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A Study of Piezoelectric Harvesters for Low-Level Vibrations in Wireless Sensor Networks

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In this paper, we aimed to study the feasibility of using a piezoelectric harvester as a potential energy source to power microsystems, such as MicroElectroMechanical Systems (MEMSs) in wireless sensor networks (WSNs). An off-the-shelf piezoelectric bimorph was first tested to determine the power output under various resonant frequencies in the range of 42 to 103 Hz. The results showed that the piezoelectric bimorph generated greater power output at lower frequencies and higher accelerations, achieving an output of 3.072 mW from a vibrational source of 53 Hz and 1 g acceleration. The same system was also examined in response to low-level vibration source found in common environments, such as areas of residence, transportation and machinery to investigate the viability of its use in an environment with inconsistent vibrational frequency. Finally, a discussion is provided regarding the use of piezoelectric harvesters for WSNs and potential approaches to increase power output.

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NOMENCLATURE

MEMS = MicroElectroMechanical Systems
VLSI = Very Large-Scale Integration
WSN = Wireless Sensor Networks
PZT = Lead Zirconate Titanate

1. Introduction

Numerous studies have previously investigated various energy harvesting methods from environmental resources.[1] There has been increasing interest in harvesting ambient energy for power using MicroElectroMechanical Systems (MEMSs). Low power very large-scale integration (VLSI) designs have been dramatically improved over time, and these improvements have contributed to the development of low duty-cycle wireless sensors, which have reduced power requirements in the tens or hundreds of microwatts.[2]

The objective of this study is to examine the feasibility of a specific ambient power source, a piezoelectric harvester, to power sensor nodes in wireless sensor networks (WSNs). This paper begins by reviewing the models of vibration sources and vibration conversion into electrical energy. Test results from a PZT (lead zirconate titanate) piezoelectric unimorph are then reported including the power output range observed under various frequency and acceleration conditions. We finally conclude with a discussion of the potential use of the harvesters in WSNs.

A WSN consists of spatially distributed sensors that monitor frequently varying conditions and transport the information through a network to the control unit. WSNs have been shown to be an effective solution to monitor environmental and military conditions[3] and also

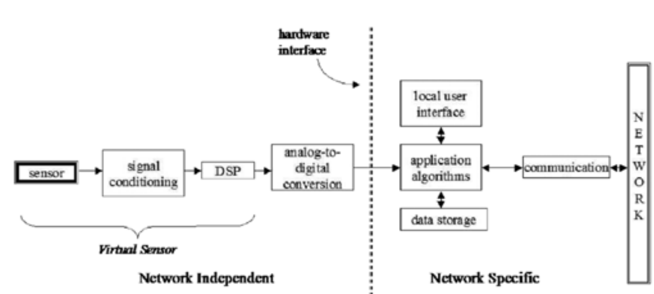

Fig. 1 A model of a smart sensor

widely used in numerous industrial monitoring and controlling systems.[4-6] A WSN has various nodes which are connected to sensors. Each sensor node normally consists of a radio transceiver, a microcontroller, an electronic circuit and an energy source. The IEEE and National Institute of Standards and Technology (NIST) have designed a standard for Smart Sensor Networks, IEEE 1451. A model of the smart sensor defined in IEEE 1451 is shown in Figure 1.[7]

The power requirement of a WSN is distributed into various functional elements. Typically, the communication function of a sensor node consumes the majority of the energy.[8] The power consumption of various commercial sensor nodes is given in Table 1.[9] The average values in Table 1 are based on operating conditions of 1% communication, 10% processing and 89% sleeping. An ideal wireless sensor node is expected to require approximately 100 ìW for the life time operation.[10]

Currently, most WSNs are powered by batteries. While battery technology has been markedly improved and power requirements of MEMS devices are continuously decreasing, contemporary batteries are unable to supply sufficient energy for the entire life of the device. Furthermore, battery replacement is an expensive and difficult procedure. Therefore, an ability to harvest energy from ambient sources, such as light, thermal, electromagnetic, or vibrational waves is crucial for the development of WSNs.

