HARNESSING ENERGY FROM MICRO VIBRATION USING SMART MATERIALS

AMEIRUL AZRAIE BIN MUSTADZA

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To my beloved wife, **Fara Fatihah** who believes in me even though I find it difficult to do so myself, my adorable daughter **Puteh ‘Arissa**, who gives me strength to complete this thesis and my parents, **Mustadza** and **Noorfah** who always believe in me and guide me in all my pursuits.

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ABSTRACT

Energy harnessing for the purpose of powering low power electronic devices has received much attention in the last few years. By harnessing ambient energy from the environment it will eliminate the need for batteries and supplying the portable electronic devices such as cell phones, laptops and MP3 players with infinite amount of energy. The ambient energy that can be harnessed to generate electricity comes from a wide range of sources but vibration energy shows a promising amount of power generation. In this study, conversion of mechanical vibration into electricity using piezoelectric vibration-to-electricity converter is undertaken with a focus to quantify the amount of power that can be generated and identify electronic devices that can fully utilize this power. The study is divided into two main parts which are simulation from the forced vibration data and laboratory experiment on vibrating mechanical equipments such as turbine and centrifugal pump. The simulation result shows that as the acceleration magnitude increases, the average direct voltage also increases from 4.5 mV to 8.1 mV and the average power output that could be harnessed also increases from 22.5 µW to 40.5 µW. Similarly, the experimental result shows that for the turbine, as the speed of the turbine increases from 1150 rpm to 1450 rpm, the average power produced increases from 1.63 µW to 2.02 µW. Also, for the centrifugal pump, as the speed increases from 1700 rpm to 1900 rpm, the average power produced increases from 3.02 µW to 3.06 µW. The experimental results also revealed that within 30 minutes, 1.84 µW of energy could be harnessed from the vibration of the turbine at speed of 1450 rpm while 3.06 µW of energy could be harnessed from the vibration of the centrifugal pump at speed of 1900 rpm. This power output is sufficient for low-powered wireless sensor networks in silent mode which can be used in variety of applications as indicated in the previous literatures.

ABSTRAK

Penggemblengan tenaga bagi tujuan membekalkan kuasa kepada peranti elektronik kuasa rendah telah mendapat perhatian sejak beberapa tahun kebelakangan ini. Dengan memanfaatkan tenaga ambien dari persekitaran, ia akan dapat mengurangkan kebergantungan kepada bateri dan membekalkan alat-alat elektronik mudah alih seperti telefon bimbit, komputer riba dan pemain MP3 dengan jumlah tenaga yang tidak terbatas. Tenaga ambien yang boleh dimanfaatkan untuk menjana tenaga elektrik datang dari pelbagai sumber tetapi tenaga getaran menunjukkan potensi jumlah penjanaan kuasa. Dalam kajian ini, penukaran getaran mekanikal kepada tenaga elektrik yang menggunakan piezoelektrik penukar getaran-kepada-elektrik dilaksanakan dengan fokus untuk mengira jumlah kuasa yang boleh dijana dan mengenal pasti peranti elektronik yang boleh menggunakan kuasa ini sepenuhnya. Kajian ini terbahagi kepada dua bahagian utama iaitu simulasi dari data getaran paksa dan eksperimen makmal ke atas peralatan mekanikal yang bergetar seperti turbin dan pam empar. Keputusan simulasi menunjukkan bahawa dengan kenaikan magnitud pecutan, voltan langsung purata juga meningkat daripada 4.5 mV kepada 8.1 mV dan kuasa purata yang boleh dimanfaatkan juga meningkat daripada 22.5 μW kepada 40.5 μW. Begitu juga, hasil eksperimen menunjukkan bahawa untuk turbin, apabila kelajuan turbin meningkat dari 1150 rpm ke 1450 rpm, kuasa purata yang dihasilkan meningkat dari 1.63 μW ke 2.02 μW. Di samping itu, untuk pam empar, apabila kelajuan meningkat dari 1700 rpm ke 1900 rpm, kuasa purata yang dihasilkan meningkat dari 3.02 μW ke 3.06 μW. Keputusan eksperimen juga mendedahkan bahawa dalam tempoh 30 minit, 1.84 μW tenaga boleh dimanfaatkan dari getaran turbin pada kelajuan 1450 rpm manakala 3.06 μW tenaga boleh dimanfaatkan dari getaran pam empar pada kelajuan 1900 rpm. Kuasa ini adalah mencukupi untuk rangkaian sensor tanpa wayar berkuasa rendah dalam mod senyap yang boleh digunakan dalam pelbagai aplikasi seperti yang dinyatakan dalam penulisan kajian terdahulu.

