A miniaturized human-motion energy harvester using flux-guided magnet stacks

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Abstract: We present a miniaturized electromagnetic energy harvester (EMEH) using two flux-guided magnet stacks to harvest energy from human-generated vibration such as hand-shaking. Each flux-guided magnet stack increases (40%) the magnetic flux density by guiding the flux lines through a soft magnetic material. The EMEH has been designed to up-convert the applied human-motion vibration to a high-frequency oscillation by mechanical impact of a spring-less structure. The high-frequency oscillator consists of the analyzed 2-magnet stack and a customized helical compression spring. A standard AAA battery sized prototype (3.9 cm^3) can generate maximum 203 μW average power from human hand-shaking vibration. It has a maximum average power density of 52 μWcm^{-3} which is significantly higher than the current state-of-the-art devices. A 6-stage multiplier and rectifier circuit interfaces the harvester with a wearable electronic load (wrist watch) to demonstrate its capability of powering small-scale electronic systems from human-generated vibration.

1. Introduction

Due to the increasing popularity of the multifunctional and low-power consuming wearable electronic devices and systems, energy harvesting from human-generated (e.g., walking, running, shaking limbs etc.) vibration is recently being interesting as an alternative to the commonly used electrochemical batteries. However, generating significant power from human-generated vibration is challenging because these vibrations have extremely low frequency, random vibration characteristics [1]. Coupling such human-generated, low-frequency random vibrations into the electromechanical transducer of an energy harvester needs a clever design choice. Among a number of design approaches proposed by the researchers, mechanical frequency up-conversion has become the mainstream approach which is executed either by mechanical (direct or transverse) impact or by plucking (mechanical or magnetic) [2-5]. It allows the transducer element to generate voltage/power at high frequency while excited by a low-frequency vibratory system in response to the human-motion. Due to convenience in spring-mass suspension, relatively low source resistance, and high power density in macro-scale, an electromagnetic generator best suits the frequency up-conversion mechanism for energy harvesting from human-generated motion. The output power of an EMEH depends on the coil characteristics (number of turns, height, resistance, relative position to magnet, etc.), relative motion between the magnet and coil, and magnetic flux linkage with the coil. The first and second factors can be optimized by proper electro-mechanical design of the harvester, the third factor can be improved either by an array of magnets, or by Halbach arrays [6-8]. However, using a number of magnets (more than two) in an array increases the size of the harvester for specific application, which, in turn, affects its power density.

The goal of this work is to improve the output performance of our recently reported proof-of-concept prototype [9] to achieve higher power density. In order for that, we choose to increase the magnetic flux densities using a flux-guided magnet stack that we have analyzed and optimized by finite element method (FEM) analysis. Other parameters (e.g., spring-mass design, damping, coil characteristics etc.) were optimized through power spectral density analysis of a vibrating body, magnet displacement within the boundaries of electromagnetic interaction as well as the magnet-coil equilibrium position. Then, output responses of a fabricated prototype were carried out for human hand-shaking motion. An interface circuit was designed and was also analyzed its charging characteristics while connected to a wearable electronic load.

2. Harvester structure and its operation

Figure 1 shows the schematic structure and basic working mechanism of the proposed EMEH. It consists of two front-facing frequency up-converted electromagnetic generators which are struck by a freely-movable non-magnetic ball placed between the ball. Each generator consists of a cylindrical shaped flux-guided magnet stack placed on a helical compression spring and a coil wound around the magnet-stack over a cylindrical housing. The magnet stack (Type-3) was formed by assembling two magnets with a spacer in a repulsive manner. This particular type of stack was chosen by analyzing a number of 2-magnet stacks using Finite Element Method Magnetic (FEMM) program, as shown in Fig. 2. FEMM simulations were done to determine the magnetic flux density distributions of the different 2-magnet stacks. Results show that among those magnetic structures, Type-3 magnet-stack has the largest magnetic flux density (increased by 40% than a single magnet). The flux lines for the first three magnetic structures interact with the coil windings along the axial direction whereas those of the Type-3 stack are guided by the ferromagnetic spacer that allows the flux lines to interact with the coil windings along the radial direction, as shown in Fig. 3. Type-3 stack significantly increases the flux linkage through the coil windings which are aligned with the flux-guided magnet stack.

