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Effect of Rubber Compound Treatment and PTFE Extension Beam on Piezoelectric Energy Harvester Power Density

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ABSTRACT

Due to a number of advantages for small power applications (milliwatts), many researchers have begun to focus on usable energy harvesting from ambience. Over the years, to further expand the applications of vibration energy harvesting technology, many researchers have focused on how to improve the reliability and efficiency of the harvester. This paper presents work on improving piezoelectric energy harvesters based on structural modifications. Two different strategies of structural modification are proposed for optimization by using additional beam structure and additional rubber compound layer on the origin of the piezoelectric beam. This work summarizes the optimum performance of the strategies at a resonance frequency of 50±2 Hz at 0.25g ms-2 of acceleration. The parameters compared among the strategies are resonance frequency, voltage and power output. In general, the structural modification PZT-MER by clamped PTFE cantilever beam at the free end of piezoelectric and rubber compound gives the best power output of 2.87mW compared to PZT-ME (0.72 mW) and PZT-M (22µW).

Keywords: *Piezoelectric, PZT, Structural Modification, Rubber Compound, Vibration Energy, Energy Harvesting.*

Introduction

There has been a significant increase in the research on vibration-based energy harvesting for low power applications in recent years. This is due to smaller electronics applications such as wireless and mobile electronics and

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the demand for better lifespan of batteries. The applications include wireless medical implants [1], electronics applications [2-3], autonomous sensors monitoring [4-8] and equipment for military needs [9]. The trend now is to develop micro power generators [10] or even nano power generator that can harvest energy [11].

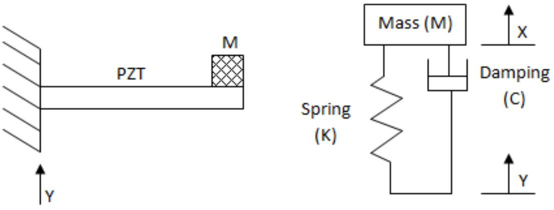
The source of ambient energy can be from vibration, thermal or solar [12]-[14]. Vibration energy harvesters are proposed to generate electricity from the available vibration energy in the environment or from vibrating system such as in machineries, car engines, railways and rotating motors. Vibration energy can be harvested by three transduction techniques namely, electromagnetic [15], electrostatic [16], and piezoelectric [17]. Most reserchers claim that piezoelectric harvester can produce thr highest power output compared to electromagnetic and electrostatic harvester besides its simple structure mechanism [18]-[21]. Previous research on piezoelectric harvester [22]-[23] reported that, piezoelectric harvester should incorporate proof mass at the end of the piezoelectric and at the resonance frequency, it can achieve its optimum power. The proof mass can increase the average strain [24] which causes the power output to increase.

In recent years, there are increasing interests in tuning the piezoelectric harvester to match the resonance frequency from the ambience and a few techniques have reported on the tuning of resonance frequency. One of the techniques is manually tuning on the mechanical method by change the stiffness of the piezoelectric rather than changing the mass of the harvester as reported in [25]-[27]. Meanwhile, there were some researchers [28]-[29] who proposed self- tuning on the mechanical method by developing passive self-tuning harvester. Other researchers have proposed manually tuning the resonance frequency by magnetic force. The stiffness of the piezoelectric can be changed by using the magnetic force as reported in [30]. The self- tuning on the magnetic force was proposed by Zhu et .al. [31] using microcontroller to self- adjust the distance between two magnets by detecting the output voltage of the piezoelectric harvester. Another method to tuning the resonance frequency of the piezoelectric harvester is by altering the stiffness using two piezoelectric actuators [32].

The aims of this study are to tune the resonance frequency of the piezoelectric at 50 Hz and to investigate the effect of structural modification to piezoelectric harvester as to decrease the resonance frequency from the original resonance frequency. The structural modification was proposed with two types of modifications. First, this work proposed a piezoelectric connecting with the PTFE beam at the free end of the piezoelectric as a strategy to decrease the resonant frequency from the origin and give high displacement at the same magnitude of the external excitation. Secondly, natural rubber compound material has the property that can improve the flexibility and best resonates the energy harvester, and currently none of the existing literatures explore into this type of application. This work is proposed by using rubber compound material as to explore the effectiveness of structural modification using rubber compound in improving the performance of the piezoelectric energy harvester.

