

## Spherical Magnetic Generators for Bio-Motional Energy Harvesting

**Benjamin J. Bowers and David P. Arnold**

Department of Electrical and Computer Engineering  
Interdisciplinary Microsystems Group  
University of Florida, Gainesville, FL, USA

**Abstract:** In this work, non-resonant, vibrational energy harvester architectures intended for human-motion energy scavenging are researched. The basic design employs a spherical, unidirectionally-magnetized permanent magnet (NdFeB) ball that is allowed to move arbitrarily in a spherical cavity wrapped with copper coil windings. As the ball rotates and translates within the cage, the time-varying magnetic flux induces a voltage in the coil according to Faraday's Law. Devices ranging from 1.5 cm<sup>3</sup> to 4 cm<sup>3</sup> in size were tested under various human activity scenarios—held in the user's hand or placed in the user's pocket while walking (4 km/h) and running (14 km/h). These harvesters have demonstrated RMS voltages ranging from ~10 mV to 700 mV and time-averaged power densities up to 0.5 mW/cm<sup>3</sup>.

**Keywords:** Magnetic Generators, Non-Resonant Device, Bio-Motional Harvester, Vibrational Energy Harvesters

### 1. INTRODUCTION

From the common cell phone to interplanetary robots, devices for everyday life and scientific research require some source of electrical energy to operate. However, such devices, either by practicality or the mode of operation, cannot always be tethered to a constant energy source such as wall outlet or conventional power generator. As such, self-sustaining system architectures have become desirable.

To address these needs, energy harvesting from human and machine motion has become a thrust for exploration [1]. Everyday, an innumerable amount of mechanical energy goes untapped as people and machines go about their daily lives and intended functions. Basic human activities such as walking, running, breathing, tapping a foot, or rocking in an officer chair all produce vibrations that can potentially be harvested. This harvested energy could then be stored to prolong the life of low power devices such as cell phones, watches, or other mobile electronics.

Many previously investigated vibrational harvesting schemes are poorly suited for human-induced energy scavenging. The most common architecture is an underdamped mass-spring-damper system that is used to convert a mechanical input into an electrical output via piezoelectric, electrodynamic, or electrostatic transduction mechanisms [2]. However, these high-Q systems are tuned for maximum power output over a small frequency range. Furthermore, it is difficult to achieve low resonant frequencies commensurate with human motion (1-10 Hz) in small device dimensions. Another issue with these systems is they are often constrained to only one motional degree-of-freedom, whereas normal human motions occur in three dimensions. Such limitations motivate the

development of a device that can produce nominal power under a large range of mechanical force amplitudes, directions, and frequencies.

In this paper, research on a non-resonant, vibrational energy harvester architecture intended for human-motion energy scavenging is discussed. The design utilizes a unidirectionally-magnetized (NdFeB) permanent magnet ball that will roll and translate inside a spherical housing based on the human input motion. The sphere containing the magnetic ball is wrapped with one or more copper coils, which “sense” a time-varying magnetic flux due to the translating ball and thus generate a voltage. This particular design approach is appealing because the ball will move under a large range of non-specific motions. Additionally, the rolling action is more favorable than previously demonstrated sliding electrostatic generators [3]. The mitigation of frictional effects is especially important as the size of the device scales down.

### 2. Device Design and Fabrication

Two different spherical prototype device architectures were investigated, as shown in Fig. 1. The first design consisted of a single coil wrapped around the equator of the spherical cage containing the permanent magnet ball. The second prototype used two series-connected, counter-wound coils that were offset on the northern and southern hemispheres. It was later found that the offset coil architecture generally afforded higher voltages and power densities.

For construction, composite powder/resin prototypes were fabricated using a Spectrum Z510 3D-printer. Two identical hemispherical structures were created with notches or pins on the outer surfaces to aid in the wire winding. After printing and infiltration

with the composite bonding agent, the inner surfaces of the cavity were sanded to provide a smooth for the magnet ball. The two halves were then glued together to encapsulate the magnet ball, and then wound with 34-gauge copper wire in the appropriate configuration. Typical coil resistances varied from 10 – 60  $\Omega$ . Fig. 2 shows some example constructions.

