Comparative Analysis of Piezoelectric Energy Harnessing from Micro Vibration Using Non-Adaptive Circuit

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Abstract: - This paper presents a comparison between simulation and experimental findings of energy harnessing from micro-vibration by using piezoelectric vibration-to-electricity converter. Vibrational data used in this study are generated experimentally using magnetic shaker. Since piezoelectric sensor produces an alternate voltage, a rectifier circuit is needed to convert it to a direct voltage. In this study, an instrumentation to harness energy from micro-vibration using non-adaptive circuit has been developed and simulated within Matlab SIMULINK environment. A comparative analysis shows that a maximal power output of 40.5 µW and 29.0 µW could be harnessed for input vibration of 0.075 m/s^2 at 10 Hz frequency, from simulation and experimental, respectively. The amount of energy generated is far smaller than required for the normal operations of most electronic devices. However, this energy could be accumulated and stored until sufficient power has been captured to develop a completely self-powered system.

Key-Words: - energy harnessing, micro vibration, non-adaptive circuit, piezoelectric, vibration-to-electric energy conversion

1 Introduction

Rapid growth and continuous development in the technology offers consumers with portable electronic devices that have comprehensive functions. Devices such as cell phones, laptops and MP3 players can be used for communication, computing and audio functions. In the last few years, considerable developments of these gadgets have been achieved, where their sizes have been reduced significantly for better mobility but with greater power consumption [1].

These devices require batteries to work. An ideal battery for a device would be the one that can power the device for an extended time. However, it would require a larger and heavier battery to operate. Current batteries could only supply power only for about one to three years before replacements are needed due to its limited capacity. As of now, the batteries that power electronic devices have become impractical due to short lifetime. Due to this drawback, there is increasing demand for self-powered electronic devices.

The progressions of self-powered electronic devices are moving forward, in parallel with the advancement of current technology. These devices do not require batteries to operate, as they can be supplied with infinite amount of energy by harnessing ambient energy from the environment. Among external sources of energies that can be harnessed for electricity generation purpose are human bodies [2], [3] and temperature gradient [4].

Another type of energy suitable for energy harnessing and has gaining considerable attention from researchers is vibration [5]-[13], which can be produced and observed in buildings, factories, vehicles, industrial machineries and household appliances. There are three methods that can be applied for conversion of vibration energy into electrical energy. This includes electromagnetic (inductive) [5]-[7], electrostatic (capacitive) [8]-[10] and piezoelectric conversion [11]-[13]. Table I compares the potential energy from different types of sources in terms of power density for 1 and 10 year lifetime. The power generation and amount of energy storage are fixed, where all power density values are normalized to the size of 1 cm^3, depending on the size of typical wireless sensor nodes [14].

A particular research work, namely PicoRadios [14] has been conducted and focusing on wireless
sensor and actuator networks. These scopes contribute to the innovation of harnessing ambient energy form the environment. The project centered on the development of small, flexible wireless platform for wireless data acquisition that minimizes power dissipation. This work by PicoRadios is important for the power system, especially the total size, where the node must be smaller than 1 cm³. Another essential target for the work is that the average power dissipation of an individual node and the target average power dissipation of a completed node is 100 μW.

The data tabulated in Table I shows that a promising amount of power density can be harnessed from vibration energy, which ranging from 50 to 200 μW/cm³. Hence, vibration energy should be able to provide from 50 up to 200 μW of power in less than 1 cm³ in order for it to be in the acceptable margin.

Vibration is the best method for harnessing ambient energy, but it is in the best interest to study the potential of vibration as a feasible power source for applications where vibration is present.

Table II summarizes commonly occurring vibration from different types of sources, which can be categorized as low level vibration. They are considered to be reliable and feasible as the source for power generation [11]. The measured vibration sources are represented in terms of their acceleration magnitude (A) and frequency of fundamental vibration mode (F_peak).

A vibration source of 2.5 m/s² at 120 Hz has been used as the basis, as it has been previously used by Roundy et al. [11] and Roundy and Wright [12]. The source is classified as the middle of wide range of low level vibration sources in terms of power output. Therefore, it can be considered as a representative of vibration source.

