# Acoustic Energy Harvesting Using Piezoelectric Generator for Low Frequency Sound Waves Energy Conversion

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***Abstract* - The applications of electronic devices with low power consumption, such as wireless sensor network and electronic communication devices, are rapidly increasing. Thus, utilizing environmental energy as an alternative to electrochemical battery, which has a finite lifespan, can be a great advantage to these electronic devices. Harvesting environmental energy, such as solar, thermal, wind flow, water current, and raindrops, has attracted increasing research interest in the field of energy harvesting. In this paper, harvesting sound energy in the form of pressure waves is investigated as an alternative to existing energy harvesting methods. In the experimental work, a piezoelectric generator lead zirconate titanate (PZT-5A) cantilever type is used to extract sound energy from the loudspeaker from various distances and then to convert this energy into electrical energy. A direct piezoelectric effect operating in 31 coupling mode is used. The maximum voltage generated by the piezoelectric generator occurs when its resonant frequency is operating near the frequency of sound. An analytical method with an appropriate equation is used to determine the resonant frequency and is then validated using the experimental result. The result shows that the maximum output voltage of 26.7 mV$_{rms}$ was obtained with the sound intensity of 78.6 dB at resonant frequency of 62 Hz at 1 cm distance in the first mode. In the second mode, the maximum output voltage of 91 mV$_{rms}$ was obtained with the sound intensity of 102.6 dB at resonant frequency of 374 Hz at 1 cm distance which is larger than that of the first mode. However, for both modes, voltage decreases as distance increases.***

**Keyword- sound energy, piezoelectric generator, cantilever, resonant frequency**

## I. INTRODUCTION

In energy harvesting technology, extracting unused or wasted energy from our environment and then converting such energy into usable energy has received considerable research interest. Harvesting energy from thermal [1-3], solar [4,5], radio frequency [6], wind [7,8] and mechanical vibration [9-12], which are environmental energy sources, has been investigated with regard to the use of these sources in powering low consumption electronic devices such as wireless sensor, portable electronics, and electronic communication devices. In addition, for wireless sensor networks, battery replacement is extremely challenging because of the remote locations of a large number of sensors, resulting in higher maintenance cost.

Sound energy is a ubiquitous, free, and sustainable energy source; thus, effectively extracting and converting this energy into electrical energy can be beneficial. Sound waves carry energy that can cause some elements to vibrate. With sufficient energy, sound waves can deform the structures of some devices. Liu et al. [13] developed an acoustic energy harvester using an electromechanical Helmholtz resonator. The conversion of acoustic energy into electrical energy was achieved via piezoelectric transduction in the diaphragm of the resonator. The experimental results indicated that approximately 30 mW of output power was harvested for an incident sound pressure level of 160 dB using a flyback converter. Horowitz et al. [14] introduced a micro-machined acoustic energy harvester using a Helmholtz resonator with a piezoelectric diaphragm. An output power density of 0.34 $\mu$W/cm$^2$ was obtained for an acoustic input of 149 dB. Under improved fabrication, acoustic energy harvesting could potentially achieve a power density of 250 $\mu$W/cm$^2$ at 149 dB. Kim et al. [15] also used a Helmholtz resonator with electromagnetic power generators driven by acoustic pressure to harvest airflow and aeroacoustic energy. An output voltage of 4 mV was measured with an input pressure of 0.2 kPa and a 140 dB sound pressure level at 1.4 kHz. Li [16] proposed an acoustic energy harvesting mechanism using a quarter-wavelength straight-tube resonator with multiple piezoelectric beams. Polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT) beams were used to harvest acoustic energy at 146 Hz and 199 Hz. With the incident wave of 100 dB at f = 146 Hz, the single PVDF beam near the tube inlet generated 0.105 V, which corresponds to 55.6 nW. For the PZT beam, the maximum output voltage and power were 1.433V and 0.193 mW at f = 199 Hz, respectively.