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LIST OF SYMBOLS

°C	-	Celsius
Φ_B	-	Magnetic flux
Ω	-	Ohm
δ	-	Mechanical strain
ε	-	Induced emf; Dielectric constant
ε_0	-	Dielectric constant of free space, Permittivity of free space
μ_0	-	Permeability of free space
σ	-	Mechanical stress
σ_y	-	Yield stress
A	-	Ampere
a	-	Acceleration
B	-	Magnetic field
C	-	Capacitance
c	-	Elastic constant
D	-	Electrical displacement (charge density)
d	-	Gap or distance between plates; Piezoelectric strain coefficient
dB	-	Decibel
E	-	Electric field
f	-	Frequency
Hz	-	Hertz
I, i	-	Current
k	-	Coupling coefficient; Piezoelectric constant
l	-	Length of one coil (2πr); Length of plate
m	-	Meter
N	-	Number of turns in coil
Q	-	Charge on capacitor
R	-	Resistance

rpm	-	Revolution per minute
s, sec	-	Second
t	-	Thickness
V, $Volt$	-	Voltage
V_p	-	Voltage peak
V_{pp}	-	Voltage peak-to-peak
W	-	Watt
w	-	Width of plate
Y	-	Modulus of elasticity (Young's Modulus)
y	-	Distance coil moves through magnetic field

LIST OF ABBREVIATIONS

A/D	-	Analog to Digital
AC	-	Alternate Current
AI	-	Analog Input
AO	-	Analog Output
AEH	-	Acoustic Energy Harvester
$BaTiO_3$	-	Barium Tinate
D/A	-	Digital to Analog
DAQ	-	Data Acquisition System
DC	-	Direct Current
DIO	-	Digital I/O
fpm	-	feet per minute
HVAC	-	Heating, Ventilation and Air Conditioning
I/O	-	Input to Output
IEPE	-	Integrated Electronic Piezoelectric
MFC	-	Macro-Fiber Composite
NI	-	National Instrumentation
PI	-	Physik Instrumente
PVDF	-	Polyvinylidene Fluoride
PZT	-	Lead Zirconate Tinate
PZT-5A	-	Hard Lead Zirconate Tinate
QP	-	Quick Pack
RFID	-	Radio Frequency Identification

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Over the last 20 years, the continuous development of technology has significantly reduced the size and increased the function of electronic devices and in parallel decreased their power consumption (Gonzalez *et al.*, 2002). Nowadays hand held and portable electronic devices such as cell phones, laptops and MP3 players provide users with comprehensive functions which include communication, computing and audio functions. Batteries are commonly used to power the electronic devices. However, due to its limited capacity, batteries could possibly supply power only for short lifetime of about one to three years and its significant size and weight has caused problem to the present hand held and portable devices. This problem has then led to the rising demand for self-powered electronic devices because the usage of current battery technology to power electronic devices has become impractical.

The advancement of current technology has helped to fulfill the demand for self-powered electronics devices by harnessing ambient energy from the environment, thus eliminating the need for batteries and supplying these electronic devices with infinite amount of energy. The ambient energy that can be harnessed to generate electricity is coming from a wide range of sources such as human body (Shenck and Paradiso, 2001; Starner, 1996) and temperature gradient (Stordeur and Stark, 1997).

Another form of energy sources that has received attention from researchers for energy harnessing is vibration (Chiu and Tseng, 2008; Glynne-Jones *et al.*, 2004; Lefeuvre *et al.*, 2006; Roundy and Wright, 2004; Roundy *et al.*, 2002; Roundy *et al.*, 2003; Williams *et al.*, 2001; Williams and Yates, 1996; Yen and Lang, 2006) which can be observed in buildings, factories, vehicles, industrial machineries and household appliances. Typically, vibration energy can be converted into electric energy by three methods, namely electromagnetic (inductive) (Glynne-Jones *et al.*, 2004; Williams *et al.*, 2001; Williams and Yates, 1996), electrostatic (capacitive) (Chiu and Tseng, 2008; Roundy *et al.*, 2002; Yen and Lang, 2006) and piezoelectric conversion (Lefeuvre *et al.*, 2006; Roundy and Wright, 2004; Roundy *et al.*, 2003). Table 1.1 shows a comparison of potential energy sources with a fixed level of power generation and a fixed amount of energy storage where all power density values are normalized to the size of 1 cm^3 based on the size of typical wireless sensor nodes (Rabaey *et al.*, 2002).

