LOW FREQUENCY VIBRATION ENERGY HARVESTER USING MSMA/PZT LAMINATE STRUCTURE AND BALL MAGNET

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Abstract: This paper presents a non-resonant vibration energy harvester using magnetoelectric composite and ball magnet, designed to harvest energy from human-body-induced motion. The device consists of freely movable spherical permanent magnets located on top of a magnetoelectric laminate fabricated with Ni-Mn-Ga-based MSMA (Magnetic Shape Memory Alloy) element and PZT (lead zirconate titanate) plate. A proof-of-concept energy harvesting device has been fabricated and characterized. Maximum output voltage of 0.54V has been obtained in response to a 3g vibration at 12Hz. Moreover, maximum output voltage of 1.88V has been achieved when the cube magnet variant of the fabricated energy harvester was mounted on a smart phone and hand-shaken.

Keywords: magnetoelectric effect, magnetic shape memory alloy, energy harvesting

INTRODUCTION

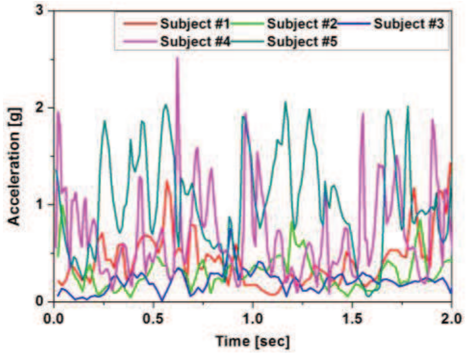
Energy harvester is receiving a considerable amount of research interest as a substitute or auxiliary module for external power sources in wireless sensor nodes and low power devices. Renewable power can be obtained by harvesting electrical energy from light, wind, temperature difference, and vibration within the device's environment. Among various energy sources, ambient vibration is especially attractive because of its abundance in nature. In general, ambient vibration is converted into electrical energy using piezoelectric, electromagnetic and electrostatic mechanisms [1].

Harvesting energy from ambient vibration in many practical applications, including the human-body-induced vibration, is challenging due to the low frequency and random nature of the vibration source, which generally disallows the employment of conventional spring-mass-damper-based resonant energy harvesting principle. To overcome these issues, various power generation mechanisms including impact based piezoelectric energy harvesting, electromagnetic power generation utilizing random motion of a ball magnet in the cavity wrapped with coil, and frequency up-conversion of electromagnetic transducers have been demonstrated [2-4].

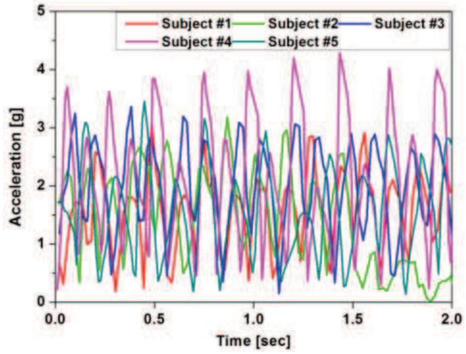
Magnetoelectric composites have been drawing attention in vibration energy harvesting applications due to inherent high output voltage characteristics, but effective conversion of low frequency vibration to variable magnetic field without using spring-mass system has not been demonstrated [5-6]. In this research, we present a non-resonant type vibration energy harvester with permanent magnets and magnetoelectric laminate using MSMA and PZT, to harvest energy from human-body-induced motion.

HUMAN-BODY-INDUCED VIBRATION

For a better understanding of the characteristics of human-induced vibration, we have measured and analyzed the vibrations generated in various situations using an accelerometer embedded in a smart phone. Vibrations generated in 2 different conditions; 1) walking with a phone in the trouser pocket, 2) hand-shaking a phone, are shown in Fig. 1. Data has been collected for 5 minutes at 100Hz sampling frequency from 5 male and female subjects, respectively.



