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# Energy Harvesting for Smart Sensor Systems

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## Summary

The University of Illinois Railroad Engineering Program developed and tested a prototype of an energy harvester to validate energy harvesting models. The prototype is intended for onboard railcar performance monitoring applications.

High reliability sensor systems are needed to support railway strategic objectives of improving the safety, reliability, and efficiency of train operations. In this Association of American Railroads' sponsored technology scanning project, a prototype device was designed for the railway vehicle operating environment. A few simple design rules from the results of this study include:

1. Create areas of high flux concentration by using two or more magnets placed end to end.
2. Minimize competing inductances by making the coil height half the height of the magnet.
3. Minimize competing inductances by designing with two opposite wound coils in the place of one.
4. Trade outer coils for a steel case.

Ubiquitous computing and smart sensor technology has seen significant growth over the last 5 years. The latest generation of very low-power microprocessors, low-power spread spectrum radio transceivers, and networking software has driven a new round of smart sensor research, development, and commercialization. A smart sensor is distinguished by the ability to not only sense and collect data, but to process, reduce, and make decisions based on its own data and data from the surrounding sensor network. The multisensor network is a key aspect of ubiquitous computing and promises to significantly lower the barriers that afflict current long-term railcar monitoring systems. Those barriers include (1) high installation and maintenance costs due to placement of sensors and routing of power/data lines, (2) limited time duration due to limited battery life, and (3) penalties associated with the physical size and weight of the data collection system.

The barriers described above establish the need for energy harvesting solutions. Smart sensors require only about 10 milliwatts (mW) of power. A visible lack of energy harvesting solutions for smart sensor systems exists today. There are many different sources of energy available from the ambient environment. These sources include solar, vibration, thermal, and wind. Each of these sources has the potential to provide the 10 mW of energy needed to power a smart sensor indefinitely. This work focuses on the design trade-offs associated with a linear electromagnetic energy harvester. The main constraint placed on the energy harvester is the overall size and cost. Because smart sensors are themselves small and low cost, the energy harvesting device must also be correspondingly small and low cost.



## INTRODUCTION

As railroad loads get heavier and operating speeds get faster, the demand for service quality and safety increase, the ability to monitor and process information about the health of myriad components of the rail transportation system increases correspondingly. Although the technology to perform this has existed for many years, the ability to apply it has been severely constrained by the cost of the hardware, the extensive preparation required to apply instrumentation, and the infrastructure required to monitor and process the information.

While low-cost and low-power smart sensor systems are now commercially available and in use in the rail industry, widespread use is constrained by the cost of powering the sensors. These costs include both initial equipment and installation costs as well as any long-term maintenance costs for any battery powered system.

A low-cost system can be achieved by harvesting energy from the ambient environment using consumer-grade rather than research-grade technologies. Several self-powered flashlights can be purchased for less than \$5.

There are many different sources of energy available from the ambient environment. These sources include solar, vibration, thermal, and wind energy. Each of these sources has the potential to provide the 10 mW of energy needed to power a smart sensor indefinitely. Solar power easily meets the initial cost objectives, but is not a viable option for any sensor that is not exposed to direct sunlight and rain for periodic cleaning. Piezoelectric-based vibration energy harvesters are still too expensive to be considered for most applications. Electromagnetic energy harvesters appear to be the most likely and reliable technology to construct a low-cost system.

For this study, the size of the device is limited to a cylinder 1 inch (2.5 cm) in diameter and having a height of 1 inch (2.5 cm) for a total volume of about 12 in<sup>3</sup> (12 cm<sup>3</sup>). This was selected to be similar in size to the energy harvester in a battery-less flashlight. The goal is to maximize power output from the device by adjusting the following design parameters: (1) number of magnets, (2) number of coils, (3) orientation of magnets with respect to coils, and (4) trading outer coils for steel casing.

## DESIGN PARAMETERS

Most energy harvester development has focused on efficiency. That is, to harvest as much electrical energy as possible from a fixed volume. A sensor system consumes negligible energy compared to the energy available from a moving railcar. In this environment, a larger, less efficient, durable and very low-cost harvester is a better solution. An energy harvester should not have

any moving parts, such as gears and bearings, in order to lower the cost and increase the reliability over a 20-year life span. Motion should be accommodated with flexible bending elements. A number of design parameters have been fixed in this study in order to construct a model of the energy harvester system. These include (1) vibration environment, (2) magnet strength, (3) coil wire gage, (4) air gap, and (5) load resistance.

Smart sensors have been mounted on the brake beams of railcars to characterize the braking force on individual wheels.<sup>1</sup> In this application, the vibrations on the brake beam have been reported to be 20 g's (acceleration) on average with peak accelerations of around 40 g's. The dominant frequency occurs at approximately 100 hertz (Hz). For this study, all energy harvesting models are excited with 20 g's at 100 Hz. Based on this choice of vibration environment, the peak-to-peak displacement is 0.04 inch (1 mm). This low level of displacement is a critical factor in the design of an energy harvester, because at this low level of displacement, the magnetic flux must be as concentrated as possible with a small area.

