A frequency up-converted electromagnetic energy harvester using human hand-shaking

M A Halim and J Y Park
Micro/Nano Devices and Packaging Lab., Dept. of Electronic Engineering, Kwangwoon University, 447-1 Wolgye-dong, Nowon-gu, Seoul, 139-701 Korea
E-mail: jaepark@kw.ac.kr

Abstract: We present a frequency up-converted electromagnetic (EM) energy harvester that is capable of powering various portable devices and systems by hand-shaking. It consists of a freely movable ball to impact periodically (at low frequency) on the parabolic top surface of a mass of a cantilever beam allowing it to vibrate at higher (resonant) frequency. Relative motion between a magnet attached to the cantilever and a coil induces voltage. A prototype of the energy harvester has been fabricated and characterized by applying vibration from hand-shaking. The frequency and acceleration of the applied hand-shaking vibration has been experimentally found to be 4.6 Hz and 2g, respectively. With an optimum distance between magnet and coil, a maximum 672 mV peak-peak open circuit voltage of 370 Hz frequency and a maximum 413 µW peak power delivered to an 85Ω matched load resistance have been obtained, respectively.

1. Introduction
With the rapid development in the fields of electronics, portable smart devices such as mobile phones, tablet computers, wireless sensor nodes, wrist watches, audio devices, hearing aids, implanted biomedical devices etc are becoming very popular due to their smaller size, low power consuming and multi-functional features. Each and every device requires power sources to be operated. Generally, electro-chemical batteries have been using as power source to supply power to these portable and smart electronic devices. Beside the advantages (e.g., high energy density, smaller size, low cost) of the electro-chemical batteries, they have some disadvantages including limited lifetime, inconvenient in recharging or sometimes, replacing. This is why, many researchers all over the world have been investigating alternatives to the electrochemical batteries. Light, wind, heat, radio wave, vibration etc. are the energy sources readily available around our environment. Extracting energy from environmental vibration has drawn much attraction over the last few decades due to its abundance in nature and unlimited lifetime [1-4]. Different vibration sources generate vibrations of different frequencies and amplitudes, but most ambient vibrations are of low frequencies and large amplitudes with various cyclic movement in different directions. Basic human activities such as walking, running, shaking limbs, jumping, breathing etc. also generate vibration which are recently being interesting to the researchers to be used for energy harvesting [5-7]. Widely used techniques for harvesting energy
from ambient vibration, as well as human and machine motion are piezoelectric, electromagnetic and electrostatic mechanisms[8-10].

Vibration energy harvesters typically employ spring-mass-damper system that makes the harvesters a resonant device. To-date most of the vibration energy harvesting devices have been tested by electrodynamic shaker in the laboratory without considering the real applications e.g., harvesting energy from human-body-induced vibration. Human-body-induced vibrations are of low frequency with large amplitude which do not allow the conventional resonant harvesting devices to employ [5]. Moreover, the maximum voltage and generated electrical power of a resonant generator is strongly dependent on the externally applied vibration frequency and drops dramatically at low frequencies [11]. In this research, our proposed device overcomes both the limitations by employing the conventional spring-mass-damper system, but in a different way that is able to meet the real application. It utilizes the electromagnetic (EM) energy harvesting method with frequency up-conversion mechanism [12]. Upon excitation applied through hand-shaking, a freely moveable non-magnetic ball impacts on a cantilevered mass at low frequency on its way of movement, allowing the cantilever to vibrate with its higher resonant frequency. The cantilever vibrates in a direction perpendicular to that of the ball movement. A magnet attached to the cantilever also vibrates along with it. A pick up coil placed at the bottom of the magnet induces voltage due to the relative motion between magnet and coil according to Faraday's law of electromagnetic induction. This frequency up-converted feature of the device makes it to supply meaningful power to the portable smart devices from human-body-induced vibration such as hand-shaking.

