Optimized Power Output from Piezoelectric Flexure Element Driven by Low Frequency Vibration

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Abstract— *Energy harvesting is the process of capturing readily available energy and converting into usable energy. Among the many different types of energy harvesting methods, piezoelectric energy harvesting has become popular as piezoelectric materials have the ability to transform mechanical energy into electrical energy. This research is focused on obtaining and optimizing the output of commercially available piezoelectric device which converts mechanical energy into usable electrical energy. Moreover this research is focused on low vibrational frequency levels as random vibration sources in the environment such as buildings, machines, human body, and vehicles as these have low frequency characteristics. The ambient energy in the form of excitations and simple harmonic motions are captured and converted into a vibration through a mechanism. Then this vibration is converted into electrical energy by means of the piezoelectric element. In this research, output power of the piezoelectric energy harvester was measured for different vibration frequencies (0 to 50 Hz range) with different tip masses (1.45 g to 6.45 g range). By considering the experimental data, values for tip mass and vibration frequency are suggested to extract the maximum power output from the energy harvester. These values can be used for energy harvesting from low vibrational frequencies to obtain maximum power output where the vibration frequency of the source is changeable.*

Keywords— *Energy Harvesting, Piezoelectric, Vibration*

I. INTRODUCTION

With the accrescence of power necessities, harvesting energy from ambient energy sources have become popular in the modern world as it allows electronics to operate where there is no conventional power sources, eliminating the need to run wires or make frequent visits to replace batteries.

Among many different types of energy harvesting methods, piezoelectric energy harvesting has become more popular. Piezoelectric elements can be used to capture the ambient energy in the form of mechanical strains and vibrations [1, 2]. Also it can harvest the energy in the radio frequency signals and the energy occurrence due to temperature variation.

Piezoelectric elements are widely used as sensors. Piezoelectric discs are used in acoustic to electrical conversion of acoustic equipment such as guitar pickups. Piezoelectric sensors especially are used with high frequency sound in ultrasonic transducers for medical imaging. Piezoelectric elements are also used in the detection and generation of sonar waves. And after late 1990s piezoelectric energy harvesting has been investigated and started developing piezoelectric energy harvesters.

This research is focused on optimizing the output of commercially available piezoelectric energy harvester (Volture V25W). This type of piezoelectric energy harvesters convert wasted mechanical vibrations into usable electrical energy. To calibrate this piezoelectric element, a specific method is used to generate vibrations with known frequencies. Moreover this paper explores the variation in output power related to source vibrations and describes how to find suitable frequency for the piezoelectric energy harvester with the compatible tip mass at low frequency levels (0-50 Hz).

II. BACKGROUND AND THEORY

Piezoelectric effect is the ability to generate electrical power when certain materials are mechanically stressed. This effect can be found in several materials such as ceramics and polymers. Non-symmetrically arranged atomics in crystalline units causes the crystals to act as dipoles. If these dipoles can be arranged symmetrically and with a higher dielectric distance, it is possible to gain a considerable electrical output. In piezoelectric materials, this dielectric distance can be increased by applying a mechanical stress on it.

Polyvinylidene Difluoride (PVDF) is a polymer that consist out of long chains with the repeating monomer [CH_2=CF_2]. Hydrogen atoms and fluorine atoms in this polymer chain are partially charged as positive and negative relatively, regard to carbon atoms [5, 7-8]. When mechanical stress is applied, these chargers develop a dielectric distance in between positive and negative charges. The electric field developed due to mechanical stress is called piezoelectricity.

Polymers has lower piezoelectric strain constant compared to ceramics. But the voltage constant of polymers are higher than the voltage constant of ceramics such as Lead Zirconate Titanate (PZT). Moreover polymers are flexible than ceramics and therefore polymers are preferable in sensors and energy harvesting applications.

Piezoelectric properties of a material can be characterized by considering the mechanical and electrical behaviour. The mechanical characteristic can be represented by strain constant and the electrical characteristic can be represented by voltage constant. After applying a stress on the piezoelectric material it induces an electric field which will gradually become to zero. Therefore it is necessary to have a variation of stress to continue the output.

A. Vibration characteristic of Piezoelectric element

This research is based on optimizing the power output of commercially available piezoelectric energy harvesting element. This piezoelectric element can be considered as an Euler–Bernoulli beam. In Euler–Bernoulli beams the deformation due to shear across the section is not accounted. The Euler-Bernoulli of slender, isotropic, homogeneous beams of constant cross-section under an applied transverse load is given by,

$$EI\frac{\mathrm{d}^4\omega(x)}{\mathrm{d}x^4} = q(x) \tag{1}$$

Where *E* is the Young's modulus, *I* is the area moment of inertia of the cross-section, applied transverse load *q(x)* and *ω(x)* is the deflection of the neutral axis of the beam [6].