Electromagnetic [17-19], electrostatic [20-22], and piezoelectric [23-25] generator types are commonly used to convert mechanical vibration into electricity in energy harvesting applications. Among the three generators, piezoelectric generators offer great advantages, such as higher output voltage, higher efficiency, small size, and simple structure, compared to electrostatic and electromagnetic generators. **Table 1** summarizes the features of these three generators in terms of maximum energy density [11,12]. However, some limitations exist when a device is integrated into a micro system as well as in the material selection for piezoelectric.

| Type | Energy density (mJ cm$^{-3}$) | Equation | Assumptions |
|---|---|---|---|
| Piezoelectric | 35.4 | $(1/2)\sigma_y^2 k^2/2c$ | PZT 5 H |
| Electromagnetic | 24.8 | $(1/2)B^2/\mu_0$ | 0.25 T |
| Electrostatic | 4 | $(1/2)\varepsilon_0 E^2$ | $3 \times 10^7$ V m$^{-1}$ |

Table 1. Summary of the maximum energy of the three types of vibration transducers

## II. PIEZOELECTRICITY

The piezoelectric effect was discovered by Pierre and Jacques Curie in 1880. They found that a number of materials, such as crystals and certain ceramic, can produce an electrical potential when mechanical stress is applied. The piezoelectric effect is classified into two types. The first is the direct piezoelectric effect in which a material tends to transform mechanical strain into electrical charge. In this condition, this material can act as a sensor. The second effect is called the converse effect wherein electrical potential is converted into mechanical strain and reacts as an actuator. In the field of energy harvesting, numerous researchers pay significant attention to the performance of piezoelectric materials in the conversion of mechanical vibration into electrical energy. PZT, PVDF and macro-fber composite (MFC) [26] are the piezoelectric materials commonly used for piezoelectric power generation. Piezoelectric generators typically work in two modes of operation called 33 mode as shown in **Fig. 1(a)** and 31 mode as shown in **Fig. 1(b).** In the 33 mode, force is applied in the same direction as the poling direction, such as the compression of a piezoelectric material. In the 31 mode, lateral force is applied in the direction perpendicular to the poling direction. The 31 mode is the most commonly used coupling mode although it has a lower coupling coefficient than the 33 mode [27]. A piezoelectric cantilever structure usually operates in the 31 mode because the lateral stress on the beam surface is easily coupled to the piezoelectric materials deposited on the beam.

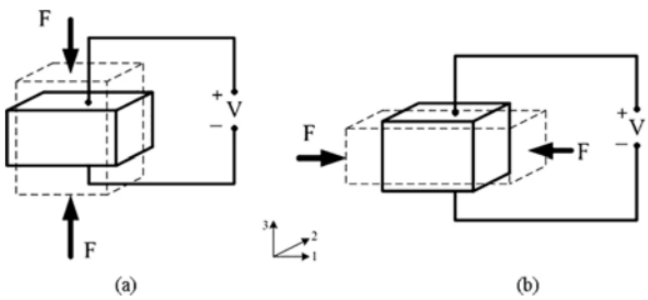


Fig. 1. Piezoelectric generator in (a) 33 mode and (b) 31 mode

The constitutive equations used to describe the mechanical and electrical behaviors of piezoelectric material under direct and converse piezoelectric effects are as follows:

$$\{S\} = [s^E]\{T\} + [d]^t\{E\} \quad (1)$$

$$\{D\} = [d]\{T\} + [\varepsilon^T]\{E\} \quad (2)$$

where {S} is the strain vector, {T} is the stress vector, {D} is the electrical displacement vector, {E} is the electric field vector, $[s^E]$ is the matrix of elastic coefficient at constant electric field strength, $[d]^t$ is the matrix of piezoelectric strain coefficient, and $[\varepsilon^T]$ is the dielectric constant matrix evaluated at constant stress. Note that these equations represent two mechanical and two electrical variables.

