enable tele-communicating and health monitoring between patients lived in a low population and no-doctor area and medical doctors stayed at medical hospital in the high-population cities. However, there are power supply problems to functionalize BAN system. Until now, the power was provided by the electric batteries. But, these have problems with the permanent energy supply. It causes the loss of important individual data. In addition, in the case of power off occurrence with the battery for implantable devices, the surgery will be required to replace with a new battery, and which causes the QOL loss [3]. Therefore, studies on the energy harvesting for the power supply equipment for mobile health monitoring have been carried out [4].

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The energy generated by the human body itself and motion was characterized as the thermal and vibration energies. Power generation using thermal energy caused by the temperature difference in the body was concluded as the inefficient process. Therefore, many studies employed the vibration energy, such as the mechanical energy. Further, the conversional energy convert method from the vibration mechanical energy into the electrical energy via the piezoelectric effect is still very effective, due to the ubiquitous presence of vibrations and the availability of piezoelectric materials with a high performance [5-10].

In this study, we develop a miniature size energy harvester to generate electricity using vibration caused by the human walking motion. An enhanced energy convert system by using the unimorph piezoelectric cantilever under the resonance free vibration is newly designed, fabricated and examined its performance.

II. Piezoelectric Cantilever Vibrator

In this study, a unimorph cantilever as shown in Figure 1, in which the piezoelectric thin film is laminated on the top surface of metal shim plate, was used to generate the electricity through the piezoelectric response. The deflection of the unimorph cantilever through the vibration with the resonance frequency generates the voltage and the electric power can be charged in the battery. A rather high frequency is obtained by the free vibration with the resonance frequency. As a result, generated voltage can be written as

$$\mathrm{V} = \frac{d_{31} \times \sigma_1 \times t}{\epsilon_{33}^T} \tag{1}$$

where V is output voltage, d_{31} the piezoelectric strain constant, σ_1 the stress, ϵ_{33}^T the permittivity, and t the element's size. By using the beam theory, the stress σ_1 is given by the applied bending moment M as follow

$$\sigma_1 = \frac{M}{I} y \tag{2}$$

where I is the second moment of area of beam, y the coordinate in the lateral direction. Bending moment in the vibration given by

$$\mathrm{M} = \mathrm{ma}(L - x) \tag{3}$$

where m is the tip mass, and a the tip acceleration. It is understood that the voltage generated in the cantilever is proportional to the tip mass and acceleration. Usually, in this vibration energy harvester, it is said that the larger the deflection and frequency, the larger the generated power.

The vibration frequency of walking is assumed 1 to 5 Hz. Generally, the low-frequency vibration, such as 1-10 Hz, can be featured as inefficient system. At present, most of the vibrational harvesters operate at high-frequency such as 10 Hz to 100 kHz [11-17]. In order to generate the power effectively through the convert from a low-frequency vibration to a high one, a hybrid convert system is designed. The high-frequency free vibration of the piezoelectric cantilever was generated by the low frequency forced deflection at the end of cantilever. A pair of magnet was used to deflect the cantilever to initiate the high resonance frequency vibration. The low-frequency vibration of the counterpart magnet can be converted to the high frequency one and consequently an effective and enhanced electric power generation was achieved.

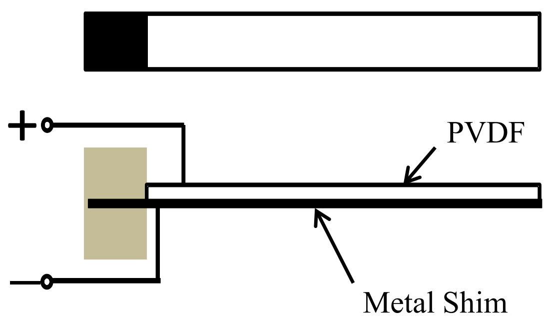


Figure 1. Schematic view of unimorph piezoelectric cantilever.