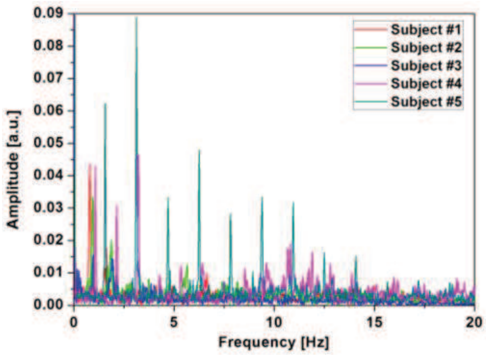
(a) Walking with a phone in the trouser pocket



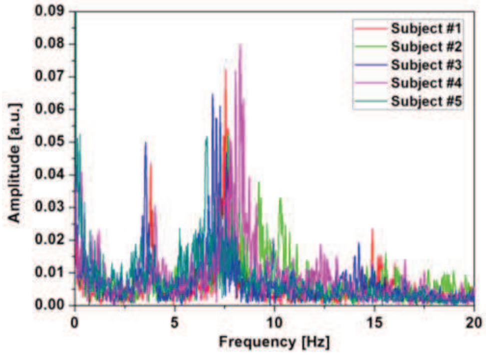
(b) Manually shaking a smart phone

Fig. 1: Part of the accelerations measured from 5 male subjects

Relatively higher accelerations were observed when the phone was hand-shaken. The maximum value of the acceleration was 1.13-4.29g (Fig. 1(b)). In general, accelerations obtained from male subjects were higher than those from female subjects in all cases. Also, typical maximum acceleration was less than 3g except for the hand-shaking case. Frequency component of the measured acceleration has been analyzed by FFT(Fast Fourier Transform) of the measured data using MATLAB. As shown in Fig. 2, noticeable peaks were observed in the 1-16Hz range, which is in good agreement with the previous observations [3]. For the hand-shaking case, relatively broader peaks were observed in the 3-15 Hz range.



(a) Walking with a phone in the trouser pocket



(b) Manually shaking a smart phone

Fig. 2: FFT result of the accelerations measured from 5 male subjects

HARVESTER DESIGN

A schematic diagram of the proposed energy harvester is illustrated in Fig. 3. The harvester consists of a ball magnet and a magnetoelectric laminate structure. The magnetoelectric laminate used is a stack of Ni-Mn-Ga-based MSMA bar bonded to a PZT plate. MSMA element elongates in response to the external magnetic field in transverse mode with maximum elongation of 6% of the total length, which is much larger than that of the typical giant magnetostrictive materials such as Terfenol-D and Galfenol. To our knowledge, this is the first attempt to utilize the MSMA-based magnetoelectric laminate in vibration energy harvester.

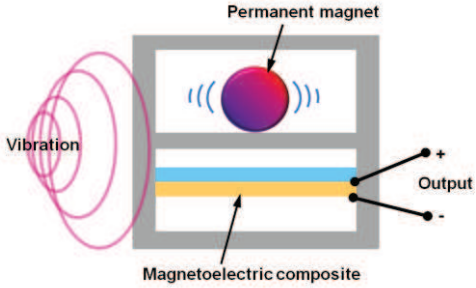
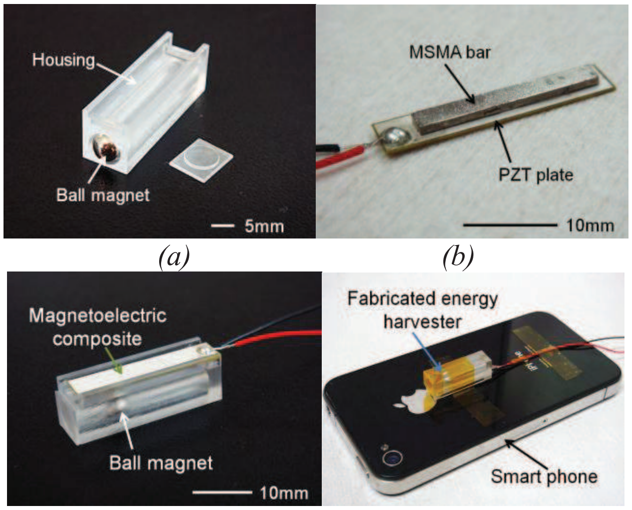


Fig. 3: Schematic of the proposed energy harvester using ball magnet and MSMA/PZT laminate structure.

When the harvester is excited, vibration of the ball magnet induces time-varying magnetic field applied to the magnetoelectric composite. As the perpendicular magnetic field elongates and parallel field contracts the MSMA element, variations in external magnetic field induces strain in PZT plate, which generates electrical power.

FABRICATION

A proof-of-concept energy harvester has been fabricated by assembling a 5mm-diameter NdFeB ball magnet, polycarbonate housing with 5.2mm-diameter channel, and a magnetoelectric component. As shown in Fig. 4, an MSMA bar ($20x2.5x1mm^3$) has been attached to a PZT plate ($25x5x0.3mm^3$) with epoxy, which has been attached to the housing in bridge configuration. The housing has been made out of transparent polycarbonate block in order to track the position of the movable ball magnet.



