The energy harvester investigation in exercising by using the piezoelectric effect

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Abstract
Energy is important in everyday human life, for that reason, energy harvesting is one of the most important issues. Many countries have aging societies, exercise is promoted to keep people in good health in old age. This work focused on an integration of the energy harvesting and exercise. Therefore, this work was aimed at producing electrical energy from exercise shoes by using the piezoelectric effect. Different piezoelectric circuits; series, parallel and combination circuits, and types; Lead Zirconate Titanate (PZT) and ceramic or buzzer types, were investigated. Then, an energy harvesting prototype was built to charge ions to a capacitor by attaching the prototype to shoe pads. From the circuit comparison results, the parallel piezoelectric circuit provided the highest current density and this circuit was carried out in other experiments. Next, the comparison was made by applying both piezoelectric types into two separate parallel circuits with 2 pieces per circuit. The PZT circuit harvested the same amount of electrical power as the buzzer circuit, but the energy harvesting by the PZT circuit took less time at 15 mins to complete its harvest. Finally, the PZT circuit was installed on the shoe pads as a prototype and investigated for its capability. The experiment was carried out by an experimenter who wore the shoes with the prototype and walked at a constant speed of 1 km per hr. The experimental distances were 200, 400 and 600 m and the electric power were calculated accordingly. From the experimental results, walking with the constant speed could enable the PZT piezoelectric materials to produce electric power of electrical energy constantly because of its elastic ability which could tolerate mechanical energy applied to it and because the time used to harvest energy by its circuit is short. It could be concluded from the experiments that the more the distance, the more electric power. Therefore, this prototype proved to produce electrical energy from the piezoelectric effect in harvesting energy and could be further developed as a renewable energy harvester.

Keywords: Piezoelectric, Energy, Energy harvesting, Exercising
1. Introduction

There are many energy harvesting methods such as from electrochemistry [1] and mechanical forces. Piezoelectricity is the appearance of 2 charges on opposite sides of particular non-conducting crystals. The 2 charges consist of the positive electric charge on one side of the crystal and the negative electric charge on the opposite side [2]. Piezoelectricity naturally occurs in ferroelectric crystals such as quartz with not very strong effects but is very stable. The Piezoelectric effect can be divided into 2 types; the direct effect which results from a distortion of the crystal lattice caused by the applied mechanical stress resulting in the appearance of electrical dipoles, and the inverse effect which happens by applying an electric field to the crystal. The electric field applied causes a distortion of the lattice resulting in an induced mechanical strain. Piezoelectricity can also be induced through poling in other materials which are ferroelectric crystals, ceramics or polymers. A piezoelectric ceramic is produced by pressing ferroelectric material grains (typically a few micrometers in diameter) together. After the ceramic powder is heated above Curie temperature and has cooled down, the Perovskite ceramic undergoes phase transformation from the paraelectric state to the ferroelectric state, resulting in the formation of randomly oriented ferroelectric domains. These domains are arranged in grains, containing either 90° or 180° domains. This random orientation leads to zero (or negligible) net polarization and piezoelectric coefficients. The application of a sufficiently high electric field to the ceramic causes the domains to reorient in the direction of the applied electric field. However, after removing the applied electric field, the ferroelectric domains do not return in their initial orientation and a permanent polarization remains in the direction of the applied electric field [3].

Thainiramit [4] designed a beam system and a circuit to harvest electrical energy using the piezoelectric effect. The PZT type was used in this project by attaching two PZTs onto both sides of a cantilever beam, resulting in parallel bimorph harvesting structure. The PZTs were connected by the parallel circuit. The frequency of the vibration applied was approximately 17-18 Hz and at a constant displacement of the beam tip. He found that the beam length affected the frequency the most and a pressure-controlled circuit to prevent overload. The generated power was enough to be used with devices that consumes 1 mW and below.

Chotwattanakankul and Khunboa [5] developed a mechanical energy harvesting system using piezoelectric materials to support a wireless sensor node. The system composed of piezoelectric materials, a power management circuit and an energy storage device attached to a sensor node. The results showed that a strum of 12.7 x 31.8 x 0.51 mm$^3$ piezoelectric plate was able to produce a maximum voltage 21.3 V and an average energy of 25.94 µJ which could be used as energy for a wireless sensor node when entered sleep mode in 1.44 seconds or in data transformation across wireless sensor nodes by 1 package per 32.29 strumming.

Putthongchai [6] studied the energy harvesting from PZT piezoelectric material with a bulk shape for its effect on mechanical energy acquisition when a mechanical force of 100-500 N was applied to the PZT with low mechanical frequency of 0.5-0.8 Hz. The different electrical circuits were also studied and a prototype was also implemented. The results showed that the diameter of the substance determines the electrical energy the PZT material may acquire. The external resistance had influence on the voltage and power of the piezoelectric material by connecting the circuit with an external resistance of 25 MΩ provided the most electric power. The half-wave rectifiers charging circuit which included a filter is appropriate for energy harvesting from piezoelectric materials under low frequency conditions (less than 1 Hz). Due to less energy loss, the voltage was enough to supply a 1.2 V battery.