Figure 2 illustrates a fundamental mechanism of magnetic induced vibration energy harvest system. Electric power generation system consists of two vibration elements. One is the magnet attached cantilever beam to generate electric power under the high frequency vibration, and the other the counterpart magnet to input the low-frequency vibration at the edge of cantilever, which locates in front of the cantilever beam. The principle of converting the vibration from the low to high frequency is indicated as follow. Beam is bent by bending stress caused by magnetic repulsive force between the pair of magnets when the counterpart magnet passes in front of the cantilever edge as shown in Figure 3. Cantilever is released from the magnetic force when the elastic resistant force of beam becomes larger than the magnet repulsive force. There the electric power generation is occurred by the eigen frequency vibration. We employ PVDF (d_{31}= 23 pC/N) for piezoelectric material, stainless (SUS304) for metal shim plate, and neodymium magnet for magnet.

III. Frequency Conversion and Performance Test of Magnetic Force Induced Mechanical-Electrical Energy Converter

Experiments of electric power harvest system using this hybrid vibration system were conducted in order to evaluate frequency convert and power generation characteristics.

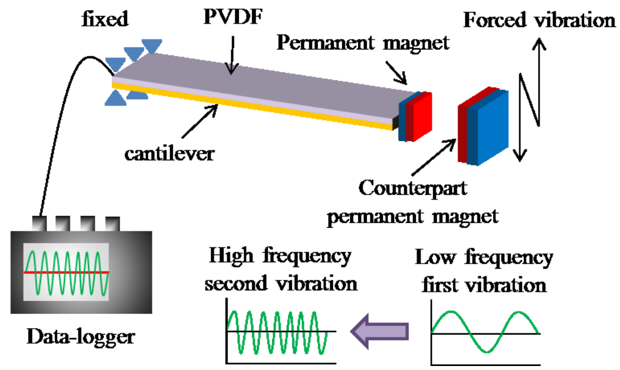
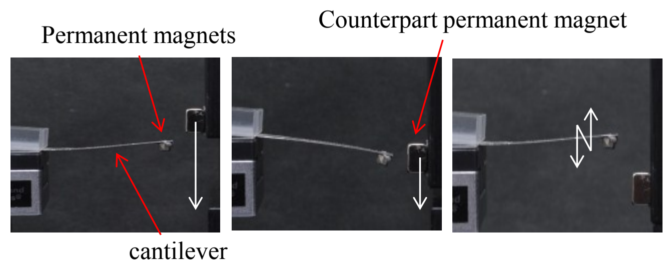
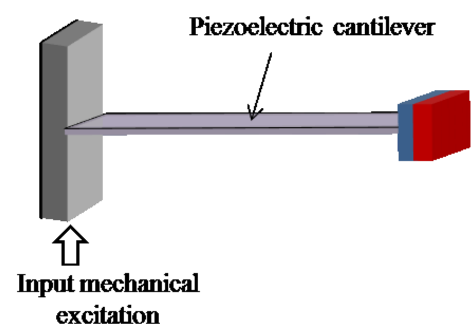


Figure 2. Energy conversion flow of magnetic induced system employing a low-high frequency vibration conversion system.

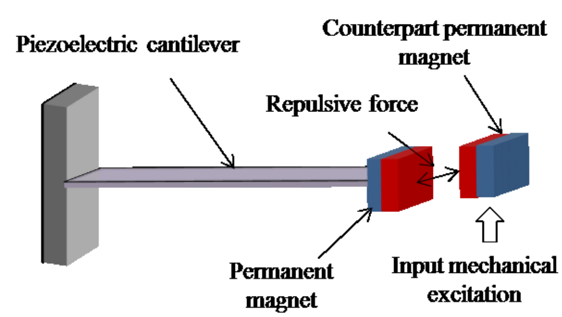


(a) Initial state **(b)** Release from magnet **(c)** Eigen vibration

Figure 3. Photos of magnet-beam motion at described stages.



(a) Conventional system



(b) Magnetic enhanced vibration system.

Figure 4. (a) The conventional piezoelectric cantilever energy harvest system and (b) the magnetic induced energy harvest system.