Table 1.1: Comparison of potential energy sources with a fixed level of power generation and a fixed amount of energy storage

Sources	Power Density ($\mu W/cm^3$) 1 year lifetime	Power Density ($\mu W/cm^3$) 10 year lifetime
Solar (outdoors)	15,000 – direct sun 150 – cloudy day	15,000 – direct sun 150 – cloudy day
Solar (indoors)	6 – office desk	6 – office desk
Shoe inserts	330	330
Temperature gradient	15 at 10°C gradient	15 at 10°C gradient
Vibration (electromagnetic conversion)	100	100
Vibration (electrostatic conversion)	50	50
Vibration (piezoelectric conversion)	200	200
Batteries (non-rechargeable lithium)	45	3.5
Batteries (rechargeable lithium)	7	0
Hydrocarbon fuel (micro heat engine)	333	33
Fuel cells	280	28

The driving force to harness ambient energy from the environment is mostly due to the development of wireless sensor and actuator networks where particular research has been conducted for a project named PicoRadios (Rabaey *et al.*, 2002). This project aims to develop a small and flexible wireless platform for ubiquitous wireless data acquisition that minimizes power dissipation. The important specifications for the power system developed by PicoRadios project researchers are the total size and average power dissipation of an individual node. The size of a node must not be larger than 1 cm^3 and the target average power dissipation of a completed node is 100 μW.

The previous research also showed a promising amount of power density about 50 to 200 $\mu W/cm^3$ that can be harnessed from vibration energy as illustrates in Table 1.1. Therefore, the measure of acceptability of an energy harnessing solution will be its ability to provide 100 μW of power in less than 1cm^3. However, this does not mean that solutions which do not meet this criterion are not worthy of further exploration but simply that they will not meet the needs of the PicoRadios project. Thus, the primary criterion to evaluate power sources in this research is power per volume with a target of at least 100 $\mu W/cm^3$.

1.2 Problem Statement

Batteries are type of energy storage devices that commonly used to power hand held and portable electronic devices as well as implanted biomedical systems. However, due to its limited capacity, batteries could possibly supply power only for short lifetime of about one to three years and its significant size and weight has caused problem to the present hand held and portable devices as well as implanted biomedical systems. While researchers continuously developed the technology to increase the energy of storage devices, the solutions are still going to have finite lifetime. This problem has led to the rising demand for self-powered devices and systems which can be solved by harnessing energy from a wide range of sources using a few technique that have been proven can supply infinite amount of power. In this study, conversion of mechanical vibration into electricity using piezoelectric material is undertaken with a focus to quantify the amount of power that can be generated and identify electronic devices that can fully utilize this power.

1.3 Objectives

The objective of this project is:

1. To design, simulate and develop an instrumentation system to harness energy from micro vibration using smart materials.

1.4 Scopes

The scopes of this project are:

1. To conduct a research on the sources of vibration, methodologies and devices of harnessing energy and its applications.
2. To design and simulate the instrumentation system to harness energy from vibration and to propose a methodology to store the energy.
3. To develop and fabricate the instrumentation system to harness energy from vibration using piezoelectric, rectifier and energy storage.
4. To verify and validate thus developed instrumentation system with an actual source of vibration from vibrating mechanical equipments.

1.5 Research Methodology

The methodologies involved in this study are shown in Figure 1.1. The project starts by collecting reading materials such as books, journals and technical papers specifically on sources of vibration, methods of converting ambient vibration energy into electrical energy, types of piezoelectric material, piezoelectric energy harnessing circuit and types of energy storage.

Research has been done continuously throughout this study to get a better understanding on the concept of harnessing energy from ambient vibration using piezoelectric material. Besides, consultation sessions with the project supervisor and few colleagues who are doing similar research were also held periodically to discuss any arising issues and problems encountered pertaining to this study.

Based on the research conducted, piezoelectric energy harnessing circuit selection process was made in order to get the suitable circuit followed by the selection of a few types of energy storage devices to be used in this study. The study on piezoelectric energy harnessing has been divided into two main parts which are (1) simulation of the vibration environment and (2) laboratory experiment on vibrating mechanical equipments. Both simulation and laboratory experiment will undergo the same process such as piezoelectric vibration to electricity conversion, rectification and energy storage.

The simulation in Matlab SIMULINK has been done using vibration data acquired from experimental study by previous researcher in order to determine the possible amount of power density output that can be produced for the specific acceleration input. With the promising amount of power density output produced during simulation, the laboratory experiment on vibrating mechanical equipments was conducted for the purpose of quantifying the amount of power that can be generated by vibrating mechanical equipments and identifying electronic devices that can fully utilize this power.

