DESIGN OF VIBRATION ENERGY HARVESTER FOR LOW VOLTAGE POWER SUPPLY USING FINITE LEMENT METHOD (FEM) ANALYSIS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	2-dimension
3D	3-dimension
AC	Alternating Current
ADS	Advance Design System
AlN	Aluminium Nitride
DC	Direct Current
FEM	Finite Element Method
HF	Hydrofluoric Acid
Hz	Hertz
IoT	Internet of Things
KOH	Potassium Hydroxide
MEMS	Microelectromechanical Systems
Mo	Molybdenum
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Ni	Nikel
Pb	Lead
PMN-PT	Lead Magnesium Niobate-Lead Titanate
PPG	Piezoelectric Power Generator
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
RF	Radio Frequency
RIE	Reactive-Ion Etching
Si	Silicon
SMT	Surface Mount Technology

SoESE	School of Electrical Systems Engineering
UniMAP	Universiti Malaysia Perlis
ZnO	Zinc Oxide

LIST OF SYMBOLS / NOMENCLATURE

$f_{1,2}$	Excitation frequency
B_{load}	Body load
T_{int}	Time interval
a_g	Acceleration due to gravity
A	Beam area
C	Damping matrix
C_o	Smoothing capacitor
D	Displacement
d	Piezoelectric constant
D_{1-4}	Diodes
E	Electric field / Young Modulus
E_p	Piezoelectric material Young's moduli
E_s	Supporting beam material Young's moduli
ε	Dielectric constant
g	Gravity acceleration (9.81 m/s^2)
I	Moment of inertia
i_{in}	Electrical current
K	Electromechanical coupling coefficient
k	Stiffness matrix
l / L	Length
m	Beam mass
M	Mass matrix
r	Radius distance

R_o	Resistive load
s	Elastic compliance constant
S	Strain
t	Beam thickness
T	Stress / Time
$V_{p\text{-}p}$	Voltage peak to peak
w	Beam width
α	Mass-proportional damping coefficient
β	Stiffness-proportional damping coefficient
δ	Displacement

ζ	Critical damping ratio
θ	Spherical Polar angle
σ	Induced stress
φ	Spherical Azimuthal angle
ω	Angular frequency resonance
Ω	Electric unit of resistance (Ohm)
a	Acceleration
π	Mathematical constant (3.142)
ρ	Density

Reka Bentuk Penangkap Tenaga Getaran untuk Bekalan Kuasa Voltan Rendah Menggunakan Analisis Kaedah Unsur Terhingga (FEM)

ABSTRAK

Pertumbuhan pesat pengecilan peranti elektronik menarik minat para penyelidik samada untuk menjimatkan ruang atau pengurangan kos. Tujuan utaman pengecilan ini adalah untuk melaksanakan konsep mudah alih untuk meletakkan peranti-peranti di mana sahaja tanpa terhubung kepada wayar kuasa. Oleh itu, penggunaan bateri sebagai pembekal kuasa adalah satu-satunya pilihan untuk merealisasikan konsep-konsep ini. Walau bagaimanapun, pelupusan bateri yang tidak bersesuaian memberi kesan –kesan buruk kepada alam sekitar dan manusia. Penuaian tenaga dicadangkan sebagai penyelesaian terbaik kerana menawarkan keselesaan dan keselamatan kepada peranti berbanding bateri. Walau bagaimanapun, pembangunan penuai getaran bebas plumbum untuk tenaga getaran persekitaran berfrekuensi rendah jarang dilaporkan. Oleh itu, penuai tenaga berdasarkan zink oksida (ZnO) bahan piezoelektrik telah dipilih sebagai pengubah tenaga getaran kepada kuasa elektrik kerana bersesuian dengan teknologi sistem mikroelektromekanikal (MEMS) yang boleh menjana tahap kuasa dari μW sehingga mW. Menjana peranti-peranti menggunakan penuai tenaga benar-benar dicadangkan kerana menyediakan tenaga bersih, tidak perlu penggantian yang kerap dan penyelesaian jangka panjang. Kajian ini menumpukan kepada mereka dan mensimulasi empat model skala mikro penjana kuasa piezoelektrik (PPG) jenis julur yang bernama PPG 1, PPG 2, PPG 3 dan PPG 4 menggunakan pendekatan COMSOL Multiphysics. Model-model dengan pemberat yang disertakan pada hujung akhir telah dianalisis untuk mengkaji keupayaan dalam menukar tenaga getaran persekitaran yang umumnya di bawah 200 Hz dan kurang daripada 1 g (1 g = 9.81 m/s^2) amplitud pecutan. Dua keadaan bekerja dipertimbangkan untuk dianalisis. Keadaan pertama adalah melekatkan peranti PPG kepada jentera, sementara keadaan kedua adalah meletakkan peranti PPG dekat dengan punca-punca kuasa gelombang bunyi di persekitaran. Simulasi kaedah unsur terhingga (FEM) telah dilakukan dengan dua jenis analisis. Bagi memperolehi keputusan yang diperlukan iaitu analisis frekuensi salunan dan penilaian kuasa keluaran elektrik, modul *eigenfrequency* dan *frequency domain* telah digunakan. Hasilnya, frekuensi salunan untuk semua model adalah di bawah 200 Hz. Sebagai penekanan untuk kerja ini, PPG 4 menunjukkan keupayaan unggul daripada model lain kerana dapat menjana kuasa keluaran tertinggi iaitu 17.11 μW apabila disepadukan dengan pengganda voltan. Sementara itu, PPG 2 lebih sesuai untuk menuai frekuensi rendah tenaga getaran kerana dapat bergetar pada frekuensi yang lebih rendah berbanding dengan model lain iaitu serendah 52.77 Hz. Berdasarkan kedua-dua dapatan tentang PPG 2 dan PPG 4, PPG 4 dipilih sebagai model yang lebih baik kerana mampu menjana kuasa keluaran lebih tinggi pada frekuensi salunan kurang daripada 200 Hz.