2. Vibrational Characterization Method

Vibration produces mechanical accelerations that cause the oscillation of mass components. This movement initiates opposing damping forces against the mass component that absorb the kinetic energy of the initial vibration and reduce the oscillation. The kinetic energy can be converted into electrical energy through an electric field, magnetic field, or mechanical strain.[11]

2.1 Vibration Sources

Because ambient vibrations contain a wide range of fundamental frequencies while most piezoelectric harvesters have a narrow operating frequency range, it is important to first understand various energy sources. Roundy et al. discussed several commonly occurring vibrations which are summarized in Table 2.[2]

The vibrations sources shown in Table 2 are mostly environmental, with a low frequency range under 1.5 g. Thus, these vibrations are likely to generate the ambient energies that are of interest in this study.

2.2 Conversion of Vibrational Energy to Electrical Energy

The general model used to convert the kinetic energy of a vibrating mass to electrical energy is based on the linear system theory proposed by Williams and Yates.[12] This model describes the conversion of the energy of an oscillating mass to electricity in terms of a linear damper in a mass-spring system.

$$m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y} \tag{1}$$

(z: spring deflection, y: input displacement, m: mass, b_e: electrically induced damping coefficient, b_m: mechanical damping coefficient, k: spring constan.)

Generated power through electric process can be separated from the mechanically produced power by electric damping. Electric power is now expressed with equation (2)

$$p = {}^{1}/_{2} b_e \dot{z}^2 \tag{2}$$

Finally, the relationship between power generation and input vibration can be expressed by equation (3).

$$|P| = \frac{m\varsigma_e \omega_n \omega^2 \left(\frac{\omega}{\omega_n}\right)^3 Y^2}{\left(2\varsigma_T \frac{\omega}{\omega_n}\right) + \left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2} \tag{3}$$

Table 2 Acceleration (m/s^2) magnitude and frequency of fundamental vibration commonly found in vibrating sources

Vibration source	A (m/s^2)	F_{peak}
Car engine compartment	12	200
Base of 3-axis machine tool	10	70
Blender casing	6.4	121
Clothes dryer	3.5	121
Person nervously tapping their heel	3	1
Car instrument panel	3	13
Door frame just after door closes	3	125
Small microwave oven	2.5	121
HVAC vents in office building	0.2 – 1.5	60
Windows next to a busy road	0.7	100
CD on notebook computer	0.6	75
Second story floor of busy office	0.2	100

Table 1 Summary of power consumption of commercial sensor network nodes[9]

	Crossbow MICAz	Intel Mote 2	Jennie JN5139
Radio standard	IEEE802.15.4/ZigBee	IEEE802.15.4	IEEE802.15.4/ZigBee
Typical range	100 m (outdoor), 30 m (indoor)	30 m	1 km
Data rate (kbps)	250 kbps	250 kbps	250 kbps
Sleep mode (deep sleep)	15 μA	390 μA	2.8 μA (1.6 μA)
Processor only	8 mA active mode	31 - 53 mA	2.7 + 0.325 mA/MHz
RX	19.7 mA	44 mA	34 mA
TX	17.4 mA (+ 0 dbm)	44 mA	34 mA (+3 dBm)
Supply voltage (minimum)	2.7 V	3.2 V	2.7 V
Average	2.8 mW	12 mW	3 mW

($|P|$: magnitude of output power, Y: amplitude of input vibrations, ζ_e: electrical damping ratio ($b_e = 2m\zeta_e w_n$), ζ_T: combined damping ratio ($\zeta_T = \zeta_e + \zeta_m$), w: input frequency, w_n: natural frequency of spring mass system)

If the resonant frequency matches with the input frequency of the mass-spring system, equation (3) can be simplified to the following equations (4) and (5).

$$|P| = \frac{m\varsigma_e\omega^3 Y^2}{4\varsigma_T^2} \tag{4}$$

$$|P| = \frac{m\varsigma_e A^2}{4\omega\varsigma_T^2} \tag{5}$$

(A: amplitude of acceleration in input vibration)

While this model is simplified for general applications, it is useful for a quick estimation to calculate the potential power output.

Some observations regarding equation (5) are listed below. Additional details will be discussed in Section 3.

