An Optimization of Electrical Output Power for Piezoelectric Energy Harvester using Different Micro-Cantilever Beam Geometries

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Abstract. A MEMS-based piezoelectric energy harvester is capable in producing the electrical output at certain level. The investigation on ability to successfully generating the electrical output power is highly recommended. Accordingly, an optimization on electrical output power based on micro-cantilever beam geometry is presented in this paper via simulation work using COMSOL Multiphysics software. Thus, four different geometries named as PPG 1, PPG 2, PPG 3 and PPG 4 are individually characterized. The simulation result shows the superior performances from PPG 2 which generating 393 mV of output voltage with 39 nA output current, while the output power is 15 nW at 10 MΩ optimal load and 1g vibration amplitude. The excitation frequency for PPG 2 is as low as 60 Hz. Therefore, the modification of micro-cantilever geometry is able to increase the production of electrical output power.

1. Introduction
The present of alternative energy sources from the ambient such as wind, solar, thermal, radio frequency and mechanical vibration offering space to green source electrical power generation [1-3]. Harvesting the mechanical vibration using piezoelectric energy harvester is mostly reported by the previous researchers either in experimental or simulation studies [4-6]. The mechanical vibration is a good candidate for alternative energy because it is said as clean, always present and sustainable energy [7-9]. However, the direct electrical power produced by the piezoelectric harvester is stated as too low [10]. Thus, an enhancement of electrical output power for piezoelectric harvester is obviously required before connected to the power management circuitry. A selection of different piezoelectric material and operating modes are the most famous approach for the output optimization rather than micro-cantilever beam geometry modification technique which is less complicated. Thus, there are four different models named as PPG 1, PPG 2, PPG 3 and PPG 4 are designed and simulated. The Zinc Oxide (ZnO) material is mainly used in this paper due to its high piezoelectric coupling, environmental friendly and flexibility in processing [11-14].

2. Piezoelectric Power Generator (PPG) 3D modelling
The micro-cantilever beam PPG sensor 3D model is designed using COMSOL Multiphysics software approach. Figure 1 gives a picture of major PPG sensor components in 3D model geometry
including the piezoelectric material, bottom electrode, top electrode, proof mass, and supporting beam. There are four different geometries are proposed to investigate the mechanical to electrical performances in terms of electrical output power. The geometric shapes are rectangular with narrow proof mass (PPG 1), rectangular with big proof mass (PPG 2), trapezoidal (PPG 3) and wide-fixed trapezoidal (PPG 4) are designed.

Figure 2 portrays the geometries with the corresponding 3D model using COMSOL Multiphysics software. The PPG sensor model is made up of Si as the supporting beam with a thin layer of ZnO deposited on top of the Si beam. A proof mass from Si material is attached at the beam free end to reduce the frequency resonance and easily match with the target vibration frequency for maximum electrical output power generation. The frequency target should be less than 200 Hz, the existence frequency in the ambient [10]. The proof mass is designed to have a dimension of 6000 x 6000 x 420 µm$^3$ except for the PPG 1 and PPG 4. The proof mass dimension for PPG 1 is 6000 x 3000 x 420 µm$^3$ meanwhile for PPG 4 is 4000 x 4000 x 200 µm$^3$. The proof mass different value is purposely given for structural firmness control to avoid the beam from broken during operation. The length dimension of PPG sensor is varied in range of 1000 µm to 5500 µm. The thickness dimension for micro-cantilever beam PPG sensor based on previous experimental work to ensure the fabrication reliability which is 0.3 µm for ZnO and 30 µm for Si [12]. The Body Load, $F_b$ boundary is assigned to the whole structure as input for a reason the PPG sensor start to vibrate and simultaneously inducing a mechanical strain. The fixed end of the PPG sensor is terminated by a load resistance in the range of $10^2$ up to $10^{10}$ for demonstration in the real applications. Thus, the optimal value of load resistance could be found and also to investigate the effect of the resistive load value to the electrical output power. This is done by adding the electrical circuit interface. The Floating Potential boundary is applied for the ZnO layer upper face, while the Ground boundary for the lower face for the electrical behavior investigation. The model is meshed to a group of simpler finite element bricks before FEM analysis conducted.

Figure 1. 3D model geometry.
Figure 2. Micro-cantilever beam shapes: (a) PPG 1; (b) PPG 2; (c) PPG 3; (d) PPG4
3. Result and discussion

This section is divided into three sections which are frequency resonance, resistive load, and electrical output result. The corresponding result for PPG 1, PPG 2, PPG 3, and PPG 4 are discussed in details.

3.1 Frequency Resonance Result

The proposed PPG sensor is purposely designed with different micro-cantilever beam geometries in order to determine the lower frequency resonance. Furthermore, a modification to length dimension is made as the change to width dimension has no significant effect on frequency resonance [5]. There are ten samples of length dimension taken into consideration starting from 1000 µm to 5500 µm with 500 µm separation. Hence, Figure 3 depicts the influence of different length dimension to PPG sensor frequency resonance.