A Design of Vibration Energy harvester for Low Voltage Power Supply using Finite Element Method (FEM) Analysis

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 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 improper battery disposal gives the detrimental effects to the environment and human being. Energy harvesting is proposed as the best solution as it provides more comfort and safety to the device compared to the old-fashioned battery. However, the development of lead-free vibration harvester for low frequency of ambient vibration energy is rarely reported. 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. Two working conditions are considered for the analyses. The first condition is to mount the PPG model to a machinery, while the second condition is to locate the PPG model close to the ambient sound wave energy sources. FEM simulation was done with two types of analysis taken. In order to obtain the required results which are resonant frequency 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. As a highlight of this work, PPG 4 shows the superior capability than other model since able to generate the highest output power which is 17.11 µW when integrated with voltage multiplier. Meanwhile, PPG 2 is more suitable for harvesting low frequency of vibration energy since able to vibrate at lower frequency compared to other models which is as low as 52.77 Hz. Based on these two findings about PPG 2 and PPG 4, PPG 4 is selected as the better model since capable in generating higher output power at resonant frequency less than 200 Hz.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Energy harvesting is an emerging research branch among the researchers since the demand on self-powered electronic devices keep increasing (Darmayuda et al., 2012, Do, Nguyen, Han, & Ha, 2015, Chiou, Member, & Hsieh, 2016). Energy harvesting is a process of accumulating energy that exist in the surrounding environment such as heat, light or vibration, and converted it into usable electrical energy by the harvester mechanism. Thus, powering the devices using energy harvester is really suggested since it can provide clean energy, no need for frequent battery replacement and long-term solution (Viehweger, Baldauf, Keutel, & Kanoun, 2012 & Balpande, Pande, & Patrikar, 2016). 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 to be paired with the wireless sensor located in remote area (Lallart, Wang, Sebald, Petit, & Guyomar, 2014 & Kanan, 2016). The basic components of energy harvesting system can be simplified as shown in Figure 1.1.

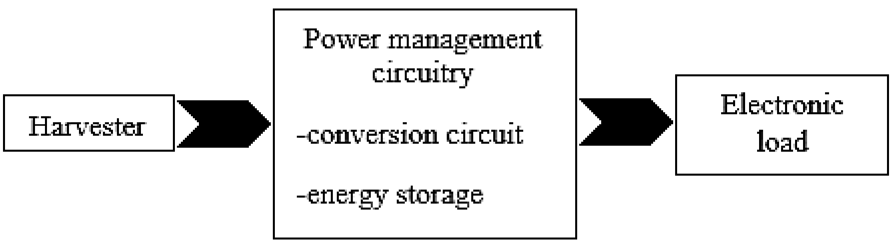

Figure 1.1: Basic components of energy harvesting system.

The energy source is collected and transformed to electricity by the harvester, while the power management circuitry manage the produced electrical energy into a suitable form for application. 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 (Galchev, Kim, & Najafi, 2011 & Berdy et al., 2012). The mechanical vibration can be harvested by several types of electromechanical devices. The devices are electrostatic (Wei, Risquez, Mathias, Lefeuvre, & Costa, 2015) , electromagnetic (Palagummi & Yuan, 2015), piezoelectric (Lei et al., 2014; Zhao, Shang, Luo, & Deng, 2015 & Xiao et al., 2016) and hybrid (Ab Rahman, Kok, Ali, Hamzah, & Aziz, 2013).

