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Power Estimation for Wearable Piezoelectric Energy Harvester

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Abstract

The aim of this research work is to estimate the amount of electricity produced to power up wearable devices using a piezoelectric actuator, as an alternative to external power supply. A prototype of the device has been designed to continuously rotate a piezoelectric actuator mounted on a cantilever beam. A MATLAB® simulation was done to predict the amount of power harvested from human kinetic energy. Further simulation was conducted using COMSOL Multiphysics® to model a cantilever beam with piezoelectric layer. With the base excitation and the presence of tip mass at the beam, the natural frequencies and mode shapes have been analyzed to improve the amount of energy harvested. In this work, it was estimated that a maximum amount of power that could be generated is 250 μW with up to 5.5V DC output. The outcome from this research works will aid in optimising the design of the energy harvester. This research work provides optimistic possibility in harvesting sufficient energy required for wearable devices.

Keywords: *Piezoelectric, energy harvester, wearable*

1. Introduction

Piezoelectric energy harvesting techniques for wearable devices have increasingly attracted attention over the past few years. The pivotal reasons behind it are the ability of this technique to discard the requirement of external power source and to reduce maintenance of the devices.

To date, most of wearable devices are powered and operated by batteries which have the disadvantage of need to be recharged from time to time. For example, smart watches have a run time between 3 hours for the Apple Watch and 4 hours for the Android when operated constantly. Apple does report a charge time of 2.5 hours corresponding to a rate of approximately 0.6 C, or about 120 mA of charge current into the battery. Made of a lithium cobalt titanate, this cell had a terminal voltage of 2.3 V and a charge capacity of 18mAh, equivalent to 0.041Wh to power the sensors and gray-scale LCD display [1]. A pulse rate meter uses lithium battery as an external power supply which have amount of electrical power less than 1.65W with the output current and voltage of 500 mA and 3.4V [2]. As for other wearable devices, most of them use battery that has approximately similar range of power, current draw and output voltage to power up the devices.

One way to overcome these power limitations is by using energy harvesting technique to operate the wearable devices. It utilizes alternative energy source to power the electricity. The energies available for harvesting are light or solar captured by photovoltaic cells, vibration or pressure captured by a piezoelectric element, thermoelectric or temperature differentials captured by a thermoelectric generator and radio frequency or radio energy or magnetic. The energy source is converted to electricity and the system includes circuitry to rectify the current, store energy and other circuitry.

For this project, energy harvesting through vibration is selected since we aim to generate power from rotating equipments. Piezoelectric, electromagnetic and electrostatic are three typical methods used in vibration based energy harvsting. Among these, piezoelectric is the most preferable due to its higher energy density, ability to change vibration motion into

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electrical energy and ease to be integrated in the system [3-6]. When piezoelectric energy harvester is tuned to applicable resonance frequency, a high output power is induced.

Kinetic energy from human body will initiate vibration to the system and tranduce to the electrical energy. Cantilever construction, in which the beam is anchored at one end is typically chosen as large mechanical strain can be produced during the vibration. Proof masses are added at the free end of the beam to lower the resonance frequency [7]. The kinetic energy transduces to electrical energy so the electrical energy depends on the proof mass and kinetic energy produced [8].

Works by [9] showed that a piezoelectric layer attached to the beam acts as generator to produce 375 µW output power with an input acceleration of 2.5 m/s² at 120 Hz of typical vibration value. Based on this piezoelectric cantilever beam, the minimum current draw of 0.1mA based on the resistive load was applied to the circuit [9]. Thus, the cantilever beam vibration geometry for piezoelectric energy harvester is sufficient to power up the wearable device based on the amount of electricity provided.

The motivation behind this work is to provide an alternative energy sources to power up wearable devices. The low voltage requirement for wearable devices made it possible that it could be powered by converting low frequency kinetic energy from human motion into into electricity [10]. This alternative energy source will indeed reduce dependencies to external power supply and promotes to utilization of clean energy.