## III. ANALYSIS OF RESONANT FREQUENCY OF PIEZOELECTIC CANTILEVER TYPE

The resonant frequency is the main parameter affecting the efficiency of a piezoelectric cantilever in converting mechanical energy into electrical energy. Maximum output power is achieved when the resonant frequency of the piezoelectric cantilever matches the environmental vibration frequency. The basic equation for resonant frequency is shown below [28, 29]:

$$f_r = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{K}{m_e}} \tag{3}$$

where $f_r$ is the resonant frequency, $\omega$ is the angular frequency, $K$ is the spring constant at the tip of the cantilever, and $m_e$ is the effective mass of the cantilever.

For a cantilever without proof mass, the resonant frequency equation is expressed in terms of bending modulus per unit width, and is expressed as [29, 30, 31]:

$$f_n = \frac{v_n^2}{2\pi l^2}\sqrt{\frac{E_o}{m}} \tag{4}$$

where $f_n$ is the $n_{th}$ mode resonant frequency, $v_n$ the nth mode eigenvalue, $l$ is a length of the cantilever and m is the mass per unit length of the cantilever beam.

For a bimorph laminated composite cantilever, $E_o$, which is the function of the Young's moduli of the two materials, is expressed as:

$$E_o = \frac{2E_p t_p^3}{3} + E_p t_s t_p^2 + \frac{E_p t_s^2 t_p}{2} + \frac{t_s^3 E_s}{12} \tag{5}$$

where $Ep$ is the Young modulus of PZT, Es is the Young modulus of brass, and $tp$ and $ts$ are the thicknesses of PZT and brass, respectively.

The mass per unit area $m$ is calculated from the thicknesses and densities, $\rho_p$ and $\rho_s$, of the two materials, and is given by:

$$m = 2\rho_p t_p + \rho_s t_s \tag{6}$$

## IV. EXPERIMENTAL SETUP

Most previous studies focused on harvesting acoustic energy in a range of kHz to MHz. However, sound waves, which exist in a lower frequency level, can be used if the technique to convert sound energy into electricity is developed. Therefore, investigating the mechanism behind sound wave energy harvesting is necessary to harvest low frequency sound energy.

A sound wave converter extracts sound wave energy from the loudspeaker and converts it into electricity. In this study, PZT 5A piezoelectric bimorph cantilever, shown in **Fig. 2,** is used as a sound wave energy converter. PZT 5A type can generate the highest output power among all types of converters, including PZT-5H and PVDH [32]. As shown in **Fig. 3**, the PZT 5A bimorph cantilever is placed under the loudspeaker to harvest sound energy from the loudspeaker. The function generator is used to generate the sound frequency and its amplitude from the speaker. When the generated sound wave from the motion of the diaphragm in the loudspeaker is applied to the piezoelectric cantilever, a pressure wave is produced that hits the piezoelectric cantilever. Sufficient energy from this generated sound can deform the piezoelectric cantilever and can generate electricity. This electricity, which is in the form of voltage signal, is measured using an oscilloscope.

To verify the resonant frequency of the piezoelectric cantilever, the frequency of the sound wave used is increased gradually from 50Hz to 70Hz for the first mode, and from 360Hz to 390 Hz for the second mode. During resonance, the maximum conversion produces the highest voltage as a result of the piezoelectric effect. In the succeeding experiment, the effect of the distance between the sound source and the piezoelectric during resonance is investigated.