B. Mathematical representation of piezoelectric effect

Piezoelectricity is a combined effect of electrical and mechanical behavior of a material. Electrical behavior can be represented by,

$$D = \varepsilon E \tag{2}$$

Where *D* is the electric charge density displacement, *ε* is permittivity and is electric field strength. The mechanical behaviour can be represented by means of Hooke's low as,

$$S = sT \tag{3}$$

Where *S* is strain, *s* is compliance and *T* is stress.

Electrical and mechanical characteristic of the piezoelectric effect can be combined by coupling the Eq. 2 and Eq. 3.

$$S = sT + \mathrm{d}^t E \tag{4}$$

$$D = \varepsilon E + \mathrm{d}T \tag{5}$$

These two equations can be represented in matrix form as,

$$[S] = \left[s^E\right][T] + \left[\mathrm{d}^t\right][E] \tag{6}$$

$$[D] = [d][T] + \left[\varepsilon^T\right][E] \tag{7}$$

Where [*d*] is the matrix for the direct piezoelectric effect and [d^t] is the matrix for the converse piezoelectric effect [4].

General matrix representation for piezoelectric effect is implemented by considering three-dimensional geometry and calculations become more complicated. Therefore several approximations are done to simplify the general matrix according to the application.

As the piezoelectric element is assumed to be an Euler–Bernoulli beam, the general piezoelectric matrix can be reduced by assuming it as a thin beam. For thin beams, the stress components other than the one-dimensional bending stress *T*1 are negligible [3]. Therefore that the piezoelectric matrix becomes,

$$\begin{bmatrix} S_1 \\ D_3 \end{bmatrix} = \begin{bmatrix} s_{11}^E & d_{31} \\ d_{31} & \varepsilon_{33}^T \end{bmatrix} \begin{bmatrix} T_1 \\ E_3 \end{bmatrix} \tag{8}$$

III. PROBLEM STATEMENT

Piezoelectric elements can transform vibrational energy into electrical energy. Transformation of vibrational energy into electrical energy requires a good coupling between the vibration source and the piezoelectric element in order to gain the maximum electrical power output. The best output power can be obtained by matching the natural frequency of the piezoelectric element and the frequency of the vibration source. For sources with low vibration frequencies, it is required to tune the piezoelectric element into a low natural frequency by adding an appropriate tip mass.

Although a maximum power output can be obtained by matching the vibration and natural frequency, the maximum of the maximum power outputs occurs in a specific vibration frequency and a specific tip mass value due to the piezoelectric behaviour of the element.

This research is focused on finding the vibration frequencies and the tip masses which gives the best power output from the commercially available piezoelectric energy harvesting element.

IV. PROPOSED SOLUTION AND ANALYSIS

A. Model to apply vibration for piezoelectric element

Piezoelectric energy harvester was required to vibrate with known frequencies for calibration of the element. For that a vibration generator was implemented by means of DC motor. A plastic gear wheel was connected to the rotor shaft of DC motor and tachometer was used to measure the rotating speed of the motor in rpm.

Piezoelectric energy harvester was clamped to a fixed point and its end point was vibrated by plastic gear wheel. This arrangement is shown in Fig. 1.

When the rotating speed of the motor is known in revolution per minute, Vibration frequency of the piezoelectric element can be obtained by Eq. 9.

$$Vibrational\ \ frequency = \frac{Motor\ \ speed\ \ (rpm)\ \times\ Number\ \ of\ \ tooth\ \ in\ \ wheel}{60} \tag{9}$$

B. Calibration of piezoelectric energy harvester

Piezoelectric energy harvester was connected to a resistive load and output voltage across the resistive load was measured for different tip masses and different frequencies. Vibrating frequency of the piezoelectric element can be changed by varying the speed of the DC motor. Also the natural frequency of piezoelectric element can be changed by adding a tip mass at the end point of the piezoelectric element. The piezoelectric energy harvester with an attached tip mass is shown in Fig. 2.

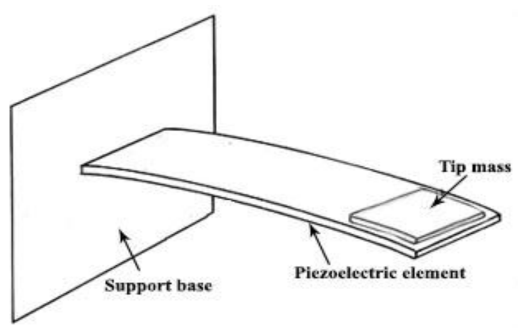

Fig. 1. Model for vibration generation and applied to piezoelectric element

This research is focused on, calibration of the piezoelectric energy harvester for 0 Hz to 50 Hz frequency range and 1.45 g to 6.45 g tip mass range. The output voltage was measured and observed by multi meter and oscilloscope for various tip masses at different frequencies.