2. Research Method

The idea for this project is to generate electricity from the vibration by utilizing a piezoelectric beam and magnet assembly. To ensure a continuous vibration to the piezoelectric and permanent magnet assembly, the device is designed to rotate. The kinetic energy from the human motion should initiate a rotational motion to the assembly. The same polarities of the permanent magnets lead to a high angular velocity to the assembly causing the piezoelectric beam to deflect, and this rapid motion will in turn vibrate the electrons in the piezoelectric beam to generate electricity. The output signals will be rectified to ensure sufficient power to run a wearable device. For this research work, the targeted output is 3V to drive a miniature vibration motor.

A prototype has been designed using SOLIDWORKS® for this purpose. Referring to Figure 1, there are four magnets in red color, which two of these are attached on the rotor and the other two are attached at one end of the piezoelectric beam. The other end of the piezoelectric beam is fixed so that the magnetic repulsion will cause the beam to pluck and deform. The shaft and bearing hold and smooth the rotation of rotor when the repulsion occurs on the magnet and piezoelectric assembly. Neodymium iron boron (NdFeB) is selected as the permanent magnet for this device as it has lightweight properties and comes in various sizes thus is suitable for wearable devices.

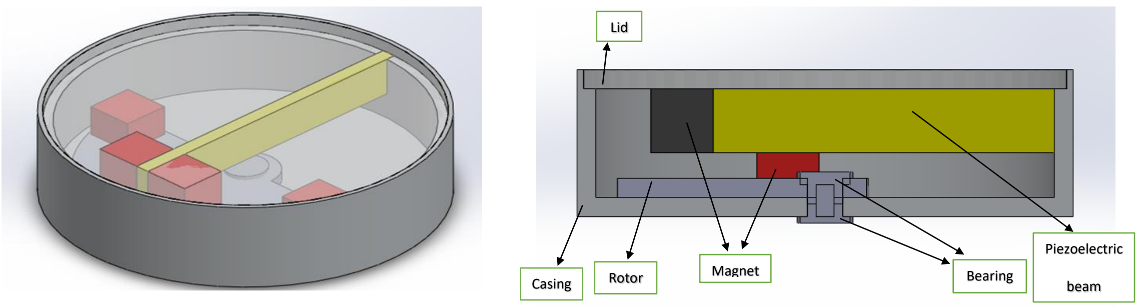

Figure 1. The isometric view (left) and the cross-sectional view (right) of the device

Once the design was complete, MATLAB® and COMSOL® simulations were done to justify the selection of the material and the dimensions for this energy harvester. A set of published data on vibration output gathered during walking activity [11] was processed in

MATLAB ® to estimate the power harvested from the vibration motion. The following equation was used to estimate the power generated.

$$P = \eta . F . l . f \quad (1)$$

where,
P = power (W),
η = efficiency,
F = force (N),
l = the distance between the mass center and rotation centre (m),
f = frequency (Hz).

In COMSOL software, the ‘Piezoelectric Devices’ multiphysics interface combines both Solid Mechanics and Electrostatics. The energy harvester analyzed in this model consists of a piezoelectric bimorph clamped at one end to the vibrating machinery with a proof mass mounted on its other end. The dimension of the beam was set to be 40x10x0.5mm (length, width, thickness). Figure 2 shows the major components of piezoelectric energy harvester which includes a piezoelectric bimorph, a proof mass (permanent magnet) and a supporting structure which clamps the beam at on end to make the other end deflect and vibrate.

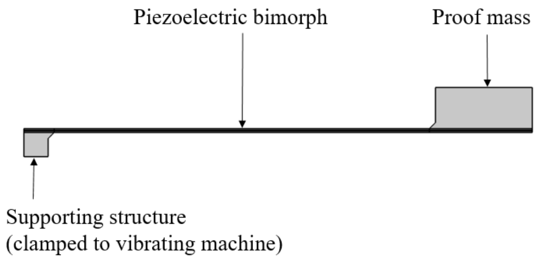

Figure 2. 2D Model Geometry

The bimorph has a ground electrode embedded within it and two electrodes on the exterior surfaces of the cantilever beam. This configuration ensures that same voltage is induced on the exterior electrodes, even though the stress above and below the neutral layer is of opposite sign. Since the clamp is mounted to a piece of vibrating machinery the device is analyzed in a vibrating reference frame.