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 (K. Fan, Chang, Chao, & Pedrycz, 2015). 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 (AlN) (Sharma, Olszewski, Torres, Mathewson, & Houlihan, 2015). Therefore, MEMS-based piezoelectric harvester is chosen in this research work for further investigation on produced electricity. Thus, an optimization of piezoelectric cantilever beam type on geometry for low frequency which is less than 200 Hz is clearly presented with voltage multiplier modification as the power management.

1.2 Problem Statement

The electronic devices downsizing continues to grow and attract interest among the researchers either to save space or for cost effective (Ferreira & Almeida, 2012 &

Iwai, 2015). The Fujitsu Semiconductor Group has released their new memory chip MB85RC64T, 64Kbit FRAM with almost 80 % of mounted surface area reduction which is from 31.8 mm^2 to 6 mm^2 (Fujitsu Semiconductor Limited, 2016). MEMS technology is one of the most encourage downsizing technique which is still being investigated and implemented by the researchers (Kundu, Sinha, Bhattacharyya, & Das, 2013, Langfelder, Laghi, Minotti, Tocchio, & Longoni, 2014 & Hu, Huang, Huang, & Wu, 2017). The main purpose of electronic devices miniaturization is to implement the concept of portable and flexibility which can be placed almost everywhere without tethering to a power strip. Thus, the use of batteries as a power source is the ultimate choice for realizing these concepts.

However, there is a big challenge for a system that contains hundreds of wireless sensor located in various place without wiring connection such as the current trend technology of Internet of Things (IoT) (Perera et al., 2014). The battery limited lifespan, bulk size, and high replacement cost are the main disturbing issues (Luo, Wang, & Li, 2015, EnOcean, 2015, Rashidzadeh, Kasargod, Supon, Rashidzadeh, & Ahmadi, 2016 & Sekine, 2017). Moreover, the improper battery disposal gives the detrimental effects to the environment and human being (Byrne, 2012 & Dionisi, Marioli, & Sardini, 2016).

Thus, energy harvesting is proposed as the best solution as it provides more comfort and safety to the device compared to the old-fashioned battery (Hannan, Mutashar, Samad, & Hussain, 2014). The ambient vibration energy is the preferred source as it is present in many systems such as structural, industrial machinery and wireless sensor (Patil & Reddy, 2016 & Mutsuda, Tanaka, Patel, & Doi, 2017). The harvested energy can be used effectively to self-powered the low power consumption sensors particularly placed in remote area without any external power source (Karimi, Karimi, & Tikani, 2016, Moure et al., 2016 & Yildirim, Ghayesh, Li, & Alici, 2017). Previous works on harvesting vibration energy sources have been widely reported by utilizing lead zirconate titanite (PZT). The development of lead-free vibration harvester has begun attract the interest among the researchers due to present of more than 60% of lead (Pb) in PZT. However, an implementation of MEMS-based of lead-free material is rarely reported for harvesting the vibration energy source less than 200 Hz. The vibration energy source from the ambient normally exist at low frequency that is less than 200 Hz. Therefore, four different shapes of zinc oxide (ZnO) piezoelectric cantilever beam are investigated on optimal MEMS dimension and performances in generating an output voltage at frequency of vibration source which is less than 200 Hz. Additionally, an implementation of voltage multiplier is considered in order to rectify the direct generated output voltage from piezoelectric. The piezoelectric energy harvester which is compatible with MEMS technology is the suitable transducer for harvesting the target vibration energy at low frequency. Hence, with the presence of energy harvesting technology as the power source, the electronic devices miniaturization is no longer obstructed.

1.3 Objectives

The main aim of the present research is to design a lead-free material of ambient mechanical vibration and sound wave energy harvester at low resonant frequency less than 200 Hz. The MEMS based piezoelectric power generator (PPG) sensor and passive voltage multiplier circuitry are proposed in harvesting the target vibration source as well as to rectify the gained output voltage into usable voltage level. Thus, the objectives can be summarized as follows:

1. To develop a cantilever beam type of ZnO PPG with resonant frequency less than 200 Hz in order to harvest the low frequency of ambient vibration energy source.

