Development of an Electro-Magnetic Transducer for Energy Harvesting of Kinetic Energy and its' Applicability to a MEMS-scale Device

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Nanopower Forum 2008
Costa Mesa, California
June 2-4, 2008

Abstract

We present a novel electro-magnetic transducer for converting ambient kinetic energy into useful electrical power. The patent pending concept has demonstrated rectified DC power production of 18 mW at 1-g (9.83 m/s^2) of acceleration, and peak-to-peak voltage production of 2 Volts at an applied acceleration of only 0.0027 g. The voltage sensitivity of the transducer for low vibration levels indicates that a micro-scale version of the concept is feasible.

Introduction

Autonomous, wireless sensor nodes are receiving increased attention due to their ability to be easily deployed for surveillance and reconnaissance missions. Furthermore, the wireless capability allows the sensors to be deployed in areas that were previously inaccessible or simply not practical. Although recent advancements in communication protocol such as IEEE 802.15.4 and Zigbee along with intelligent power management systems have resulted in lower power consumption of these sensor nodes, the batteries used to power these systems have a finite lifetime and need to be replaced. Replacement of the batteries comes at a price, however: a material cost for the batteries; a cost due to down time of the sensor; a cost in human life due to do potential increased exposure in hostile areas during battery replacement and/or deployment of new sensors; an environmental cost due to disposal of the spent batteries; and a cost in human labor to replace the batteries. Methods for increasing the lifetime of batteries or for creating self-powered sensor nodes is required to mitigate the costs outlined above. One possible method is through the use of energy harvesting / scavenging devices that utilize the ambient environmental energy and convert it to a usable electrical power source.

Numerous sources of ambient environmental energy exist to extract useful electrical power. Sources include solar and kinetic energy, thermal gradients, radio waves, and acoustic energy to name a few. Lumedyne Technologies in collaboration with Space and Naval Warfare (SPAWAR) Systems Center, San Diego is currently developing an energy harvesting device based on the use of ambient kinetic energy within the environment to produce usable rectified power. The method by which the energy conversion is done is through the use of an electromagnetic transducer utilizing a novel configuration which is the subject of a pending US patent. The novel configuration not only increases the efficiency of energy conversion allowing more usable power to be generated but also demonstrates maximum sensitivity for small displacements which are compatible with micro-scale devices.

Concept

The concept is based on the use of Faraday’s law which states that a time varying magnetic field incident normal to the surface of a coil will produce a voltage proportional to the number of coils (N), the area of the coils (A), the velocity of the spatially varying magnetic field (2πf), and the magnitude of the time varying magnetic field (B_o) as given in equations (1)-(2) below.

$$\oint_{\ell} E \cdot d\ell = -\frac{d}{dt}\int_{S} B \cdot ds = -\frac{d\psi_m}{dt} \tag{1}$$

$$V(t) = N 2\pi f B_0(x,t) A \tag{2}$$

To increase the voltage generation, any of the above mentioned parameters may be increased. However, all have finite physical limitations and / or trade-offs in terms of performance. For example, a larger number of turns, N, can be generated but at the expense of increased coil resistance which will reduce power production since power is inversely proportional to resistance. Coil geometry also plays a role in conversion efficiency since the time varying magnetic field gradient must be integrated through the entire thickness of the coil. In some cases, this could result in cancellation of the magnetic flux lines thereby reducing power production. In addition, a higher velocity, i.e. vibration frequency, will also increase voltage production but at the expense of decreased displacement of the moving element through the magnetic field.

The work that Lumedyne has done in collaboration with SPAWAR Systems Center, San Diego has been focused in two main areas. The first is the optimization of the static spatial magnetic field gradient. The larger this static spatial gradient, the larger the time varying portion of the magnetic field once a velocity vector is introduced via an external excitation due to vibration. The second area is in the design and fabrication of the coils to maximize both the number of turns while minimizing resistance and optimizing the shape of the coil with respect to the spatial magnetic field gradient.