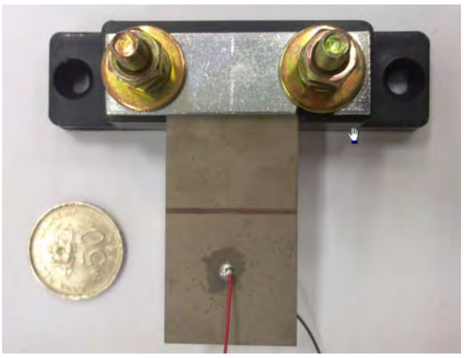

Fig. 2. PZT 5A bimorph cantilever

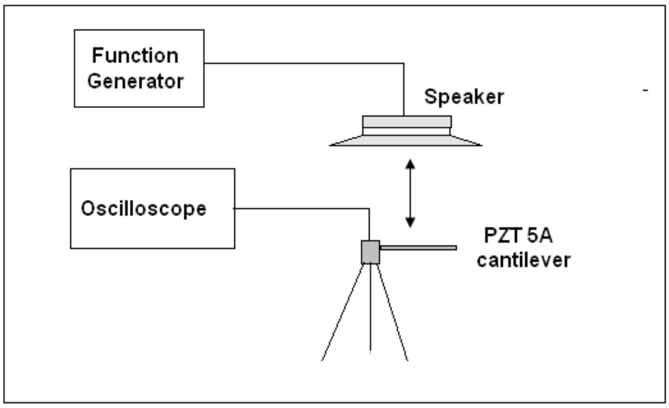


Fig. 3. Schematic of the experimental setup

## V. RESULT AND DISCUSSION

Maximum efficiency in converting vibration energy to electrical energy is achieved when the resonant frequency of PZT 5A matches the sound frequency. The resonant frequency of the two modes under various distances of the PZT 5A is thus determined using an analytical method with Equations (4),(5), and (6).

| **Distance (cm)** | **Resonant Frequency (Hz)** | | **Sound Intensity (dB)** | **Output Voltage ($mV_{rms}$)** |
|---|---|---|---|---|
| | **Analytical** | **Experimental** | | |
| 1 | 55.1 | 62 | 78.6 | 26.7 |
| 3 | 55.1 | 62 | 75.6 | 13.3 |
| 5 | 55.1 | 69 | 74.0 | 8.7 |

Table 2. Resonant frequency in the first mode

In this section, the resonant frequencies obtained from the analytical method are 55.1 Hz and 369 Hz in the first and second modes, respectively. In the first mode, as shown in **Table 2**, the resonant frequencies obtained are 62 Hz, 62 Hz, and 69 Hz at 1, 3, and 5 cm, respectively. In the second mode, as shown in **Table 3**, the resonant frequencies occur at 374, 375, and 376 Hz at 1, 3, and 5 cm, respectively, which are close to the frequencies obtained using the analytical method for both modes.

| **Distance (cm)** | **Resonant Frequency (Hz)** | | **Sound Intensity (dB)** | **Output Voltage ($mV_{rms}$)** |
|---|---|---|---|---|
| | **Analytical** | **Experimental** | | |
| 1 | 369 | 374 | 202.6 | 91.0 |
| 3 | 369 | 375 | 99.6 | 55.7 |
| 5 | 369 | 376 | 95.6 | 30.0 |

Table 3. Resonant frequency in the second mode

Sound intensity is measured at different distances, and the results are 78.6 dB at 1cm, 75.6 dB at 3 cm, and 74 dB at 5 cm in the first mode. In the second mode, the sound intensities obtained are 102.6 dB at 1cm, 99.6 dB at 3 cm, and 95.6 dB at 5 cm. These results show that when the piezoelectric cantilever is placed near the sound source, the pressure gradient of the sound wave is at maximum; thus, for both modes, sound intensity increases as the distance decreases.

In case of voltage, the output voltage obtained from the experiment shows that at the resonant frequency of each state, 26.7 mV rms at 1cm, 13.3 mV rms at 3 cm, and 8.7 mV rms at 5 cm are produced in the first mode, as shown in **Fig. 4**. **Fig. 5** shows that in the second mode, the voltages produced are 91 mV rms at 1cm, 55.7 mV at 3 cm, and 30 mV at 5cm, which are higher than those produced in the first mode. When the piezoelectric cantilever is placed near the speaker, the pressure gradient and frequency of the sound wave are hi gher; thus, a considerable amount of energy is applied to increase the deformation of the piezoelectric cantilever. As a result, maximum voltage is produced by the piezoelectric.