3. Results and Analysis

The results are divided into two sections. The first section estimates the power generated from a walking activity that should give indication on how much kinetic energy required in providing sufficient electricity for a wearable device. The second section describes the vibration frequency required at the piezoelectric beam in order to harvest the required energy.

3.1. Power Estimation from Kinetic Energy

The following parameters in Table 1 were used to estimate the power generated by the device.

Table 1. Parameters for estimation of Power

Parameters	Values
Force, F	0.1 N
Distance between mass center and rotation centre, l	0.012 m
Frequency, f	2
Energy efficiency, η	0.7

This system was assumed to operate at 2Hz which is the within the frequency range of human motion [12]. Using the published vibration data as shown in Figure 3, the power harvested was estimated as shown in Figure 4.

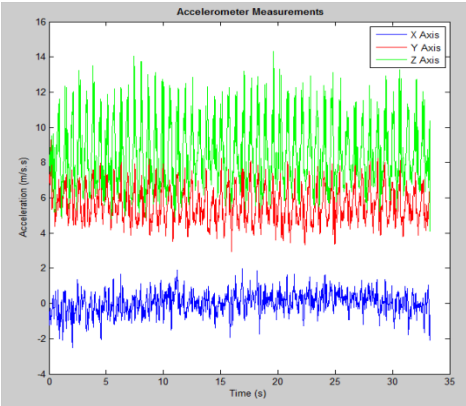

Figure 3. Vibration data from walking activity (ms^{-2})

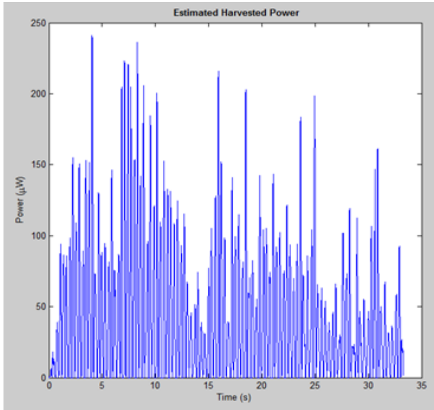

Figure 4. Power harvested from walking activity (μW)

The range of vibration recorded from the walking activity is between 6 to 8 ms^{-2}. Based on the acceleration recorded, the range of power harvested is estimated between 0 to 250 μW. This result tallies with works by Khalifa [11] in recognizing human activities based from vibration produced by human.

3.2. Power Estimation from Vibration Frequency

Using COMSOL®, three analyses of the mechanical part of the energy harvester system were conducted. First, the peak vibration frequency of the designed cantilever beam was determined as shown in Figure 5. With the load impedance of 12kΩ and the acceleration (gravitational) magnitude of 1G, the system shows a peak at 112 Hz, which is the resonant frequency of the cantilever beam.

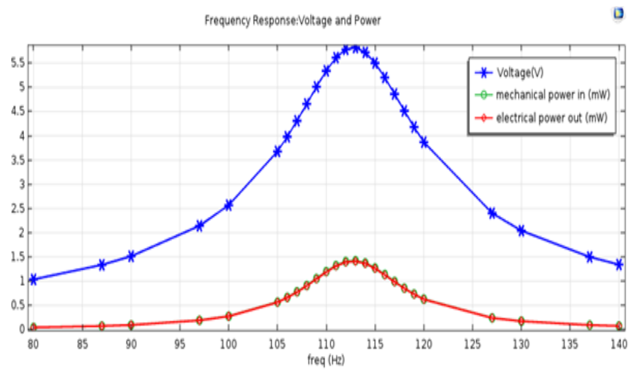

Figure 5. Determination of peak vibration frequency (Hz) of the designed cantilever beam

Focusing on the obtained peak vibration frequency of 112 Hz, the estimated power harvested for varying electrical load was investigated, as shown in Figure 6. The graph for the load dependence shows the peak in energy harvested corresponds to an electrical load of 12 kΩ. Finally, by selecting electrical load of 12 kΩ and operating at peak vibration frequency of 112 Hz, the DC voltage outputs as well as mechanical power output were estimated as shown in Figure 6.