Mathematical model

Figure 1 (a) shows a diagram of a piezoelectric cantilever beam attached with proof mass at the free end. Figure 1 (b) shows the equivalent of the system described as the equivalent of the lumped spring mass with the external excitation of the vibration.



(a) (b)

Figure 1: (a) Piezoelectric cantilever beam with proof mass and (b) equivalent lumped spring mass

The source of vibration is shown with arrow at the base of the contact point. The basic governing equation of a lumped spring mass can be expressed as:

$$M\ddot{z} + C\dot{z} + Kz = M\ddot{y} \tag{1}$$

Where $z = x - y$ is the net displacement of mass. Equation (1) can also be written in terms of damping constant and natural frequency. A damping factor ζ can be expressed as Equation (2)

$$\lambda = \frac{c}{2\sqrt{mK}} \tag{2}$$

The natural frequency of a spring mass system is defined by Equation (3)

$$\omega_n = \sqrt{\frac{K}{M}} \tag{3}$$

Where K is stiffness, and $K = 3EI/L^3$. E is the modulus of elasticity, I is the moment inertia and L is the length of beam. $I = (1/12)bh^3$ where b and h are the width and thickness of the beam. Equation (4) shows the resonance frequency in terms of

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{4}$$

Resonance frequency for piezoelectric harvester

The resonant frequency of the cantilever beam with a proof mass can be written in terms of *n*th mode given by [23]:

$$f_n = \frac{\alpha_n^{'2}}{2\pi}\frac{1}{I^2}\sqrt{\frac{K}{m_o + m_e}} \tag{5}$$

Where $\alpha_n'^2 = \alpha_n^2\sqrt{0.236/3}$ is the and α_n is the Eigen value of the *n*th mode. The first Eigen value is 1.875 at the first mode. The $K' = (0.986)^2K$. m_o is the effective mass of the piezoelectric cantilever beam and m_e is the mass of the proof mass attached at the end of the piezoelectric cantilever beam. Therefore, the spring constant of a cantilever and resonance frequency can be written as:

$$K^{'} = \frac{(0.986)^2 3EI}{L^3} \tag{6}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K^{'}}{m_o + m_e}} \tag{7}$$

The first mode of the resonance frequency of the PZT-ME can be simplified as the series of lumped spring mass model. The piezoelectric cantilever beam is modeled as $K_1$for the spring constant and K_2 is the spring constant for PTFE plastic part that was extended from the end of the piezoelectric cantilever beam. The proof mass m_e is attached at the free end. The resonance frequency is calculated by the equation:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_{eff}}{m_e}} \tag{8}$$

$$\frac{1}{K_{eff}} = \frac{1}{K_1} + \frac{1}{K_2} \tag{9}$$

Power and voltage output

When piezoelectric mechanically deformed, the electrical charge was produced since the physically piezoelectric material deformed in the presence of an electrical field. The output voltage of the piezoelectric can be measured when a stress is applied on the piezoelectric material. Typically, the stress is the relationship between strain, electrical displacement and electrical field of the piezoelectric. These relations can be given in terms of strain-charge form as follows:

$$S = s^E T \ + d \ E \tag{10}$$

$$D = dT \ + KE \ K^T \tag{11}$$

Where T is the stress (N/m^2), S is the strain (m/m), E is the electrical field (V/m), D is the dielectric displacement (C/m^2), s is the elastic compliance (m^2/N), K is the permittivity dielectric constant (F/m) and d is the piezoelectric coefficient (C/N or m/V).

In PZT-MER, only output voltage is generated due to piezoelectric bimorph part. As shown in Figure 5, the effect of the PTFE beam on the piezoelectric cantilever beam is modeled using forced F_t and momentM_t. F_t is the reaction forced exerted due to inertial force of proof mass and M_t is the moment on the piezoelectric cantilever beam due to this inertial force. The piezoelectric is typically connected to the electrical load resistance to transfer the power generated by the piezoelectric. In this work as in Figure 5, the piezoelectric cantilever beam is modeled as a voltage source with an open circuit voltage V_{OC} and impedance Z_S is connected to the PZTE. Thus, the equivalent circuit of PZTE is a voltage source V_{OC} and impedance Z_S connected with a load resistance Z_L as in Figure 2 and Figure 3.

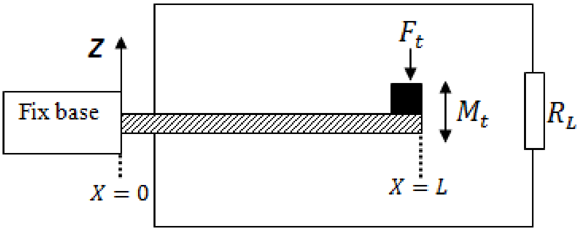


Figure 2: Diagram representing piezoelectric cantilever beam

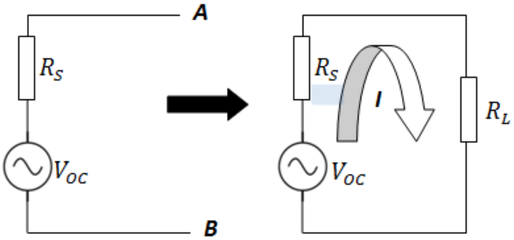


Figure 3: Equivalent electrical circuit of piezoelectric cantilever beam

The current I in the closed circuit can be calculated using Ohm's law:

$$I = \frac{V_{OC}}{R_S + R_L} \tag{12}$$

The average powered transferred to the load resistor can be expressed as [24]:

$$P = I^2 Z_L = \frac{(V_{OC})^2 R_L}{(R_S + R_L)^2} \tag{13}$$

The open circuit voltage across the individual piezoelectric cantilever beam can be calculated as:

$$\begin{aligned} V_{OC} &= -\frac{E_{piezo}}{K}\frac{h_{piezo}}{L_{piezo}}\int_0^{Lpiezo} S(x)dx \\ &= \frac{6E_{piezo}}{K}\frac{h_{piezo}\left(h_{piezo} + h_{ptfe}/2\right)}{L_{piezo}^2\left(L_{piezo} + 3L_{ptfe}\right)}\left(\frac{1}{2}\left(L_{piezo}\right) + L_{ptfe}\right)\alpha \end{aligned} \tag{14}$$

Where E_{piezo} is the elastic modulus of the piezoelectric, K is the dielectric constant of the piezoelectric, L_{piezo} is the length of the piezoelectric, h_{piezo} is the thickness of the piezoelectric, h_{ptfe} is the thickness of *ptfe* material, L_{ptfe} is length of the ptfe material, and α is the deflection of the piezoelectric. According to the maximum power transfer theorem, the maximum power occurs when the load impedance is equal to the source impedance. Therefore, the optimum load resistance for the PZTE is equal to Z_S. The average power transferred to the optimum load resistance can be calculated as:

$$P_{av} = \frac{1}{2} I^2 Z_L = \frac{1}{2}\frac{(V_{OC})^2}{(2Z_S)^2}(Z_S) = \frac{1}{4}\frac{V_{OC}^2}{Z_S} \tag{15}$$

Design and prototype

As shown in Figure 1, the origin of the piezoelectric with magnet at the free end of piezoelectric cantilever beam as a tip mass. The piezoelectric was held by a holder and clamped on the shaker which will produce a vibration. This prototype was aimed for the piezoelectric energy harvesting devices to operate at the 50Hz resonant frequency and 0.25g ms-2 of acceleration. The origin piezoelectric cantilever beam in Figure 1 measured the resonant frequency at 80 Hz which needed to be modified on the structural of the piezoelectric to match the 50Hz on resonant frequency and at the same time maintaining the tip mass. Figure 4 shows 3 different piezoelectric cantilever beams which proposed 2 structural modifications from the origin piezoelectric. This work proposed PZT-ME by connecting the free end of the PZT with the PTFE cantilever material beam and maintaining the same mass to get lower frequency (50 Hz) compared to the origin PZT. The PZT-MER was proposed by putting rubber compound around the PZT and clamped at the free end of PZT with the PTFE cantilever beam.

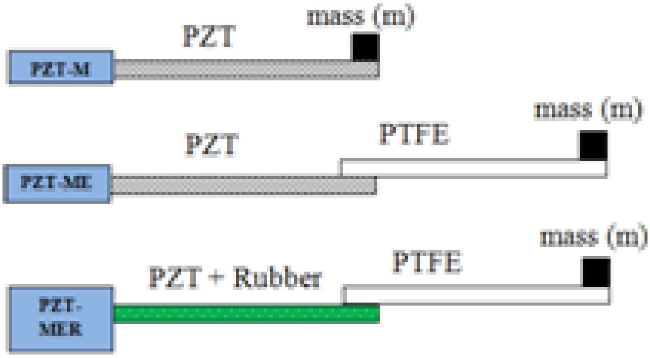


Figure 4: The configuration of the piezoelectric energy harvester.

Experiment

The experimental setup for characterization of the three configuration of piezoelectric energy harvesters (PZT-M, PZT-ME and PZT-MER) is shown in Figure 5. The input frequency of the vibration shaker was set by using function generator, in this case 50 Hz. The function generator was connected to the amplifier before connected to the shaker. The laser vibrometer measured the vibration of the shaker and gave a feedback reading of the vibration to the computer through a DAQ card. The computer was installed with the Labview software which was connected with the DAQ card and the laser vibrometer. Two frequency and acceleration of the vibrations were measured. The shaker was controlled to vibrate at 50Hz at an acceleration of 0.25g ms^{-2}. The resonance frequency of the piezoelectric was determined by measuring the open circuit voltage of the piezoelectric. The open circuit voltage was measured at every frequency change by sweeping the frequency at the function generator from 0 Hz to 100 HZ. The frequency with the highest value of output voltage was identified as the resonance frequency. The power output of the piezoelectric was measured using the voltage across the load resistor R_L as in Figure 2 and Figure 3.

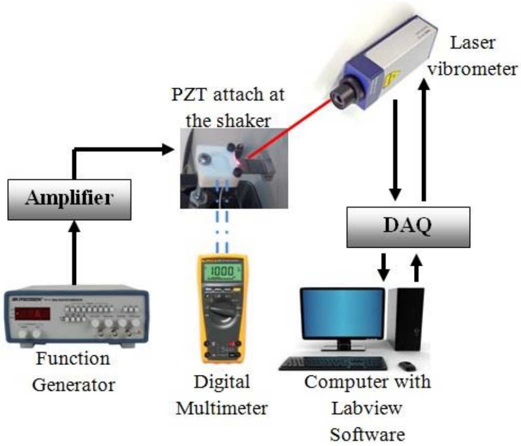


Figure 5: Schematic diagram of the experimental setup

Result and Discussion

Resonance frequency

The frequency responses of all three configurations at acceleration 0.25g ms-2 are shown in Figure 6. The resonant frequencies of PZT-M, PZT-ME and PZT-MER are experimentally obtained at 80 Hz, 50 Hz and 48 Hz. By maintaining the same mass as attached at PZT-M and putting the PTFE cantilever beam at the free end of the PZT, the resonant frequency for PZT-ME and PZT-MER decreases approximately 38% from the PZT-M. The output voltages of the open circuit of PZT-M, PZT-ME and PZT-MER at the resonant frequency are 1.43 V, 5.6 V and 16.6 V. The output voltage of the PZT-MER significantly improved as compared to PZT-M and PZT-ME. The Figure 7 shows the effect of length for extension at the end of the piezoelectric as to reduce the resonance frequency for PZT-M. It clearly shows that by adding more length of the extension, it can give effectiveness in reducing the resonance frequency of the system by maintaining the same mass. This research aims for the 50 Hz of the resonance frequency and it needs to lengthen the extension by putting different material of beam at the end of the PZT-M is 58 mm long.

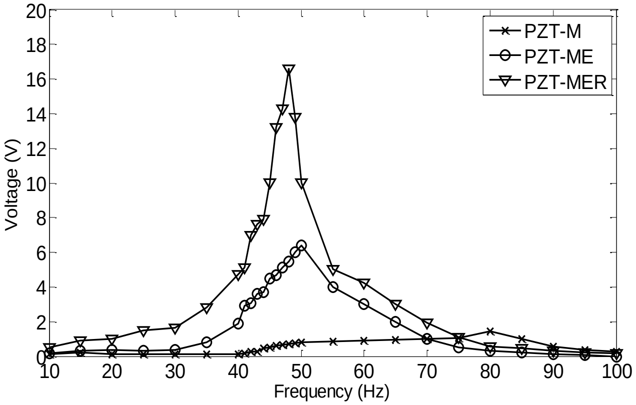


Figure 6: Resonance frequency of PZT-M, PZT-ME and PZT-MER at 0.25g of acceleration.

As the impedance of a piezoelectric energy harvester is a function of frequency, the optimum load resistance and hence optimum power generated are dependent on resonant frequency. Therefore, one more set of experiment was conducted to compare the power output of all three configurations. The results are discussed in the next section.

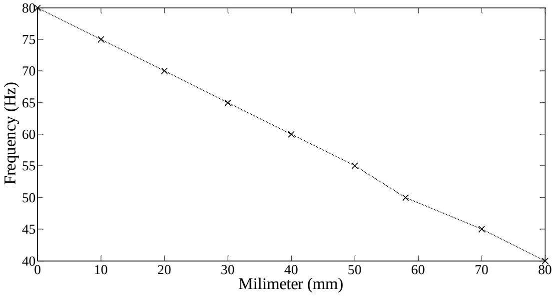


Figure 7: Effect of length of the extension beam at the end of the piezoelectric to reduce the resonance frequency of the PZT-M.

Comparison of the output power

An experiment was conducted for a comparative study for the power output of three configurations (PZT-M, PZT-ME and PZT-MER) at 0.25g ms^{-2} acceleration levels and at each resonant frequency. The maximum power occurs when the load resistance R_L matches with the impedance ofeach configuration. The load resistance R_L was set by using variable resistor and swept from 500 Ω to 150 kΩ. The graph in Figure 8 to Figure 10 shows the output power for each configuration. The maximum power of PZT-M, PZT-ME, PZT-MER at 0.25g is 22 µW, 0.72 mW, and 2.87 mW. The optimum load resistance R_L is 20 kΩ for PZT-M and PZT-ME but 30 kΩ for PZT-MER. It can be seen that, by connecting and clamping with the PTFE cantilever beam as soft spring, the PZT-ME and PZT-MER are able to harvest more energy extremely if compared to PZT-M and at the same time reduce the resonance frequency of the harvester from the origin of PZT-M. The power output of PZT-MER increased 300% from PZT-ME after adding with rubber compound at the piezoelectric cantilever beam and connected with the PTFE cantilever beam. Table 1 shows the summary of the characterization for all the configurations.