Casimiro [7] invented a device which could generate electricity by walking. The piezoelectric materials were applied in a shoe sole and were experimented that it could produce electrical energy. Although this product was not in the stage to be sold, his design was a great benefit to many people worldwide.

This work aimed to find the optimal circuit to develop a prototype which could produce electrical energy from the piezoelectric effect. The different piezoelectric circuits; series, parallel and combination circuits, and types; Lead Zirconate Titanate (PZT) and ceramic or buzzer types, were investigated. Then,
the piezoelectric circuit most suitable was installed on a shoe pad and was connected to an energy harvesting circuit to charge ions to a capacitor.

2. Experimental Setup

2.1 The study of piezoelectric circuits

Three piezoelectric circuits were studied; a series circuit, a parallel circuit and a combination circuit. A circuit which does not refute each other and produces the most electric current would be applied to connect the piezoelectric materials. The electric current can be calculated from Ohm’s law as following:

\[ V = IR \]  

Each circuit in this study had resistors with an exact value of resistance. After acquiring the suitable circuit, the electric circuit with a purpose to harvest energy would be designed. The three circuits; the series circuit (Figure 1), the parallel circuit (Figure 2) and the combination circuit (Figure 3) were studied. The formula used for calculation from the series circuit as following:

\[ V_T = V_1 + V_2 + V_3 + \cdots + V_n \]  
\[ I_T = I_1 = I_2 = I_3 = \cdots = I_n \]  
\[ R_T = R_1 + R_2 + R_3 + \cdots + R_n \]  
\[ P_T = P_1 + P_2 + P_3 + \cdots + P_n \]

The formula used for calculation from the parallel circuit as following:

\[ V_T = V_1 = V_2 = V_3 = \cdots = V_n \]  
\[ I_T = I_1 + I_2 + I_3 + \cdots + I_n \]  
\[ 1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \cdots + 1/R_n \]  
\[ P_T = P_1 + P_2 + P_3 + \cdots + P_n \]

The formula used for calculation from the combination circuit as following:
Figure 3. The combination circuit [9].

\[ \text{IT} = \text{ETRT} \]  
\[ \text{RT} = R_1 + R_2 + R_3 \] where \( R_2, R_3 \) could be calculated from \( R_2, R_3 = \frac{R_2 R_3}{R_2 + R_3} \)  
\[ \text{PT} = \frac{\text{ETIT}}{\text{IT}} \]

2.2 The study of piezoelectric materials

The two piezoelectric materials; which were the buzzer type with a diameter of 3.5 cm and the PZT type (Figure 4) with dimensions as 5.54 cm in length, 2.34 cm in width and a thickness of 0.46 cm, were connected in two separated circuits. The piezoelectric circuits chosen in the study contained 2 pieces of each piezoelectric material. The voltage of the two circuits were obtained and recorded in a constant period by using an oscilloscope. The frequency used in vibrating the piezoelectric materials; 0.55 Hz, 3.33 Hz and 5 Hz, were studied. The electric current was calculated after connecting each piezoelectric circuit with a capacitor with a capacity of \( 1000 \, \mu\text{F} \) and voltage of 5 V by assessing the time in seconds that a light bulb could maintain its brightness. After recording the time, the electric current can be calculated as following:

\[ I = qt \]

When the electric current was calculated, the time used by each circuit in harvesting the current was compared. The electric power can be calculated after attaining both voltage and electric current by Ohm’s law as following:

\[ P = IV \]

Each of the piezoelectric circuits was connected to a capacitor of 1000 \( \mu\text{F} \) and 100 V. As a consequence, the voltage obtained from the capacitor was measured. The PZT parallel circuit was investigated by deforming the piezoelectric with a torsion displacement of 1 cm at a constant frequency of 3 Hz. The buzzer parallel circuit was investigated by tapping with a frequency of 3 Hz. The voltage obtained from the capacitor was recorded in different periods; 10, 20, 30, 40, 50 and 60 s. The electric power obtained from the capacitors of both circuits were calculated subsequently. After achieving the suitable piezoelectric type for harvesting energy, the piezoelectric circuit was installed on a shoe pad.
2.3 The experiment and analyzing the results of the prototype

The circuit with a higher level of the electric power installed on the shoe pad was connected to an energy harvesting circuit containing an energy harvester and a boost converter. The circuit was an experimental prototype and investigated for its capability. The experiment was carried out by a volunteer who had a constant weight wearing shoes with the prototype installed and walking at a constant speed of 1 km per hr on a treadmill. The factors studied was the distance. 3 different distances; 200 m, 400 m, and 600 m, were investigated.

