

# ELECTROMAGNETIC ENERGY HARVESTING FROM SWING-ARM MOTION USING ROTATIONAL ECCENTRIC MASS STRUCTURE

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## ABSTRACT

We present an electromagnetic energy harvester using rotational eccentric mass structure that generates power from extremely low-frequency motion of a driven mechanical swing-arm (i.e. pendulum) that is intended to mimic wrist motion during regular walking. It consists of two aligned eccentric rotors, which rotate together, containing multiple N52 permanent magnet pole-pairs with back iron shields. The shields allow the magnetic flux densities to increase in the middle of the rotor structure, where the coils are located, by 63%. The stator is formed by multiple series connected self-supported copper coils in a PCB interconnect. Voltage is induced in the coils due to magnetic flux change while the eccentric rotor moves because of swing-arm motion. The output power of a fabricated prototype was measured for various swing-arm motions and compared with the simulation. The prototype generates maximum 55  $\mu$ W average power at  $\pm 25$  degree rotational amplitude and 0.8 sec period (1.25 Hz).

## KEYWORDS

Swing-arm motion, rotational eccentric mass, pole-pairs, back iron shields, PCB interconnect.

## INTRODUCTION

The miniaturization and low-power consumption of modern electronic components have opened the development of self-powered wearable devices by exploiting various techniques of energy harvesting from the human-body. Basic human activities (e.g., walking, running, jogging, hand-shaking etc.) are of great interest as sources of energy to harvest [1-3]. Among the different locations on the human-body, the most common and easiest is the wrist. Typically, vibration-based energy harvesters employ linear spring-mass-damper systems having a narrow-band resonance. Employing a resonant, linear mechanism to harvest energy from human-body motion is challenging due to the extremely low-frequency and random characteristics of human-body motion [4]. The power output of a linear energy harvester is limited by the internal travel range of its proof-mass motion. Harvesters with a rotational proof mass overcome some of the limitations of linear motion based energy harvesters for power generation from human-body motion [5, 6]. An eccentric rotor structure is generally used which couples the kinetic energy generated by the human-body-induced motion (while walking, running, or jogging) into the transducer element (e.g., piezoelectric, electromagnetic etc.). However, effective design of both the rotational unit and the transducer element would significantly increase the output performance of the harvester [7]. Most rotational energy harvesters reported to date are based on

piezoelectric transduction mechanism [1,8]. However, these devices use direct/indirect force mechanism that can cause damage to the piezoelectric material, especially after many cycles. A planar electro-magnetic energy harvester was presented in [6]. Those harvesters were tested by mounting mostly on the knee-joint, ankle and upper-arm for power generation rather than on the wrist during walking, jogging, or running.

In this work, we have designed, built and tested an electromagnetic energy harvester to generate significant power from swing-arm motion. A dual eccentric rotor structure (containing magnet pole-pairs) and an array of coils in the middle, constitutes the electromechanical transducer. Simulations (finite element analysis and numerical Matlab- based) were performed to determine the optimized harvester parameters. Test results from a fabricated prototype have been obtained by a human-arm-like mechanical swing-arm test setup and have been compared with the numerical simulations.

## HARVESTER DESIGN

During design, we followed our previously demonstrated generalized three-dimensional model of an eccentric rotor rotating freely on a bearing that includes both mechanical and electrical dampers, representing the energy losses due to friction in the bearing and energy extraction from an ideal energy transducer [5]. Figure 1 shows the schematic structure of the proposed swing-arm driven electromagnetic rotational energy harvester. It consists of two eccentric rotors (rotates together using low-friction bearing) containing five NdFeB (N52) magnet pole-pairs with back iron shields and ten self-supported copper coils (series connected) which are placed in the middle of the rotor using a PCB interconnect. The back iron shields on either side of the dual-rotor allow the magnetic flux densities to increase in the middle. To determine the magnetic flux densities in

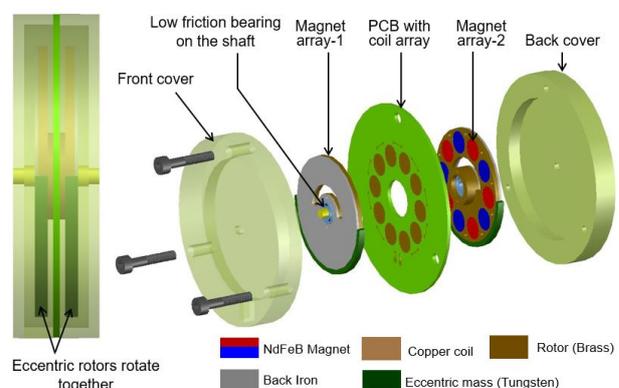


Figure 1: Schematic structure of the proposed electromagnetic rotational energy harvester for swing-arm motion.