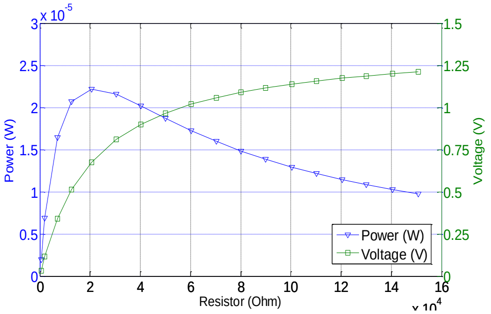


Figure 8: Power output of the configuration piezoelectric energy harvester for PZT-M

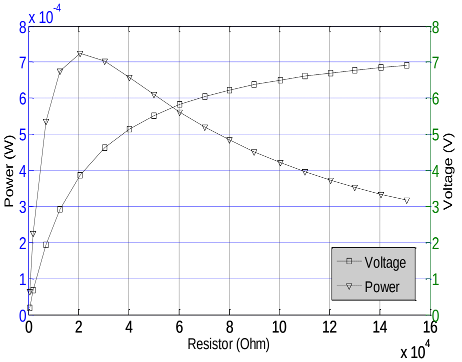


Figure 9: Power output of the configuration piezoelectric energy harvester for PZT-ME

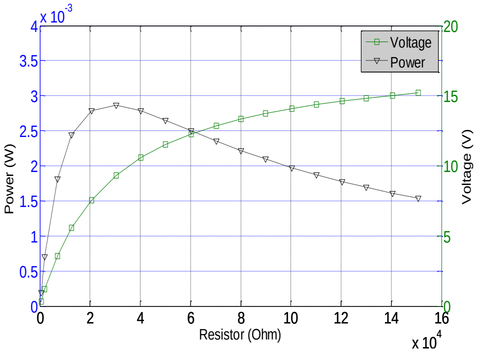


Figure 10: Power output of the configuration piezoelectric energy harvester for PZT-MER

Table 1: Characterization of Three Configurations

Characteristic	**PZT-M**	**PZT-ME**	**PZT-MER**
Proof mass (g)	2.8	2.8	2.8
External beam	No	Yes	Yes
f_n (Hz)	80	50	48
R_L (kΩ)	20	20	30
P (Watt)	22 µW	0.72 mW	2.87 mW

Table 2 shows the performance comparison with others researchers work for the piezoelectric energy harvester at the range of 50 Hz to 60 Hz. It also shows the comparison of the tuning mechanism of the harvester to achieve optimum power output.

Table 2: Performance Comparison of the Energy Harvester

Ref	**Tuning Mechanism**	**Freq (50-60Hz)**	**Acc. (grms)**	**Power (W)**
This work	**Extension+Rubber**	**50±3**	**0.25**	**2.87m**
[37]	Hybrid	50	0.4	5.9m
[38]	Hybrid	55	1	1.6m
[39]	Manual	50	0.06	58µ
[40]	Mems	47	1	51.3n
[41]	Hybrid	55.9	0.2	40.62µ
[42]	Electromagnetic	52	0.06	46µ
[43]	Tuning with mass	50	1	8m

Since all designs have different sizes and volumes, the power density were calculated to compare based on the power output produced divided by the volume of active PZT (power density) and the power output produced divided by the total cubical volume of the overall arrangement (spatial power density). Table 3 shows the comparison of the power density, spatial power density and specific power density performance followed by PZT-M, PZT-ME and PZT-MER.

Table 3: Piezoelectric Power Density, Spatial Power Density and Specific Power Density

Characteristic	**PZT-M**	**PZT-ME**	**PZT-MER**
Power density (mW/cm3)	11	36	140
Spatial power density (mW/cm3)	0.21	3.43	12.14
Specific power density (mW/cm3/g)	0.84	13.72	48.56

Conclusion

This work investigated structural modification strategies to the piezoelectric energy harvester by an addition of PTFE cantilever beam at the free end of the piezoelectric and natural rubber compound at each resonant frequency, 80 Hz to the PZT-M, and 50±2 Hz for the PZT-ME and PZT-MER at 0.25g ms^{-2} of acceleration. The modification of the structure PZT-MER has shown the best performance when compared to the PZT-M and PZT-ME. By applying PTFE cantilever beam as an extension to the PZT and compounding it with the rubber, it made the piezoelectric energy harvester acted as soft spring and gave more displacement which resulted to better power output.

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