Power Enhancement for Piezoelectric Energy Harvester

Sutrisno W. Ibrahim, and Wahied G. Ali

Abstract—**Piezoelectric energy harvesting technology has received a great attention during the last decade to activate low power microelectronic devices such as wireless sensor nodes (WSN). This paper investigates the necessary conditions to enhance the extracted AC electrical power from the exciting vibration energy using piezoelectric material. The effect of tip mass and its mounting position on maximum power extraction are investigated theoretically and experimentally. The optimal load impedance is also investigated to maximize the output power. The experimental results validated the theoretical and concluded remarks in the paper.**

***Index Terms*—energy harvesting, piezoelectric materials, resonance frequency, impedance matching**

I. Introduction

ENERGY harvesting techniques is a technology to generate electrical power from natural (green) energy sources. The concept of energy harvesting generally relates to the process of using ambient energy, which is converted into electrical energy in order to activate low power electronic devices. The research on power harvesting technology became progressively larger over the last decade to design self-powered electronic devices.

With the advances being made in wireless technology and low power electronics, wireless sensors are being developed and can be placed almost anywhere. Wireless sensor networks are progressively used in many applications such as: structure health monitoring, automation, robotics swarm, and military applications. However, these wireless sensors require their own power supply which in most cases is the conventional electrochemical battery. Once these finite power supplies are discharged, the sensor battery has to be replaced. The task of replacing the battery is tedious and can be very expensive when the sensor is placed in a remote location. These issues can be potentially alleviated through the use of power harvesting devices.

One source of typically wasted energy is an ambient vibration that presents around most of machines and biological systems. This source of energy is ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy and vice versa [1]. In general, there are three mechanisms to harvest the energy from the vibration: electrostatic, electromagnetic and piezoelectric techniques. Piezoelectric materials are perfect candidates for harvesting power from ambient vibration sources, because they can efficiently convert mechanical strain to an electric charge without any additional power and have a simple structure [2], [3].

In general, a piezoelectric energy harvesting can be represented using a schematic depicted in Fig. 1. The mechanical energy (e.g., applied external force or acceleration) is converted into mechanical energy in the host structure. Then, this energy is converted into electrical energy by the use of piezoelectric material, and is finally transferred into electrical form to a storage stage [4]. Therefore, three basic processes are performed: conversion of the input energy into mechanical energy (strain) using a cantilever structure, electromechanical conversion using piezoelectric material, and electrical energy transfer.

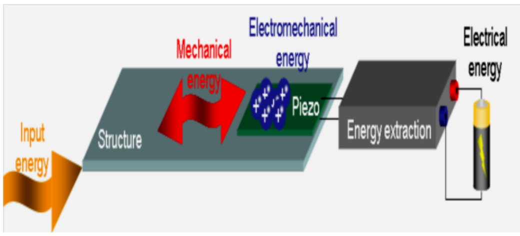

Fig. 1. General schematic of piezoelectric energy harvester [4]

In the literature, several books are recently published in this research domain [5]-[8]. Several review papers are also published in all different aspects concerning energy harvesting technologies [9]-[15]. This paper investigates the necessary conditions to enhance the extracted AC electrical power from the exciting vibration energy using piezoelectric material. The paper is organized as follows: Section II presents the theoretical background and the important considerations to maximize the generated electrical power. Section III describes the experimental setup to carry out the real time results. Section IV discusses the experimental results; while Section V concludes the paper and highlights the future directions of the research.

II. THEORETICAL BACKGROUND

The piezoelectric effect is a direct transformation of mechanical energy into electrical energy. Piezoelectricity was discovered by Jacques Curie and Pierre Curie in 1880 [16]-[18]. They observed that certain crystals respond to pressure by separating electrical charges on opposing faces and named the phenomenon as piezoelectricity. In the

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literature, several design parameters have been investigated to maximize the generated power from mechanical vibration to electrical output using piezoelectric material.