Two types vibration system were employed, such as the conventional system as shown in Figure 4(a) and the magnetic induced system as shown in Figure 4(b).A PVDF thin film (40 ×10 ×0.1 mm) was bonded on the SUS304 plate (40 ×10 × 0.1 mm) surface. Experiments of excitation were performed with 5 Hz and 5 mm amplitude at the right fixed boundary and the left end points in two systems, respectively. Figure 5 shows the experimental results. The maximum voltage occurs at every 0.2 second interval in both systems. In order to investigate the frequency spectrum of the output voltage, FFT analysis was carried out and the result was shown in Figure 6. Theoretical value of first-order eigen frequency of cantilever beam was obtained through the linear theory as,

$$f = \frac{1}{2\pi}\left(\frac{1.875}{L}\right)^2 \sqrt{\frac{EI}{\rho A}} \tag{4}$$

where L is the length of beam, EI the bending stiffness, ρ the density, and A the cross-sectional area. A theoretical first-order eigen frequency of the beam was obtained as 39.2 Hz, which coincided with the experimental result, such as 40 Hz as shown in Figure 6. In the magnet enhanced hybrid system, 5Hz to 40 Hz frequency conversion was achieved.

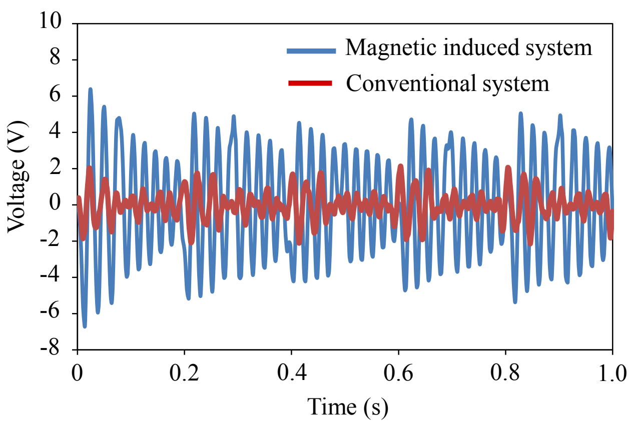


Figure 5. Comparison of output voltage in cases of magnetic induced and conventional systems at 5 Hz vibration.

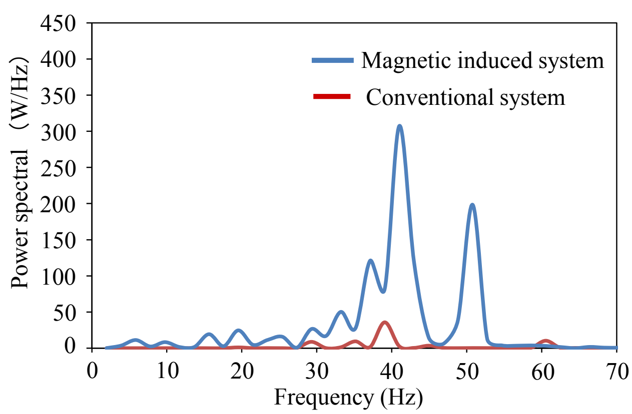


Figure 6. Results of FFT analyses of the magnetic induced system and the conventional one.

Further, we found two values of resonant frequency, 40 Hz and 50 Hz in the case of the hybrid system in Figure 5 and 6, which had the features of large deflection. It could be related to the increase of the stiffness, such as hard spring cantilever, mainly caused by the large deflection and the large repulsive force from the counterpart permanent magnet.

The maximum voltage of conventional system was 2.1 V. On the other hand, the magnetic induced system showed the maximum voltage 6.3 V. In addition, a large voltage can be generated continuously through the free high frequency vibration induced by the low frequency magnet vibration. Consequently, the magnetic induced system was validated as the power generation system at low frequency.

IV. Prototype and Measurement

The magnet induced system was adopted to design an enhanced energy convert system in conjunction with the ubiquitous device. A newly designed system was consisted of the piezoelectric cantilever and the pendulum, which were attached the permanent magnet at the tip, as shown in Figure 7. In this harvester, the pendulum pushes up the piezoelectric beam and induces eigen frequency, as shown in Figure 8. Actually, the pendulum vibrator was occurred by the human walk motion. By using this enhanced energy harvester, 2 Hz low-frequency human walking vibration was inputted and the generated voltage was measured as shown in Figure 9. A PVDF thin film (25 ×10 × 0.1 mm) was bonded to SUS304 plate (25 × 10 × 0.1 mm). The maximum voltage 1.2 V was obtained. Figure 10 shows the output voltage and power delivered to the load. The optimum load resistance (R_L) can be firstly estimated as

$$R_L = \frac{1}{\omega_r C_p} \tag{5}$$

where ω_r is the resonant frequency, and C_p the capacitance of the piezoelectric cantilever. The harvester was then connected with a continually adjustable load resistance from 100 kΩ to 1 MΩ, which can cover the estimated value at the initial design. As expected, the output voltage increases with the load resistance. The maximum electric power 1.2 μW was obtained at the optimum resistance value, namely 600 kΩ as shown in Figure 10.

