Proceedings of IMECE2005
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-80426

SCAVENGING ENERGY FROM PIEZOELECTRIC MATERIALS FOR WIRELESS SENSOR APPLICATIONS

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ABSTRACT

Wireless sensors are an emerging technology that has the potential to revolutionize the monitoring of simple and complex physical systems. Prior research has shown that one of the biggest issues with wireless sensors is power management. A wireless sensor is simply not cost effective unless it can maintain long battery life or harvest energy from another source. Piezoelectric materials are viable conversion mechanisms because of their inherent ability to covert vibrations to electrical energy. Currently a wide variety of piezoelectric materials are available and the appropriate choice for sensing, actuating, or harvesting energy depends on their characteristics and properties. This study focuses on evaluating and comparing three different types of piezoelectric materials as energy harvesting devices. The materials utilized consisted on PZT 5A, a single crystal PMN 32%PT, and a PZT 5A composite called Thunder. These materials were subjected to a steady sinusoidal vibration provided by a shaker at different power levels. Gain of the devices was measured at all levels as well as impedance in a range of frequencies was characterized. Results showed that the piezoelectric generator coefficient, g33, predicts the overall power output of the materials as verified by the experiments. These results constitute a baseline for an energy harvesting system that will become the front end of a wireless sensor network.

INTRODUCTION

Research in the area of wireless sensors and sensor networks has been increasing steadily over the past five years because of their potential applications in military, environmental, health, and commercial areas [1]. Conventional sensors are still preferred but have problems with power consumption, wiring, and networking. Networking many types of sensors that can monitor different types of physical quantities within a designated environment is called sensor networks.

The concept of wireless sensors networks began as a Defense Advanced Research Projects Agency (DARPA) sponsored workshop with Carnegie Mellon University in 1978. At the time the military had an interest in developing wireless sensor networks for surveillance. Since then, DARPA has sponsored a total of 29 projects at 25 educational institutions [2].

A wireless sensor or node refers to a physical device consisting of a sensing unit, a processing unit, a transceiver unit, and a power unit. Application specific components may furthermore be included in the architecture [1]. Wireless sensors were designed to run on batteries but with advances in Micro-Electro-Mechanical Systems (MEMS) and Very Large Scale Integration (VLSI) design, which lower power requirements, it is possible that a wireless sensor can scavenge its own energy from the environment or the system that it is monitoring. The underlying idea behind energy scavenging is the extraction of energy that would otherwise be wasted, from one system to power another system or device. Potential energy sources that can be used for energy scavenging include solar, indoor lighting, vibrations, acoustic noise, and temperature gradient.

Previous research has shown that scavenging vibrations using piezoelectric conversion is an efficient means for powering a wireless sensor [3, 4]. In this paper the relative power density of each material and their impedances are characterized to provide a baseline for the coupling of impedance matching circuitry.

Wireless Sensor Power Issues

Power management is very important in the design of wireless sensors and sensor networks. Two ways in which power can influence the hardware constraints of a wireless sensor are through the behavior of the source and the consumption of the system. Until recently the only energy source for a wireless sensor is a battery. Since the overall power consumption of a wireless sensor is low, sources such as batteries and fuel cells have a long but ultimately finite life. The lifetime of a sensor node is important because when nodes go down the other nodes must reroute and reorganize which extra power. It becomes impractical to replace the batteries of thousands of nodes in a high-density network, accordingly alternative energy sources such as solar, and vibrations, sound, and wind can be used to power a sensor. Power consumption has been linked to the operation of the transceiver and the switching of CMOS circuits. Operating the transceiver in stand-by mode with a low duty cycle lowers the power consumption and is the preferred method when implementing a design. The current architecture of wireless sensor nodes allow them to operate in receive, transmit, sleep, and power down modes. Communications circuitry consumes proportionally high amounts of power and is inefficient to turn on and off. Future developments in power management will be dependent on the algorithm used to optimize the transition. One example of a wireless sensor platform is the Mote manufactured by Crossbow Technology, which has an operating voltage range of 2.7-3.6V, a current consumption of 7-19.7mA in receive mode, 1mW of power can be transmitted at between 10-17mA, and a sleep mode current of 0.010mA. For normal use the current consumption is 0.2369mA-hr making a 1000mA-hr battery only last 5.78 months.