1. The power magnitude is proportional to the square of the acceleration magnitude of the input vibrations.
2. The power magnitude is inversely proportional to the input frequency, which implies that the harvesters should be designed to resonate at the lowest frequency in their bandwidth while other parameters remain unchanged. Roundy et al. verified that the acceleration spectrum is relatively at.[2]
3. The power magnitude is linearly proportional to the mass. In Section 3.1, it is shown that mass indirectly affects the frequency of the piezoelectric harvester. Therefore, the largest proof mass within the range of allowable space, deflection and plastic deformation of the harvester should be used.

2.3 Piezoelectric Harvester

A piezoelectric harvester converts mechanical energy to electrical power by straining a piezoelectric material. This strain induces a charge separation across the device, which produces an electric field that is proportional to the applied stress.

Common piezoelectric materials in energy harvesting systems are lead zirconate titanate (PZT), barium titanate (BaTiO3) and polyvinylideneflouride (PVDF). PZT has generally been preferred for vibration-based energy harvesting devices due to the high electro-mechanical coupling coefficient (k) which describes the efficiency of energy conversion between mechanical and electrical forms. This value is used to determine the efficiency of a resonant generator.[13] However, PZT material is extremely brittle and must be handled with care to avoid damage when strained.[14]

Conventional piezoelectric power harvester comprises a piezoelectric cantilever beam with a proof mass attached to the vibrating part of the device. A low stiffness cantilever is required for the application of low-level low-frequency vibrations. Bimorph arrangement with 2 layers of piezoceramics bonded to a substrate is commonly used to improve the efficiency of the harbester because this configuration allows larger strain with lower resonant frequency.

3. Results

An off-the-shelf piezoelectric harvester, Volture V22BL, and EHE001c conditioning electronics (from MIDE Technology) were used in this study.

3.1 Forced Vibration Testing of Piezoelectric Harvester

A PZT harvester, Volture V22BL, and rectifier board, EHE001C, were connected by mating the connectors and supporting electronics. The device was clamped to the shaker as shown in Figure 2. The shaker, which was the vibration source of this experiment, was connected to a waveform generator to create sinusoidal waves similar to ambient vibrations. All testing was performed on an optical table, which was able to isolate our system from unexpected environmental vibrations.

The harvester needed to be calibrated for the use of a broadband system because generated power was very small when the vibration frequency was deviated from the resonant frequency of the device. In Table 3, the resonant frequency of the harvester is shown as a function of the mass attached to the harvester. Figure 3 shows the power output as a function of resonant frequency, ranging from 42 Hz to 103 Hz, for an acceleration of 1 g.

A maximum power of 3.072 mW was harnessed from a vibrational source of 53 Hz. A generally decreasing trend in the output power was found with increasing input frequency. This result agrees with the observation that power magnitude is inversely proportional to input frequency. However, an opposite trend was found in a small frequency region between 42 Hz and 50 Hz. This discrepancy may be a result of overstressing of the piezoelectric material with a large mass, which is

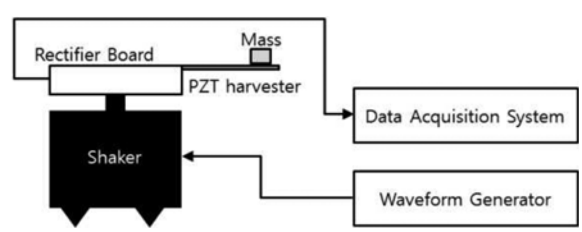

Fig. 2 A schematic of experimental set up shows the piezoelectric harvester connected to the shaker and waveform generator. The shaker mimics environmental vibration using a sinusoidal waveform provided by the waveform generator

Table 3 Tabulation of the resonant frequencies (Hz) of the piezoelectric harvester under different masses and the distances of mass center from the end of the PZT material

Distance from the end of PZT (cm)	Mass placed on harvester (g)						
	0	0.1	0.2	0.3	0.4	0.5	0.6
1.0	103	73	60	55	50	44	42
1.5		78	67	60	53	51	48
2.0		81	74	67	61	58	55
2.5		87	79	73	68	65	61
3.0		91	85	79	75	71	68
3.5		94	90	87	82	79	78
4.0		98	95	92	87	86	86
4.5		100	99	97	95	94	93

inevitable to produce low frequencies. This is a common problem in the design of piezoelectric harvesters. The mass must be large enough to allow the harvester to resonate at low frequencies and create sufficient strain on the material although the piezoelectric material should not be damaged by its own mass.