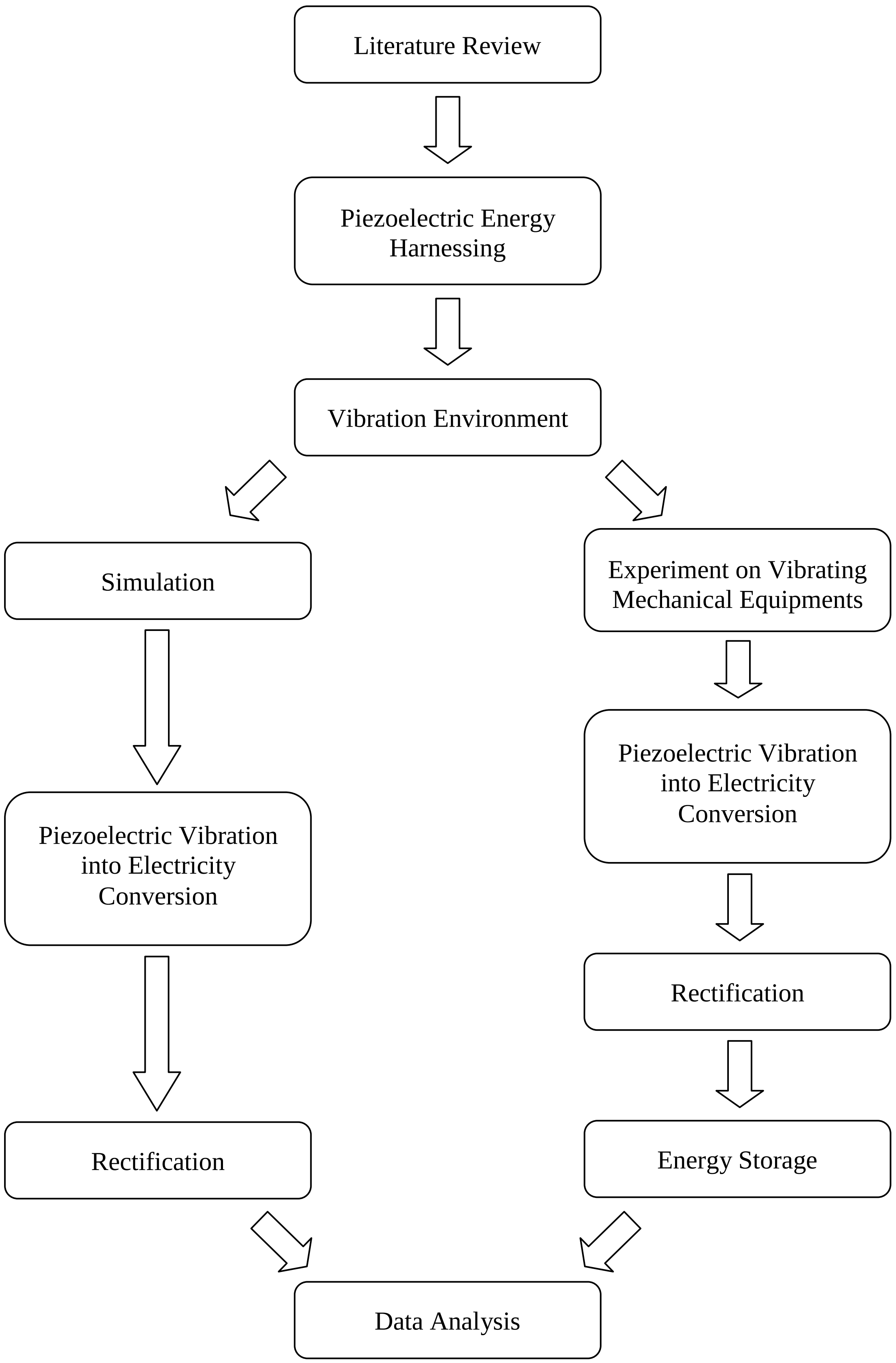

Figure 1.1: Methodology of the study

1.6 Project Activities

NO.	ACTIVITIES	WEEKS															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Selection of project title	■	■														
2	Collecting reading materials			■	■	■	■	■									
3	Literature review of previous research				■	■	■	■	■	■	■	■	■	■	■	■	
4	Understanding the concept of piezoelectric energy harnessing from vibration				■	■	■	■	■	■	■	■					
5	Familiarization with Matlab SIMULINK						■	■	■	■	■	■	■				
6	Simulation of vibration environment using data acquired by previous researcher										■	■	■	■			
7	Simulation of energy harnessing												■	■	■		
8	Analysis of the results from the simulation of energy harnessing													■	■	■	
9	Report writing								■	■	■	■	■	■	■	■	
10	Preparation for seminar presentation														■	■	
11	Seminar 1																■

Figure 1.2: Gantt chart for Master Project 1

NO.	ACTIVITIES	WEEKS															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	Literature review																
3	Experimental setup: Integration and development of data acquisition and instrumentation system																
4	Experiment on vibrating mechanical equipments (turbine and centrifugal pump)																
6	Analysis of the experimental results																
7	Report writing																
10	Preparation for seminar presentation and submission of draft thesis																
11	Seminar 2																
12	Submission of the thesis																

Figure 1.3: Gantt chart for Master Project 2

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