(a) *(b)*

(c) *(d)*

Fig. 4: Assembled device: (a) housing and magnet, (b) MSMA/PZT laminate, (c) assembled energy harvester, (d) harvester mounted on a smart phone

RESULTS AND DISCUSSION

Assembled device (25.5x7.6x8.7mm^3) has been tested based on the observations from the human-body-induced vibration analysis. As the acceleration peaks occur at frequencies smaller than 16Hz and reach up to 2-3g, except for the hand-shaking case, vibration exciter test has been performed with variable frequency and acceleration up to 20Hz and 3g, respectively. Vibrations with very low frequency (<6Hz) and higher acceleration (>3g) could not be applied due to the limitation of the test equipment. Moreover, output from the harvester has been measured while manually vibrating the fabricated device mounted on a smart phone. Figure 5 shows the experimental setup for the vibration exciter test (left) and manual vibration test (right), respectively.

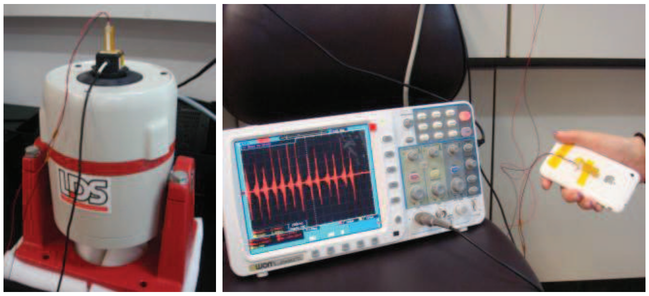
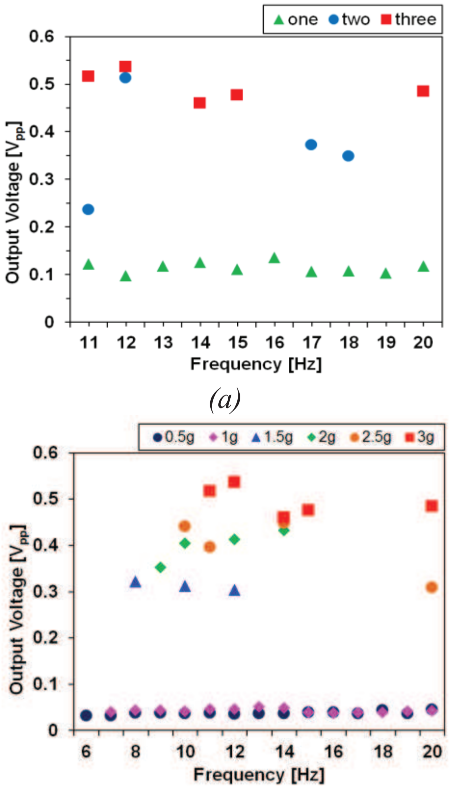


Fig. 5: Experimental setup for the vibration exciter test (left) and manual vibration test (right)

Vibration exciter test

As shown in Fig. 5, fabricated device has been mounted vertically on the vibration exciter, so that the ball magnet can generate vertical motion along the channel in response to the excitation. To improve the output by increasing the effective area where the external magnetic field is applied, up to 3 magnets have been attached in series and tested. As the length of the channel is 23mm, 3 magnets attached in series can travel 8mm in single direction. Output voltage in response to 11-20Hz sinusoidal vibration with 3g acceleration has been measured while changing the number of magnets. At frequencies lower than 11Hz, 3g vibration could not be applied due to the limitations of the exciter. As shown in Fig. 6(a), substantially increased output voltage has been observed as the number of magnets was increased. Although the attraction force due to the non-zero relative permeability of the MSMA element has been compensated by increasing the number of magnets, magnets showed irregular stiction behavior and resulted in zero output in some of the cases. Missing data points in the output for the 2 and 3 magnets case in Fig. 6(a) corresponds to these cases. Despite the irregularities, increase of output voltage in response to increasing number of magnets is clearly visible.

We have measured the output voltage of the device with 3 magnets at 6-20Hz sinusoidal inputs while the acceleration has been changed from 0.5 to 3g with 0.5g step. As shown in Fig. 6(b), output voltage showed an increasing trend as the acceleration was increased. Maximum peak-to-peak output voltage of 0.54V has been obtained at 3g vibration at 12Hz (Fig.7).



