Green Energy Supply: Mechanical Vibration to Electricity Energy Transduction using Optimized Piezoelectric Power Generator

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***Abstract*— The rapid growth of electronic devices miniaturization attract the researchers interest either to save space or for cost reduction. The main purpose of miniaturization is to implement the concept of portable and flexibility in order to locate the devices everywhere without connected to a power strip. Therefore, the use of battery as a power supply is the only choice to realizing the concepts. However, the battery limited lifespan, bulky size, and high replacement cost are the main disturbing issues. Moreover, the improper battery disposal gives the detrimental effects to the environment and human being. Thus, energy harvester based on zinc oxide (ZnO) piezoelectric material has been chosen as a vibration energy to electrical power transducer as it is compatible with microelectromechanical systems (MEMS) technologies, which can generate power from µW up to mW level power. Powering the devices using energy harvester is really suggested as it can provide clean energy, no need for frequent battery replacement and long-term solution. This research focus on designing and simulating the four different models of micro scale piezoelectric power generator (PPG) cantilever beam type named as PPG 1, PPG 2, PPG 3 and PPG 4 using COMSOL Multiphysics approach. The models with attached proof mass at the end tip were analyses to investigate the capability in converting the ambient vibration energy which is commonly below than 200 Hz and less than 1 g (1 g = 9.81 m/s^2) acceleration amplitudes. Finite element method (FEM) simulation was done with two types of analysis taken. In order to obtain the required results which are frequency resonance analysis and evaluation of electrical output power, eigenfrequency and frequency domain modules were used. As a result, the frequency resonance for all models is below than 200 Hz. PPG 2 shows the superior performances that produce the highest output voltage which is 192 mV, and 66 nW of output power at 562 kΩ of resistive load.**

Keywords— Energy harvesting; MEMS; Piezoelectric; Vibration energy; ZnO

I. Introduction

Energy harvesting is a process of accumulating the energy exist in the surrounding environment such as heat, light or vibration and converted into usable electrical energy by the harvester mechanism. Thus, powering the devices using energy harvester is really suggested due to provide clean energy, no need for frequent battery replacement and long-term solution [1-3]. The concept of “place and forget” has been introduced based on the long lasting lifespan provided by the energy harvesting system. Therefore, a power source with this concept is really suitable for paired with the wireless sensor located in remote area [4] as well as installed in a building. The basic components of energy harvesting system can be simplified as shown in Figure 1.

Among the energy sources available from the ambient, the mechanical vibration energy gained most interest from the researchers because of their abundance, always present and transmissibility through different media [5]. The mechanical vibration can be harvested by the several types of electromechanical devices. The devices are electrostatic [6], electromagnetic [7], piezoelectric [8-10] and hybrid [11].

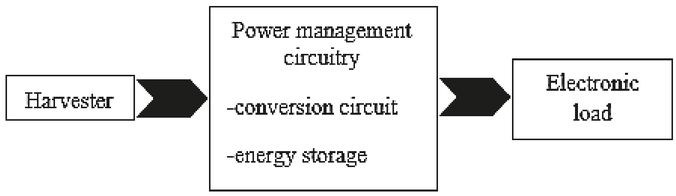

Figure 1. Basic components of energy harvesting system.

However, piezoelectric harvester has attract more attention due to no external voltage required, compact and simpler architectures, exhibit higher energy density, compatible with microelectromechanical system (MEMS) technology for miniaturization and able to directly convert strain energy into electrical energy [12]. The vibration energy can be harvested by the piezoelectric harvester using the material such as lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), zinc oxide (ZnO) and aluminium nitride (AIN) [13]. Therefore, MEMS-based zinc oxide (ZnO) piezoelectric harvester is chosen in this research work for further investigation on the electricity production. Thus, the optimization on geometry of piezoelectric cantilever beam type is clearly presented with voltage multiplier modification as the power management circuitry.

II. STATE OF THE ART

A. Energy Harvesting Background

The present energy in the ambient as a result from the natural environmental phenomenon or industrial process are captured and transformed into electrical energy using the corresponding energy harvester. The example of available energy sources such as mechanical energy obtained from vibration, stress and strain [14-15], thermal energy from the human body [16-17], solar energy from light sources [18], wind and fluid generated by air and fluid flow [19] and widely used radio frequency (rf) energy from ubiquitous radio transmitters and television broadcasting [10]. Hence, Table I summarizes the power density obtained from some of available energy source in the ambient based on the previous research works.