Figure 1 below is an optical photo of a first generation prototype constructed using rapid prototyped plastic and chemically etched stainless steel springs. The design is sufficiently flexible to allow for the replacement of the springs thereby allowing the device to easily be characterized at various resonant frequencies using different spring designs. The prototype can also handle up to 5/8” diameter or smaller disc magnets up to ¼” in thickness. The overall volume and mass of the prototype were 27 cubic centimeters and 27 grams.

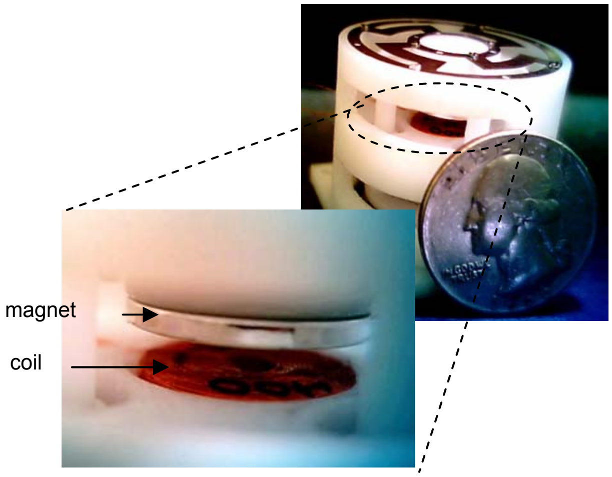

Figure 1. First generation prototype is shown next to a quarter. The inset is a detail photo showing a Neodymium magnet and a custom wound coil.

8,000 Turn Coil, ½” Magnet

Two versions of our first generation prototype have been assembled and tested. The first version contains two 4,000 turn coils for a total of 8,000 turns and multiple ½” diameter, ¼” thick N45 Neodymium magnets. The total coil resistance is 6500 Ohms. The energy harvesting prototype was tested by mounting it on a Labworks vibration table alongside a Dytran 3055B3 reference accelerometer for feedback control of the vibration table. Figure 2 is a plot of the measured open circuit voltage with an applied RMS acceleration of 0.77 g resulting in a total of 43.8 Volts peak-to-peak or 16.5 Volts RMS.

Due to the patent-pending configuration of our prototype we are able to generate very large spatial magnetic field gradients near the steady-state position of the integrated coil. Small perturbations in the position of either the coil or the magnets results in a large time varying magnetic field and hence significant voltage and power production. In general, the smaller the displacement and / or input vibration level, the larger the differential voltage gain produced. Figure 3 demonstrates this voltage sensitivity. In the figure, a 2 Volt peak-to-peak voltage was measured with an applied input acceleration of only 0.0027 g RMS. This represents a total differential voltage sensitivity of 260 V/g. It should be noted that this is a non-optimized design at this point and further optimization can be achieved to further increase the differential voltage gain as well as energy conversion efficiency.

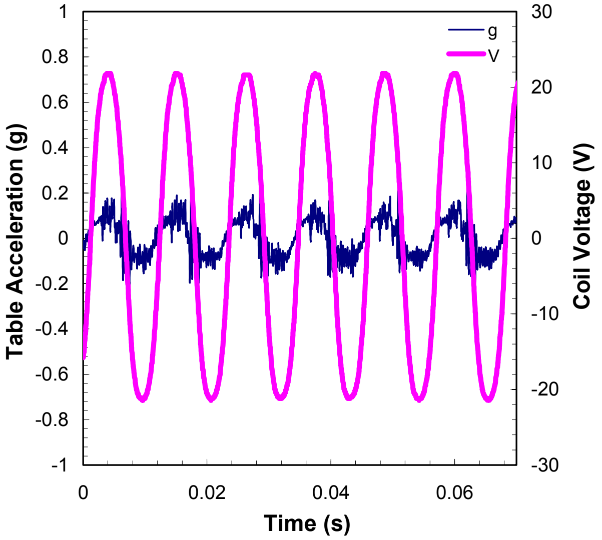

Figure 2. Measured first generation prototype with a 8,000 turn coil at an applied RMS acceleration of 0.77 g.