On low frequency excitation (in the axial direction) generated by human-limb motion with sufficiently large acceleration amplitude, the freely-movable ball oscillates within its displacement limit between the two front facing high-frequency oscillatory systems and impacts on the magnet stacks consecutively with a certain force $F(t)$ at its peak displacement. This allows each magnet stack to vibrate with higher frequency (at its resonance). Following basic mechanical vibration theory [10], the resultant response is an oscillatory motion with exponential decay between two consecutive impacts

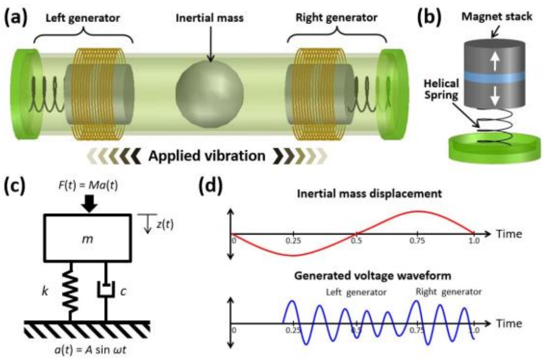

Figure 1. Schematics of the (a) proposed energy harvester, (b) flux-guided magnet stack, (c) equivalent mechanical model of one generator, and (d) basic operation principle.

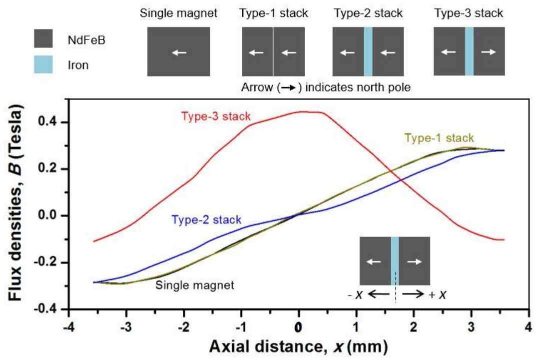

Figure 2. Change of magnetic flux densities with axial distance of the magnetic structures (sketched at the top of the graph) at 1.25 mm radial distance from the magnet wall.

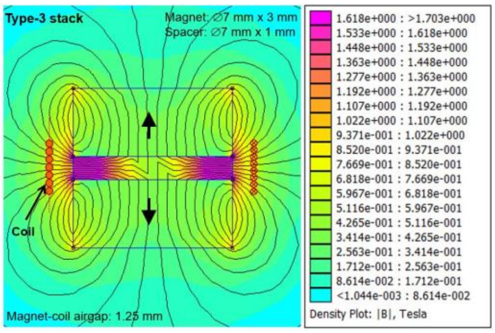

Figure 3. Magnetic flux distribution of the Type-3 magnetic structure obtained from FEMM simulation. The flux lines interact with the coil windings along the radial direction.

Figure 4. Photographs of the (a) harvester components before assembling, (b) assembled prototype alongside a standard AAA battery, and (c) complete package including multiplier and rectifier circuit for AC to DC conversion.

(by the ball). The kinetic energy generated by human-limb motion is transferred to the helical compression spring, which converts it to electrical energy by the relative motion between the flux-guided magnet stack and the coil. The maximum power delivered to a matched load resistance is

$$P_{\max} = \frac{(NBl)^2}{8R_l}\left[\frac{MA\omega_r e^{-\zeta\omega_r t}}{k\sqrt{1-\zeta^2}}\sin\left(\omega_r\sqrt{1-\zeta^2}\right)\right]^2 \tag{1}$$

where N is the number of coil turns, B is the magnetic flux density, l is the coil height, M is the mass of the ball, A is the applied acceleration, k is the stiffness of the helical spring, ω_r is the resonant frequency of the high-frequency oscillator, ζ is the total damping, and R_l is the load resistance. We fabricated, characterized and demonstrated the newly designed prototype to drive a wearable electronic load (wrist watch). The fabricated prototype, along with a 6-stage multiplier (and rectifier) circuit and a storage capacitor, was accommodated in a 3D printed ABS package, as shown in Fig. 4.