These parameters can be summarized as follows [1], [3]:

- ***Material*** type as PZT, PVFD, Quick-Pack, and PVFD. Material with high quality factor (Q-factor) produces more energy and recently piezoelectric micro fiber composite (MFC) has more efficiency to generate electrical power up to 65% of the input vibration energy.
- ***Geometry***, tapered form produces more energy while the strip form is commonly available in the market.
- ***Thickness***, thin layers produce more energy.
- ***Structure***, bimorph structure doubles the output than unimorph structure.
- ***Loading mode***, d_{31} produces large strain and more output power for small applied forces.
- ***Resonance frequency*** has to be matched with the fundamental vibration frequency.
- ***Electrical connection***, parallel (current source) and series (voltage source).
- ***Fixation***, cantilever produces more strain than simple beam.
- ***Load impedance,*** it has to be matched with the piezoelectric impedance at the operating frequency.

In this paper, the development is focused on the necessary conditions to maximize the AC output power from the piezoelectric harvester using MFC material with fixed dimensions. The piezoelectric harvester is a cantilever with effective length $\boldsymbol{L_b}$ extends from a clamped end structure to a free end with tip mass (***m***) as shown in Fig. 2. Electrodes must be plated onto the piezoelectric material to collect the charge built up as the beam flexes.

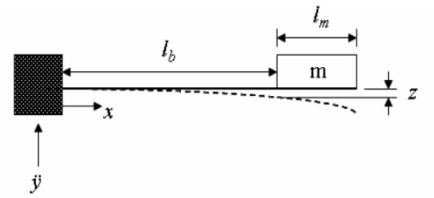

Fig. 2. Piezoelectric cantilever [3]

Williams and Yates developed a generic model based on inertial kinetic energy [19]. The model is a lumped second order dynamic system to relate the input vibration *y(t)* to the output relative displacement *z(t)* as shown in Fig. 3.

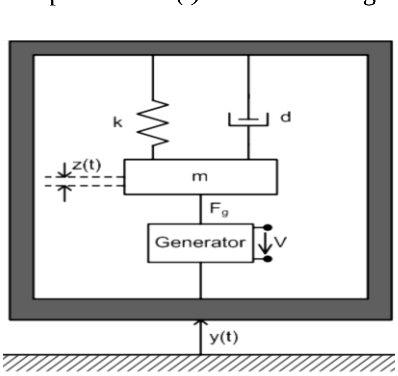

Fig. 3. Dynamic model of vibration-based harvester [19]

By applying D'Almbert's law, the dynamic equation is given by

$$m\,\ddot{z}+d\,\dot{z}+k\,z= -m\,\ddot{y} \qquad (1)$$

Where *y(t)* is the input vibration, *ÿ(t)* is the input acceleration, *z(t)* is the relative displacement of the mass with respect to the vibrating cantilever, *k* is the spring constant (device stiffness), *d* is the total damping (parasitic damping and electrical damping), *m* is the effective mass of cantilever. By taking Laplace transform to compute the transfer function between *z(t)* and the vibration force ($-m\,\ddot{y}$), the resulting transfer function is given by

$$G(s)=\frac{1}{m\,s^2+d\,s+k} \qquad (2)$$

The natural frequency is given by

$$\omega_n=\sqrt{\frac{k}{m}}=\sqrt{\frac{Ywh^3}{4l^3(m_t+0.24\,m_c)}} \qquad (3)$$

Where Y is young's modulus, cantilever dimensions w, h, and l are width, thickness, and length respectively, m_t is the tip mass, and m_c is the cantilever's mass. The total damping factor η (mechanical and electrical) is given by

$$\eta=\frac{d}{2\,m\,\omega_n} \qquad (4)$$

The total quality factor is given by [3], [6]

$$Q=\frac{1}{2\,\eta}=\frac{f_n}{f_{bw}} \qquad (5)$$

The quality factor is inversely proportional to the damping factor and can be computed as the ratio between the resonance frequency (f_n) and the frequency bandwidth (f_{bw}). For a sinusoidal vibration signal ($y(t)= A\sin(\omega t)$), the instantaneous dissipated power (P) within the damper equals the product of the velocity ($\dot{z}$) and the damping force $[d\,(\dot{z})]$. The power is given by [6]

$$P=\frac{m\,\eta\,A^2\left(\frac{\omega}{\omega_n}\right)^3\omega^3}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left[2\eta\,\frac{\omega}{\omega_n}\right]^2} \qquad (6)$$