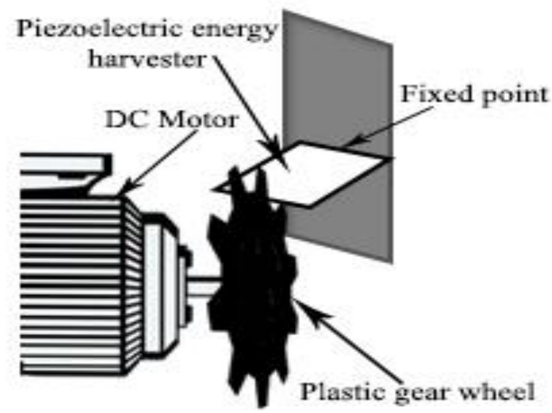

Fig. 2. Piezoelectric energy harvester loaded with a tip mass

C. Result Analysis

Using mechanical vibration system, output power was measured for different frequencies by adding various tip masses. For each tip mass, a maximum output power was observed at the resonance frequency. The resonance frequency for each tip mass was obtained for the affordable frequency range by using the curves generated by curve fitting tool in MATLAB. These resonance frequencies for relevant tip masses can be used to obtain the maximum power output. Obtained power vs. frequency curves for different tip masses are shown in Fig. 3.

Then final result is obtained as a Fourier equation.

$$\begin{aligned} f(x) = {} & a0 + a1*\cos(x*w) + b1*\sin(x*w) + a2*\cos(2*x*w) \\ & + b2*\sin(2*x*w) + a3*\cos(3*x*w) + b3*\sin(3*x*w) \\ & + a4*\cos(4*x*w) + b4*\sin(4*x*w) \end{aligned} \tag{10}$$

Where *f(x)* is the output power generated by piezoelectric energy harvester, *x* is the vibration frequency and *a0*, *a1*, *a2*, *a3*, *a4*, *b1*, *b2*, *b3*, *b4* and *w* are constants which are depending on vibration frequency, tip mass and tip to tip displacement.

Obtained maximum output power for various tip masses at different frequencies are tabulated in Table I. From the values shown in Table I, the frequency of various tip masses for maximum power output was then obtained for an optimum power gain from changeable vibration frequency sources.

Moreover, after analysing the experimental data, an optimal output power of 2.70 mW is observed at 37.3 Hz vibration frequency for 4.45 g tip mass.

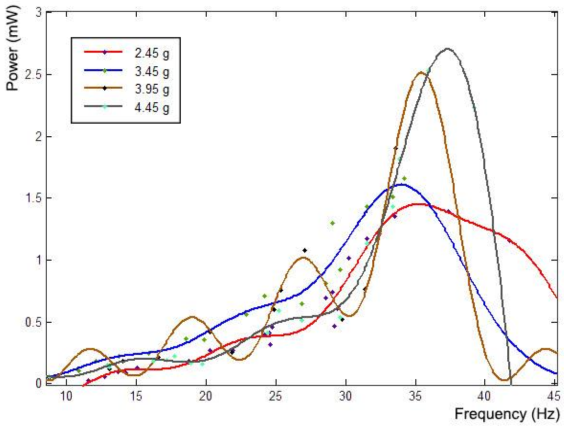

Fig. 3. Harvested power versus frequency for four different tip masses

Table 1. Maximum output power for various tip masses at different frequencies

Tip Mass (g)	**Frequency (Hz)**	**Power (mW)**
1.45	36.6	0.24
1.95	36.8	0.77
2.45	35.2	1.45
2.95	42.9	0.53
3.45	34.0	1.61
3.95	35.4	2.51
4.45	37.3	2.70
4.95	32.0	0.45
5.45	31.4	0.85
5.95	46.6	0.73
6.45	31.4	1.19

IV. CONCLUSION

Various types of commercially available piezoelectric energy harvesters are used for different type of applications to harvest the ambient energy of waste mechanical vibrations. In all those applications, the output of energy harvester depends on the vibration frequency, tip mass and amplitude of the vibration. This research is focused on optimizing the power output of piezoelectric energy harvester by calibrating it based on above mentioned factors.

Output power of the piezoelectric energy harvester was measured for different vibration frequencies (0 to 50 Hz range) with different tip masses (1.45 g to 6.45 g range). By considering the experimental data, values for tip mass and vibration frequency are suggested to extract the maximum power output from the energy harvester. These values can be used for energy harvesting from low vibrational frequencies to obtain maximum power output where the vibration frequency of the source is changeable.

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