

# EFFECT OF COIL WIRE GAUGE IN ELECTROMAGNETIC POWER HARVESTERS

S. Luschas<sup>1</sup>, I. Kozinsky<sup>1</sup>, A. Kuligovszky<sup>1</sup>, and M. Illing<sup>1</sup>  
<sup>1</sup>Bosch Research and Technology Center, Palo Alto, CA, USA

**Abstract:** This work investigates the optimal coil wire gauge for an electromagnetic power harvester. Theoretically, the power harvested increases proportionally with the radius of the coil wire. However, the magnitude of the voltage induced is proportional to the inverse of the coil radius. A mesoscale (6.5cm<sup>3</sup>, 21grams) prototype device was built and tested to verify this theory. The prototype with 22awg wire generated 1.1mW of RMS power and 12mV peak voltage for an excitation of 0.25G at resonance. The exact same design with 32awg wire generated only 0.4mW of power but a peak voltage of 50mV.

**Keywords:** Electromagnetic power harvester, Vibrational energy scavenger, Coil wire gauge

## INTRODUCTION

Research in vibrational energy harvesters as power sources for portable applications has increased recently [1-4]. Although outdoor solar harvesting has superior power density, the harvester must be in direct outdoor sunlight [5]. Thermal harvesting necessitates a large temperature difference for decent power levels [6,7]. Therefore, vibrational harvesters have advantages for portable applications where the sun may not be shining and there is no large temperature difference. Vibrational harvester technology includes piezoelectric, electromagnetic, and electrostatic mechanisms. The power density and efficiency of electromagnetic harvesters appears to trump the other two technologies [1,4,10].

Recent papers on electromagnetic power harvesters have focused on optimizing harvesting magnet configurations [1,8,9], repelling magnet configurations [8], coil diameter and coil height [9]. This work studies the optimal gauge of wire used in the harvesting coil.

Analytical theory is developed to compare the power output as a function of coil wire gauge. These equations highlight the tradeoff between power harvested and output voltage. Three mesoscale electromagnetic power harvesters with different coil wire gauges were built to verify this theory. Measurements on these devices correlate well with predictions from the analytical theory.

## THEORY

The electromagnetic device under study is a simple magnet in a plastic tube as shown in Figure 1. The coil is wound around the plastic tube over the same vertical distance,  $l$ , in all cases. The coil is assumed to be wound in one single layer, with as many turns as possible over the distance  $l$ .

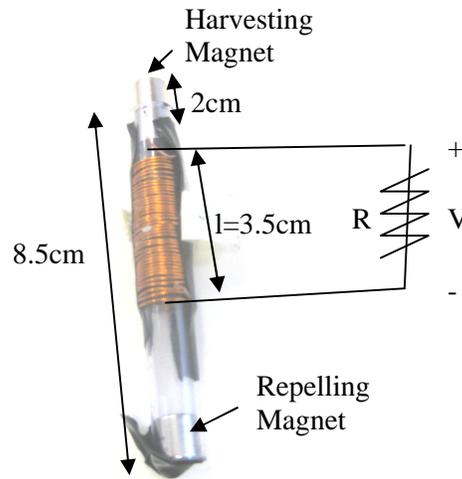


Fig. 1: Electromagnetic device used in this work.

The theoretical power generated is:

$$P = \frac{V^2}{R} = \frac{(N \frac{d(B \cdot A)}{dt})^2}{R} \propto \frac{N^2}{R} \quad (1)$$

where  $N$  is the number of turns of coil and  $R$  is the resistance of the load. The magnetic field strength of the magnet  $B$  and coil cross sectional area  $A$  do not vary with the gauge of wire used in the coil. The smaller the coil wire radius  $r$ , the more turns  $N$  can be wound over a length  $l$ :

$$N \propto \frac{1}{r} \quad (2)$$

The load resistor  $R$  depends on the design. The case considered here is designed for an electrical match, where the load resistance equals the resistance



Fig. 2: Three prototype harvesters of varying wire gauge used to test theory.

of the coil,  $R=R_{coil}$ . Another option would be designing  $R$  for an optimal power match, which is a function of both the electrical and mechanical damping. This design of  $R$  is not easily analytically tractable, so it is the subject of future study. Experimentally, similar results to those presented here have been observed.