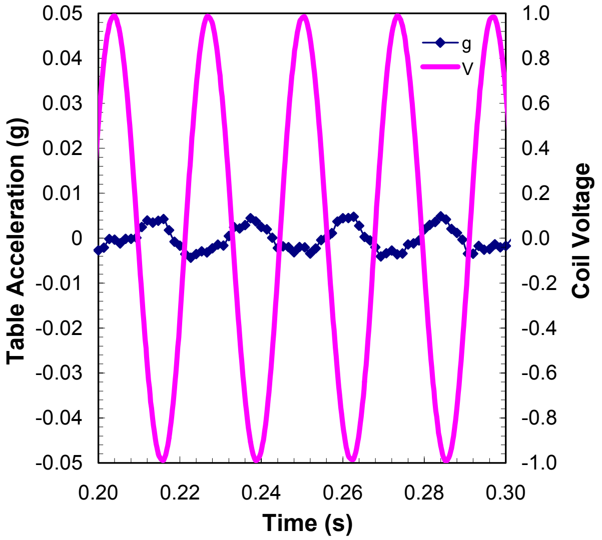

Figure 3. Measured first generation prototype with a 8,000 turn coil at an applied RMS acceleration of 0.0027 g producing 2 Volts peak-to-peak.

15,000 Turn Coil, 5/8" Magnet

A second first generation prototype was assembled that contained a coil with 15,000 turns and larger 5/8" diameter, ¼" thick N45 Neodymium magnets. While the overall volume of our prototype did not increase, the overall mass did increase due to the slightly larger magnets. Resonant frequencies also decreased with the current spring designs due to the increased mass of the magnets.

As expected, the larger magnets and increased number of turns in the coil increased both voltage and power production. Figure 4 is a measurement of the energy harvester with an input acceleration of 0.063 g RMS producing a peak-to-peak voltage of 19 Volts.

Of course, what is ultimately of interest is not the peak voltage or peak power production but rather the maximum DC power available after rectification. The rectification electronics in our case consisted of either a full wave Germanium diode rectifier with turn-on voltage of approximately 0.2 Volts or zero-bias Schottky diodes also with a turn-on voltage of about 0.2 Volts but with typically lower on resistance than the Germanium diodes. Figure 5 is a plot of the

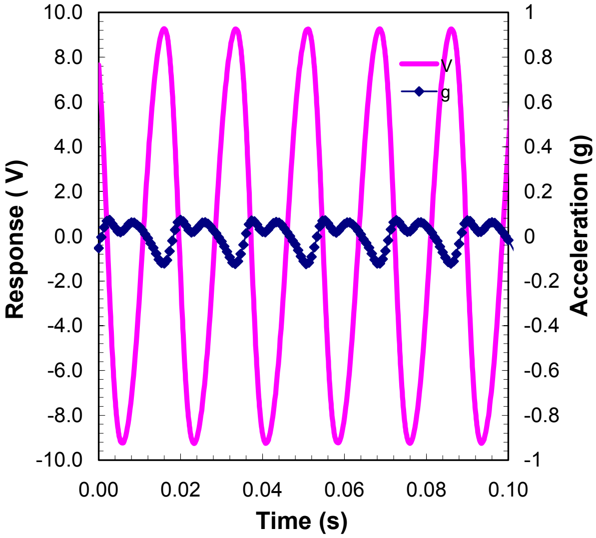

Figure 4. Measured first generation prototype with a 15,000 turn coil at an applied RMS acceleration of 0.063 g producing 19 Volts peak-to-peak.

output versus frequency for three different vibration levels. As expected, maximum power production occurs near resonance of the device with a typical half width full max (HWFM) of about 6 Hz. At an input acceleration level of only 0.1 g total rectified power production of nearly 1.2 mW is achieved. Power production, to first order can be shown to be proportional to the input acceleration level squared as given in equation (3) below.

$$P_{DC} \propto \upsilon g^{2} \qquad (3)$$

This relationship to the input acceleration level suggests that a 1-g input vibration would result in a total rectified power production of nearly 120 mW or 4.4 mW/gram. In fact, the difference in peak power between an applied acceleration of 0.01 g and 0.1 g goes as $g^{2.27}$ and goes as $g^{2.45}$ for accelerations between .05 g and 0.1 g implying that the dependence of the input acceleration level actually begins to increase with increased input acceleration. The fact that the dependence on input acceleration increases with increasing acceleration level may be indicative of better efficiency from the rectification circuitry with increasing power levels or it may be indicative of an increased static spatial field gradient for larger coil to magnet relative displacements. More experimental tests need to be run to determine whether the nonlinear magnetic field gradient or the efficiency of the rectification electronics is dominating the performance of the energy harvester for increased acceleration levels.

