UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEVELOPMENT OF A VIBRATION BASED ELECTROMAGNETIC ENERGY HARVESTER (EEH) USING GRAPHENE/SILVER CONDUCTIVE DIRECT-WRITE PROCESS FOR AUTOMOTIVE THERMAL-SENSOR

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MASTER OF MECHANICAL ENGINEERING (AUTOMOTIVE)

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Faculty of Mechanical Engineering

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A dissertation submitted
in fulfillment of the requirements for the degree of Master of Engineering
in Mechanical Engineering (Automotive)

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2018

DECLARATION

I declare that this thesis entitled "Development of a Vibration Based Electromagnetic Energy Harvester (EEH) using Graphene/Silver Conductive Direct-Write Process for Automotive Thermal-Sensor" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Name	:	NORHISHAM BIN ISMAIL
Date	:	...................................…..

APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Mechanical Engineering (Automotive).

Signature	:…………………………………
Supervisor Name	: DR. MOHD AZLI BIN SALIM
Date	:…………………………………

DEDICATION

To my beloved family

ABSTRACTS

Vibration Energy Harvesting is the concept of converting the kinetic energy inherent in vibrations to electricity. Vibration comes from many sources either natural vibration or forced vibration and vibration also can cause severe issue that may produce noise, impede stability and generate crack in structure. However, it can be beneficial in energy harvester as one of the power source which can be harvest and turn into electricity. With the development of low power energy harvester in recent years have given many opportunities to these sensors to functioning autonomously and wireless, especially in automotive. Furthermore, microelectromechanical systems (MEMS) concept has been on focus lately and become most important aspect in energy harvesting in micro-size device because the advantages of low-volume, low-weight and integration capability with other MEMS components. A double electromagnetic energy harvester (EEH) with three layer of conductive ink as coil was developed. The coil was made from graphene and silver conductive ink as a replacement of initial copper coil winding which limited for its bulky size and heavy weight. This research had study the conductivity of the conductive ink and development of the EEH's device and system. EEH device also focused on its layers of the conductive ink coil and output power. The coil was printed on TPU or PET substrate due to their flexibility. Test was done on the conductive ink to find the most conductive material for the coil, which 40% loading composition of graphene and 80% laoding composition of silver gave most lower resistivity which resistivity, R is inversely proportional with current, I. Furthermore, damping test was done to measure damping coefficient of both conductive ink which graphene conductive ink's damping coefficient is 0.01585 and for silver conductive ink is 0.00654. This damping coefficient will be used to obtain the output power of the EEH. Lastly, vibration experiment was done and from the experiment, EEH produce more power with more layers was printed but the power output was decreased with the increasing of the frequency.