2 Energy Harnessing using Piezoelectric Materials

The conversion of vibration into electricity can be conducted using three commonly established methods. They are electromagnetic (inductive), electrostatic (capacitive), and piezoelectric, and are usually used for inertial sensors, as well as for actuators. In this study, piezoelectric is selected as the mechanism for converting vibration into electric energy. This is because piezoelectric materials can convert and produce the highest energy density compared to other methods.

2.1 Piezoelectricity

The word piezoelectricity originated from Greek word, which means “electricity by
pressure”. It was first discovered by Jacques and Pierre Curie brothers in 1880. They discovered that certain crystals were polarized when mechanical strain was applied, and the degree of polarization was proportional to the applied strain. In contrast, deformation occurred when these materials were exposed to an electric field.

2.2 Conversion Mechanism

Wasted vibration energy from surrounding is utilized rather than just letting it dissipates. Piezoelectric materials are used for energy harnessing of this wasted energy and converting it into electrical energy, which can later be utilized for powering electronic devices. The concept and mechanism of harnessing vibration energy using piezoelectric materials is shown in Figure 1.

Firstly, vibration energy is harnessed by the piezoelectric materials, which functioned as vibration-to-electricity converter. The output of this converter is alternate voltage, of which later rectified using signal conditioner. The final output is direct voltage, produced from the conversion of alternate voltage by the rectifier.

3 Methodology

The simulation setup of piezoelectric vibration-to-electricity conversion used in this study is described in the following sub-sections.

3.1 Piezoelectric Sensing Element

A piezoelectric behavior can be modeled in terms of acceleration and voltage as given by equation 1.

\[ V = k x L^2 x a \]  

(1)

where \( k \) is a piezoelectric constant. This relation can be presented by the block diagram as shown in Figure 2.

The evaluation of output voltage from the piezoelectric converter was based on equation 1. The sensing element modelled in Matlab SIMULINK was shown in Figure 3. The acceleration input used for the sensing element is obtained from the vibrational data acquired experimentally. The ideal gain of transfer function for piezoelectric element is taken as one.

\[ \text{Acceleration, } a (\text{ms}^{-2}) \quad \rightarrow \quad V \text{ (volt)} \]

Figure 2. Block diagram for piezoelectric accelerometer

3.2 Harnessing Circuit

Alternate voltage and current are produced from piezoelectric material when it is deformed mechanically. They are not really useful as most of the electronic devices nowadays operate on direct current. In order to optimize the energy harvested from vibration environment, harnessing circuit is used and rectified this alternate voltage and current.

In this study, non-adaptive circuit [15] is used as the harnessing circuit because it has been proved that more power can be harnessed as compared with adaptive circuit [16]. The non-adaptive circuit is illustrated in Figure 4 which includes a conventional diode bridge rectifier and a passive circuit.

Diodes are used in this circuit and it is assumed that there is no voltage drop across it. Capacitance value, \( C \) for the filtering capacitor is calculated by using equation 2 where \( i \) is the load current across the capacitor, \( V_p \) is the bridge rectifier output peak voltage and \( f \) is the frequency of the AC supply where in this experiment, the value of frequency was taken at 10 Hz.

\[ C = \frac{5i}{V_p f} \]  

(2)

Next, the value of load resistance, \( R \) is determined by using the basic electric law which is Ohm’s Law as given by equation 3, where \( V \) is the voltage across it and \( I \) is the current.

\[ V = IR \]  

(3)
The non-adaptive harnessing circuit that was simulated in Matlab SIMULINK environment is shown in Figure 5. Data for voltage input was taken from piezoelectric sensing element simulated in the Matlab SIMULINK environment earlier.

Figure 5. Non-adaptive harnessing circuit developed using Matlab SIMULINK

4 Results
The following sub-sections present the simulation result of forced vibration data which includes acceleration data generated experimentally and simulation output of alternate voltage and direct voltage as well as the experimental result for the purpose of comparing and validating the simulation result.