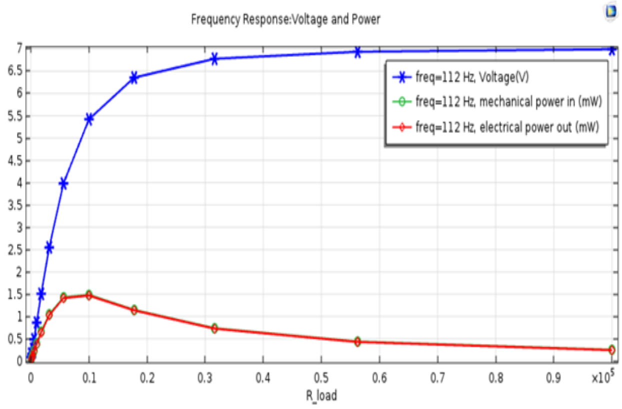

Figure 6. Estimated power harvested for varying electrical load

It could be observed in Figure 7 that the voltage increases linearly with the load, whilst the harvested power increases quadratically. To obtain the targeted voltage output of 3V, the vibration acceleration from human kinetic motion should be 0.5G which could be achieved as it is within the vibration range of human motion, which is up to 1G. Therefore, the highest possible voltage that could be harvested with this design set-up is 5.5V, which would be adequate for wearable devices.

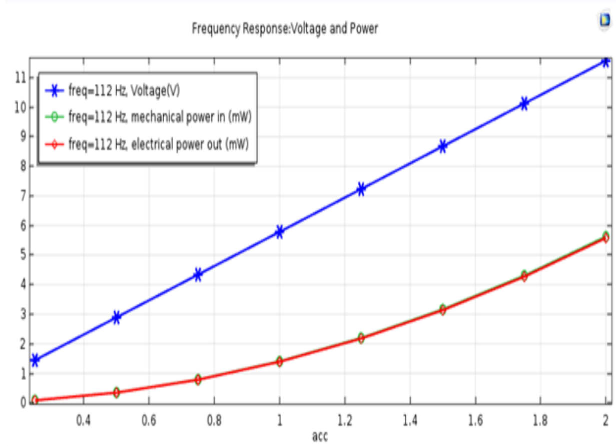

Figure 7. Estimated voltage (V), mechanical and electrical power (mW)

A preliminary simulation has also been conducted for the piezoelectric bimorph beam with half of the length of the designed prototype (20 mm). It was observed that the peak voltage at the resonance frequency of the beam is lower as the length of the beam is decreased. This is because the length of beam affects the vibration output. The longer the beam is, the higher the vibration will be generated due to the larger bending area of the beam. This results in a higher voltage produced. However, as the energy harvester is designed for wearable devices, it is desirable that it should be light weight and not bulky. Therefore the prototype with 40 mm length piezoelectric beam is deemed the most suitable for this application.

4. Conclusion

The objectives of this project which are to develop a piezoelectric device that is capable to generate enough electricity to power up body worn devices using only the energy harvested by human body have been achieved. With a peak vibration frequency of 112 Hz on the designed cantilever beam, the energy harvester is capable to produce up to 5.5V DC output which is sufficient to power up wearable devices. The next stage of this research work is to fabricate the device and conduct further tests to assess its capability to harvest energies. This research work have shown that producing clean energy based on human kinetic motion, without relying on external souces is achievable in the near future.

Acknowledgement

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