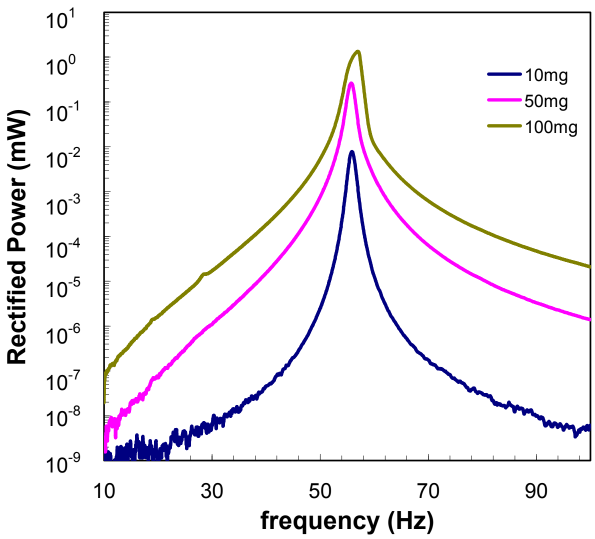

Figure 5. Measured frequency sweep of a device containing 15,000 turns and 5/8" diameter magnets.

Figure 6 is a plot of the rectified power measured while at resonance for various acceleration levels. This device while it still contains a coil with 15,000 turns had a different coil than the device reported in Figures 4 and 5. With this new coil it can be seen that the increase in rectified power with RMS acceleration has a dependence on the input acceleration which decreases with input acceleration. This is in direct contrast to the results reported in Figure 5 where the dependence on the input acceleration level increased with increased acceleration. The reason for this is still under investigation but the coils themselves while they contained the same number of turns had markedly different resistances and ideal load impedances. For the coil used in Figures 4 and 5, the coil resistance was measured to be 10,500 Ohms while the second coil used in Figure 6 measurement was 11,500 Ohms. In addition, the ideal load resistance after rectification was 12,000 Ohms for the former and 67,000 Ohms for the later. It is unclear at this time what is causing the discrepancy and how much coil geometry plays into the overall efficiency of the device.

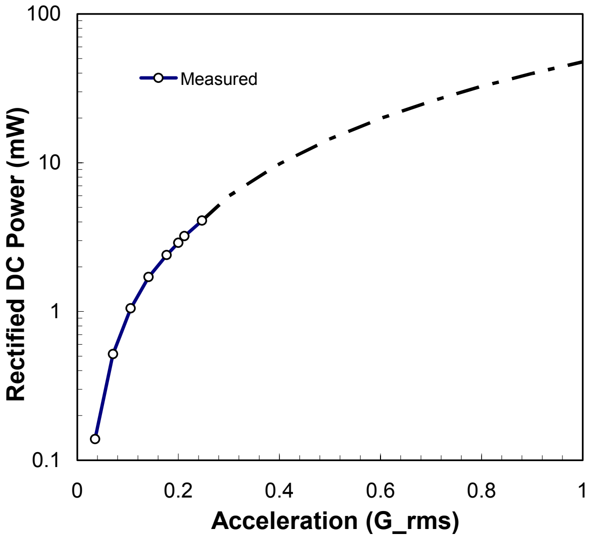

Figure 6. Measured rectified power versus RMS acceleration when operated at resonance.

In both cases, Figures 5 and 6, the power production for such small acceleration levels is very good with Figure 6 reaching a maximum measured rectified power of 4.1 mW at 0.24 g which extrapolates out to 48 mW at 1 g as shown by the dashed line.