The resistance of the coil,  $R_{coil}$ , is equal to the resistivity of the wire times the length of the wire. The resistivity of the wire  $\rho$  decreases as the radius increases, and the total length of the wire also decreases as  $N$  increases, giving  $R$  a cubic dependence on the coil wire radius  $r$ :

$$R = R_{coil} = \rho l \propto \left(\frac{1}{r^2}\right)(\rho l N) \propto \left(\frac{1}{r^3}\right) \quad (3)$$

This means that the harvested power should increase proportionally with the radius of the wire:

$$P \propto \frac{N^2}{R} \propto \frac{\left(\frac{1}{r}\right)^2}{\left(\frac{1}{r}\right)^3} \propto r \quad (4)$$

However, the generated voltage decreases with the radius of the wire:

$$V_{coil} = N \frac{d(B \cdot A)}{dt} \propto \frac{1}{r} \quad (5)$$

## DEVICE DESIGN

This theory was verified by three electromagnetic devices with different wire gauges, as shown in Fig. 2. The harvesters have hand-wound coils that are attached to plastic tubes with electrical tape. An attempt was made to wind all the coils over the same distance  $l$  as shown in Fig. 1.

Table 1: Number of turns and total resistance of the coils in Fig. 2.

Wire gauge	$r$	$N$	$N_{theory}$	$R_{coil}$	$R_{theory}$
22awg	0.32mm	41	54	0.09 $\Omega$	0.08 $\Omega$
26awg	0.21mm	68	81	0.49 $\Omega$	0.34 $\Omega$
32awg	0.10mm	135	173	3.22 $\Omega$	2.7 $\Omega$

The hand-built nature of the devices creates a discrepancy between the theoretical number of turns and actual number of turns as shown in Table 1. The theoretical number of turns is calculated assuming that each turn of wire is perfectly aligned with the neighboring turns. The theoretical resistance is calculated from the theoretical wire resistivity and length of wire. The values differ ~20-30% from theory due to the hand-wound nature of the coils.

## RESULTS

Each harvester in Fig. 2 was tested with the same repelling magnet and harvesting magnet as shown in Fig. 1. The performance was measured on a shaker table with a 0.25G sinusoidal stimulus.

The peak voltages generated from each harvester with an electrically matched load for a 0.25G sinusoidal stimulus are shown in Fig. 3. The corresponding RMS power is shown in Fig. 4. The values at resonance are plotted in Fig. 5 as a function of the coil wire radius  $r$ . The values off-resonance at 10Hz are plotted in Fig. 6. Although there are only three data points, curves are provided with the appropriate dependencies (Equations 4 and 5) to guide the eye.

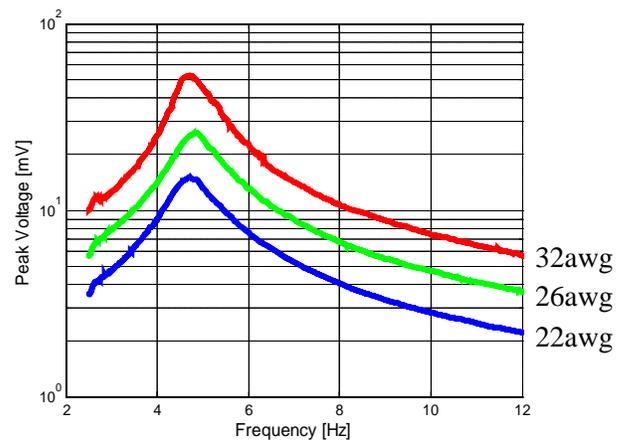


Fig. 3: Peak voltages for the three devices in Fig. 2 with electrically matched loads. These results are measured on a shaker table with a 0.25G sinusoidal stimulus.

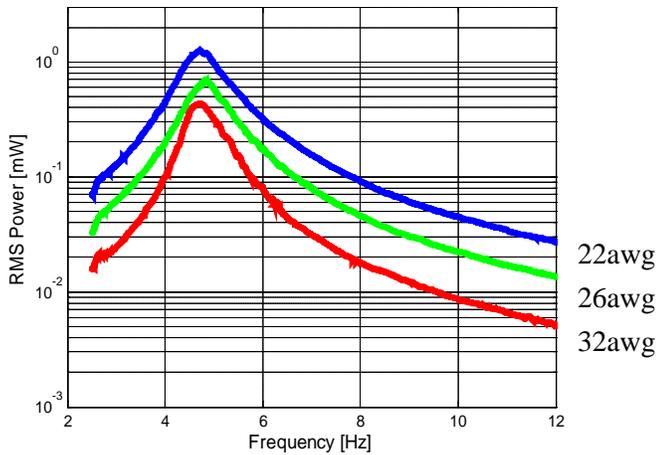


Fig. 4: RMS Power delivered to the electrically matched load. These values are calculated from the peak voltages measured in Fig. 3 and the resistances in Table 1.