Table I. Power density for ambient energy sources.

Energy source	Source	Power density	Reference
Solar	Sunlight Illumination	Outdoor = 60 µW/cm^2 Indoor = 3 µW/cm^2	[17]
Vibration	Machine Vibration Human motion	Electromagnetic = 1.39 mW/cm^3 Electrostatic = 6.45 µW/mm^2 Piezoelectric = 249 µW /mm^3	[14-15]
Thermal	Temperature different	0.41 mJ/cm3	[16]
Ambient Radiation	RF signal	32 µW	[10]

B. Vibration to Electricity Energy Harvesting

Mechanical energy receive more attention because able to obtained almost everywhere at any time where thermal or light energy is not available. Thus, the mechanical energy harvesting process which converting the vibration to electricity is achieved using three electromechanical mechanisms known as electromechanical, electrostatic and piezoelectric. Based on these three vibration harvester, electrostatic harvesters need separate voltage sources [11]. Meanwhile, the development of electromagnetic harvester is difficult to be fabricated in micro-scale [13]. In contrast, the piezoelectric harvester has the ability to exhibit higher energy density and therefore suitable for practical applications [14]. In addition, piezoelectric harvester has simple architectures compared to electrostatic and electromagnetic harvesters, also compatible to be fabricated by micromachining techniques and directly integrated with MEMS devices [15].

C. Piezoelectric Vibration Energy Harvester

Piezoelectric effect or piezoelectricity is a term used as to describe the transduction of mechanical vibration to electricity or electricity to vibration by piezoelectric materials. An electricity is generated from the piezoelectric materials when shape deformation occurred during subjected to a stress. This condition also known as direct piezoelectric effect, while the converse piezoelectric effect does the reverse. Therefore, the constitutive equations to describe the direct piezoelectric effect according to IEEE Standard, 1987 [6] is given in Equation (1) where S is the strain component resulted from the product of s as the elastic compliance constant (m^2/N) and T as the stress component (N/m^2) at constant stress. Then, summed up to the product of d, the piezoelectric constant (m/V or C/N) and E, the electric field component (V/m) at constant electric field. However, Equation (2) is referred to describe the slight change in piezoelectric material dimension due to applied electric field where D is the resulting displacement component (V/m) at constant displacement and ε is the dielectric constant of the piezoelectric material (F/m).

$$S = s^E T + dE \quad (1)$$
$$D = dT + \varepsilon^T E \quad (2)$$

Two main types of piezoelectric materials which known as natural crystal and synthetic or man-made. The materials that classified under natural category are Rochelle salt, cane sugar, quartz and semi-precious tourmaline stone. However, developing the synthetic piezoelectric material gained more interest among the researchers due to high electromechanical coupling [7]. The man-made piezoelectric ceramic known as lead zirconate titanate (PZT) shows the superior high charge compared to other materials [8]. Additionally, the ability in MEMS fabrication process has attract the researchers to continue using PZT as the main materials for the piezoelectric vibration energy harvester [9]. Thus, several studies and experimental works have been done on the performance of piezoelectric energy harvester made from PZT [10-11]. However, the critical drawback of PZT is the present of more than 60 % lead (Pb) by weight and creates hazards during processing and potentially environmentally toxic during disposal [12]. Nevertheless, the electronic industry excluded from the strict restrictions by the regulatory agencies on the use of lead due to lack of a suitable replacement to PZT [13]. As the technology advances, the lead-free synthetic piezoelectric material such as aluminium nitride (AlN) and ZnO have been reported as a good alternative for replacing the most performing but toxic PZT [14] since both of the materials compatible with existing semiconductor processes [2].