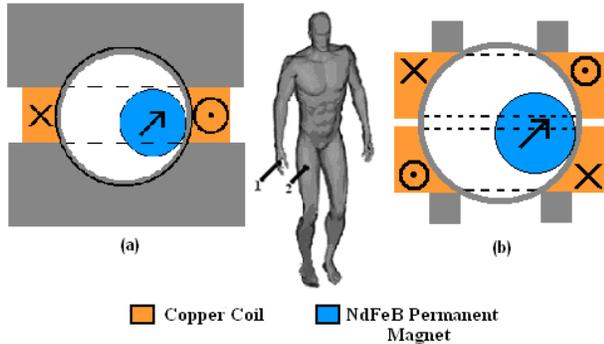


Figure 1. Schematic of (a) equator-wrapped and (b) offset-wrapped harvesters. The human figure shows mounting position (1) hand and (2) pocket.

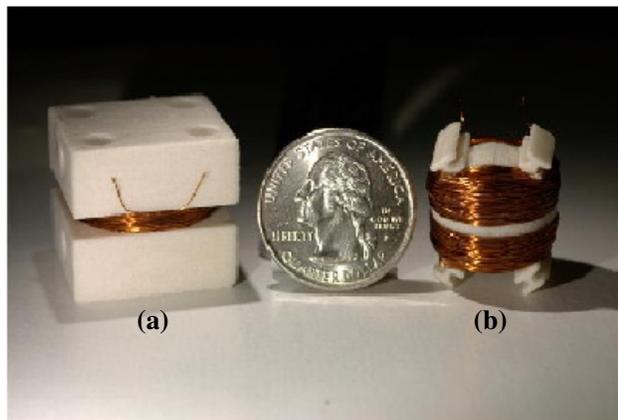


Figure 2. Picture showing the (a) equator-wrapped and (b) offset-wrapped harvesters.

### 3. Device Characterization

The random nature of the input vibration to the harvesters from the human body provides a myriad of challenges for effective analytical modeling of the plan device. As such, it was necessary to devise a test plan to experimentally characterize how the system works under various input conditions. Furthermore, this test also had to provide a means for defining which physical characteristics of the harvester provided the greatest effect on the output power.

Different designs were characterized through parametric tests varying (i) the number of coil turns (300-800), (ii) the overall system size (0.635 – 1.91 cm diameter cavity), and (iii) the ball-to-cavity diameter

ratio (0.375 – 0.75). To accurately represent “real-world” operating conditions, the system performances were characterized by a person walking (4 km/h) or running (14.5 km/h) on a treadmill with the harvester held in the user’s hand or placed in their pocket.

A PC-based data acquisition test bed was developed to enable multiple harvesters to be measured simultaneously under a common vibrational input. A rapid prototyped powder/resin structure (18 cm x 8 cm x 3 cm) provided a rigid backbone onto which three harvesters could be attached along with a, 3-axis accelerometer (Freescale Semiconductor KIT3109 MMA7260QE). The accelerometer data provided a reference between each set of tests to ensure consistent acceleration levels. An 8-channel (differential) 12-bit USB connected data acquisition card (Measurement Computing Corporation 1208FS) provided a sampling rate of 8 kHz for measurement of the energy harvester open-circuit voltages and accelerometer data.

### 4. Results

Data from each test was analyzed and plotted in MATLAB to determine the RMS voltage. From this, the maximum deliverable power (assuming matched resistive load) and power density of each harvester were calculated. The spherical structure and coil windings were included in the volume for the power density calculations. Fig. 3 shows the best results for the four test conditions indicating that the offset counter-wound coil configuration produced higher power densities compared to the equator-wrapped design. Fig. 4 shows example open-circuit voltage waveforms for a 500-turn offset-wrapped harvester, indicating maximum RMS voltage (0.703 V) and power (1.44 mW) when running with the device in the pocket.

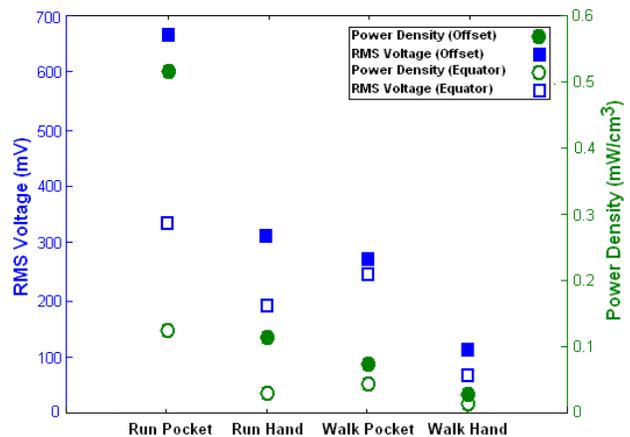


Figure 3. Best results of RMS voltages (mV) and power densities (mW/cm<sup>2</sup>) for both types of harvesters under each human motion test case.