2. To evaluate the proposed PPG model performances for mounted and unmounted condition in harvesting the target vibration and transform into electrical energy using FEM module.
3. To propose the integration of passive voltage multiplier with the PPG model for output voltage rectification and step up to desired direct current (DC) voltage level using Advance Design System (ADS) software.

1.4 Scope of Work

The overall scopes of research are as follows:

1. The proposed research starts with MEMS-based 3-dimension (3D) modelling design of cantilever beam type PPG model with four different beam shapes using COMSOL Multiphysics software.
2. Then, the simulation analysis is conducted to determine the resonant frequency for each PPG model. The PPG model is designed to have a match frequency with the target vibration source frequency which is less than 200 Hz for maximum electrical energy generation.
3. The investigation on mounted PPG model condition is performed to determine the electrical output voltage and output power. The frequency dependence analysis is applied to extract the electrical output from the PPG model as resulted from the vibration input.
4. The influence of damping factors is included during the analysis in order to investigate the energy loss of the PPG model close to the real application. The time dependence analysis is conducted to analyse the vibration pattern and

corresponding produced output voltage before and after considering the damping factors.

5. Based on the evaluation results for mounted condition, the PPG model performances analysis is continued with an unmounted condition. The spherical wave radiation boundary condition is applied as to represent the ambient sound wave energy source.
6. Finally, the number of stage for the voltage multiplier is defined by simulating the proposed circuitry with a surface mount technology (SMT) HSMS 2850 Schottky diode.

1.5 Thesis Organization

This thesis is organized to have five main chapters which consists of introduction, literature review, research methodology, result and discussion and the last one is conclusion. Chapter 2 provide a review of energy harvesting background by focusing on the ubiquitous vibration energy in order to justify the proposed improvement on transduction of vibration energy to electricity using piezoelectric.

Chapter 3 provides detailed process flow of PPG model in 3D modelling using COMSOL Multiphysics with two working condition for electrical energy determination. The required settings for FEM analysis are clearly descripted such as the boundary condition, the match mesh element as well as the materials selection.

Chapter 4 reveals the overall obtained results and brief discussion on FEM analysis findings. There are four major parts contain in this thesis which are resonant frequency, electrical energy determination and the voltage multiplier circuitry performances.

Thus, the entire works is concluded in Chapter 5. The conclusion is made as to conclude the proposed methodologies and the corresponding obtained results have successfully fulfilled the stated objectives. It is then, followed by the recommendations for future work which give the initial ideas for the next research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Energy harvesting can be defined as a process of capturing the nature source from the ambient and transformed to electricity using the corresponding harvester. Based on Figure 2.1, energy harvesting shows the ability in powering the small electronic products that are traditionally thought of as being not applicable. An implementation of electromechanical mechanism such as piezoelectric gives the opportunities to the microelectromechanical systems (MEMS) devices to be powered by the green source and at the same time realizing the demand for self-powered. Therefore, this chapter provides a review of energy harvesting background by focusing on the ubiquitous vibration energy.

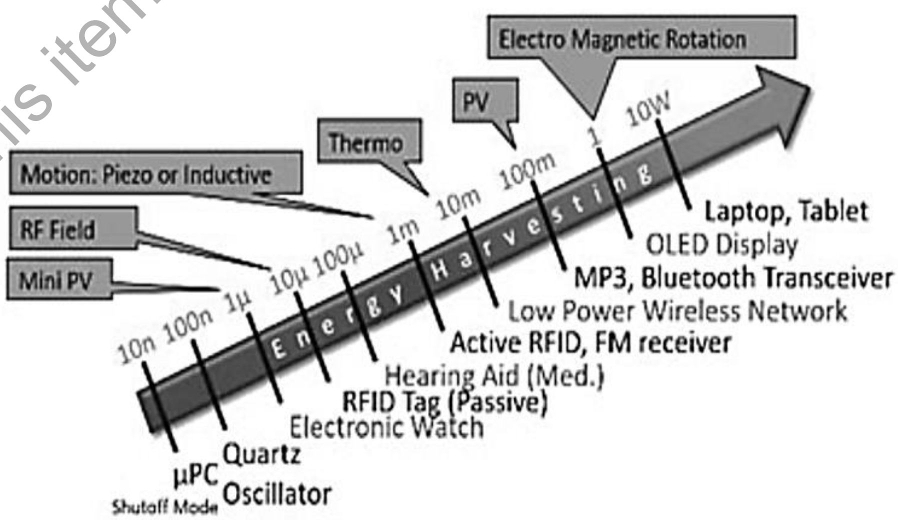

Figure 2.1: Power consumption for various applications (Zahnstecher, 2017).