High-performance magnets come with a correspondingly high price. In this study, standard size magnets are used in the energy harvester model that can be easily purchased from many hardware suppliers. The highest strength magnets are the rare-earth magnets. For the model, 0.5 inch (12.7 mm) diameter Neodymium-Iron-Boron magnets of varying heights are used.

Based on the power requirements for a smart sensor, the power goal for the energy harvester is set at 50 mW root mean square while operating at nominal vibration with at least a 3-volt (V) root mean square output from the coils. Therefore, the wire diameter was chosen large enough to carry 17 milliamperes (mA) root mean square. According to American Wire Gauge specifications, the minimum gauge wire meeting the power specifications is 38-gauge wire.

For the model, the air gap between the magnet stack and coils is set at a very conservative 0.03 inch (0.75 mm). The actual size of the air gap that can be manufactured is likely much smaller, and therefore greater power output would be realized.

The external circuit is a simple full-wave diode rectifier, as Figure 1 shows. The load resistance of the circuit is set at 200 ohms. This load is based on the power consumption of a typical smart sensor at a moderate load, which is 20 mA at 4 V.

An external capacitor is chosen with a resistance and capacitance time constant corresponding to four vibration cycles. This keeps the ripple voltage down to an acceptable 0.2 V to 0.3 V level in the final design.

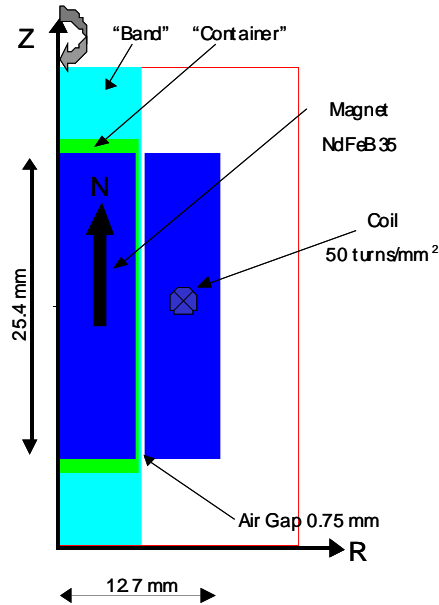


Figure 1. One Coil and One Magnet

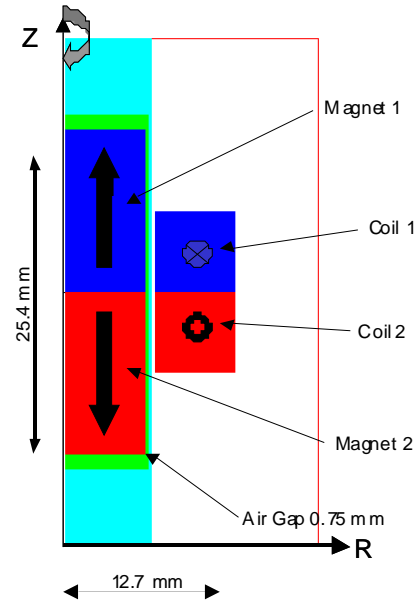


Figure 2. Two Coils and Two Magnets

**MODELING**

The state of the art in commercial electromagnetic finite element analysis software is Ansoft Corporation’s line of Maxwell FEA 2D and 3D software. The software can model both linear and nonlinear systems. Generally, each region was meshed with 100 elements. Figure 1 shows the necessary regions for the finite element analysis (FEA) model. The “band” is that region of the FEA model in which the moving parts are allowed to travel. The band acts as a mesh interface between the dynamic and static elements. The “container” is a region that contains all the moving parts and acts as a mesh interface between the moving components and the band.

The power output from one magnet and one coil is essentially zero. The highest concentrations of magnetic flux emerge from the ends of the magnet.

Figure 2 shows a two-magnet and two-coil design. The north poles of the two magnets are forced together to concentrate the magnetic flux in the center. The two coils are wound in opposite directions so that small movements in either direction will produce large changes in the magnetic flux field in the coils. This design produces 80 mW of power.

Increasing the number of magnets and coils decreases the power generated. Four magnets and four coils only generate 34 mW, and eight magnets and eight coils generate 24 mW of power. As the number of magnets and coils increase, they become smaller because the overall size remains fixed. The air gap is also fixed and a smaller magnet with a lower magnetic field strength will reduce the overall flux change.

In the final design, the coil diameter (number of turns) was reduced and a steel case was placed around the assembly to further concentrate the magnetic field. For the two magnet-two coil design, power was increased from 80 mW to 230 mW.

**PROTOTYPE**

The modeling effort led to the prototype energy harvester shown in Figure 3. The steel outer case is removed to show the two coils. The coils in this device are 1 inch (2.5 cm) in diameter. The magnets are inside the coils and remain fixed in space and the coils are free to vibrate. Otherwise the energy harvester would not work when attached to a magnetic surface.

Four identical curved leaf springs are used to support the coil, as Figure 4 shows. This configuration results in linear motion. A stacked configuration of different spring stiffness values could be used to give a broader frequency response. The design resonant frequency was 100 Hz and the prototype had a resonant frequency of 130 Hz. No attempt was made to tune the prototype to the design resonant frequency, as this design frequency could be different for each specific application.