3. Results and discussions

3.1 Results and discussions of the study of piezoelectric circuits

It was found that to produce electric current the total voltage has to be equalled; hence, the series circuit is not suitable because it would lead to the piezoelectric materials refuting each other. From the Equations (6) to (12), we had made a comparison between the parallel circuit and the combination circuit as shown in Figure 5 by assuming the exact values of the resistance (5Ω) and the voltage (10V):

![Figure 5. The parallel circuit (left) compared with the combination circuit (right).](image)

To make comparison, the electric current was calculated from Equation (1). From Figure 6 both circuits had the same voltage. In the parallel circuit, the electric current was calculated resulting in 6 A. The electric current from the combination circuit was calculated resulting in 1.33 A. From the results, when studying circuits theoretically, it influenced decision making to make it less difficult and more precise because the decision was made by the theory supported in Figures 1 to 3. Hence, the parallel circuit was
the most suitable for harvesting energy because it provided the most current at 6 A. The difference between the parallel circuit and the combination circuit in percentage was 77.83%. Therefore, the further experiments were conducted by using the parallel circuit. The design for the piezoelectric circuits to be experimented on further were made as shown in Figures 6 and 7:

Figure 6. The buzzer type parallel circuit.

Figure 7. The PZT type parallel circuit.

3.2 Results of the study of piezoelectric materials
From the experiments, the voltage from the parallel circuit of the PZT type was greater than the voltage produced from the parallel circuit of the buzzer type as shown in Figure 8. In a constant period, it could be elaborated from Figure 8 that, from all experimental tests, the voltage from each piezoelectric material fluctuated. The average values of the voltage from the PZT type at 0.55, 3.33, and 5 Hz were 1.14, 2.56 and 3.7 V, respectively. The average voltage of the buzzer type at 0.55, 3.33, and 5 Hz was approximately 0.64, 1.08 and 1.98 V, respectively. As a consequence, by comparing the two types, the PZT type could produce greater voltage. Next, it was found that the electric current from both circuits were the same as shown in Figure 9. From Figure 9, the electric current harvested from the PZT type and the buzzer type were shown with a constant value at 50 µA. Even though the amount of electric current produced was the same, the time used to harvest energy of the PZT parallel circuit was less than the buzzer parallel circuit. The PZT circuit took 15 minutes to finish its harvest while the buzzer circuit took 60 minutes to finish its harvest.

Figure 8. The voltage from the buzzer and PZT circuit.
Figure 9. The electric current from the buzzer and PZT circuit.

After having the values of voltage and the electric current, the electric power was calculated using equation (14), resulting in the PZT circuit having electric power of $57 \mu W$, $128 \mu W$ and $185 \mu W$ at an average when conducted with a frequency of $0.55 \text{ Hz}$, $3.33 \text{ Hz}$ and $5 \text{ Hz}$, respectively. The buzzer circuit produced electric power at $32 \mu W$, $54 \mu W$ and $99 \mu W$ at average when conducted with a frequency of $0.55 \text{ Hz}$, $3.33 \text{ Hz}$ and $5 \text{ Hz}$, respectively, as shown in Figure 10.

Figure 10. The electric power from the buzzer and PZT circuit.

When the voltage obtained from the capacitor in each circuit was investigated, as shown in Figure 1, it could be seen that the voltage of the capacitor connected to the PZT circuit and the buzzer circuit increased during 6 different periods; $10 \text{ s}$, $20 \text{ s}$, $30 \text{ s}$, $40 \text{ s}$, $50 \text{ s}$ and $60 \text{ s}$. The voltage obtained from the capacitor connected with the PZT circuit was the same as the buzzer circuit during $10 \text{ s}$. However, the voltage of both circuits began to differentiate at $20 \text{ s}$ with the PZT circuit producing greater voltage than the buzzer circuit.
After having the values of voltage from the capacitor of both circuits, the electric power was calculated using the equation (14), resulting in the capacitor connected to the PZT circuit having electric power of 4 µW, 8 µW, 12 µW, 18 µW, 22 µW, and 26 µW when conducted for 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s, respectively. The capacitor connected to the buzzer circuit produced electric power at 4 µW, 6 µW, 10 µW, 12 µW, 14 µW, and 18 µW when conducted for 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s, respectively. Thus, as shown in Figure 12, it could be noticed that the electric power from the capacitor connected to the PZT circuit was greater than the capacitor connected to the buzzer circuit.

3.3 Results of the experiment and analyzing the results of the prototype

From the experiment’s results, it was found that walking further distances could produce more electric power as shown in Figure 13. The average electric power calculated was 85.9 µW followed by 135.3 µW and 214.15 µW which represented the average electric power from the distances of 200 m, 400 m and 600 m consecutively.
4. Conclusion
This project aimed to produce a prototype which could harvest energy from the piezoelectric effect. Different circuits: series, parallel and combination were studied. The study resulted in the parallel circuit producing the most electric current without refuting each other. The latter experiment was to compare piezoelectric material types which are Lead Zirconate Titanate (PZT) and ceramic or buzzer types. The PZT type produced greater electric power than the buzzer type. Hence, the energy harvesting circuit was designed using the PZT type. The PZT piezoelectric circuit was installed onto a shoe pad and connected to the energy harvesting circuit resulting in the prototype which was experimented with afterwards. The results elaborated that the prototype could be used as an energy harvester. Therefore the energy harvested from the piezoelectric effect installed on shoe pads could be applied as a renewable energy and developed further.

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Figure 13. The electric power produced from the piezoelectric circuit.