D. Microelectromechanical Systems (MEMS) Based Piezoelectric Vibration Energy Harvester

Based on aforementioned vibration to electricity energy harvester in Section C, the piezoelectric transduction is most suitable for integration with MEMS devices and wireless sensors which can be effectively placed in small volume [15] and able to harvest the vibration energy over a wide range of frequencies. The low-level vibration level is targeted because of the wide range of applications that could be used as a power generation. Thus, Table II summarizes the source of low level vibration energy from the surrounding equipment which obtained using a data logger SKF CMVA55 with CMSS787A accelerometer [16]. Based on the recorded data, has proven the vibration energy exists in the low frequency range which normally less than 200 Hz. Therefore, the piezoelectric harvester should be design to have a resonance frequency close with the vibration source frequency for optimum electrical energy generation. Previous researchers have agreed that piezoelectric harvester with cantilever beam configuration is suitable for low frequency condition for the low self-vibration frequency since the structure has a limited maximum displacement when subjected to a force [17]. As to conclude, Table III summarises the previous works on development of MEMS-based piezoelectric vibration to electricity harvester with various materials.

Table II. Frequency, Hz and acceleration, m/s2 for various ambient vibration sources [16].

Vibration source	Peak Frequency, Hz	Peak acceleration, m/s^2	Sensing Location
Microwave oven	40	0.49	Top cover
Household refrigerator	110	0.14	Near compressor
Drilling machine	150	0.81	Drill head
Washing machine	62	0.82	Motor stand
Cloth dryer	59	4.21	Motor stand

Table III. Summary of previous works on MEMS-based piezoelectric harvester.

Author	Device	Dimension	Resonant frequency, Hz	Harvested voltage, mV	Harvested power, µW
[10]	AIN cantilever	2 mm x 0.75 mm x 0.5 µm	114	-	0.054
[12]	AIN cantilever	9 mm x 7.2 mm	438	20	-
[9]	Array PZT cantilever	8 mm x 5 mm x 5 µm	32.8	42	-
[6]	ZnO cantilever	1000 µm x 500 µm x 1.4 µm	1300	-	0.98
[15]	PZT cantilever	0.7690 mm^3	183.8	101	416

III. METHODOLOGY

This section describes the PPG sensor 3D modelling process using COMSOL Multiphysics software approach. The PPG sensor structure is introduced as a cantilever beam type with one end is fixed and another end is free to vibrate. There are four different cantilever beam PPG sensor geometries are designed with corresponding novel dimensions. The PPG sensor is made of two materials layered to each other. The supporting beam and proof mass are made from silicon, Si while the ZnO is selected as the piezoelectric material. The 3D model is designed based on blocks combination. 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) which designed in piezoelectric devices interface sub-branch from structural mechanics module found in physics toolbar. The PPG sensor is designed below than 200 Hz for both applications in order to obtain the maximum electrical energy generation. Figure 2 portrays the geometries with the corresponding 3D model using COMSOL Multiphysics software. 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. 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 based on the previous work [17] 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 [17].The Body Load, F_v 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. 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. FEM simulation is conducted with two types of analysis taken. The eigenfrequency and frequency domain modules have been used in order to obtain the required results which are resonance frequency analysis and evaluation of electrical output power.

IV. RESULT AND DISCUSSION

A. Resonance Frequency

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 [15]. 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. The frequency resonance is revealed to decrease when the length dimension is increasing. Both PPG 2 and PPG 3 are discovered to achieve the match frequency at 1000 µm and 1100 µm, while the PPG 1 and PPG 4 at 1700 µm and 3300 µm respectively. The PPG 2 tends able to operate at the lowest frequency resonance as low as 52.77 Hz at 5500 µm of length