Four resonant frequencies, 43 Hz, 50 Hz, 60 Hz, and 103 Hz, were tested on the harvester in a series of accelerations from 0.5 g to 1.5 g (Figure 4).

Greater amplitudes were found to produce higher excitation levels and greater power outputs for all four systems. Although further studies are required to fully validate the relationship, this observation agrees with equation (1), which indicates that power magnitude should be proportional to the square of the acceleration magnitude of the input vibrations. In all tested amplitude levels, consistent linear correlations were found between output power and input frequencies of 50 Hz, 60 Hz and 103 Hz. The relationship for the 43 Hz system, however, appeared stronger than the other systems. This behavior may be related to an inability to strain the heavily massed piezoelectric material with relatively small forces.

3.2 Ambient Vibration Testing of Piezoelectric Harvester

When all vibration parameters are known, the energy harvesting system can be designed to resonate at the input frequency. The

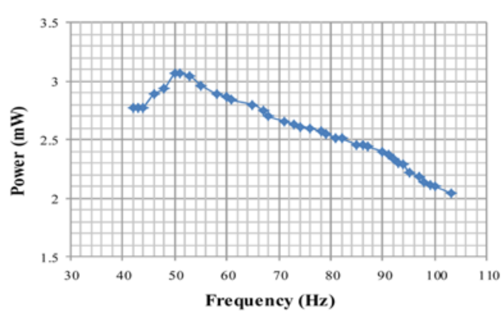

Fig. 3 The output power of the harvester under different resonant frequencies using 1 g acceleration amplitude as the vibration source

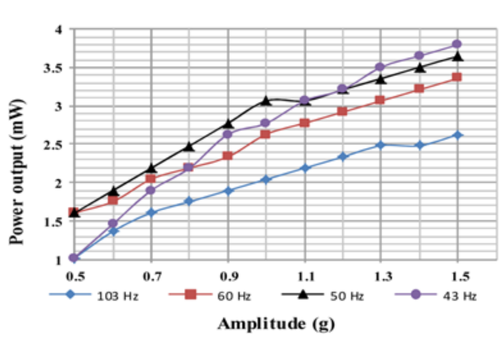

Fig. 4 The output power of the piezoelectric harvester under four resonant frequencies using acceleration ranging from 0.5 g to 1.5 g

Table 4 Output energy of the harvester when placed in vicinity of environmental sources of vibration under normal conditions

Harvester	Window	Train Seat	Machine
Frequency (Hz)	94	42	71
Voltage (V)	1.8	2.1	4.8
Current (mA)	Negligible	Negligible	0.05

frequency of the input vibrations, however, is unknown or unstable in most ambient vibration cases. This section serves to investigate the energy harnessed under ambient vibrations with an unknown vibration spectrum.

Three different experimental vibration sources (residential vibration from windows, transportational vibration from a passenger seat in a train and machinery vibration from a small sized milling machine) were selected. For each case, the harvester was secured to a preselected position in the vicinity of each vibration source. The mass of the harvester was adjusted to maximize the voltage measured by a multimeter and the resonant frequency was identified as the frequency at which the maximum voltage was achieved. Table 4 displays the maximum voltages measured in each of the three vibration conditions.

The non-uniform frequency of the environmental vibrations may result in relatively low power generation and inaccurate calibration of resonant frequency.

4. Discussion

Although we successfully demonstrated the potential of vibration-based piezoelectric energy harvesting system in WSNs, consistent input vibration was found to be crucial for the reliable power generation. Ambient vibration sources, however, do not produce a consistent frequency, and the frequency varies depending on the operating condition and environment. Figure 5 displays the power output of the harvester when the resonant frequency of the energy converter was pre-determined to be 60Hz. This graph shows a gradual decrease in power output as the input frequency diverges from the resonant frequency of the harvester.

