Faculty of Mechanical Engineering

ENERGY HARVESTING FROM MECHANICAL VIBRATION OF AUTOMOTIVE COMPONENT

Nur Shakira Suhana Binti Abu Bakar

Bachelor in Mechanical Engineering

2018

ENERGY HARVESTING FROM MECHANICAL VIBRATION OF AUTOMOTIVE COMPONENT

NUR SHAKIRA SUHANA BINTI ABU BAKAR

A report submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering with Honours

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I here declare that this thesis entitled "Energy Harvesting from Mechanical Vibration of Automotive Component" 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.

Signature : …………………………………….

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor in Mechanical Engineering.

Signature :.......................................

Supervisor Name :.......................................

Date :.......................................

DEDICATION

To my beloved mother and father

ABSTRACT

Vibration energy is a wasted energy that can be accumulated from the surrounding of us for beneficial power. Furthermore, energy harvesting devices are self generated that normally used for activating low power electronic components which have low power electrical consumption. According to this project, it is use vibration energy which is in the form of mechanical energy that needs to be transforming into the useful electrical energy using piezoelectric devices. Energy harvesting system using piezoelectric devices is a system that provides the user with free flowing energy that can be used without any consequences to the environment. This system enables users to generate energy for their uses by transform the mechanical energy produced by the car components vibration into electrical energy. The aims of this project is in general about designing and build a circuit to test the performance and characteristic of piezoelectricity. The system is then is installed at a car components to produce energy from the car vibration when the car is switched on. The output voltage of each component is compared whether it is produce a suitable vibration needed for the piezoelectric generating system or not. As a conclusion, this project shows a self-power sustainable electronic system for long lasting low power electronic application.

ABSTRAK

Tenaga getaran adalah tenaga yang terbuang yang dapat dikumpulkan dari sekeliling kita untuk kuasa yang bermanfaat. Selain itu, peranti penuaian tenaga dihasilkan sendiri yang biasanya digunakan untuk mengaktifkan komponen elektronik berkuasa rendah yang mempunyai penggunaan kuasa elektrik yang rendah. Menurut projek ini, ia menggunakan tenaga getaran yang berupa tenaga mekanikal yang perlu diubah menjadi tenaga elektrik yang berguna menggunakan peranti piezoelektrik. Sistem penuaian tenaga menggunakan peranti piezoelektrik adalah sistem yang menyediakan pengguna dengan tenaga mengalir bebas yang boleh digunakan tanpa apa-apa akibat kepada alam sekitar. Sistem ini membolehkan pengguna menjana tenaga untuk kegunaan mereka dengan mengubah tenaga mekanikal yang dihasilkan oleh getaran komponen kereta menjadi tenaga elektrik. Matlamat projek ini secara amnya merancang dan membina litar untuk menguji prestasi dan ciri piezoelektrik. Sistem ini kemudian dipasang pada komponen kereta untuk menghasilkan tenaga dari getaran kereta apabila kereta dihidupkan.Voltan keluaran setiap komponen dibandingkan sama ada ia menghasilkan getaran yang sesuai untuk sistem penjanaan piezoelektrik atau tidak. Sebagai kesimpulan, projek ini memperlihatkan sistem elektronik lestari berkuasa sendiri untuk aplikasi elektronik berkuasa rendah yang tahan lama.

ACKNOWLEDGEMENT

First of all, thanks to Allah for giving me strength, love and guidance until I finally completed my final year project. Next, I would like to express my gratitude and appreciation to all the person who have help me to complete my final year report and thank you for my Faculty of Mechanical Engineering, University Technical of Malaysia Malacca for giving me this opportunity to carry out this project.

I am very thankful and pay my gratitude to my supervisor on this project, Dr Kamarul Ariffin Bin Zakaria for his support, idea, guidance and encouragement throughout my final year project. Without his guidance and moral support, I would not be able to complete my final year project in this manner.

Besides that, I would like to express my gratitude towards my parents and my siblings who are always supported me morally as well as economically. Last but not least, special thanks to all my friends who direct or indirectly support and help me during to complete this project. They had also given me some useful advices and never hesitated to lend me a hand in any situation.