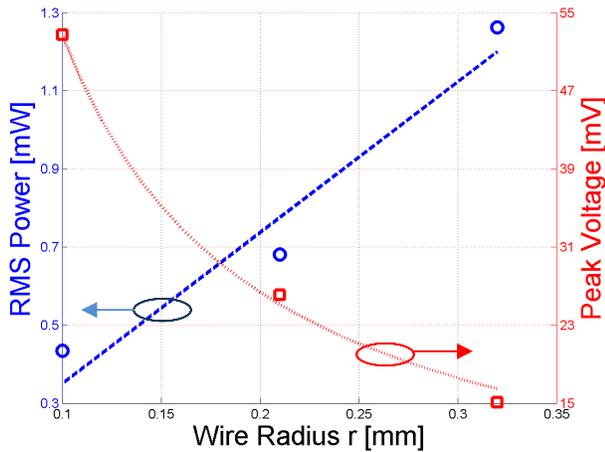


Fig. 5: RMS power and peak voltage versus coil wire radius  $r$ . These values are extracted from Fig. 3 and Fig. 4 at resonance.

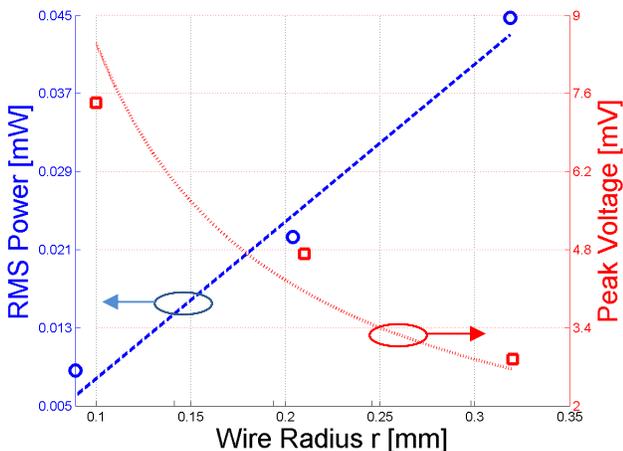


Fig. 6: RMS power and peak voltage versus coil wire radius  $r$ . These values are extracted from Fig. 3 and Fig. 4 at 10Hz.

The measurements are consistent with the linear increase in power with coil wire radius ( $r$ ) and the inverse decrease in harvested voltage with wire radius. The measurements also confirm that the theory is valid over a wide frequency range, both near and far from resonance.

## CONCLUSION

Theory and measurement results verify that the power-optimal coil for an electromagnetic power harvester is as thick as possible. However, this decreases the peak harvested output voltage, which makes building efficient power conversion circuits more difficult.

## REFERENCES

- [1] Saha C et al. 2008 Electromagnetic generator for harvesting energy from human motion *Sensors and Actuators*, **147** 248-253
- [2] Naruse Y et al. 2008 Electrostatic micro power generator from low frequency vibration such as human motion *PowerMEMS 2008 (Sendai, Japan, 9-12 November 2008)* 19-22
- [3] Bowers B, Arnold D 2008 Spherical Magnetic Generators for Bio-Motional Energy Harvesting *PowerMEMS 2008 (Sendai, Japan, 9-12 November 2008)* 281-284
- [4] Hudak N Amatucci G 2008 Small-scale energy harvesting through thermoelectric, vibration, and radiofrequency power conversion *J. Applied Physics*, **103** 101301-1 - 10301-24
- [5] [http://en.wikipedia.org/wiki/Solar\\_power](http://en.wikipedia.org/wiki/Solar_power) Webpage accessed on September 4, 2009
- [6] [http://www.micropelt.com/download/powerbolt\\_measurement\\_data.pdf](http://www.micropelt.com/download/powerbolt_measurement_data.pdf), Webpage accessed on September 4, 2009
- [7] <http://www.poweredbythermolife.com/techdata.htm>, Webpage accessed on September 4, 2009
- [8] Cheng S, Arnold D 2008 A multi-pole magnetic generator with enhanced voltage output for low-frequency vibrational energy harvesting *PowerMEMS 2008 (Sendai, Japan, 9-12 November 2008)* 125-128
- [9] Spreemann D, Folkmer B, Manoli Y, Comparative study of electromagnetic coupling architectures for vibration energy harvesting devices *PowerMEMS 2008* 257-260
- [10] [http://www.perpetuum.com/resources/PMG17\\_technical\\_datasheet.pdf](http://www.perpetuum.com/resources/PMG17_technical_datasheet.pdf), Webpage accessed on September 4, 2009