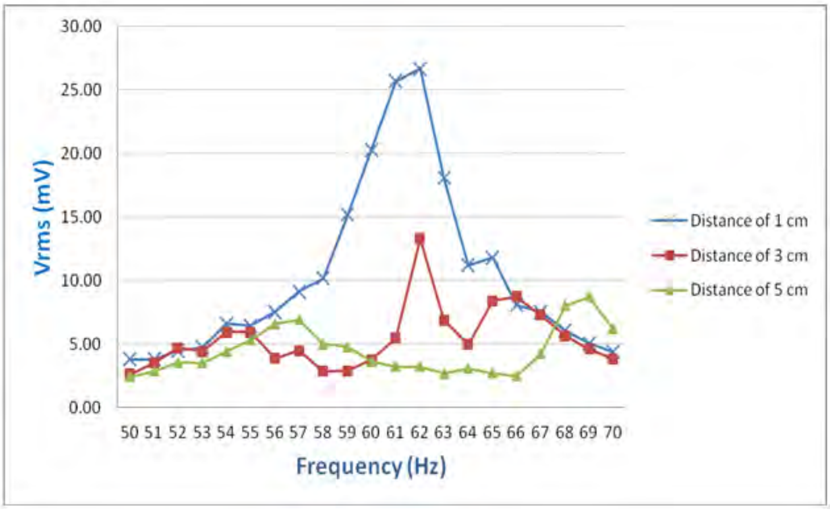


Fig. 4. Relationship between frequency and output voltage in the first mode

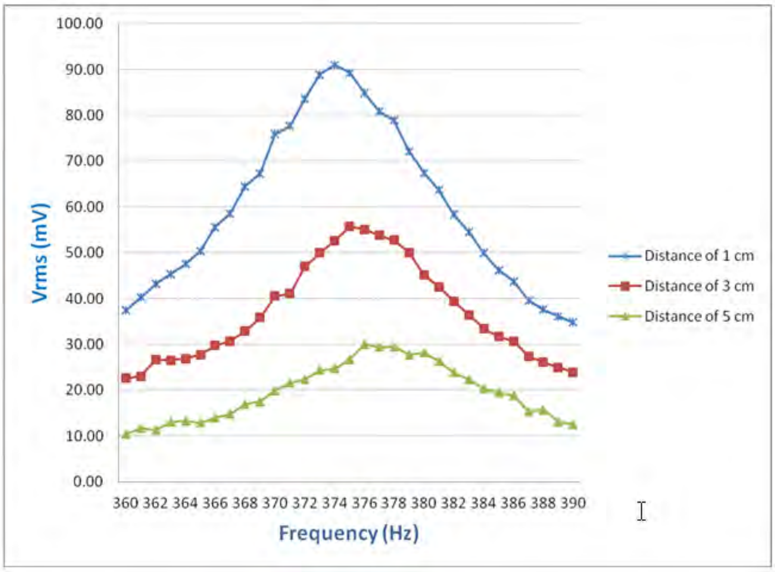


Fig. 5. Relationship between frequency and output voltage in the second mode

## VI. CONCLUSION

In this study, a novel sound wave energy harvesting mechanism using a PZT 5A bimorph cantilever and the sound wave generated by a loudspeaker is proposed. Sound intensity is an important parameter to effectively extract and convert energy using a piezoelectric cantilever. At resonant frequency, compared to the first mode, the second mode has more energy carried by the sound waves, particularly at the nearest distance, as well as has higher frequency, which deforms the piezoelectric cantilever and increases voltage production. Moreover, results show that less voltage is produced as distance increases. This study therefore shows that the proposed technique used to harvest sound wave energy is relevant and has great potential in terms of converting free energy into useful energy.


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