3. Experimental results and discussion

The performances of the fabricated EMEH were evaluated by applying hand-shaking vibration. It generates 1.54 $V_{p\text{-}p}$ (123 mV_{rms}) open circuit voltage when both the generators were connected in series, as shown in Fig. 5(a). The maximum average power delivered to 43 Ω matched load resistance is 203 µW, as shown in Fig. 5(b). To use the generated power for driving an electronic load, we built a multiplier and rectifier circuit with a 22 µF storage capacitor by soldering surface-mount devices on a

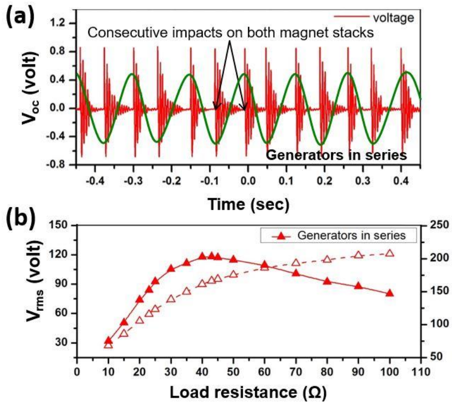

Figure 5. (a) Generated open circuit voltage and (b) voltage (dotted line) and power (solid line) from series connected generators while hand-shaken.

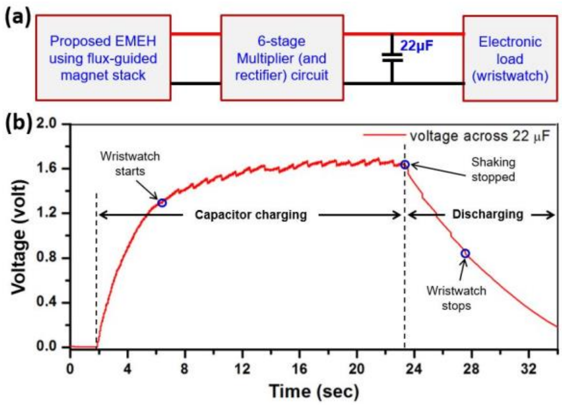

Figure 6. (a) Block diagram of the system with electronic load (wristwatch) and (b) charging-discharging characteristics of storage capacitor while the electronic load is in operation.

Table 1: Comparison of recently reported energy harvester operated by human-motion vibration.

Reference	**Tested by**	**Prototype volume (cm^3)**	**Operating condition**	**Max. average power (μW)**	**Avg. power density (μWcm^{-3})**
[3]	Handy motion	19.2	5.8 Hz, 2 g	103.55	5.4
[5]	Running motion	5	2 Hz, 2 g	43[a]	8.6[a]
[9]	Hand-shaking	7.16	4.6 Hz, 2 g	110	15.4
[11]	Walking motion	51.84	5 kmh^{-1}	51	0.74
This work	*Hand-shaking*	*3.9*	*4.9 Hz, 2 g*	*203*	*52*

[a] Peak value

self-designed printed circuit board (PCB). Figure 6(b) shows that the wrist watch starts running when the capacitor voltage rises to 1.3 V_{dc} after 6 sec and kept running as long as the harvester was being excited. Until then, the capacitor voltage increased up to 1.66 V_{dc} at about 24 sec. The wrist watch kept running even after the excitation was stopped until the capacitor voltage dropped to 0.86 V_{dc} at 28 sec. Note that, the storage capacitor discharges very fast. However, a proper choice of energy regulation process and a suitable storage unit (e.g., supercapacitor) could store the energy for a long time to use the stored energy later. The performances of vibration energy harvesters are generally compared using the power density. Table 1 presents a performance comparison of this work with similar works (human-motion driven) recently reported.

4. Conclusions

We have proposed, designed and demonstrated a miniaturized EMEH using flux-guided magnet stacks for harvesting energy from human hand-shaking motion to power wearable electronics. Flux-guided magnet stacks were designed by analyzing electromagnetic fields characteristics of several magnetic structures by FEMM simulation. It not only increases the resultant flux densities but also improves the flux linkage with the coil windings in the radial direction, rather than in the axial direction for other magnetic structures. We built a standard AAA battery sized prototype by connecting two high-frequency generators in series which were struck consecutively by a freely movable ball during human hand-shaking. The device generates 203 μW average power and offers maximum 52 μWcm^{-3} average power density which is significantly higher than the current state-of-the-art devices designed for human-motion operation. A complete harvesting system was built by incorporating the harvester unit, an ac/dc converter (6-stage multiplier and rectifier circuit), and a storage capacitor in a single package to drive a wearable electronic load (wrist watch).

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