Micro-Scale Version

One very interesting result of our first generation prototype was the measurement of 79 mV for a coil / magnet displacement of only 4.3 microns and a vibration table displacement of only 0.3 microns when operated at 90 Hertz. This measurement was performed on a device with an 8,000 turn coil. The fact that such a relatively large voltage could be produced for such a small displacement and relatively low frequency suggests that a micro-scale version of the technology could be developed. At the micro-scale displacements on the order of microns is what one would expect given proper design while resonant frequencies and hence velocities increase to 100's of Hertz to Kilohertz ranges thereby actually increasing potential voltage production.

The first question to answer, however, is there enough kinetic energy available at the micro-scale to make such a device feasible? Figure 7 is a plot of the available power of a 250 micro-gram mass versus resonant frequency for mechanical quality factors, Q, of 500 and 1000 respectively. In either case, the available power for frequencies below 10,000 Hertz is above 1 mW.

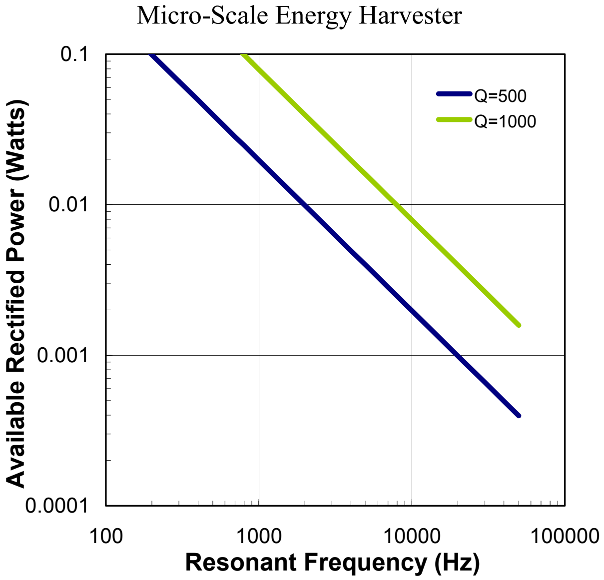

Figure 7. Calculated available power for a 250 micro-gram device versus resonant frequency.

The second question to answer is do we get enough displacement of the 250 micro-gram mass to achieve significant voltages. Figure 8 is a plot of the displacement of the mass versus frequencies again using the same mechanical Q factors as before. For frequencies below 7,000 Hz, displacements in excess of 4.3 microns are possible. Going back to our previous result with the first generation prototype producing 79 mV at a resonant frequency of 90 Hz would suggest that given the same number of coils and same displacement levels but operating at 9000 Hz would produce a voltage of 7.9 V. This is more than sufficient for passive rectification and the extraction of usable energy.

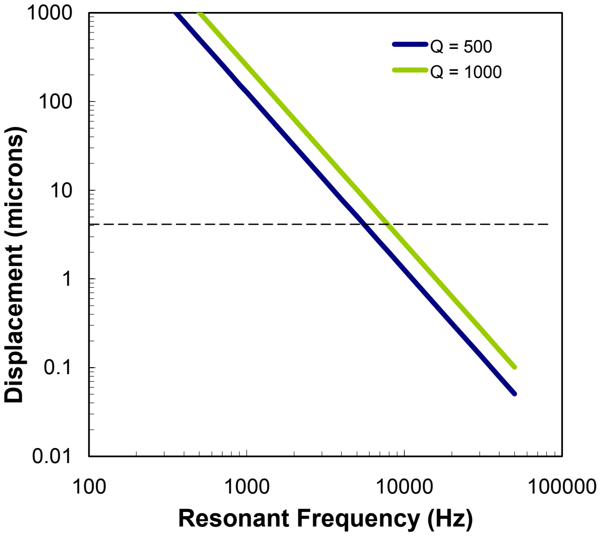

Figure 8. Calculated displacement of a 250 micro-gram mass versus frequency.