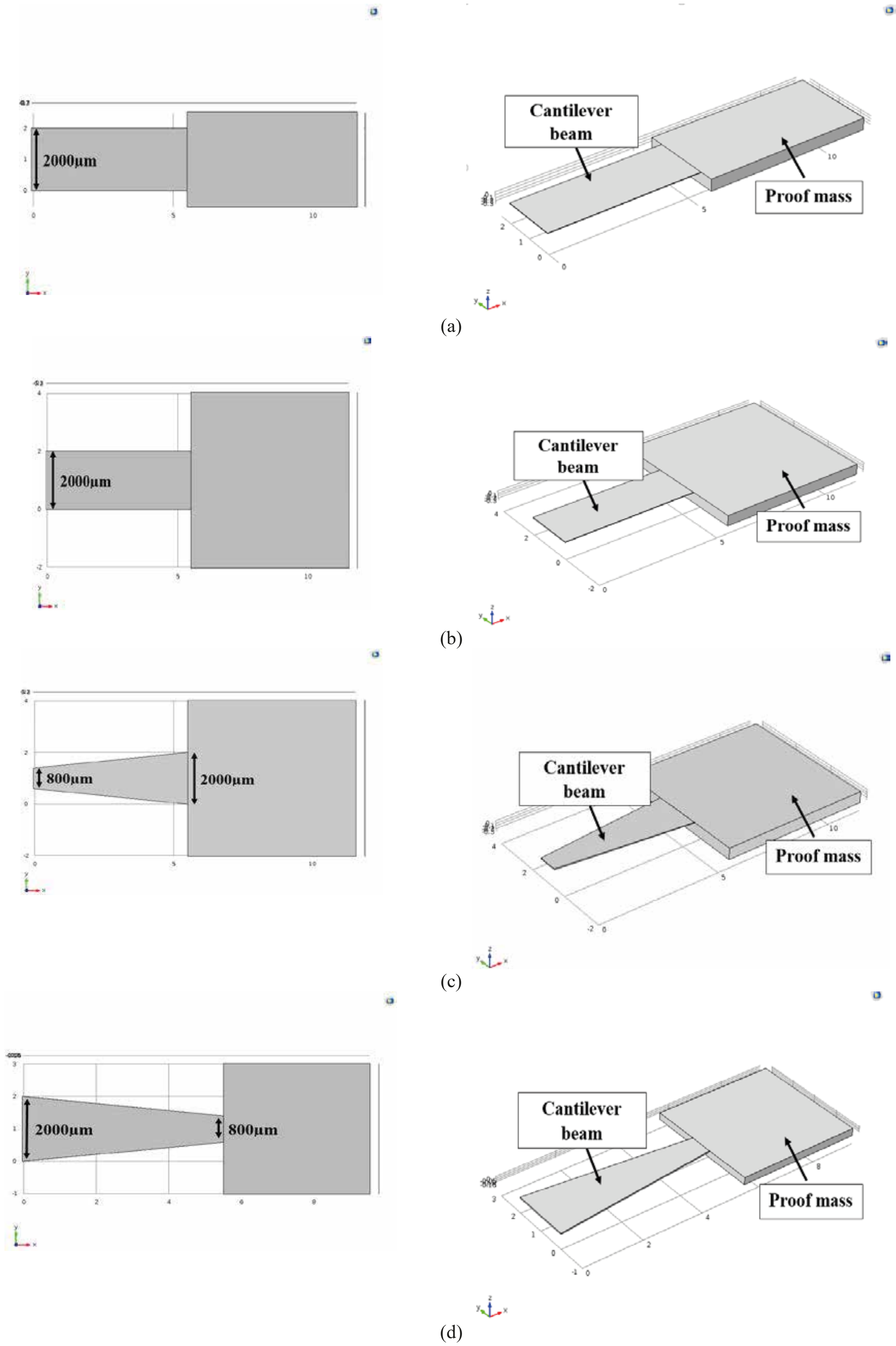

Figure 2. Micro-cantilever beam shapes: (a) PPG 1; (b) PPG 2; (c) PPG 3; (d) PPG4

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. However, PPG 4 indicates the higher frequency resonance which is 120.17 Hz. The main factor contributes to this condition is the longer length dimension resulting lower beam stiffness as shown in (3). Besides, the total mass of the PPG model also give an impact on the frequency resonance based on the relationship between them as shown in (4) where f_r is refer to resonance frequency and *m* is the mass of PPG sensor.

$$k = \frac{3EI}{L^3} \tag{3}$$

where,

E	=	Young modulus
I	=	Moment of inertia
L	=	Length
k	=	Stiffness

$$f_r = \frac{1}{2\pi}\left(\sqrt{\frac{k}{m}}\right) \tag{4}$$

The total mass of the PPG models are obtained directly from the software by integrating the density and shown in Table IV. Thus, from the mass value, it is obviously revealed that PPG 2 able to operate at the lowest frequency due to high value of total mass compare to other models.

Table IV. Mass value for each PPG model.