(a)

(b)

Fig. 6: Vibration exciter test results: (a) output voltage vs. frequency at different number of magnets (3g acceleration), (b) output voltage vs. frequency at various input accelerations (device with 3 magnets)

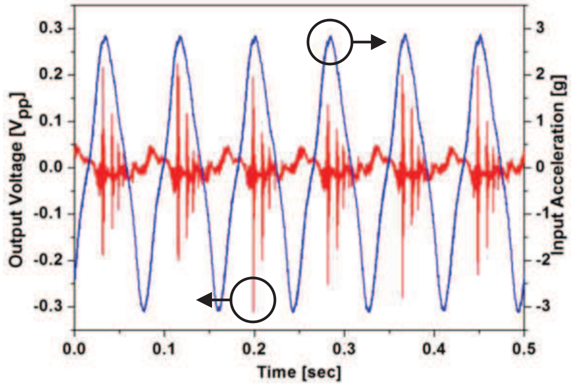
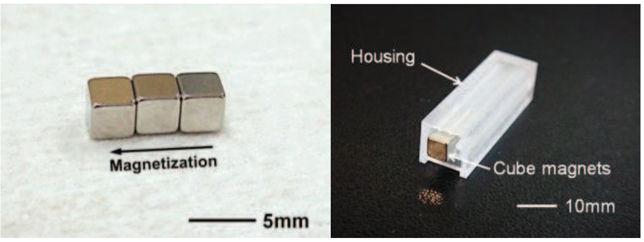


Fig. 7: Output voltage waveform at 3g acceleration at 12Hz (device with 3 magnets)

Manual vibration test

Fabricated energy harvester has been mounted on the backside of a smart phone (Fig. 4(d)) and output voltage has been measured while the phone was shaken manually. Typical output voltage of the harvester with 3 ball magnets attached in series was 1.06V. For further improvement of the output, device with 3 cube magnets (3.2mm on one side) connected in series have been tested (Fig. 8(a)). Cross-section of the channel has been designed to minimize the contact between the channel sidewall and magnets with 50µm clearance on one side (Fig. 8(b)). As shown in Fig. 9, maximum output voltage of 1.88V has been obtained by manual excitation after mounting on a smart phone. In contrast to the results obtained with the vibration exciter, relatively high output voltage was observed without notable stiction to the channel sidewall. As the acceleration can go over 4g in manual vibration case, both the direction and amplitude of the applied acceleration are distinct from those of the vibration exciter test conditions.



(a) *(b)*

Fig. 8: Device with cube magnets: (a) 3 cube magnets connected in series, (b) cube magnets and housing

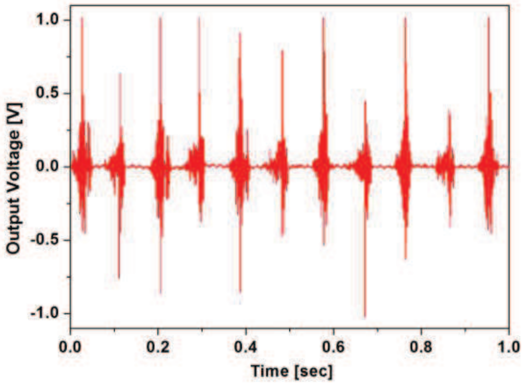


Fig. 9: Output voltage waveform when the harvester is mounted on a smart phone and hand-shaken (harvester with 3 cube magnets used)

For further improvement of the performance, attraction force between the permanent magnets and MSMA element has to be reduced by optimization of the magnetic circuit. As the magnetoelectric laminate consists of off-the-shelf MSMA bar and PZT plate, shape and size of the elements could not be controlled. Moreover, attachment method of MSMA bar and PZT plate, surface topography and friction of the channel sidewall, and polarization of the MSMA and PZT have to be optimized.

CONCLUSION

We have developed a non-resonant vibration energy harvester to scavenge energy from human-induced motion using permanent magnets and MSMA/PZT laminated magnetoelectric composite. A proof-of-concept energy harvester has been fabricated and characterized. For the device with 3 ball magnets, maximum output voltage of 0.54V has been obtained at 3g vibration at 12Hz. Moreover, we have achieved maximum output voltage of 1.88V with a harvester fabricated with 3 cube magnets mounted on a smart phone by hand-shaking. Although demonstrated devices require further optimization, we have successfully verified the concept of providing time-varying magnetic field to an MSMA-based magnetoelectric laminate from low frequency human-body-induced vibration to generate electrical power.

ACKNOWLEDGEMENT

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