Where; A is the amplitude of vibration. The maximum power dissipated in the damper occurs at the natural frequency and can be calculated by following formula

$$P_{max}=\frac{m\,A^2\omega_n^3}{4\,\eta} \qquad (7)$$

Where; the peak of input acceleration a is given by $A\omega^2$. Maximum power conversion to electrical domain occurs when mechanical losses equal to damping arising from electrical domain. Therefore, the maximum electrical output

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power equals half the value in equation (7).

$$P_e(max) = \frac{m\,A^2\omega_n^3}{8\,\eta} = \frac{m\,a^2}{8\eta\omega_n} = \frac{m\,a^2 Q}{4\omega_n} \quad (8)$$

The above equation indicates that the maximum power is directly proportional with the effective mass, the input acceleration and the quality factor. Whatever, it is inversely proportional with natural frequency and total damping. The piezoelectric cantilever itself can generate output voltage due to the (mechanical strain) relative displacement (*z(t)*). The strain effect utilizes the deformation of the piezoelectric material to generate positive and negative charges on both sides. The equivalent electrical circuit can be considered as shown in Fig. 4. The piezoelectric harvester has high resistive impedance in Mega Ohm and capacitive value in nano Farad. At resonance, the current source $I_{piezo} = m\,A\omega_n^2$.

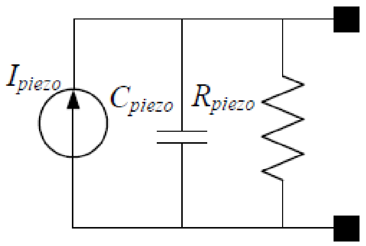

Fig. 4. Equivalent circuit at resonance [6]

The harvester's resistive value could be ignored due to its too high value in mega Ohm, therefore its effective impedance is a capacitive type. This impedance can be computed using the following equation

$$Internal\ Impedance = \frac{1}{\omega_n C_{piezo}} = \frac{1}{2\pi f_n C_{piezo}} \quad (9)$$

The maximum power transfer to the external load occurs when the value of this load is closely matched with the internal impedance.

III. EXPERIMENTAL SETUP

The experimental set-up is shown in Fig. 5; it consists of:

- Amplifier module to generate the vibration signal at different levels and different frequencies ranged from 5 Hz to 60 Hz with incremental step of 1 Hz
- Desktop shaker to generate mechanical vibration
- Cantilever with MFC 8528-P2 harvester module
- Variable impedance module VIM
- NI-PXIe system with DAQ card as a powerful hardware platform
- NI-LabVIEW for monitoring and analyzing the acquired signals

A Micro Fiber Composite (MFC, M-8528-P2 *Smart Material*) was used as piezoelectric harvester with active dimensions of 8.5 cm x 2.8 cm. The MFC is glued on a flex cantilever substrate that is mounted on a shaker. The dimension of the cantilever is 22 cm x 3.5 cm x 0.1 cm. To generate vibration, the shaker is excited by an amplifier module (both shaker and amplifier module are *Smart Material* products). Under exciting vibration, the piezoelectric harvester will produce AC electrical output. Then, the output signal from the harvester is connected to a variable resistive load. NI-PXIe (PC based platform) with DAQ card is used to perform real time measurements.