When the input vibration frequency was 40 Hz, the generated power was approximately 0.3 mW, which is approximately 10% of the maximum 3 mW output of the system. As the frequency of the input

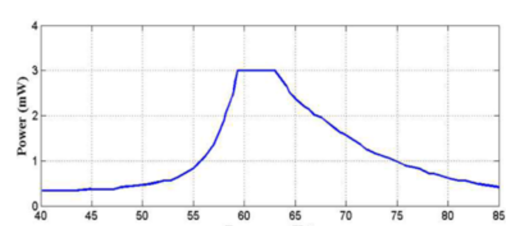

Fig. 5 Plot of the output power produced by the 60 Hz harvester when subjected to varying frequencies by the waveform generator

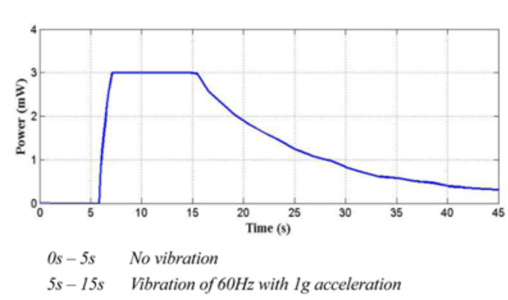

Fig. 6 Plot of the output power produced by the harvester through the period of testing

vibration approached the natural frequency (60 Hz) of the harvester, the output power was observed to exponentially increase. When the frequency of vibration exceeded the natural frequency of the system (60 Hz), power generation dramatically dropped. The power production at 85 Hz was only 13.3% of the maximum power of the harvester around the natural frequency. Although this result indicates that the resonant frequency of the converter needs to be similar to the dominant frequency of the input vibrations for the maximum power generation, this finding is uncommon because ambient vibration is not controllable. Thus, frequently varying ambient vibration may not be suitable for the vibration based energy harvesting system.

Self-tuning mechanism offers a potential solution to optimize the resonant frequency of the converter to match the input vibration. A simple self-tuning harvester where the mass was designed to be adjustable to allow the natural frequency of piezoelectric structure to be tuned. This method may not, however, be directly applicable to sensor nodes with inaccessible or limited-access interiors. An alternative solution for WSNs is to use a combination of different masses, which would provide a wide bandwidth for energy conversion.[15-18]

Because the vibration source is unstable, intermittent, or cyclic in many real cases, the output power may be insufficient for various applications. To find the effect of a cyclic vibration source on the power generation, a simulation of one cycle was conducted for the 60 Hz harvester. The results are plotted in Figure 6.

The harvester was able to generate maximum power within 3 seconds of the energy source activation and was almost fully dissipated within 30 seconds after the removal of the energy source. This result suggests that an energy reservoir or a capacitor may need to be incorporated into the vibration based energy conversion device.

In addition to power generation capacity, it is also important for the converter to provide an AC voltage. Since the AC power is dependent on the magnitude of unstable input vibrations, the AC power output will also be unstable. Consequently, an energy reservoir and voltage regulator or DC-DC converter may be necessary.[19] The power must also be generated at a suitable voltage/current level to reduce the number of voltage level conversions, resulting in undesired energy dissipation. This requirement has been identified as a problem for WSN piezoelectric harvesters. To address this issue, switch-mode electronics can be used to optimize energy conservation by controlling the amount of voltage or electric charge of the piezoelectric device relative to the mechanical input.[20]

Finally, the presence of an energy harvesting device can affect the frequency and amplitude of the vibration source, which will influence the amount of energy that can be extracted. Therefore, the mass of the harvesting device should be kept small relative to the vibrating mass.

5. Conclusion

The PZT piezoelectric harvester has shown considerable potential by generating 3.072 mW when subjected to a vibrational source of 53 Hz with 1 g acceleration. The power output in ambient conditions, however, was found to be much less than expected. This reduction in performance may be due to the unknown and (most likely) unstable operational environment, which is not expected to match the resonant frequency of the system. Design optimization schemes minimizing uncertainties in MEMS processes[21] would be useful for the reliable fabrication of PZT harvesters.[22-25]

Future recommendations include testing the vibration frequency of the surface to which the harvester is affixed and embedding an advanced control system for the enhancement of energy harvesting efficiency.[26] A real time plot can be used to both characterize the actual condition of the vibration source and estimate the viability of the ambient vibration as an energy source.

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