ABSTRAK

Penuaian tenaga getaran adalah satu konsep untuk mengubah tenaga kinetik daripada getaran kepada elektrik. Terdapat banyak sumber yang menghasilkan getaran samada getaran semulajadi atau getaran yang dipaksa dan getaran juga boleh menyebabkan masalah-masalah serius seperti menghasilkan bunyi bising, mengganggu kestabilan, dan menyebabkan retak di dalam struktur. Walaubagaimanapun, kelebihan di dalam penuaian tenaga sebagai salah satu sumber tenaga yang boleh dituai dan ditukarkan kepada elektrik. Dengan perkembangan arus penuaian sumber tenaga di dalam masa-masa sekarang telah memberi banyak peluang kepada sensor untuk berfungsi dengan kendiri dan tanpa wayar, terutamanya di dalam bidang automotif. Lebih-lebih lagi, konsep sistem mikro-elektromekanikal (MEMS) telah pun tertumpu sekarang dan menjadi aspek yang paling pentingdi dalam alat penuaian tenaga yang bersaiz mikro desebabkan kelebihan seperti isipadu yang rendah, ringan dan kebolehan untuk digabungkan dengan komponen MEMS yang lain. Tiga lapisan dakwat konduktif untuk alat penuai tenaga elektro-magnetik berganda (EEH) telah dibangunkan. Coil ini diperbuat daripada dakwat konduktif graphene dan perak sebagai pengganti coil asal yang menggunakan gulungan wayar tembaga dimana ia terhad untuk saiz yang besar dan berat. Penyelidikan ini akan mengkaji mengaliran elektrik oleh dakwat konductive dan pembangunan alat EEH dan sistemnya. Alat EEH juga menumpukan hubungan antara lapisan dakwat konduktif dengan kuasa yang dihasilkan. Coil akan dicetak di atas substrat TPU atau PET kerana sifatnya yang boleh dilenturkan. Ujian telah dilakukan ke atas bahan-bahan konduktif ini dengan 40% jumlah komposisi untuk graphene dan 80% jumlah komposisi untuk perak ttelah memberi nilai rintangan yang paling rendah, dimana rintangan adalah berkadar songsang dengan arus electric. Disamping itu, ujian 'damping' juga dilakukan untuk mengukur 'damping coefficient' untuk kedua-dua dakwat konduktif dimana 'dampinig coefficient untuk graphene adalah 0.01585 dan untuk perak adalah 0.00654. 'Damping coefficient' diperlukan di dalam menentukan nilai kuasa yang dihasilkan oleh EEH. Akhir sekali eksperimen getaran dilakukan, dan EEH menghasilkan lebih banyak kuasa dengan bertambahnya lapisan yang dicetak tetapi kuasa yang dihasilkan berkurang apabila frekuensi yang diberi semakin meningkat.

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Alhamdulillah, praise to Allah, with his inayah', Finally, I have successfully completed my master project report entitled "Development Of a Vibration Based Electromagnetic Energy Harvester (EEH) using Graphene/Silver Conductive Direct-Write Process for Automotive Thermal-Sensor" successfully.

For this golden opportunity, I would like to express my deepest gratitude to my supervisor, Dr. Mohd Azli Bin Salim his professional ways in giving the guidance and for understanding upon my problem and obstacles, and help to complete this report.

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Wassalam.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

e	Magnitude of the emf induced inside the coil or the circuit
N	Number of coil turn
Φ	Flux linkages
$d\Phi/dt$	Rate of change of flux
B	Magnetic flux density
w	Width
t	Thickness
d_o	Coil outer
d_i	Inner dimension
s	Spacing between coil
L_{MT}	Length of the mean turn
A_{Coil}	Coil cross-sectional area
R_c	Coil resistance for a single layer coil
T	Period of oscillation
δ	Logarithmatic decrement
$x(t_n)$	Displacement at the *n*th peak
ω_n	Natural frequency
ω	Angular frequency of vibration
ζ , c	Damping coefficient/ factor
m	mass

k	Spring of stiffness
u , v	velocity
C_m	Mechanical damping
C_e	Electric damping
P_{max}	Maximum power
ζ_T	Total damping factor
ζ_m	Mechanical damping factor
ζ_e	Electrical damping factor
Y	Amplitude of vibration
a_v	Acceleration level

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

A car is comprised of numerous parts that incorporate with suspension, engine and its components which speak to the numerous subsystems and need many sensors to support, monitor or activate all the components. In earlier usage of sensors, it depends on the vehicle battery as theirs power sources which quite complicated to the sensor and wiring layout. With the development of low power energy harvester in recent years have given many opportunities to these sensors to functioning autonomously and wireless. Energy harvesting devise use renewable power source or surrounding condition as power source. Solar cells, electromagnetic, radiation, radio frequency, vibrations and thermal gradients was some of the power sources that energy harvester can obtain to produce the electricity. Furthermore, microelectromechanical systems (MEMS) concept has been on focus lately and become most important aspect in energy harvesting in micro-size device because the advantages of low-volume, low-weight and integration capability with other MEMS components. The miniaturization of consumer electronics and mechanical structures has been receiving a great deal of attention for a considerable time. Extensive fabrication techniques have been developed.

In this paper, electromagnetic energy harvester (EEH) will be review from previous study. A three-axis dispenser was used to demonstrate conductive-structure fabrication on EEH. Current vibration energy harvesters are based on piezoelectric, electromagnetic, or electrostatic conversion mechanisms. There had been continuous improvement to overcome the limitation for energy harvester such as device size and weight, and effectiveness in harvesting output power. To increase the output voltage and power, a few layers of conductive ink or insulating material as fig. 1.1 were stacked on a cantilever microstructure, which enabled the all-additive fabrication of layers of coils without using vacuum deposition or any high-temperature process. By excite the generator that consist of magnet and coil turning the vibration energy into electrical energy. In the system flux that formed by magnetic core was cut through by the coil that causes induction of electromotive force as per state from Faraday's Law. The output power would increase as the numbers of coil turns increase. A schematic of the micro-generator with two coils is shown in fig. 1.2.

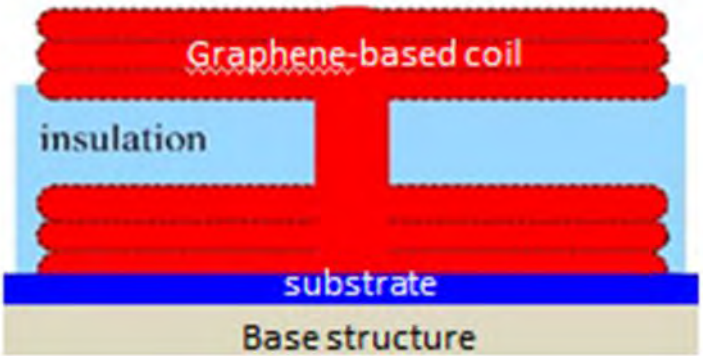

Fig 1.1 Layers structure of the printed coil

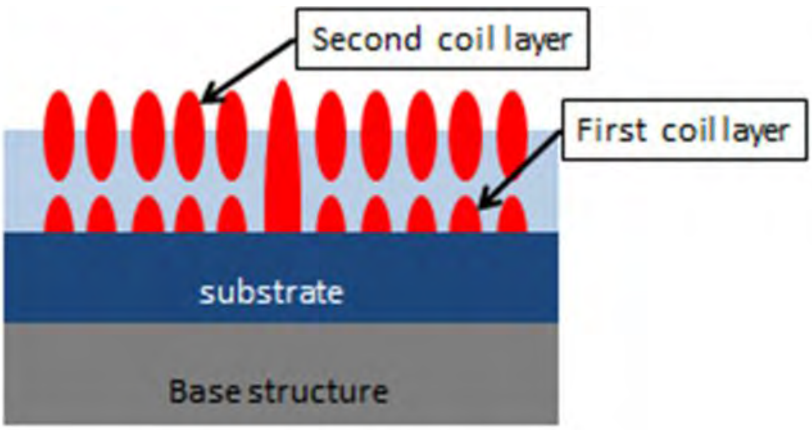

Fig 1.2 The generator structure used for the EEH

The generator coil was fabricated with graphene conductive ink which is a single thin layer of pure carbon that the carbon atoms was firmly packed layer and hexagonal honeycomb lattice bonded. A few three-dimensional (3D) fabrication techniques was introduced recently for the fabrication of conductive layer of the coil with electrical functionality, which include continuous writing, inkjet printing, micro-stereolithography, micro-laser-sintering, and direct-write. These techniques proved advantages in terms of low cost, large area, and a quick processing time compare than typical techniques and others various generator types such as wire coil winding, but still suffer from some disadvantages with respect to the structure and material. Laser writing creates patterned structures through ablation or selective sintering. Feng Y. Y. et al (2017) stated the work done by Regenfuss et al that they performed laser micro-sintering with sub-micrometer grained metal powders but realized that its quite challenging due to the high temperature and porosity because the techniques often require expensive equipment or costly photopolymers. The functional 3D structures of material layer by layer with their electrical properties have been widely studied which contribute to lower cost inkjet printing. Kullmann et al used piezoelectric inkjet printing that was selectively combined with simultaneous in-situ laser annealing to print micro-wires and micro-walls but the rough edges and low viscosity of the materials have limit the performance of the printer. Micro-nozzles or syringe needles was developed in order to get a good flat surface in a short time at a low cost to make continuous conductive structure in direct-write technique as per Lebel et al which they had used direct-write micro-extrusion to fabricate carbon nanotube or polymer nano-composite coils through a micro-nozzle and then cured using UV irradiation which followed the extrusion point.

1.2 Problem Statement

There are several sources that can be used for a system to harvest their own energy such as photonic energy, thermal energy, and mechanical energy. Photonic energy such as solar cells is widely used because it provides great power density but light base energy harvesting has limited usage in low light or closed environment and also dirty environment. Thermal energy is also limited because its energy harvesting depends only on thermal sources. Meanwhile, mechanical energy depends on moving object or vibrating structure and also abundant in many environment.

Electromagnetic energy harvester is one of the methods in harvesting mechanical energy. An electromagnetic coil generator use a moving coil between two magnets or vice versa working concept to generating power but produce very low of output voltage and inconsistent output voltage produce based on the ambient vibration frequency. When output voltage and power harvest by the system is too small, there are some factors that need to envision during developing the system such as harvesting and storing energy for period of time, before taking and transmitting a reading, then continue with further period of harvesting. Other than small output power and voltage, by using magnet-coil generator require coil winding around the magnets and this structure is quite bulky and also not suitable to be applied for MEMS. From that limitation, many researchers had study energy harvester by using printed coil with small thickness of each layer or some other material that suitable for very small energy harvester such as conductive ink and piezoelectric.

This material is suitable for the MEMS but the small thickness of each layer of the printed coil would give high series resistance for the coil. In addition, most of energy harvester was designed to generate maximum power from low amplitude vibrations by having a high Q-factor and mostly generators always developed to work only at one fixed resonant frequency. However when ambient vibration frequency is much lower than the natural frequency which will cause the resonant frequency do not match, the output power of the energy harvester will drop significantly and it will not produce the power that can support the system. This means with lower Q-factor, the maximum power generated would be decreased. There are researchers that have studied and developed a prototype of self-powered system of monitoring application device which use a step-up transformer to harvest more voltage and power but it has some loses in aspect of rectification and the regulation plus with disadvantage of its heavy weight due to the weight of the transformer.

1.3 Research Hypothesis

This research is experimental model strategy that can be utilized for finding estimated answer for the vibration issues in surrounding condition especially for automotive system. This vibration produce from ambient surrounding can be utilized into electrical energy rather than being wasted and EEH can harvest vibration energy that enough to self-operate the sensor. This experiment can recreate the transmissibility performance in ambient vibration. Another working hypothesis brought up in this research is that the usage of graphene or silver conductive ink as coil is more efficient compares other materials used for the coil generator. Likewise, another conceivable theory can be made is that the coil of the EEH can be functioned as thermal sensor due to lattice effect when there are heat being transfer through the coil.

1.4 Objectives

The objectives of this project as below:

i. To investigate the conductive level of graphene/silver conductive ink at varying filler loading.

ii. To develop vibration-based electromagnetic energy harvester for graphene and silver conductive ink for various ambient vibration.

1.5 Scopes and Limitation

In this research it will focus on electromagnetic energy harvester with graphene and silver conductive ink coil. This project aim is to evaluate the relationship between vibration rom ambient frequency and power output using experimental approach.

Below is the following scope and limitations in this research:

i. Using direct-write process for printing method

ii. Investigate the relationship of EEH among;

- PET/ TPU substrate
- Wood fiber insulation
- The output voltage
- Power
- Number of frequency

1.7 Thesis Outline

This thesis has five main chapters. Chapter 1 briefly describe about EEH and their problem statement about the previous EEH. It also presents the research objective, scope and hypothesis. Chapter 2 is about literature review from others researcher related to the derivation of the energy harvester model. The harvester model consists of the magnet and its relationship with the coil, the equations of damping of first degree of freedom model, the equations of the electrical conversion of the EEH, conductive ink coil characteristic and thermal expansion, and recent development of the EEH. Then, the literature related to the transverse vibration is also reviewed. Additionally, the chapter elaborates about the