2. Structure of the proposed EM harvester
The schematic structure of the proposed frequency up-converted EM energy harvester is shown in figure 1. It consists of a freely moveable non-magnetic ball within a rectangular channel having an opening at the centre of its bottom surface. A cubic mass with parabolic extension at the top edge is attached to (at the centre of one side) a fixed-fixed cantilever beam that works as the spring-mass-damper system. The beam is placed at such a position that the parabolic top surface of the mass can be positioned within the opening of the rectangular channel so that it would be impacted by the freely movable ball. A cylinder magnet is attached to the cantilever, opposite to the mass. A pick-up coil is also placed below the magnet, on the bottom cover of the device structure. When the device is shaken, the ball, inside the channel hits on the parabolic top of the mass allowing the cantilever to vibrate that makes the magnet to vibrate relative to the coil, inducing electromotive force within the coil. The vibration frequency (resonant frequency) of the cantilever beam is much higher than the applied vibration that can be determined by material and structural parameters of the cantilever beam.

![Figure 1. Schematic drawing of the proposed frequency up-converted electromagnetic energy harvester.](image-url)
3. Characteristics of hand-shaking vibration

In order to characterize the behaviour of hand-shaking vibration, we measured and analyzed the vibration generated by hand-shaking using an accelerometer (LSM330DLC 3-axis accelerometer; ST Microelectronics) embedded in a smart phone (Galaxy SIII; Samsung Electronics). In fact, it is obvious to characterize the vibration behaviour generated by hand-shaking because we are intended to operate the proposed EM energy harvester under hand-shaking. We have collected the data from four subjects at 50 Hz sampling rate for one minute. Figure 1(a) shows peak acceleration values were ranged from 15 ms\(^2\) (~1.5g) to 20 ms\(^2\) (~2g). Frequency components of the measured acceleration values were analyzed by FFT (Fast Fourier Transform) of the measured data. Figure 1(b) shows that the frequency of hand-shaking vibrations falls between 2.5 Hz and 6 Hz range for different subjects.

![Figure 2](image)

**Figure 2.** (a) Measured acceleration of vibration generated by hand-shaking a smart phone and (b) their frequency components obtained by FFT.

4. Prototype fabrication

A prototype was fabricated by using a Ø6×5 mm\(^2\) NdFeB cylinder magnet and a cubic mass (Fe) of length, 6 mm with a parabolic extension of 1 mm height at the top attached on either side of a FR4 cantilever beam (40×6×0.5 mm\(^3\)), a 1000-turn coil (0.1 mm copper wire) with 8 mm bobbin diameter, and a Ø10.3mm steel (type 316) ball moving in a rectangular channel (inner area 10.5×10.5 mm\(^2\) assembled within an aluminium structure (40×30×16 mm\(^3\)) as shown in Figure 3. The prototype has been tested by manual shaking. The cantilever was assembled in such a way that the parabolic top of the cubic mass is occupied inside by the opening (7 ×7 mm\(^2\)) of the channel making an overlap of 0.5 mm with the ball so that the ball can impact on the top while shaking the prototype.

![Figure 3](image)

**Figure 3.** Photomicrographs of (a) components before assembling and (b) fabricated macroscale prototype of the proposed energy harvester.
5. Experimental results and discussion
The output terminals of the fabricated prototype were connected to a digital storage oscilloscope (Tektronix TDS5052B) to measure its output response. Vibrations could not be applied to the prototype by the electrodynamic shaker (TMS 2004E) because of its limitation in producing vibration of low frequency (<6 Hz) and higher acceleration (>10 ms$^{-2}$). Figure 4 shows the peak-peak open circuit voltage vs. distance to determine the optimum distance between magnet and coil. A maximum voltage of 672 mV was obtained at -1 mm optimum distance.