V. Conclusion

We have developed the magnetic induced harvester – the hybrid vibration system – employing the piezoelectric cantilever. This harvester converts the low-frequency human motion to high frequency resonance vibration of the cantilever beam. Through the frequency conversion, it is possible to generate electricity without dependence on the ambient vibration frequency. We confirmed this frequency convert system's availability for the effective energy harvest.

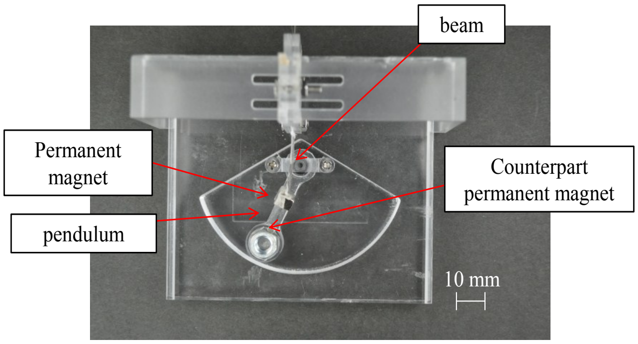


Figure 7. Schematic view of magnetic induced harvester.

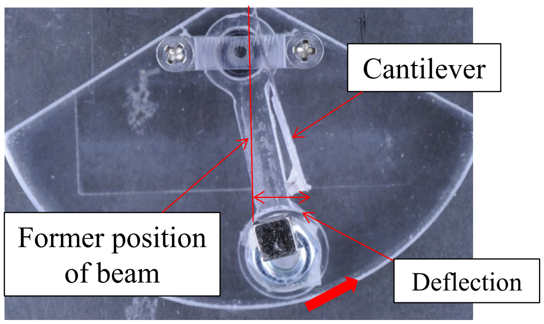


Figure 8. Photo of pendulum motion.

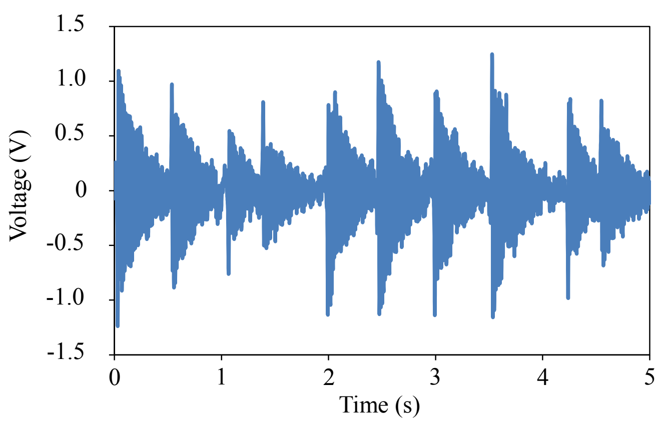


Figure 9. Time history of generated voltage.

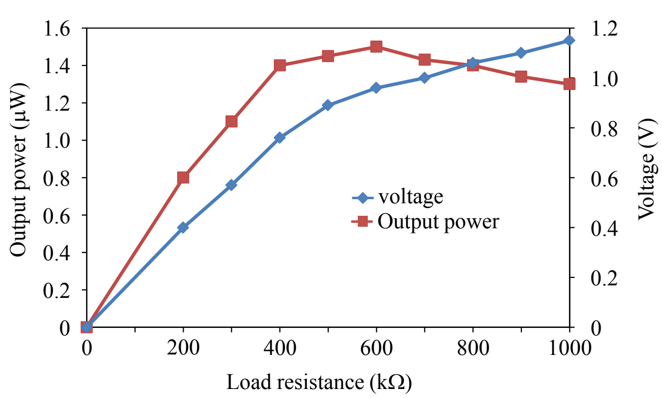


Figure 10. The generated voltage and power vs. load resistance at resonant frequency in the magnetic induced harvester.

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