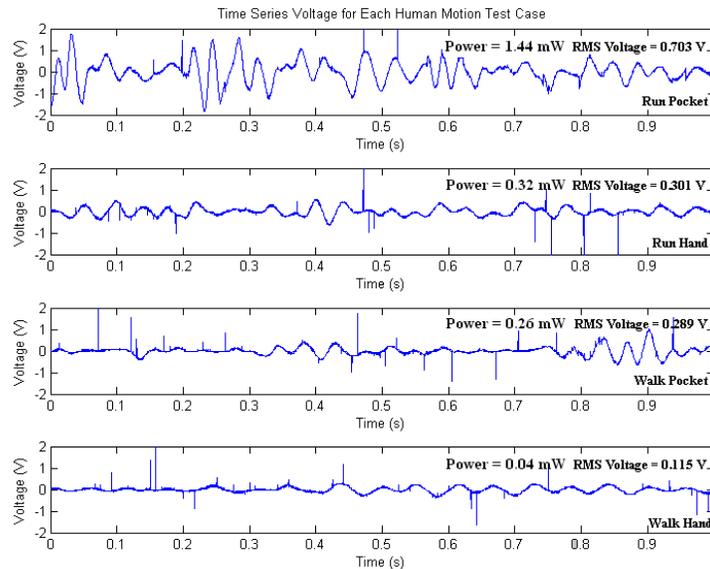


Figure 4. Time series open-circuit voltage for the offset-wrapped coil harvester for each human motion test case.

#### 4.1 Number of Coil Turns

One of the parametric tests conducted was to increase the number of turns while keeping other parameters of the device constant (30% ball-to-cavity diameter ratio and 1.27 cm cavity diameter). For the offset coil, the total number of turns was divided up into two series-connected coils in the northern and southern hemisphere of the device (half of the total number of turns in each hemisphere).

As seen in Fig. 5, the RMS voltages and power densities decreased with an increase in the number of turns for the equator-wrapped coil. To explain this, it is hypothesized that there may be counteracting voltages in the coil due to its large size compared to the magnetic ball—this originally motivated the offset-wrapped coil. For the offset coil design, the voltages increased with increasing turns, but a maximum power density was achieved at 600 turns. Above this value, the volume is increasing faster than the power, resulting in this power density maximum. In other words, increasing the number of windings increased the maximum power output, but not the power density because of the larger overall volume. The additional turns are further from the magnetic ball, and thus not as well coupled with the field from the magnetic ball.

#### 4.2 Cavity Diameter

All of the harvesters tested were on the mesoscale (0.635 – 1.91 cm diameter cavity). However, it was important to test the ability of the harvesters to produce nominal RMS voltages and power densities while reducing the system size towards the MEMS scale. For this test, the ball-to-cavity ratio was held constant at 30%, and the total number of turns was held at 300.

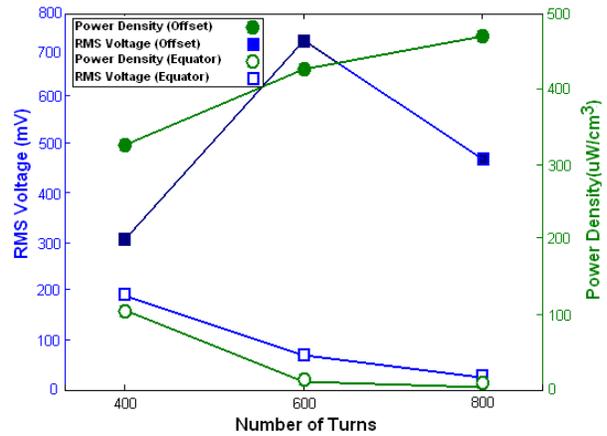


Figure 5. RMS voltages and power densities while varying the number of turns but maintaining a 30% ball-to-cavity diameter ratio and 1.27 cm cavity diameter.

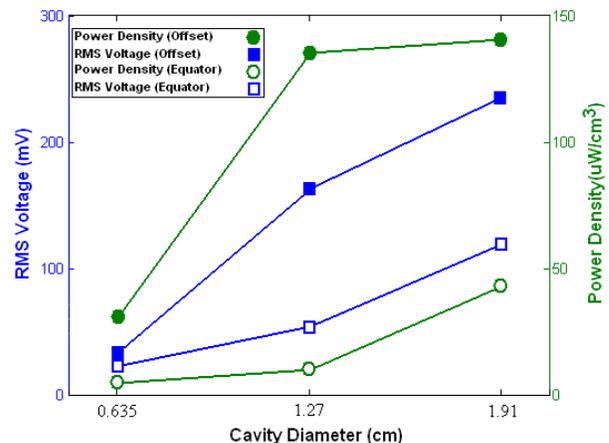


Figure 6. RMS voltages and power densities while varying the cavity diameter but maintaining 30% ball-to-cavity diameter ratios and 300 total turns.