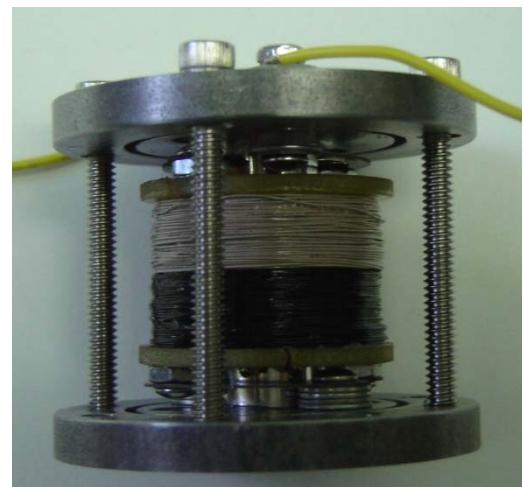


Figure 3. Prototype Energy Harvester

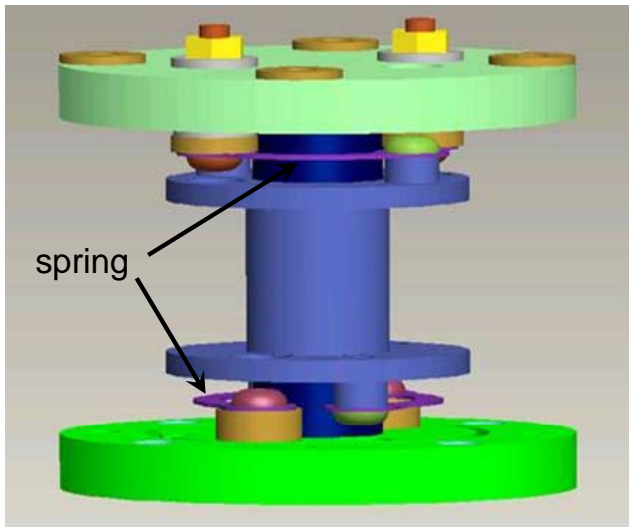


Figure 4. Spring System

The energy harvester prototype was tested using an electromagnetic vibration shaker with a range of frequencies to develop a power generation-frequency response curve. An accelerometer was used to monitor the acceleration of the energy harvester during testing. The power produced was measured and normalized by the square of the g-force exerted on the energy harvester. Figure 5 shows the power output for the energy harvester with a 1 k $\Omega$  load over a range of frequencies. Understanding the best location for energy harvesters on railcars will require further study to characterize their long-term vibration environment. The prototype sensor work on brake beams on freight cars operating on a Class I railroad exhibited different vibration characteristics than brake beams on a different type of car operating at the Transportation Technology Center, Pueblo, Colo. Remember that repeated impact loading generates all frequencies so that a fixed frequency harvester will always generate some power. This harvester is designed to be big enough to get power even when it is not excited in a resonance condition. Thus, it is a universal component which can be applied to most all vehicles operated on North American freight railways.

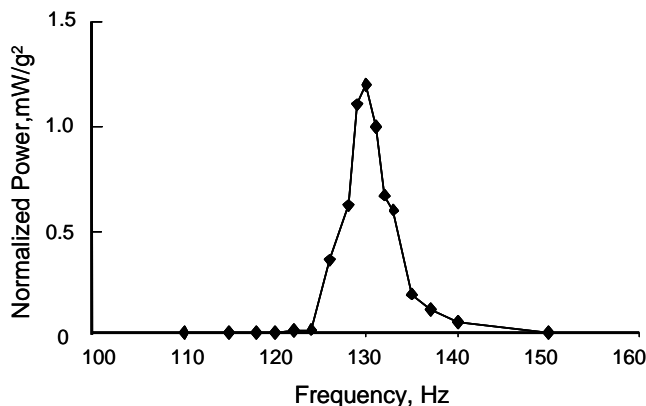


Figure 5. Power Output

Results were normalized with the experimental vibration amplitudes. Extrapolating this data to the model conditions of 20 g's and 100 Hz results in a power level of 285 mW, compared to the model results to 230 mW.

Additional work not described here included the design and testing of a battery charging system for the energy harvester.<sup>2</sup> Also, durability testing of sensor and energy harvester attachment methods to freight car brake beams was conducted. These tests show the components can survive the railway service environment.

## CONCLUSION

A low-cost energy harvester suitable for use in railcar applications was designed and fabricated. The analytical model for coil and magnet configurations gave considerable insight into how such an energy harvester should be designed. A sensor system consumes negligible energy compared to the energy available from a moving railcar. In this environment, a larger, less efficient, durable and very low-cost harvester is a better solution.

## FUTURE WORK

This project completed the proof of concept evaluation. Remaining is the development of a product for specific railway condition monitoring applications. Railroads and suppliers are considering applications for monitoring brakes (including hand brakes), bearing and wheel temperatures, and the condition of insulated rail joints in track.

## ACKNOWLEDGEMENTS

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