The range of frequencies at the micro-scale is obviously higher than for a meso or macro-scale device. The frequencies obtainable with a micro-scale device, however, is compatible with either acoustic signals or impulse functions due to movement of the energy harvesting element. In addition, due to their small size, arrays of elements can be fabricated in a very small volume where each element of the array is tailored to a specific resonant frequency through modification of the spring suspension. Figure 9 is an optical micrograph of a previously fabricated micro sensor at the SPAWAR Systems Center, San Diego. This micro-scale device could serve as the basis for a micro-scale energy harvesting element. Figure 10 is an example of a large array of these devices previously fabricated illustrating both the packing density and very small size of the devices. Finally, Figure 11 is an example of what a completed micro-scale energy harvesting element might look like where an array of micro-sensors has been positioned between two permanent Neodymium disc magnets.

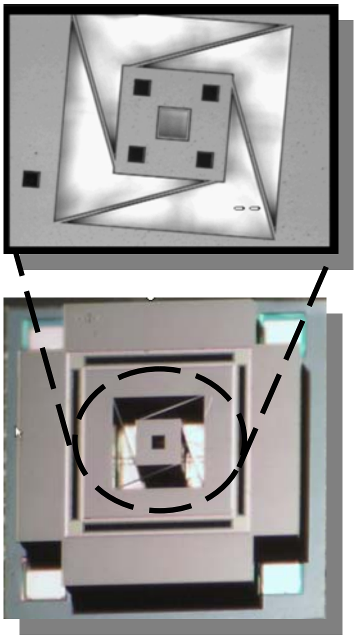

Figure 9. Previously fabricated micro-sensors at SPAWAR Systems Center, San Diego.

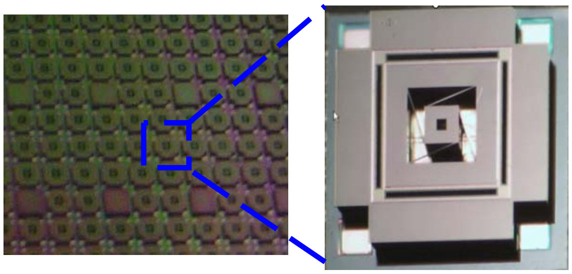

Figure 10. Array of micro-scale devices. Each element of the array measures 2.75x2.75 mm.

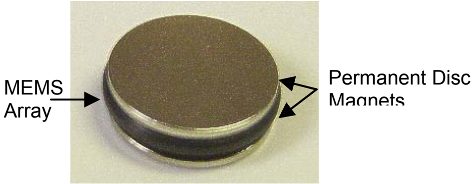

Figure 11. Example of a finished micro-scale energy harvesting element containing an array of sensors each tailored for a specific operational frequency.

Technology Demonstration

To demonstrate the energy harvesting technology a Crossbow mica2 wireless transceiver mote, typically powered using 2 AA batteries and equipped with five sensors, was powered exclusively by our energy harvesting device. The Mica2 mote contains five sensors including a temperature, pressure, humidity, light intensity, and 2-axis accelerometer. The distance between the Mica2 mote and the base station was over 420 feet. Maximum transmission distance was limited by our line of site where the test was conducted. The energy harvesting device was driven at approximately 70 Hertz and an RMS acceleration of 0.3 g.

Total energy consumption between transmissions was approximately 0.175 Joules which included receive and transmit power consumption, processing power, and sensor power. To minimize energy the sensors were placed in a sleep mode between transmissions. Based on our observations the total energy consumed by the sensors in sleep mode was approximately 0.075 Joules leaving the remaining 0.1 Joules for receive / transmit as well as processing. Lower power wireless sensor nodes would enable us to decrease the required vibration level even further or increase transmission bandwidth or update rate.

Summary

In summary, Lumedyne Technologies in collaboration with SPAWAR Systems Center, San Diego has developed an extremely sensitive electro-magnetic transduction technique for the conversion of kinetic energy into usable DC power. New designs are in the works that will enable higher-g operation and much higher rectified power levels. The differential voltage sensitivity of the device has been shown to be compatible with micro-scale devices with each element of a micro array capable of producing 1-10 mW of rectified power.