ENERGY HARVESTING

Piezoelectric Materials

Piezoelectricity is a property of a material that allows it to produce a voltage when a mechanical force is applied to and conversely a mechanical action when a voltage is applied. This electromechanical coupling allows the material to be used as a sensor and an actuator.

Heating certain non-metallic materials until these materials become hard, brittle, heat-resistant, and corrosion resistant produces ceramics. Ceramics that are of the polycrystalline structure and are ferroelectric exhibit strong piezoelectric properties [5]. Polycrystalline ceramics are made up of randomly distributed crystallites, which are divided into domains having a similar dipole configuration. During manufacturing, the ceramic is exposed to a strong electric field, which orients the domains along polarity lines. The constitutive equations that describe the behavior of piezoelectric materials are shown in their tensor form in equations 1 and 2 as:

$$Di = \varepsilon ijEj + dijkTjk \qquad \text{Eq. (1)}$$

And,

$$Sij = dijkEk + s^{E}_{ijkl}Tkl \qquad \text{Eq. (2)}$$

Where, T = stress, E = electric field, D = displacement, S= strain, s = compliance, d = strain constant, and ε = permittivity.

Piezoelectric ceramics can be manufactured in a variety of configurations depending on the application. Size, shape, thickness, and the layering of the ceramic within other materials have an effect on the performance of the piezoelectric device [5]. One of the most widely used materials is Lead Zirconate Titanate (PZT), which has become a popular material in transducer fabrication. Bonding the PZT to a metal with an adhesive produces commercially piezoelectric composite devices. The composite is pressed while being heated to a high temperature forming a composite. Rainbows, and Thunder® devices fall into this category.

Other new materials, single crystals have become popular because of their high electromechanical coupling constant and high piezoelectric strain coefficients. The domains of piezoelectric crystals are in near alignment with the direction of the electric field that it is poled in. The more perfectly aligned domains with the direction of the applied electric field are present in the crystal, the greater the performance of the crystal.

Circuitry

The purpose of the energy harvesting circuitry is to efficiently convert and filter the signal from the piezoelectric device into a form that can be utilized by the load. The electrical charge generated from a piezoelectric device is usually insufficient to power a commercial sensor, but by rectifying and regulating the signal, a usable voltage can be applied to the sensor directly or used to charge a battery [6].

The type of circuitry used to harvest the energy from a piezoelectric transducer is determined by the desired output to the load, which often times needs to be rectified, filtered, and regulated. The output signal from the transducer can be modeled as an AC source in parallel with a capacitor. To convert this signal into a useful one, an AC-DC converter is used to rectify the noisy AC signal. The output from this converter is then sent to a DC-DC converter where it is regulated to the desired voltage. Capacitors are used to aid in filtering of the ripple voltage caused by rectification. Some types of DC-DC converters are the buck (step down), boost (step up), and buck-boost (step up/down.), and fourth order circuits such as the cuk and the Single-Ended Primary Inductance Converter (SEPIC) [7]. Energy harvesting circuitry typically falls into three generally accepted categories with hybrids also being utilized. Each category, its attribute and configuration are listed in Table 1.