Fig. 6 shows the RMS voltages and power densities of the harvesters as the overall size of the harvester was scaled down. As the harvester size is decreased, the power density and RMS voltages decrease for both types of harvesters, as could be expected from general theory [2].

### 4.3 Ball-to-Cavity Diameter Ratio

The final parameter that was varied—the ball-to-cavity ratio—yielded the most interesting results. Fig. 7 shows that the optimal ball size was dependant upon the type of input vibration to the harvester. If the harvester was being operated in the walking regime, it was better to have a smaller ball-to-cavity diameter ratio. However, if the input vibration was running the opposite was true.

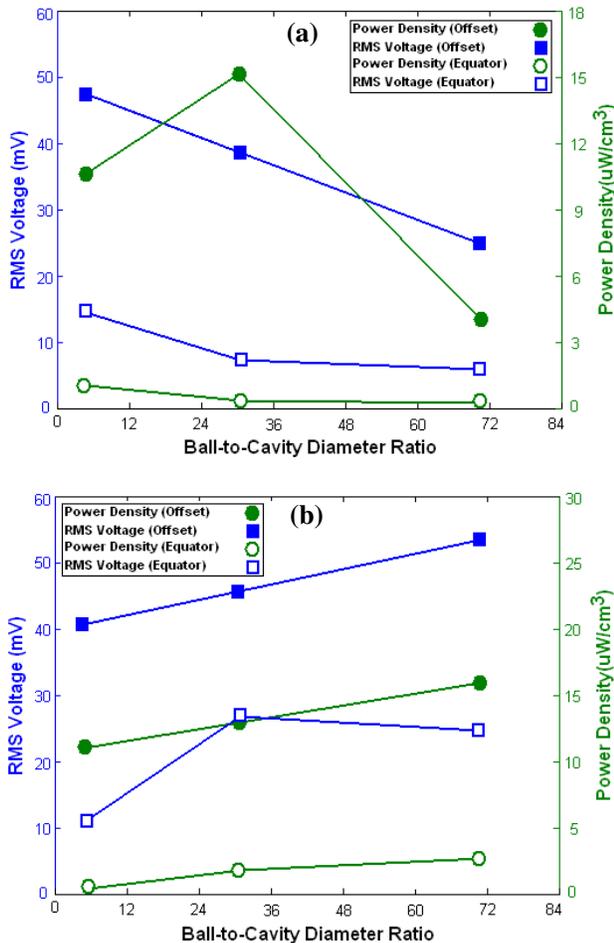


Figure 8. RMS voltages and power densities while varying the ball-to-cavity diameter ratios but maintaining a 1.27 cm cavity diameter and 300 total turns for (a) walking condition and (b) running condition.

## 5. Conclusions

Several conclusions can be drawn from the parametric characterization process. In nearly all cases, the offset-wrapped design exhibited higher voltages and power densities as compared to the equator-wrapped design.

For the dependence on coil turns, it was observed that increasing the number of turns past approximately 400 for the equator-wrapped coil and 600 for the offset coil decreased the power densities, indicating some optimum range. For the scalability test, there was a clear decrease in the RMS voltages and power densities corresponding to a decrease in the device's diameter. However, the offset coil harvester demonstrated a 71% reduction in power density while the equator-wrapped harvester's power density was diminished by 98%.

For the ball-to-cavity diameter ratio test, it was observed that ball-to-cavity ratios less than 70% yield different power densities and RMS voltages depending upon the regime of the input vibration. Vibrational input due to walking requires a smaller ball in order to allow for greater excursion throughout the cavity. However, a running vibrational input produces higher RMS voltage and power densities with a much larger ball. This fact indicates that the harvester can take greater advantage of flux changes due to motion of the ball under the running condition. Therefore, the harvester overall design and the parameters must be tailored to the typical regime of operation that the harvester will experience, which is application dependant.

Based on the results, further investigation into rolling magnetic ball architectures is warranted. Some of the results, while promising, do not offer clear explanations as to why the device behaves as it does. As such, further research into the area of parameter optimization and the overall mechanical characteristics and response of the system given a certain regime of input vibration is needed.

## References

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