![Figure 4](image1.png)

**Figure 4.** The measured peak-peak open circuit voltages at various distances between magnet and coil.

Figure 5 illustrates the peak-peak load voltage and peak power delivered to the load while the device was hand-shaken. The output terminals of the prototype were connected with a continually adjustable load resistor and the resistance values were swept from 50 Ω to 200 Ω range. A maximum 413 μW peak power was obtained from 85 Ω matched load resistance. Figure 6 shows the instantaneously generated voltage waveform generated across the matched load. The maximum peak-peak voltage was found to be 340 mV which was attenuated exponentially with time due to the damping of the cantilever beam vibration. As we found, the attenuation is not perfectly exponential due to the process variation in assembling the components. Two consecutive maximum peaks were generated in one cycle of the applied vibration because the ball impacted on the parabolic top of the mass twice in one cycle of its movement. By applying FFT, frequency of the generated voltage waveform was found to be 370 Hz.

![Figure 5](image2.png)

![Figure 6](image3.png)

**Figure 5.** The measured peak-peak output load voltages and peak output powers of the fabricated device across various load resistances.

**Figure 6.** Waveform of the instantaneously generated output load voltage across 85Ω optimum load resistance.
whereas the frequency of the applied hand-shaking vibration was 4.6 Hz. The applied acceleration was measured as 20 ms$^{-2}$ (~2g). It clearly indicates the frequency up-conversion behaviour of the proposed energy harvester which can be used to generate significant amount of power from hand-shaking. In order to improve its performance, the damping of the cantilever beam vibration needs to be reduced which can be done by changing the cantilever material and geometry. Beside this, the shape of the mass's top surface and the overlap area of the mass top and the ball needs to be optimized.

6. Conclusions

We have proposed and demonstrated a frequency up-converted electromagnetic energy harvester that is capable of generating significant power from hand-shaking vibration. The vibration behaviour of the hand-shaking has been characterized. A macroscale prototype has been fabricated and tested as a proof of concept. It generated maximum 672 mV peak-peak open circuit voltage of 370 Hz frequency and 413 µW peak power delivered to 85 Ω load resistance at a hand-shaking vibration with the frequency 4.6 Hz and acceleration 20 ms$^{-2}$ (~2g). The frequency up-conversion feature increased the power flow of the device. Although the generated voltage (and power) level was not sufficient to power up an electronic circuit, the test results showed its ability in powering portable smart devices from hand-shaking. With further optimization in design parameters (e.g., stiffness, damping, overlapped contact area), it is possible to improve the performance of the proposed frequency up-converted electromagnetic energy harvesting device.

Acknowledgements

The authors are grateful to acknowledge the Basic Science Research Program (2010-0024618) and the Pioneer Research Centre Program (2010-0019313) through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning, Korea.

References

[1] Amirtharajali R, Meninger S, Mur-Miranda J, Chandrakasan A and Lang J 1998 IEEE J. Solid-State Circuits 33 687-95
[2] Roundy S, Wright P K and Rabaey J 2003 Computer Communications 26 1131–44
[3] Beeby S P, Tudor M J and White N M 2006 Meas. Sci. Technol. 17 R175-95
[4] Harne R L and Wang K W 2013 Smart Mater. Struct. 22 023001
[5] Saha C R, O'Donnell T, Wang N and McCloskey P 2008 Sens. Actuators A 147 248-53
[6] Bowers B J and Arnold D P 2008 J. Micromech. Microeng. 19 094008
[7] von Büren T, Mitcheson T J, Yeatman E M, Holmes A S and Tröster G 2006 IEEE Sens. J. 6 28-38
[8] Renaud M, Fiorini P, van Schaijk R and van Hoof C 2009 Smart Mater. Struct. 18 035001
[9] Munaz A, Lee B-C and Chung G-S 2013 Sens. Actuators A 201 134-40
[10] Tashiro R, Kabei N, Katayama K, Ishizuka Y, Tsuboi F and Tsuchiya K 2000 JSME Int. J. C. 43 916-22
[11] Kulah H and Najafi K 2008 IEEE Sens. J. 8 261-68
[12] Halim M A, Khym S and Park J Y 2013 J. Appl. Phys. 114 044902