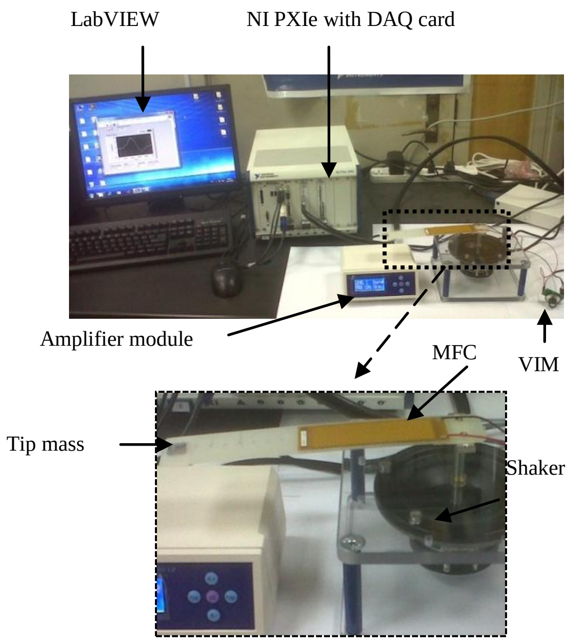

Fig. 5. Experiment set-up

The vibration frequency and its excitation level (amplitude) can be varied to test the performance of the harvester. The peak-to-peak voltage (V_{pp}) or maximum power can be used to evaluate the system performance. The real time monitoring and analysis for the harvested electrical signal is performed using LabVIEW software. The harvesting cantilever has to be selected with high Q-factor to increase the output power. Higher Q-factor indicates a lower rate of energy loss relative to the stored energy. Unfortunately, high Q-factor also means narrow operational frequency bandwidth. The harvester will only produce quite significant power when working under excitation frequency that closely matches with its resonant frequency.

The resonance frequency of the harvesting cantilever under a given set conditions can be identified experimentally by monitoring the peak of output power. The resonance frequency can be changed by adding or removing tip masses. Different tip masses (vary from 1 to 5 gram) are used to investigate their effect to the resonance frequency. The effect of different mounting positions for this tip mass will be investigated also.

The equivalent electrical circuit for a piezoelectric harvester to generate AC electrical output can be represented as described in Section 2. The maximum power transfer happens when the load impedance is closely matched with the harvester's internal impedance. The harvester's internal impedance is a capacitive type and consequently not only depends on MFC characteristics but also the excitation frequency. The harvester resonant frequency will be investigated firstly to achieve optimal frequency excitation. Such experiment using maximum power point tracking (MPPT) method will be performed to

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determine maximum power transfer and its corresponding optimal load. A variable impedance module (VIM, *Smart Material product*) is used as variable resistive load (as potentiometer) to change the electrical load easily. VIM can be varied from 0 to 500 kΩ.

IV. RESULTS AND DISCUSSION

4.1 Resonant frequency without tip mass

The generated AC electrical power from the piezoelectric harvester has been monitoring in real time using LabVIEW software as shown in Fig. 6.

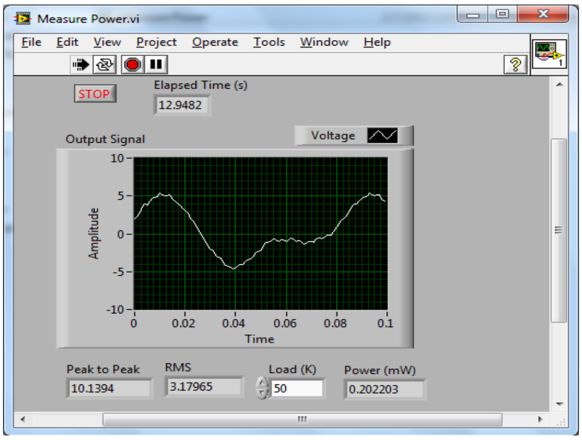

Fig. 6. LabVIEW front panel for power measurements

The resonant frequency under fixed excitation level (level 2) is identified by monitoring the maximum output power as a function of excitation frequency. The excitation frequency from amplifier module varies from 11 to 30 Hz. In this experiment, no tip mass is mounted on the cantilever and the load is fixed to be 50 kΩ. Figure 7 shows the generated power from the harvesting system without tip mass.

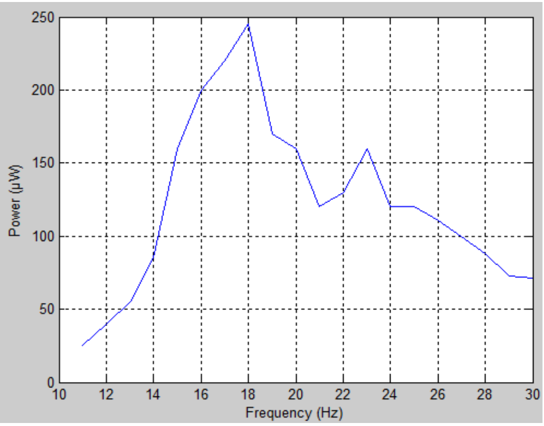

Fig. 7. Generated power without tip mass

It is observed that the resonant frequency of the harvester is 18 Hz at maximum peak of the extracted power. Under this excitation frequency; the output power reaches to the maximum value (250 μW). Another local peak is also observed at 23 Hz with less output power value. This phenomenon is commonly known for physical systems, in which such systems have multiple resonant frequency modes due to its flexible structure.