4.1 Simulation Results
In this research, forced vibration was generated experimentally and the data obtained was used as an input data in Matlab SIMULINK environment. Figure 6 shows the vibration result in term of acceleration at different amplitude of (a) 0.05 V<sub>pp</sub>, (b) 0.10 V<sub>pp</sub> and (c) 0.15 V<sub>pp</sub>.

The acceleration is then fed into piezoelectric vibration-to-electricity converter sensing element with the ideal transfer function of piezoelectric is taken as 1 V/(m/s<sup>2</sup>) and with assumption of no voltage drop. A signal conditioning of non-adaptive rectifier circuit is employ to convert the alternate voltage produce by piezoelectric vibration-to-electricity converter to direct voltage.

Figure 7 shows the simulation output versus time at different amplitude of (a) 0.05 V<sub>pp</sub>, (b) 0.10 V<sub>pp</sub> and (c) 0.15 V<sub>pp</sub> where alternate voltage is the output from piezoelectric vibration-to-electricity converter and direct voltage is the output from non-adaptive rectifier circuit.

Figure 6. Acceleration versus time at different amplitude of (a) 0.05 V<sub>pp</sub>, (b) 0.10 V<sub>pp</sub> and (c) 0.15 V<sub>pp</sub>.

Figure 7. Acceleration versus time at amplitude (a) 0.05 V<sub>pp</sub>, (b) 0.10 V<sub>pp</sub> and (c) 0.15 V<sub>pp</sub>.
Figure 7. Voltage versus time at different amplitude of (a) 0.05 Vpp, (b) 0.10 Vpp and (c) 0.15 Vpp

From Figure 7, it shows that as the acceleration magnitude increases, the average direct voltage also increases from 4.5 mV to 8.1 mV. It also shows that as the direct voltage increases, the average power output that could be harnessed also increases from 22.5 µW to 40.5 µW. In simulation 3, the maximal power output is 40.5 µW with input vibration of 0.075 m/s² at 10 Hz frequency. Table III summarizes all the results obtained through simulation using Matlab SIMULINK.

Table 3. Summary of Simulation Results

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Amplitude, m/s²p-p (with frequency 10 Hz)</th>
<th>Direct Voltage, mV</th>
<th>Power Output, µW (with i = 5 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>4.5</td>
<td>22.5</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>5.3</td>
<td>26.5</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>8.1</td>
<td>40.5</td>
</tr>
</tbody>
</table>

4.2 Experimental Result

The experimental analysis is done as a comparison to the simulation analysis. The input data is adapted from the forced vibrational data generated experimentally. Direct voltage that produced from rectifying circuit is captured by LabVIEW. The data is analyzed and then imported to Matlab for graph plotting as shown in Figure 8.

5 Discussion

In this section, the simulation results are compared with the experimental results. Figure 9 shows the comparison graph between both results.

From both simulation and experiment results, comparative study is conducted for the performance of the direct voltage obtained. All results show that, as the acceleration amplitude increases, the piezoelectric alternate voltage and the direct voltage also increases.

In experiment 3, the maximal power output is 29.0 µW with input vibration of 0.075 m/s² at 10 Hz frequency. Table 4 summarizes all the experimental results obtained.

Table 4. Summary of Experimental Results

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Amplitude, m/s²p-p (freq 10 Hz)</th>
<th>Direct Voltage, mV</th>
<th>Power Output, µW (i = 5 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>3.5</td>
<td>17.5</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>4.0</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>0.15</td>
<td>5.8</td>
<td>29.0</td>
</tr>
</tbody>
</table>
Figure 8. Voltage versus time at different amplitude of (a) 0.05 V_{pp}, (b) 0.10 V_{pp} and (c) 0.15 V_{pp}

Figure 9. Comparison graph for acceleration at different amplitude of (a) 0.05 V_{pp}, (b) 0.10 V_{pp} and (c) 0.15 V_{pp}
6 Conclusion
With the input vibration of 0.075 m/s\(^2\) at 10 Hz frequency, simulation results show that the maximal power output is 40.5 µW while experimental results show that the maximal power output is 29.0 µW. Based on both simulation and experimental results obtained, it can be concluded that as the acceleration magnitude increases, the direct voltage and direct current produce are also increased which means more power can be harnessed.

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References: