

**DEVELOPMENT OF LOW FREQUENCY
ELECTROMAGNETIC VIBRATION ENERGY
HARVESTER**

WAN MASRURAH BINTI HAIRUDIN

UNIVERSITI SAINS MALAYSIA

2016

**DEVELOPMENT OF LOW FREQUENCY ELECTROMAGNETIC
VIBRATION ENERGY HARVESTER**

by

WAN MASRURAH BINTI HAIRUDIN

Thesis submitted in fulfilment of the requirements

for the degree of

Master of Science

June 2016

ACKNOWLEDGEMENTS

Alhamdulillah, my highness praises and thanks to Allah SWT, who gives me the patience, strength, knowledge and courage to complete this research.

I would like to express my gratitude to my supervisor Prof Dr. Zaidi B Mohd Ripin, who has never given up correcting the mistakes I made, has encouraged me to broaden my viewpoint, and taught me the meaning of the life. His patience and dedication in directing me on the way to success, and his goal of providing a reliable research working environment encouraged me to keep going.

I also want to extend my gratitude to the technicians especially Mr. Wan Mohd Amri, Mr. Jamaluddin Che Amat and my research partner, Mr Izzudin bin Alisah who work with me for the experimental and measurement work. Apart of that, I want to thank to all my fellow friends from Vibration laboratory whose give their help, moral support and some valuable hints for completing my research.

Besides that, a special thanks to Collaborative research in Engineering, Science and Technology Centre (CREST), for providing a fund for this research project. In addition, a special gratitude to National Instruments (NI) for their help and guide us the knowledge of data acquisition and equipment.

Last but not least, I would like to express my deepest gratitude to my husband, Mr Mohd Taufik bin Abd Hamid, my daughter Nur Madihah binti Mohd Taufik and my whole family for their kindly love and continuous support during my intricate times in completing this research.

TABLE OF CONTENTS

Acknowledgements	ii
Table of Contents	iii
List of Tables.....	vii
List of Figures	viii
List of Abbreviations.....	xiv
List of Symbols	xv
Abstrak	xvii
Abstract	xviii

CHAPTER 1 - INTRODUCTION

1.1 Background on energy harvesting	1
1.2 Energy harvesting from bridge structures	2
1.3 Problem Statement	3
1.4 Objectives	4
1.5 Research Contributions	4
1.6 Scope.....	4
1.7 Thesis Outlines.....	5

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction.....	6
-----------------------	---

2.2	Vibration Energy Harvesting	6
2.3	Vibration Energy Harvesting Mechanism.....	7
2.3.1	Piezoelectric.....	7
2.3.2	Electrostatic	9
2.3.3	Electromagnetic	11
2.3.4	Hybrid.....	14
2.3.5	Comparison.....	15
2.4	Principles of electromagnetic harvester	16
2.5	Vibration energy harvesting at low frequency vibration	19
2.6	Vibration energy harvesting in the bridge structure environment	26
2.7	Summary	30

CHAPTER 3 - METHODOLOGY

3.1	Introduction.....	31
3.2	Overall methodology	31
3.3	Bridge vibration measurement.....	45
3.4	Vibration energy harvester structure design	46
3.4.1	Design geometry and setup.....	46
3.4.2	Harvester characterization	37
3.5	Electromagnetic vibration energy harvester characterization.....	38
3.5.1	Dynamic measurement test setup	38
3.5.2	Static force constant measurement setup	40
3.6	Impact Testing	42

3.7	Assembly electromagnetic harvester performance setup.....	43
-----	---	----

CHAPTER 4 - MODEL DEVELOPMENT

4.1	Overview	45
4.2	Development of mathematical model	45
4.2.1	System description and principle of operation	45
4.2.2	Electrical Subsystem.....	46
4.2.3	Mechanical Subsystem	49
4.2.4	Electromechanical Model for SDOF system	51
4.3	Determination of the harvester characteristics.....	52
4.4	Model implementation	53

CHAPTER 5 - RESULT AND DISCUSSION

5.1	Introduction.....	59
5.2	Bridge vibration	59
5.2.1	Bridge vibration when a lorry passed by	60
5.2.2	Bridge vibration when a car passed by	61
5.3	Impact Testing	62
5.4	Damping and stiffness test result	62
5.5	Electromagnetic vibration energy harvester characterization results	63
5.5.1	Dynamic performance results	63
5.5.2	Static force results.....	93
5.5.3	Determination of value K_f and K_b	67

5.6	Experimental measurement of assembly harvester.....	72
5.6.1	Open circuit voltage generation.....	72
5.6.1.1	Influence of vibration amplitude (g).....	76
5.6.1.2	Scalability of harvester	77
5.6.2	Maximum output power.....	78
5.6.3	Comparison of power output	80
5.7	Model verification.....	82
5.8	Parametric analysis	83
5.8.1	Effect of frequency	83
5.8.2	Effect of amplitude accelerations (g).....	84
5.9	Summary	85

CHAPTER 6 - CONCLUSION AND RECOMMENDATION

6.1	Conclusions.....	86
6.2	Recommendation for future work.....	87
	References	88

Appendices

List of Publications

LIST OF TABLES

	Page
Table 3.1 Specification of voice coil actuator (PBA CVC40-5)	35
Table 4.1 Assembly harvester constant for Simulink model	56
Table 4.2 Parts and function in the Simulink diagram	56
Table 5.1 New PBA (CVC40-5) Specifications	71
Table 5.2 Comparison of reported power densities in electromagnetic vibration energy harvester	81

LIST OF FIGURES

		Page
Figure 2.1	Schematic diagram of piezoelectric method (Rammohan et al., 2014)	8
Figure 2.2	Schematic of electrostatic method (Boisseau et al., 2012)	11
Figure 2.3	Electromagnetic conversion device (Amirtharajah et al., 1998)	12
Figure 2.4	A schematic diagram of the linear electromagnetic generator (William et al., 1996)	13
Figure 2.5	The power density comparison of the three different harvesters versus frequencies (Mathúna et al., 2008).	15
Figure 2.6	Schematic diagram of an electromagnetic vibration energy harvester (Munaz et al., 2012)	16
Figure 2.7	A close loop wire of rectangular shape moving through field B with velocity (v) along the x axis.	18
Figure 2.8	A tuneable electromagnetic micro harvester (Beeby et al., 2007)	19
Figure 2.9	Repulsively magnet attached in electromagnetic harvester (Saha et al., 2008)	20
Figure 2.10	Experiment setup of micro generator (Dayal et al., 2011)	21

Figure 2.11	Schematic of the prototype four pole generator (Cheng et al., 2008)	22
Figure 2.12	Electromagnetic harvester by using FR-4spring(Lee et al., 2012)	22
Figure 2.13	Energy harvester by using FR- 4 spring (Hatigpoglu et al., 2010)	23
Figure 2.14	The prototype and test setup structure (Kulah et al.,2008)	24
Figure 2.15	The prototype of energy harvester chips using mFCUP principle with two mechanical barrier arms (Zorlu et al., 2013)	26
Figure 2.16	The tubular linear generator (Li et al., 2007)	27
Figure 2.17	A parametric frequency increased generator (Galchev et al., 2011)	28
Figure 2.18	A modular magnet levitation generator (Dierks, 2011)	29
Figure 2.19	The device and experimental of electromagnetic energy harvester (Kwon et al., 2013)	30
Figure 3.1	Flowchart of methodology of electromagnetic vibration energy harvester	32
Figure 3.2	Testing and measure the bridge vibration at Parit Buntar-Bandar Baharu Bridge	33
Figure 3.3	Voice coil actuator (PBA CVC4-5)	34

Figure 3.4	Schematic diagram of excitation electromagnetic vibration energy harvester	36
Figure 3.5	CAD model of assembly harvester	36
Figure 3.6	Fabrication of assembly harvester	37
Figure 3.7	Block diagram of voltage - velocity measurement in Lab view	39
Figure 3.8	Dynamic performance measurement setup	39
Figure 3.9	Block diagram of the static force test system in the Lab view	41
Figure 3.10	Mechanical system of static force constant test setup	41
Figure 3.11	Experimental setup for impact testing	42
Figure 3.12	Block diagram of electromagnetic setup	44
Figure 3.13	Experiment setup for overall electromagnetic vibration energy harvester setup	44
Figure 4.1	Schematic of electrical diagram (Chen Yan, 2012)	48
Figure 4.2	The schematic diagram of the electromagnetic vibration energy harvester	49
Figure 4.3	A schematic diagram of the coupled electromagnetic vibration energy harvester	51

Figure 4.4	Electrical subsystem	53
Figure 4.5	The schematic diagram of conversion from current to force	54
Figure 4.6	Mechanical subsystem	54
Figure 4.7	The block diagram for voltage (V_{emf})	55
Figure 4.8	Full Simulink block diagram for one harvester	57
Figure 4.9	Full Simulink block diagram for four harvester	58
Figure 5.1	Bridge acceleration response of bridge when lorry passed through	60
Figure 5.2	The frequency response spectrum of the bridge when lorry passed through	60
Figure 5.3	Bridge acceleration response over time along the bridge when car passed by	61
Figure 5.4	The frequency response spectrum along the bridge when car passed by	61
Figure 5.5	Frequency response for the assembly harvester system	63
Figure 5.6	The value of damping ratio for the harvester system	63
Figure 5.7	Open circuit voltage over time with different stroke for frequency of 10Hz (a) Stroke 0.5mm (b) Stroke 0.05mm and (c) Stroke 0.005mm	64
Figure 5.8	Open circuit voltage versus position along the axis for	65

frequency of 10Hz

Figure 5.9	Graph of static force data versus stroke for different frequency.	69
Figure 5.10	Graph of voltage load versus load resistance at location $x = 13$ mm and stroke of 0.5 mm of 10 Hz.	66
Figure 5.11	Graph of voltage load and power load versus load resistance at location $x = 13$ mm and stroke of 0.5mm of 10Hz.	67
Figure 5.12	Graph of force versus time with stroke 0.5 mm at position of $x = 13$ mm at 10 Hz	68
Figure 5.13	Graph of current versus time with stroke 0.5 mm at position of $x = 13$ mm at 10 Hz.	68
Figure 5.14	Graph of force versus current with stroke 0.5mm at position of $x = 13$ mm at 10 Hz.	69
Figure 5.15	Velocity output versus time with stroke 0.5mm at the position of $x = 13$ mm at 10 Hz.	70
Figure 5.16	Voltage output versus time with stroke 0.5mm at the position of $x = 13$ mm at 10 Hz.	70
Figure 5.17	Voltage output versus velocity with stroke 0.5mm at the position of $x = 13$ mm at 10 Hz	71
Figure 5.18	Open circuit voltage (V) waveform of electromagnetic harvester (a) 10 Hz, (b)8 Hz, (c) 6 Hz (d) 4 Hz under vibration amplitude of 0.35g for one harvester.	73

Figure 5.19	Open circuit voltage (v) waveform of electromagnetic harvester (a) 4 Hz, (b) 6 Hz (c) 8 Hz and (d) 10 Hz under vibration amplitude of 0.35g for four harvesters.	74
Figure 5.20	Open circuit voltage (v) waveform of electromagnetic harvester 20 Hz under vibration amplitude of 0.45g for (a) one and (b) four harvester.	75
Figure 5.21	Graph of open circuit voltage (v) at one cell under different vibration amplitude (g).	76
Figure 5.22	Graph of open circuit voltage (v) at four cells versus frequency under different vibration amplitude (g)	77
Figure 5.23	Graph of open circuit voltage (v) versus number of cells under different vibration amplitude (g) at 10Hz.	77
Figure 5.24	The output power versus load resistance under difference frequency level.	79
Figure 5.25	The power density per acceleration of developed vibration energy harvester versus previous VEH	81
Figure 5.26	The comparison between experiment and simulation voltage response under different frequencies for one harvester	82
Figure 5.27	Graph of open circuit voltage versus acceleration amplitude (g) for different frequencies	83
Figure 5.28	Graph of open circuit voltage versus frequency for different amplitude (g)	84

LIST OF ABBREVIATIONS

AC	Alternating Current
CAD	Computational Aided Design
DC	Direct Current
DDHO	Driven Damped Harmonic Oscillation
EM	Electromagnetic
EMF	Electromotive force
FFT	Fast Fourier Transform
FRF	Frequency Response Function
mFCUP	Micro mechanical frequency up conversion
MEMs	Micro electro mechanicals
NDFeB	Neodymium magnets
PFIG	Parametric frequency increased generator
PZT	Material of zirconatetitanate of piezoelectric
PVDF	Polyvinylidene fluoride
RF	Radio energy
TPMS	Tire pressure monitoring systems
VCA	Voice coil actuator
VEH	Vibration Energy Harvesting
VEMF	Back electromotive voltage
WSN	Wireless Sensor Network

LIST OF SYMBOLS

A	Surface Area of the coil
$A(\omega)$	Calculated acceleration (radian per second)
B	Magnetic field
c_T	Total Damping coefficient
c_e	Electrical damping coefficient
c_m	Mechanical damping coefficient
f	Frequency
F	Force
F_{lorentz}	Lorentz force
i	Electrical Current
k	Stiffness spring
K_f	Force constant parameter
K_b	The back electromotive force parameter
l	Length
L_{coil}	Inductance of coil
n	Number of the turns in the coil
Φ	Magnetic flux
P_{mean}	Mean power
R_{coil}	Internal coil resistance

R_{load}	Load Resistance
$V_{emf,back}$	Electromotive force voltage
\dot{x}	Velocity
w	width
ω	Base excitation frequency
ω_n	Natural frequency
ζ	Damping ratio

PEMBANGUNAN PENJANA TENAGA ELEKTROMAGNET GETARAN BERFREKUENSI RENDAH

ABSTRAK

Tesis ini membentangkan pembangunan penjana tenaga getaran berdasarkan sistem elektromagnet yang menjana tenaga getaran yang berfrekuensi rendah pada struktur jambatan. Tujuan kajian ini adalah untuk menjana tenaga bagi penderia tanpa wayar. Penjana elektromagnet difabrikasi menggunakan empat unit penggerak gegelung suara yang dibuat daripada magnet Neodymium dan gegelung tembaga. Voltan maksimum 2.6 V dan kuasa maksimum 25 mW telah dihasilkan oleh penjana elektromagnet pada frekuensi 10 Hz dan pecutan 0.35g. Model penjana dibina dengan menggabungkan sistem mekanikal jisim-pegas-peredam dan sistem elektromagnetik yang menghasilkan arus akibat gerakan mekanikal gegelung. Keputusan simulasi menunjukkan perbandingan yang baik dengan eksperimen pada julat frekuensi 4Hz - 10 Hz untuk satu unit penjana mempunyai perbezaan sebanyak 4.3%. Sumbangan utama dalam kajian ini adalah pembinaan prototaip sistem penjana tenaga getaran yang rendah dan pembangunan model simulasi dalam Simulink. Ketumpatan kuasa system penjana adalah $602 \mu\text{W}/\text{g}\cdot\text{cm}^3$ dan $1308.2 \mu\text{W}/\text{g}\cdot\text{cm}^3$ pada 4 Hz dan 10 Hz dan cukup berupaya untuk menghidupkan peranti penderia tanpa wayar.

DEVELOPMENT OF LOW FREQUENCY ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

ABSTRACT

This thesis presents the development of an energy harvester based on electromagnetic system to harvest energy from the low frequency vibration in particular structural vibration of the bridge. The eventual intended application is to power up a wireless sensor node that can be used to monitor structural integrity of a bridge. The electromagnetic vibration energy harvester is developed with four units of voice coil actuators using Neodymium magnets and copper coils. An open circuit voltage of 2.6 V and maximum output power of 25 mW were generated at 10 Hz under constant acceleration of 0.35g respectively. A model of the harvester is made by combining the mechanical of mass-spring-damper system with the electromagnetic resistance and inductance where the velocity of the moving coil from the mechanical system will produce current in the system. The simulation model showed a good agreement with the experimental results at 4 - 10 Hz for one cell harvester with 4.3% difference. The main contribution of this research is the prototype construction of low vibration energy harvester system and development of the energy harvester model using Simulink. The power density of the harvester system is $602 \mu\text{W}/\text{g}\cdot\text{cm}^3$ and $1308.2 \mu\text{W}/\text{g}\cdot\text{cm}^3$ at 4 Hz and 10 Hz respectively and enough to power up the wireless sensor network device.

CHAPTER 1

INTRODUCTION

1.1 Background on energy harvesting

Energy harvesting is the process of acquiring the energy from environment and converting into usable electrical energy to provide power for electronic devices (Roundy et al. 2003). It has been developed and widely used by many researchers in this decade due to the environmental and economic reasons.

There are several energy sources which are widely used including kinetic energy (waves, wind, gravity and vibration), electromagnetic energy (radio frequency (RF), photovoltaic), thermal energy (solar indoor and outdoor, temperature differential, combustion), biological and chemical energy (biofuels, biomass) or nuclear energy (radioactive decay) (Sari et al. 2009 and Matiko et al. 2014).

Energy can be harvested from the ambient environment using several transducers. Transducer is a device that converts ambient energy into electrical energy. Three transducers most widely reported in vibration energy harvesting are piezoelectric which is a special materials that can be produce electricity when subjected to load, electrostatic which is based on the variable capacitors to extract the energy and electromagnetic which is based on the electromagnetic induction to produce the voltage from the motion of coil and magnet.

1.2 Energy harvesting from bridge structures

Wireless monitoring of civil engineering structures such as bridges and overpasses has gained a lot of interest in the recent years (Ntotsis et al. 2009). The application of sensor node has been extensively used for the measurement of the vibrations in order to generate the appropriate power. In order to monitor the structural damage to the bridge, the strain level must be measured and recorded typically using wireless sensor. Wired connection system is generally used for monitoring the bridge vibration (Wang et al., 2006). However, this wiring involves considerable cost, maintenance and difficulty of installation of the sensor (Lynch et al. 2003). In California, the total cost for the bridge is \$300 000 for 60 accelerometers where \$5000 is spent for each the installed sensor (Li et al. 2011). The batteries are used to power the wireless system. However, these have to be replaced and scheduled frequently (Arroyo et al. 2012).

The researchers consider another solution for the battery alternative for powering of wireless sensor nodes which is based on harvesting the available vibration energy and converting it into electric power.

Vibration harvesting was the focus of this study because the standard operating conditions of bridge structure often produced a low level vibration spectrum. The typical structures have basic vibration level that occur at frequencies less than 5Hz (Beeby et al. 2006) and had input acceleration (peak less than $\pm 0.2g$). Therefore, there is a need to develop vibration energy harvester to work in the frequency range of fundamental structure of models.

1.3 Problem Statement

The bridge structures have to be monitored periodically to ensure structural integrity. Several techniques exist to monitor an infrastructure, for example a conventional resistive strain gauging, embedded or attached optical fibre sensors, accelerometers and linear variable displacement transducer (Coolins et al., 2014). It is very challenging to harvest since the bridge vibration has low amplitude and frequencies. Application of the Wireless sensor network is more preferable because the wired sensors are weak, expensive to install and to maintain. However, the main issue of implementing wireless sensor is the limited battery life. The battery used need to be replaced, difficult to dispose and less energy capacity lifetime (Galchev et al., 2011). An alternative approach to the battery for powering the monitoring system of the structure system is by harvesting the vibration energy from the bridge structures.

There are many different designs of harvester and it is difficult to select the optimal design for vibration energy harvesting. This is because the vibration source is often nondeterministic in nature and contains impulse and other non-uniformity (Spreeman et al., 2008). In addition, most harvesters in the literature operate at frequencies of more than 30Hz, including many harvesters based on piezoelectric, electrostatics and electromagnetic energy conversion (Gu and Livermore, 2011). The aim of this research is to develop vibration energy harvester frequency of low frequency at range of 10Hz and below which is to provide perpetual power for wireless sensor network on the bridge structures.

1.4 Objectives

The main objectives of this work are

- To develop an energy harvester based on electromagnetic system in order to harvest energy at low frequency at range 4 to 10 Hz.
- To construct the model based on the governing equations of electromagnetic system and simulated in Matlab Simulink in order to characterize the energy harvester system.
- To determine the generating of voltage and power on different frequencies, vibration amplitudes and load resistors.

1.5 Research Contributions

The first contribution of this research is the model construction of low vibration energy harvester system which can be expanded for a higher power system. A second contribution is the development of simulation model of low frequency vibration energy harvester using Matlab Simulink.

1.6 Scope

This research is focused on the modelling and experiments for electromagnetic vibration energy harvester for low vibration energy harvester for frequency of 10Hz and below. The study is limited to the construction of vibration energy harvester consisting of four cells. The experiments also limited until the load power only. The range of low frequency is 4Hz to 10Hz and only employ for the bridge structure application.

1.7 Thesis Outlines

The following is a brief overview of each chapter of this thesis, which illustrates the sequence of tasks required to develop the vibration energy harvester for the bridge.

Chapter 1 presents consists of brief introduction of the thesis, problem statement, objectives, contribution and scope of the research. The background information on energy harvesting and WSN technologies, technical benefits, and bridge applications is described.

Chapter 2 describes comprehensive literatures on the vibration energy harvesting device. Piezoelectric, electromagnetic and electrostatic energy harvesters developed by researchers are discussed in depth. This section summarized the application and characterization of the low frequency vibration energy harvesting technologies.

Chapter 3 fully describes the proposed electromagnetic vibration energy harvester system. It explains the concepts and development by analytical modelling, prototyping, fabrication and experimentation of energy harvester system. This chapter ends with the summary of the performance for the proposed electromagnetic vibration energy harvester.

Chapter 4 describes the model development of the electromagnetic vibration energy harvester in Simulink software.

Chapter 5 explains the result and discussion of the proposed electromagnetic vibration energy harvester system.

Chapter 6 contains a summary of the work and conclusion as well as future work.