4.2 *Effect of tip masses*

From equation (3), the resonant frequency is inversely proportional to square root of effective mass. Theoretically, increasing cantilever mass will decrease the resonant frequency (nonlinear characteristics). This theoretical result has been validated by experimental work as shown in Fig. 8.

The additional masses (varied from 1 to 5 gram) were mounted at fixed position 1 cm from the free end of the cantilever with vibration excitation level 2. The resonant frequency shifts to 17 Hz, 15 Hz, 14 Hz, 13 Hz, and 13 Hz respectively for 1, 2, 3, 4 and 5 gram additional tip mass. In real time applications, this method could be used effectively to tune the resonant frequency if the fundamental frequency of vibration source is pre-determined.

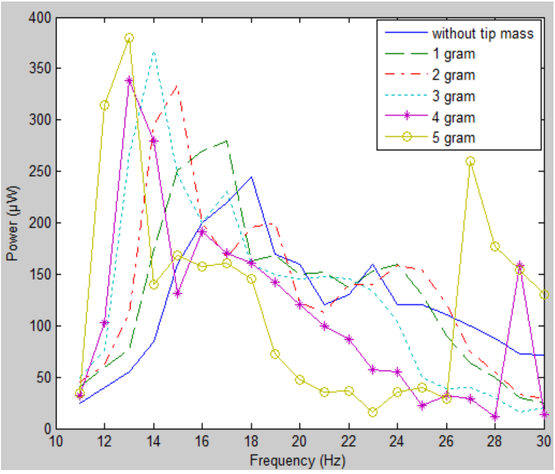

Fig. 8. Generated power with different tip masses

It is observed also that the output power increases as the value of tip mass increases that means; the Q-factor is also increased. This result was expected from equation (8). The output power increases by factor 60% by adding 5 gram tip mass (380 μW) rather than without tip mass (245 μW). As stated before, high Q-factor also means narrow operational frequency bandwidth. Although, with 5 gram additional tip mass; the harvester able to produce maximum power, its frequency bandwidth is too narrow. With resonant frequency at 13 Hz, a slightly deviation from this resonance causes significant degradation in performance of the harvester. TABLE I summarizes the complete results for this experiment.

TABLE I
EXPERIMENT RESULT WITH DIFFERENT TIP MASSES

EXP.	P_{max} (μW)	f_n (Hz)	f_{BW} (Hz)	Q-factor
Without tip mass	245	18	11	1.64
+ 1 gram	280	17	11	1.55
+ 2 gram	334	15	6	2.5
+ 3 gram	368	14	5	2.8
+ 4 gram	338	13	2	6.5
+ 5 gram	380	13	2	6.5

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4.3 Effect of mounting positions for tip mass

Resonant frequency of a cantilever depends on its effective mass rather than its total mass. Two cantilevers with similar material and mass but with different shape or mass density distribution will have distinct resonant frequency. The closer the center of gravity to the free end of the cantilever the greater the effective mass is achieved, hence the lower resonant frequency and more power can be extracted. Fig. 9 shows the experiment results using 3 gram tip mass with different mounting positions on the cantilever at vibration excitation level 2. The tip mass mounting position varies from 1 to 7 cm from the free end of the cantilever. The resonant frequency is 14, 15, 15, and 16.5 Hz respectively for 1, 3, 5, and 7 cm mounting position from the free end.