Table 1 Energy Harvesting Circuitry

Approach	Attributes	Configuration
(1) Passive Rectifier Circuit	Low power generation	Piezo → Diode Bridge → Voltage Regulator → Storage
(2) Resonant Rectifier Circuit	Higher power generation, narrow frequency range	Piezo → Diode-Inductor → Voltage Regulator → Storage
(3) Active Switching Circuit	Higher power generation, wide frequency range	Piezo → Switching Amplifier → Voltage Regulator → Storage

Roundy et al. [4] explored the possibility of scavenging low-level vibrations to use as a power source for wireless sensor nodes. In this study the geometry of the piezoelectric device was optimized while the load resistance of the circuitry, which consisted of a series inductor with an active bridge, was varied. The researchers modeled a piezoelectric generator as a AC source in series with a capacitor, and a resistor. Roundy optimized the geometry of the piezoelectric device and the load resistance in Matlab to achieve a theoretical maximum power. A cantilever beam setup using a PZT bimorph and a PVDF bimorph was used in the model. The optimized model produced energy densities of 250μW/cm3 from a vibration source input magnitude of 2.5m/s^2 at 120Hz. The model was proven experimentally by using the optimized values from the model to construct prototypes. The experimental results were in agreement with the PZT bimorph demonstrating a power density of 70μW/cm^3 [4].

Impedance matching is the process of adjusting the impedances of the source and load to achieve maximum power transfer. Whenever a source of power, such as an electric signal source, a radio transmitter, or even mechanical sound operates into a load, the greatest power is delivered to the load when the impedance of the load (load impedance) is equal to the "complex conjugate" of the impedance of the source (i.e. of its internal impedance). For two impedances to be complex conjugates, their resistances must be equal, and their reactances must be equal in magnitude but have opposite signs. To match electrical impedances, combinations of transformers, resistors, inductors and capacitors can be combined within a circuit and, tuned filters match impedances for specific frequencies.

Ottman, et al., modeled the power flow characteristics of a strain-piezoelectric device called Quickpack, which consists of piezoelectric layers adhered to polyimide high temperature resistant film with inter-digitized electrodes [8]. Using this model they determined circuitry requirements needed to obtain optimal power flow in order to recharge a battery. A Quickpack® QP20 excited by a shaker was used in the experimental setup along with an adaptive controller which sensed the battery current and adjusted the duty cycle to maximize it, an AC-DC converter, and a DC-DC converter. The results of this study showed that a DC-DC controller with adaptive control harvested energy at four times the rate of direct charging without a controller [10]. Ottman and Lesieutre expanded on this study by simplifying the control circuitry. They determined that a converter operating in discontinuous conduction mode would hold the optimal duty close to a constant as the excitation is increased on the transducer. This approach harvested energy at three times the rate of direct charging [9].

Sodano, Lloyd, and Inman compared the ability of a Macro-Fiber Composite (MFC) actuator, the Quick Pack IDE model QP10ni, and the Quick Pack model QP10n to convert mechanical strain into electrical energy by exciting them while attached to an aluminum beam. Their result suggests that there is a correlation between the type of transducer and capacitance. Low capacitance contributes to high impedance according to the equation

$$Z = \frac{1}{j\omega C} \quad \text{Eq. (3)}$$

Where, Z is the complex impedance, ω is the input frequency, and C is the capacitance of the piezoelectric transducer. This study concluded that the MFC performed poorly on power output because of it low capacitance. The MFC is constructed using piezo-fibers and inter-digitized electrodes (IDE). This creates an array of capacitors that when connected in series the voltage adds but the current remains constant [10]. An important concept from this study is that impedance matching between the transducer and the circuit is critical when optimizing for power [11].

ASSOCIATED THEORY

The average power (P) or real power is the power in a circuit that is transformed from electric to non-electric energy. Power can be written as,

$$P = \frac{V_m I_m}{2}\cos(\theta_v - \theta_i) \quad \text{Eq. (4)}$$

where V_m is the amplitude, I_m is current, $_v$ is the phase of the voltage and θ_i is the phase of the current. In root mean square (rms) form, the average power delivered to a load resistance R is written as

$$P_{rms} = \frac{V_{rms}^2}{R} = I_{rms}^2 R \quad \text{Eq. (5)}$$

Whenever a source of power, such as an electric signal source, a radio transmitter, or even mechanical sound operates into a load, the greatest power is delivered to the load when the load impedance is equal to the complex conjugate of the impedance of the source. For two impedances to be complex conjugates, their resistances must be equal, and their reactances must be equal in magnitude but have opposite signs.

The maximum average power transfer between a load impedance Z_L and a source occurs when the complex conjugate of the Thevinin impedance of the source Z_{Th} is equivalent Z_L or,

$$Z_L = Z_{TH}^* \quad \text{Eq. (6)}$$

The maximum average power (P_{max}) is delivered to a load when this is true and the *rms* load current is

$$I_{rms} = \frac{V_{TH}}{2R_L} \qquad \text{Eq. (7)}$$

Then,

$$P_{\max} = \frac{|V_{TH}|^2}{4R_L} = \frac{V_m^2}{8R_L} \qquad \text{Eq. (8)}$$

EXPERIMENTAL SETUP

The materials used in this study are PZT 5A and PMN-32%PT <001>, and a PZT-5A composite (THUNDER®). The properties of the materials are shown in Table 2.

Table 2 Material Properties

	PZT-5A	PMN-32%PT
d_{33} [C/N] x 10^{-10}	3.90	0.196
g_{33} [Vm/N] x 10^{-02}	2.42	1.58
k_{33}	0.72	0.86
s_{33} [m^2/N] x 10^{-12}	9.60	0.10
Area [m^2] x 10^{-04}	1.59	1.00
Thickness [m] x 10^{-04}	1.00	5.00
Volume [m^3] x 10^{-08}	1.59	5.00

The HP4194A Impedance/Gain-Phase Analyzer was used to measure the impedance and gain-phase for frequency sweeps between 100Hz and 10,000Hz. In addition, The HP4194 was to measure the relative power of the devices by measuring the output of the devices in dBm as shown in the schematic of figure 1. Relative power is then calculated by referencing all the signals to 1mW of power supplied by the impedance analyzer. P_{rms} is the level of power the shaker is set to vibrate.

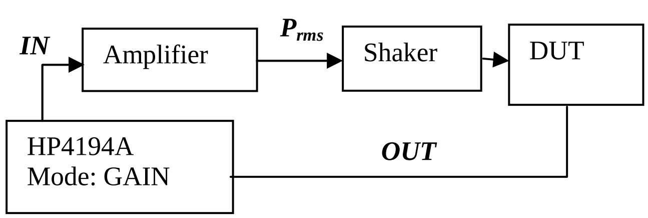

Figure 1 Experimental Setup where DUT is the Device Under Test

The HP4194 built in signal generator is driving a Labworks ET-132 Shaker through a Labworks pa-138 Power Amplifier. Data acquisition was done using Labview and a National Instruments BNC 2120 Breakout Box.

RESULTS

To calibrate the system an accelerometer was put on the system. A typical curve for the accelerometer is shown in Fig. 1 at different power levels applied to the shaker. In this manner, a measure of the mechanical power applied to the system can be recorded.