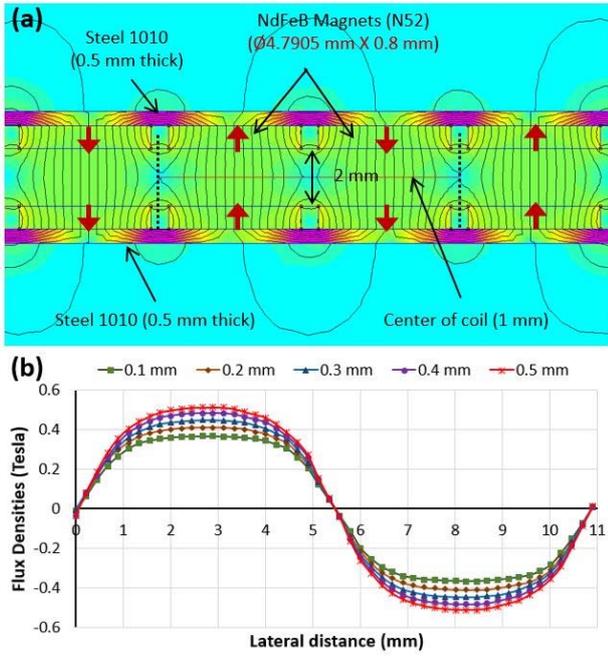


Figure 2: FEMM simulation: (a) magnetic flux distribution of the magnet arrays with back iron shields and (b) change of magnetic flux densities (in axial direction of a pole-pair) with the change of back iron shield thickness, in the middle of the magnet arrays (where the coils are located).

the middle of the dual-rotor structure (where coils are located), Finite Element Method Magnetic (FEMM) simulations were performed, as shown in Figure 2(a). In the FEMM simulation, the thickness of each back iron shield was varied from 0.1 mm to 0.5 mm. Figure 2(b) shows that the magnetic flux density (in the middle of the dual-rotor) for a pole-pair increases up to maximum 0.513 T for 0.5 mm thick back iron shields which significantly increases the flux linkage with the coil. Considering a pseudo-walking input (single sinusoid derived from the motion of a driven pendulum that approximates the swing of a human-arm during vigorous walking), a numerical analysis was done in Matlab to determine optimal system parameters that predict the optimum output response. According to the Faraday's Law of Electromagnetic Induction, the induced open circuit e.m.f. voltage will be

$$|v_{em}(t)| = N \frac{d}{dt}(\varphi_B) = NBl_{eff}\dot{\phi}_z \quad (1)$$

where  $N$  is the number of coil turns,  $\varphi_B$  is the net magnetic flux,  $B$  is the magnetic flux density,  $l_{eff}$  is the effective coil length,  $\phi_z$  is the relative angular displacement between the rotor and the stator (coil) that can be obtained by numerically solving the equations of rotational motion of the rotor, presented in [5]. Then, the instantaneous power delivered to an optimum load resistance  $R_l$  is

$$P(t) = \frac{v_{em}(t)^2}{4R_l} \quad (2)$$

We performed a time-domain numerical simulation using Matlab to predict the output voltage generated by the rotational energy harvester while excited by a pseudo-

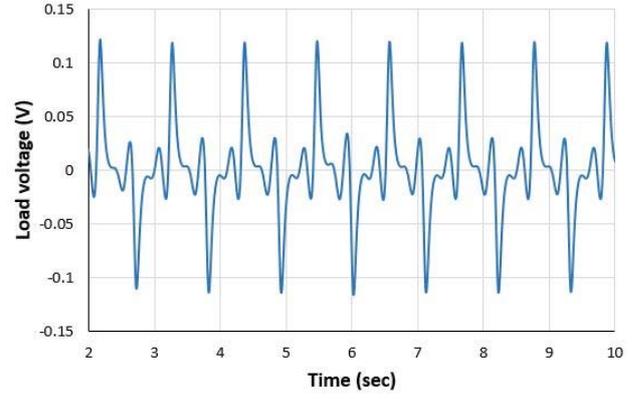


Figure 3: Simulated output voltage response (across 240  $\Omega$  optimum load resistance) at  $\pm 25$  degree rotational amplitude and 1.1 sec period (0.91 Hz) of swing arm motion.