![Figure 3. The influence of length dimension against frequency resonance.](image)

From the plotted result, the frequency resonance for the PPG sensor designs are matched to the frequency target which is less than 200 Hz at the specific length dimension. Both PPG 2 and PPG 3 are discovered to achieve the match frequency at 1500 µm, while the PPG 1 and PPG 4 at 2000 µm and 3500 µm respectively. The frequency resonance is revealed to decrease when the length dimension is increasing.

The PPG 2 tends able to operate at the lowest frequency resonance as low as 52.77 Hz at the longest length dimension compared to other designs. The PPG 3 offers second lower frequency resonance which is 54.70 Hz followed by PPG 1 with 74.59 Hz, while PPG 4 indicates the higher frequency resonance which is 120.17 Hz. Fortunately, the frequency resonance for all four proposed PPG sensor are less than 200 Hz. The main factor contributes to this condition is longer length dimension resulting lower beam stiffness. The beam stiffness is measured based on the induced stress at the beam fixed-end where the lower induced stress indicates the beam at lower stiffness. The lower stiffness allow the beam to swing easily when subjected to enough energy at resonance. Moreover, the low frequency resonance is easily reachable when the beam stiffness is low. As to strengthen these arguments, an analysis on length dimension against induced stress is made and the result clearly plotted in Figure 4. Thus, from the result, the lowest induced stress is obtained at the longest length dimension. Therefore, both results in Figures 3 and 4 prove the longer length dimension resulting a lower induced stress that offers lower frequency resonance.
Consequently, a new excitation frequency is required as to avoid any failure due to PPG sensor reaching the maximum strength when vibrates exactly at the resonance. Table 1 is listing the obtained PPG sensor frequency resonance and the corresponding arbitrarily adjusted frequency.

### Table 1. The PPG sensor adjusted excitation frequency.

| PPG sensor | Frequency resonance, Hz | Adjusted frequency, Hz |
|------------|--------------------------|------------------------|
| PPG 1      | 74.59                    | 80                     |
| PPG 2      | 52.77                    | 60                     |
| PPG 3      | 54.70                    | 65                     |
| PPG 4      | 120.17                   | 130                    |

### 3.2 Resistive Load Result

An analysis on determining the optimal load resistance, $R_{load}$ is conducted in order to demonstrate the proposed PPG sensor to the real application. Based on the result plotted in Figure 5, PPG 2 precedes with 393 mV followed by PPG 1 with 376 mV. Then, the output voltage produced by PPG 3 is 127 mV, while 158 mV from PPG 4. There is obviously seen the output voltage for each PPG sensor is remain constant starting from 10 MΩ.
The Kirchhoff’s Voltage Law (KVL) is applied to describe the finding on output voltage remains constant starting from 10 MΩ although the \( R_{\text{Load}} \) value is continue increased. The \( R_{\text{Load}} \) is parallel connected with PPG sensor. The KVL states that the total voltage in a closed loop is equal to zero as simply derived in Equations (1) and (2) based on the circuit in Figure 6.

\[-V_{\text{in}} + V_{\text{Load}} = 0\]  

Thus,

\[V_{\text{in}} = V_{\text{Load}}\]  

![Figure 6](image-url)  

**Figure 6.** The load resistance, \( R_{\text{Load}} \) connection.

Therefore, based on Equation (2), the PPG sensor accumulated voltage from harvested vibration is revealed when the \( R_{\text{Load}} \) at the optimal value.

### 3.3 Electrical output power result

Figures 7 and 8 depict the electrical output results due to vibration amplitude dependence at 10 MΩ, the optimal \( R_{\text{Load}} \) value. As clearly seen, the relationship between acceleration and produced electrical output is directly proportional.

![Figure 7](image-url)  

**Figure 7.** The output voltage for each PPG sensor.
Figure 8. The output power for each PPG sensor.

The produced electrical output is increasing when the acceleration value is further increased. Hence, the obtained result at 1 g vibration amplitude is referred in order to describe the electrical output performance for each PPG sensor. 1 g is equal to the acceleration from gravity which is 9.81 m/s². Therefore, the PPG 1 is producing 376 mV of output voltage, while 14 nW for the corresponding output power. Then, PPG 2 produces 393 mV of output voltage, while the output power is 15 nW. The next proposed PPG sensor namely as PPG 3 is able to generate 127 mV, and 2 nW of output voltage, and output power correspondingly. The fourth PPG sensor which is PPG 4 is successfully producing 158 mV of output voltage, while 2 nW for the output power.

4. Conclusion

This research paper deals with electrical output power optimization by the simple and less complicated micro-cantilever beam modification. The main focus is to design the PPG sensor with lower vibration frequency to easily match with the target ambient vibration frequency. The different micro-cantilever beam geometry produced different performance outputs based on the obtained results. From the frequency resonance analysis, all the proposed PPG sensor tend able to operate at lower frequency which is less than 200 Hz. From the finding, the proposed geometries are suitable to be used as ambient vibration harvester. However, the PPG 2 sensor gives a superior performances with producing the higher electrical output power at lowest frequency.

5. References

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