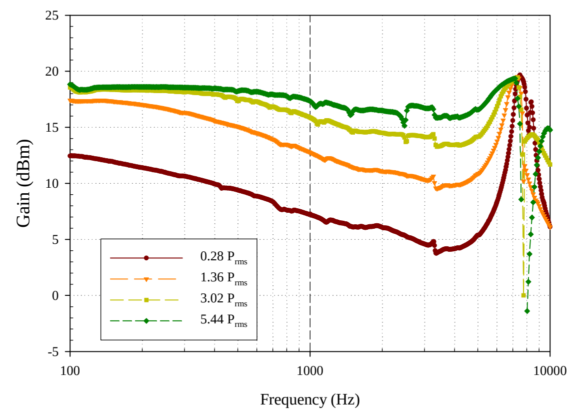

Figure 2 Accelerometer Calibration

By using the lowest setting on the shaker, $0.28P_{rms}$, a response was measured for each of the tested materials in dBm. A relative power can be calculate in reference to 1mW of power and the volume of material used on the testing normalizes the results. These tests are performed in an open circuit mode assuming no losses. Results, seen in Fig. 3, show that the PZT has the maximum relative power density obtained, 30µW per cubic cm at 5363Hz; for the PMN 32%PT was 0.57µW per cubic cm at 5120Hz; and for the Thunder device, 14.8µW per cubic cm at 1671Hz. Note that for frequencies below 1 kHz the PZT and the thunder device exhibit very similar trends in power density. The trend changes at higher values possible due to changing of the stiffness of the composite PZT. For the case of PMN 32%PT the power is smaller than the other two devices but following a similar trend to the PZT for the range of frequencies tested. These results were expected since the generator coefficient, g_{33}, shown in Table 2 for PZT and PMN-PT shows that PMN-PT has a lower coefficient than PZT.

To further investigate the trend for each material under the same testing conditions, excitation levels of the shaker were increased and the response of each one of the materials tested was recorded as shown in Fig. 4 through Fig. 6. The results and the trends are consistent for the three materials except at the peaks and valleys were the values shift to other frequency values. For instance, for PZT, Fig. 4, at the lowest power level, the maximum value of power measured is 30µW/cm^3 at a frequency of 5.12kHz. At the highest power applied to the shaker, the maximum measured power was 243.4 µW/cm^3 at 4.8kHz. In fact, at close inspection this type of trend is observed at the 4 power levels applied to the shaker. This type of behavior has also been observed when applying fields to piezoelectric materials and it is attributed to softening of the PZT [12].

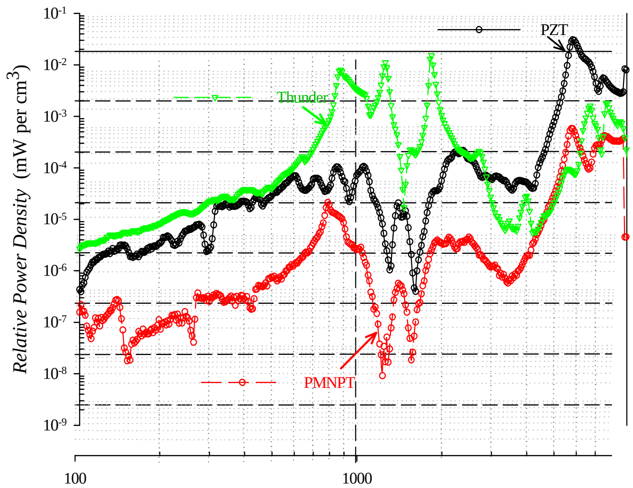

Figure 3 Relative Power Density (mW/cm3)

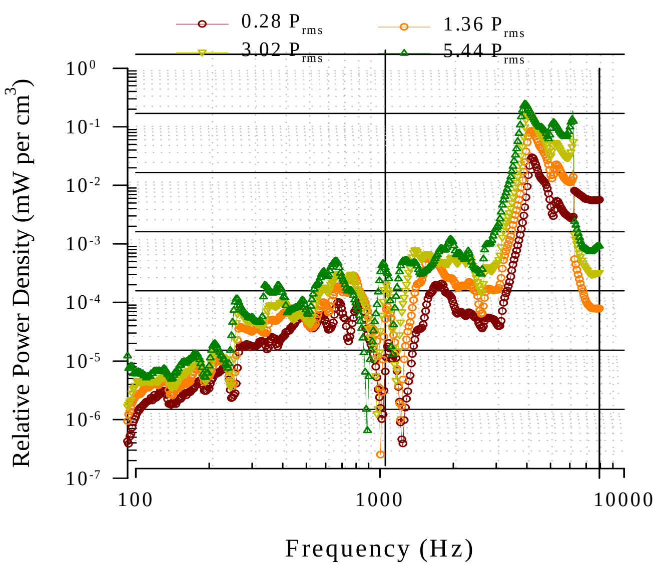

Figure 4 Relative Power Density for PZT at different Vibration Levels

For the case of single crystal, Fig. 5, PMN 32%PT, the maximum relative power density obtained was very low compared to PZT with a maximum value of 4μW/cm^3 at 7.5kHz. Finally, the thunder device, Fig. 6, showed a similar trend than the PZT producing a maximum power density of 154μW/cm^3 at 1.03kHz. It is worth noticing that this device shows peaks at lower frequencies than the other materials as well as peaks at the higher end as well. This characteristic may be of advantage for particular applications.

Impedance Measurements

Impedance sweeps for the three devices were performed and results for PZT, PMN 32%PT, and Thunder are shown in Fig. 7, 8, and 9 respectively. For clarity purposes, a log-log scale was utilized for the impedance, and a semi-log for the phase angle. In the case of PZT, Fig. 7, in the range of 100 to 1x10^4 Hz the impedance is in the range of 400Ω to 4MΩ with no electrical resonance values present. For the same frequency range, the impedance of PMN 32%PT, Fig. 8, ranges between 1kΩ to 0.1MΩ. Finally for the Thunder device, Fig. 9, the impedance varies between 2kΩ to 2x10^{5}kΩ with a resonant frequency in the range of 1-2kHz. This type of resonance, not observed with the other materials, is probably due to the composite nature of the device and it is dictated by the geometry and materials utilized in its construction. The other two materials are utilized in their normal state.

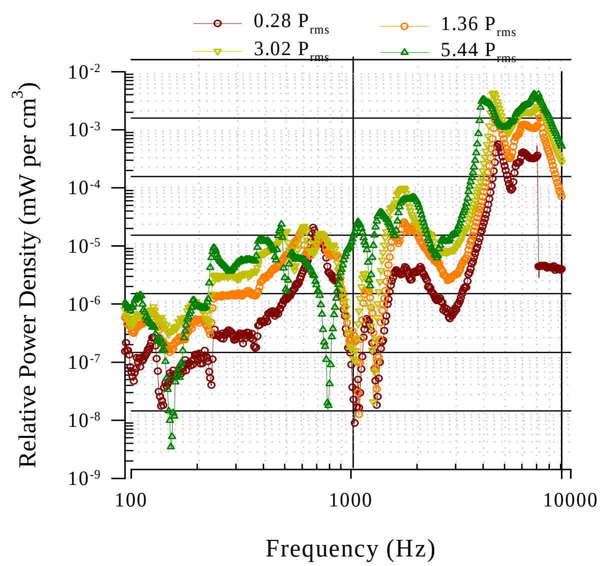

Figure 5 Relative Power Density for PMN 32%PT at different Vibration Levels

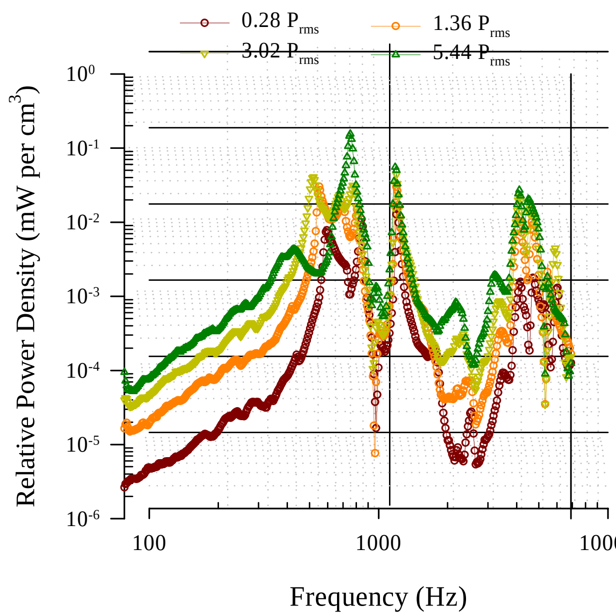

Figure 6 Relative Power Density for Thunder at different Vibration Levels

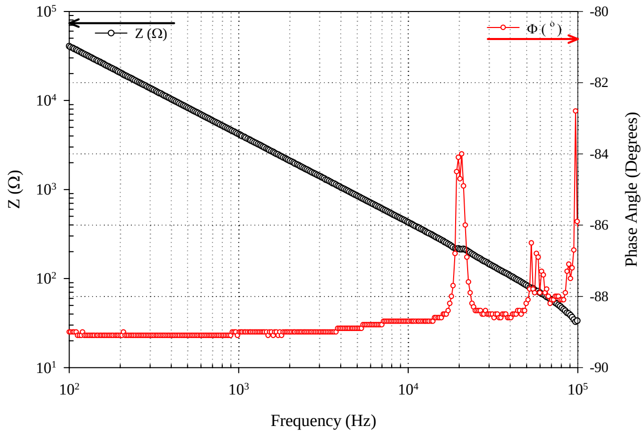

Figure 7 Impedance and Phase for PZT

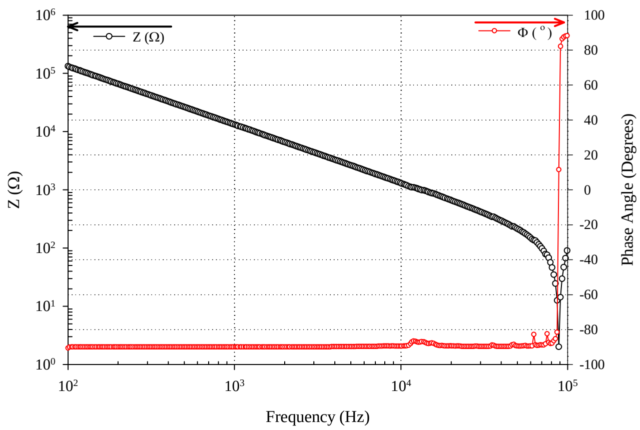

Figure 8 Impedance and Phase for PMN 32%PT

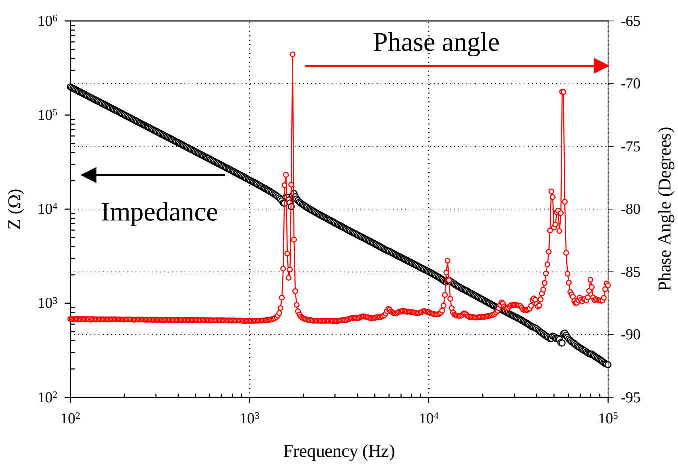

Figure 9 Impedance and Phase for Thunder

CONCLUSION

This paper makes a case for the use of alternative energy sources particularly piezoelectric devices for energy harvesting for wireless sensors. A baseline study of impedance and gain under a steady sinusoidal excitation with an open circuit was performed. Relative power densities per device were characterized for different input vibration levels. Maximum values of 243 μW per cubic cm were obtained for a layer of PZT and comparable values obtained with a composite PZT. Single crystal on contrast had very low power density. This difference may be justified by the value of the voltage constant, g_{33}, between PZT-5A and PMN-32%-PT.

Options to extract electrical energy from the vibrational energy of mechanical systems need to be explored and developed. This energy can be used to power auxiliary systems, sensors, or other items that might be embedded within the physical system. Energy generated directly at the site of the sensor or system being powered eliminates the cost and maintenance of cabling and batteries.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of NASA Langley Research Center, Hampton, VA.

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