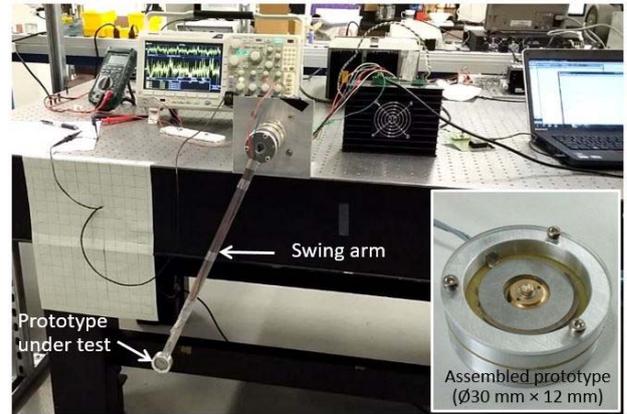


Figure 4: Photographs of the fully assembled prototype harvester (inset) and swing arm test setup.

walking input signal. The simulation parameters have been determined from the geometry and material parameters of the device components. Figure 3 shows the simulation result of the instantaneous output voltage waveform across a 240  $\Omega$  optimum load resistance resulting from a  $\pm 25$  degree rotational amplitude and 1.1 sec period (0.91 Hz).

## PROTOTYPE FABRICATION

To illustrate the proof-of-concept, a prototype of the proposed swing-arm driven rotational energy harvester was fabricated and tested. Figure 4 shows photographs of a fully assembled prototype energy harvester (inset) and the prototype under test on a custom-built mechanical swing-arm test setup. The rotational unit comprises a dual-rotor (rotate together on two bearings around the shaft) structure having ten holes in each to carry the magnets ( $\text{\O}4.8 \text{ mm} \times 0.8 \text{ mm}$ ). Adjacent magnets are placed with opposite polarities, constituting a pole-pair. The back irons (of same outer diameter of the rotor,  $\text{\O}23.2 \text{ mm}$ ) are attached to the outer sides of the rotors. A half-moon shaped tungsten piece is attached to the outer edge of each rotor that makes the rotor structure eccentric. The stator is made by connecting ten self-supported coils ( $\text{\O}4.8 \text{ mm} \times 0.8 \text{ mm}$ ) in series in a 0.8 mm thick coil carriage (made of PCB) with interconnects and is placed in the middle of the dual-rotor structure. The stator is

supported by the prototype housing. The gap between the coil and magnet surfaces are 0.6 mm. Each coil has 300 turns and the coil resistance is 24  $\Omega$ . The shaft is fixed to the housing. Both are made of aluminum.

## RESULTS AND DISCUSSION

The harvester was tested in a pseudo wrist-worn situation by a custom-built, micro-processor controlled, stepper motor driven, mechanical swing-arm setup to produce the pseudo-walking signal as input. The prototype harvester was mounted on the swing arm and a series of pseudo-walking motions was created by varying the swing profile (angle and speed) to compare the measurement results with simulation.

We started with the measurement of optimum load resistance to compute the maximum power generated by the harvester prototype for different pseudo-walking input excitations. The output terminals of the prototype were connected to continually adjustable load resistors and the resistance values were swept in a range from 100  $\Omega$  to 500  $\Omega$ . The RMS voltage across the load increases as the value of load resistance increases. Figure 5 shows that the optimum load resistance was measured as 240  $\Omega$  to which maximum average power of 5.24  $\mu$ W was delivered, while the prototype was excited at  $\pm 25$  degree rotational amplitude and 1.1 sec period (0.91 Hz). Generated power is experimentally equal to  $V_l^2/R_l$ , where  $V_l$  is the RMS voltage across the load resistance  $R_l$ .

Figure 6 shows the instantaneous voltage waveforms across the 240  $\Omega$  optimum load resistance at  $\pm 25$  degree rotational amplitude and various excitation speeds. Results show that the value of peak-peak voltage increases as the excitation speed increases. The prototype generates 222 mV, 348 mV and 545 mV peak-peak voltage when the swing-arm is excited at 1.1 sec (0.91 Hz), 0.91 sec (1.1 Hz) and 0.8 sec (1.25 Hz) periods, respectively. In other words, the voltage (as well as the average power) increases with the increase in frequency of the swing-arm motion. It is seen from the waveforms that the angular velocity of the magnet pole-pairs (in the dual-rotor structure) relative to the coil (fixed to the housing) increases with the increase in the excitation frequency which allows the voltage to increase significantly.

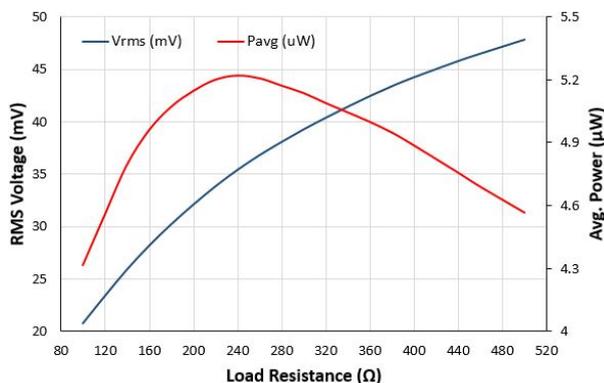


Figure 5: RMS voltage and average power vs. load resistance obtained from the swing-arm test at  $\pm 25$  degree rotational amplitude and 1.1 sec period (0.91 Hz).

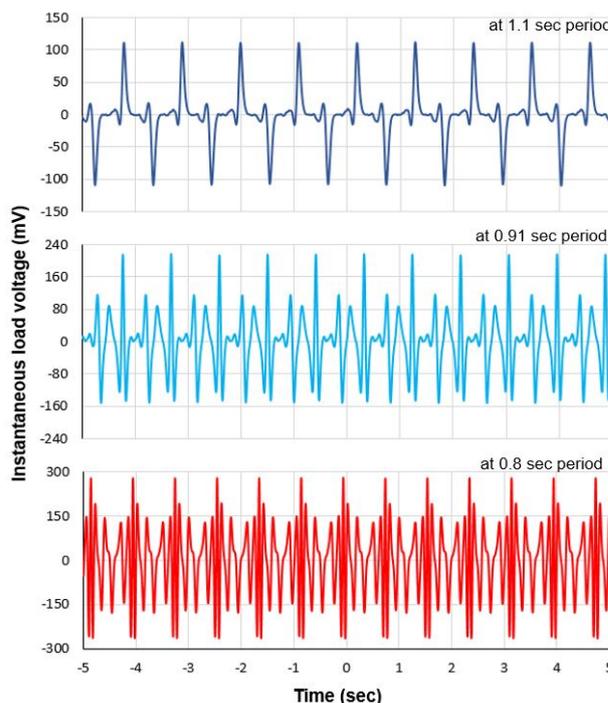


Figure 6: Measured instantaneous voltage waveforms across 240  $\Omega$  optimum load resistance at  $\pm 25$  degree rotational amplitude and various periods of swing arm motion

Since the swing of the human-arm during walking, running, or jogging may vary for different human subjects, the harvester performance (average power generation) for various pseudo-walking input signals was measured. Figure 7 shows the comparison of the measured and simulated output power at different rotational amplitudes ( $\pm 12.5$ ,  $\pm 18$  and  $\pm 25$  degrees) and excitation periods (0.8, 0.91, 1.1 and 1.5 sec) or frequencies (0.67, 0.91, 1.1 and 1.25 Hz). The prototype generates the highest power (55  $\mu$ W) while the pseudo-walking input signal has an amplitude of  $\pm 25$  degree and a frequency of 1.25 Hz (0.8 sec period) which is considered as fast walking. Looking at the generated voltage waveforms presented in Figure 6, it is obvious that power

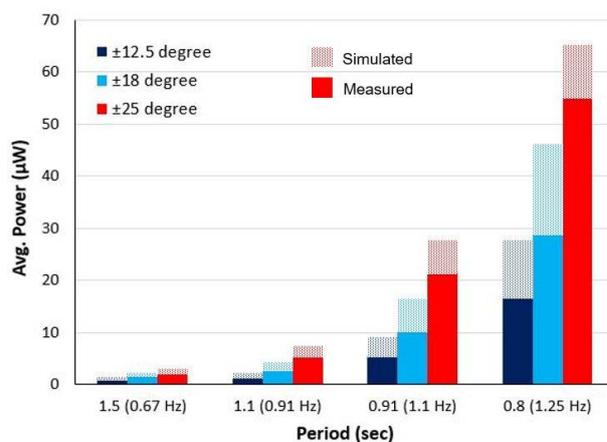


Figure 7: Maximum average power generated (across 240  $\Omega$  optimum load) by the harvester while excited with different rotational amplitudes and periods of the swing arm motion.

generation increases with the increase in the excitation frequency, meaning higher power can be generated when a person wearing the harvester on his wrist moves from walking to running. There are slight differences between the simulation and experimental result that could be due to imperfect assembly of the harvester components. Also, the effects of damping due to the friction (Coulomb friction) in the bearing, which may have a significant effect on the dynamical behavior of the rotor, was ignored in the numerical calculation.

## CONCLUSIONS

This paper presents a rotational electromagnetic energy harvester using a dual eccentric rotor structure excited by mechanical swing-arm motion. Five magnetic pole-pairs with back iron shields increases the magnetic flux densities in the middle where an array of coils cut the magnetic flux when excited by pseudo-walking input signals. FEMM and numerical simulations were performed to determine the optimum harvester parameters to achieve the best performance from the harvester. The experimental results are in good agreement with the simulation results. The device generates a maximum of 55  $\mu$ W at a  $\pm 25$  degree and 0.8 sec period (1.25 Hz frequency) pseudo-walking excitation input from a mechanical swing arm. Our future work will include checking the harvester performance from basic activities (walking, running, jogging etc.) of a number of human subjects by wearing the harvester on their wrists.

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