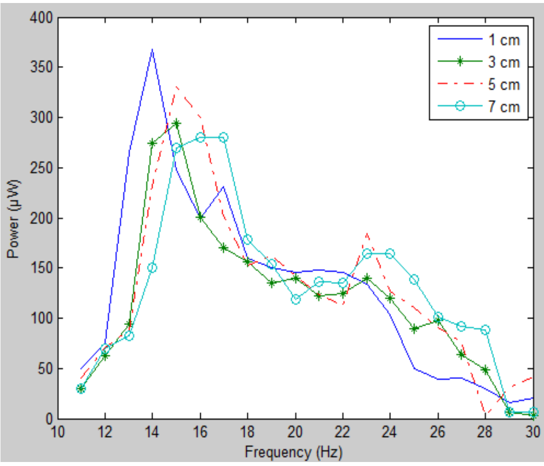

Fig. 9. Generated power with different mounting positions

4.4 Optimal resistive load

As stated before, the maximum power transfer can be extracted when the load impedance is closely matched with the harvester's internal impedance. Due to highest resistive value for piezoelectric material, the internal impedance could be simplified as capacitive type. From the datasheet the internal capacitance for the MFC (M-8528-P2) is 172 nF; this value has been measured also using a high sensitive capacitance meter. To investigate optimal load for the generator, no mass is mounted on the cantilever. The harvester was excited at its resonant frequency 18 Hz. By using equation (9), the internal impedance could be computed as follows:

$$Internal\ Impedance = \\ = \frac{1}{2\ x\ (3.14)\ x\ 18\ x\ (170\ x\ 10^{-9})} \\ = 51.47\ \text{k}\Omega$$

The harvester was predicted to generate maximum output power if the (external) load is closed to the above value as the internal impedance. The variable impedance module (VIM) is set to various values from 0 Ω to 500 kΩ, the extracted output power is shown in Fig. 10. The maximum power is obtained at 50 kΩ, which is closed to the harvester's internal impedance.

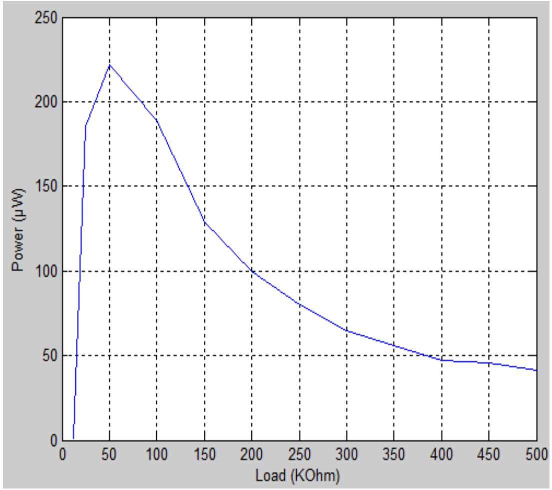

Fig. 10. Output power with different external load

V. Conclusions and Future Directions

Piezoelectric energy harvesting is a promising avenue of research to develop self powered microelectronic devices. Wireless remote monitoring of mechanical structures, low power wireless sensors, and biomedical sensors are strongly candidate for piezoelectric energy harvesting applications. The piezoelectric energy harvester has a limited power and optimization to extract maximum power in the whole stages is necessary to enhance the device performance. The maximum (mechanical/electrical) power transfer depends on piezoelectric material properties and other matching conditions. In this paper, the experimental work validated the theoretical results to enhance the system performance in increasing the output power. The experimental results highlighted the following points:

- Resonance frequency of the harvesting cantilever can be identified experimentally by tracking the maximum extracted electrical power.
- Increasing tip mass will decrease the resonance frequency.
- Output power increases as the value of tip mass increases that means; the Q-factor is also increased.
- After certain limit; increasing tip mass will decrease Q-factor due to damping effect. This phenomenon not yet addressed in this paper.
- The change of tip mass position has a great effect on the effective mass of the harvesting cantilever, and hence its resonance frequency and the output power are also changed.
- Piezoelectric harvester has effective internal impedance as capacitive type which depends on the operating frequency.
- Maximum power transfer to the resistive load occurs at matching condition between harvester's internal impedance and the resistive load.
- For a fixed level of excitation, the output power is inversely proportional to the natural frequency of a harvesting structure and hence it is desirable to operate at the first harmonic (fundamental frequency) within the available vibration spectrum.

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In this paper, resonance frequency is affected by the value of tip mass and its mounting position. In the future, the design of autonomous frequency tracking will be investigated using these parameters to enhance the system performance. In this case, the piezoelectric harvester will be smarter to autonomously adapt its resonance frequency to match the fundamental frequency in the exciting vibration signal. The system performance with capacitive load will also be investigated where the most of wireless sensor nodes are capacitive type loads.

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