PPG model	Mass, kg
PPG 1	1.4×10^{-5}
PPG 2	3.6×10^{-5}
PPG 3	3.5×10^{-5}
PPG 4	8×10^{-6}

B. Electrical Output Generation

An analysis on electrical output generation is done at resonance frequency as obtained in section A. A resistive load is purposely added in order to define the electrical output power for each PPG model. The incorrect resistive load value prevent the PPG model from generating the required maximum output power. Based on the simulation result, the optimal resistive load for PPG 1 is 562 kΩ which resulting 161mV of output voltage and 46 nW of output power. Then, the output voltage generated by PPG 2 is 192 mV and producing 66nW of output power at similar resistive load value as PPG 1. The maximum output power generated by PPG 3 is 7 nW, while the output voltage is 86 mV at optimal resistive load of 1 MΩ. Lastly, PPG 4 produce 82 mV of output voltage and 12 nW of output power at optimal resistive load value similar with PPG 1 and PPG 2 which is 562 kΩ. Figure 4 indicates the relation of output voltage and resistance value while Figure 5 shows the generated output power for each PPG model.

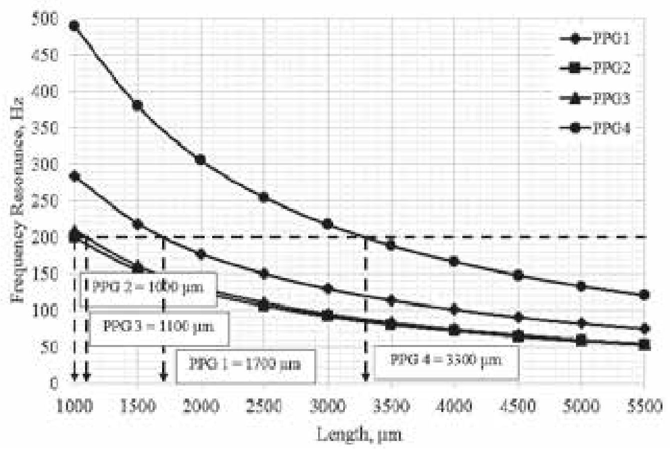

Figure 3. The influence of length dimension against frequency resonance.

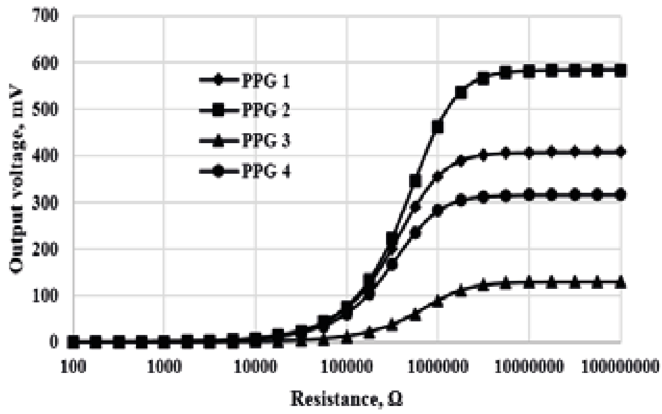

Figure 4. An influence of resistance value to the produced output voltage for each PPG sensor.

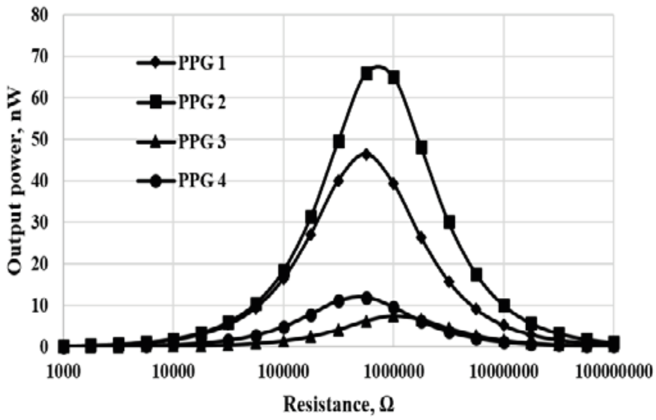

Figure 5. Output power produced by each PPG sensor.

V. 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.

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