LIST OF FIGURES

LIST OF TABLE

LIST OF APPENDICES

LIST OF ABBREVIATION

PCB	Printed Circuit Board
LED	Light Emitting Diode
AC	Alternating Current
DC	Direct Current
MEMS	Micro Electro Mechanical Systems
IC	Integrated Circuit
PZT	Lead Zirconate Titanate
Mw	Millimeter Watt
Si	Silicon
NdFeb	Neodymium Iron Boron

TABLE OF CONTENT

CHAPTER 1

INTRODUCTION

1.1 Background

Energy harvesting is a system which involves in capturing and assembles by product energy into a usable electrical energy (Amos Kingatua, 2016). It is also defined as a technique of generating electrical energy from normally unused energy sources found in the surrounding environment. It is conversion of little amounts of readily available energy in the environment into usable electrical power. The energy can be achieved when there is collecting energy for a period of time and building it into a form that can be used afterwards. The example used in energy harvesting is to control the microprocessor with its limit.

Energy harvesting has its own criterion that can hold both promises for low voltage and low power applications in various movable or mobile markets. For example, these energy harvesting system applications are quite used in health equipments, transport, military, consumer devices and industrial controls. In other words, it provides a powerful challenger on behalf of applications that required a support battery, especially if the battery is in a remote location or hard to reach (Michele Kinman, 2010).

The good things about energy harvesting are it enabled a new circuit to capture and accumulate these small power packets and change it into functional outputs. Moreover, the performance provided by the circuit should have a high energy efficiency in order to capture and store this small power packet. Also it needs high energy retention to accumulate the energy for a long time. Additionally, it requires proper power conditioning to complete the task of desire. According to Figure 1.1, it is show the step for vibration energy harvesting in block diagram. Energy management must be in good condition and allow for various voltage, current and waveform inputs. It is also include more voltage, more charge and other irregular input circumstances (Michele Kinman, 2010). Furthermore, this energy harvesting has their advantage which it very useful that it can reduce the energy consumption and its impact on the environment.

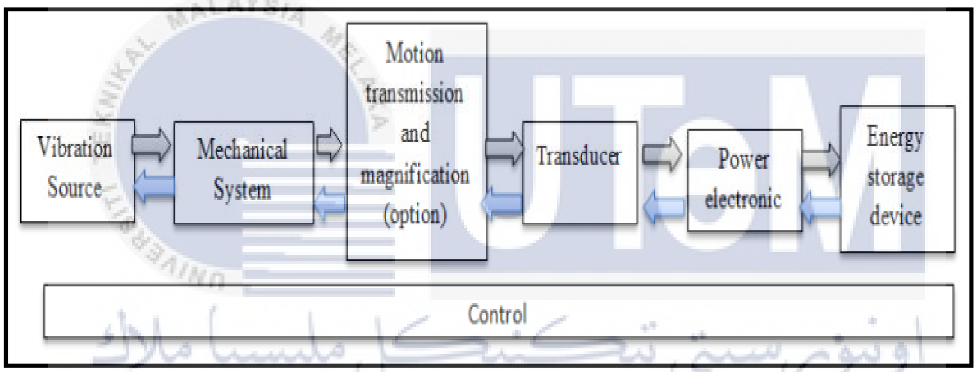


Figure 1.1: Vibration energy harvesting system in block diagram

(Source: Wang et.al, 2013)

There are a lot of materials or sensor that are commonly used to transform wasted energy into electricity. This sensor is available which it can be harvested, accumulated and conditioned used for wireless sensor applications and many low voltages wearable that previously vital batteries or AC power supplies. For instance, a crystal composite or piezoelectric fiber (PZT), a solar indicator coils are the example of energy generator. These materials provide currents and various output voltage. High efficiency is needed to capture, accumulate and store the small packets of electricity energy. The effectiveness need to be increase because the energy used by the circuit is less than the energy provided by the vibration.

In 1880, two French physicists, Brothers Pierre and Paul-Jacques Currie had discovered the piezoelectric effect found in crystal of quarts, tourmaline and potassium sodium tartrate (Chris Woodford, 2017). Piezoelectricity is the form of electric potential or the voltage across the crystal sides when subject to mechanical pressure (Carmen Emily Yang, 2016). The characteristic of piezoelectricity is it can be reversible hence means the materials that exhibit electricity generation when the pressure is applied will exhibit pressure generating when an electric field is applied.

In 2009, Haresh Khemani stated that the piezoelectricity generator converts mechanical vibrations, tension or pressure into electrical voltage or current. Many different sources come from this mechanical tension, such as human motion, air plane or vessel ambiance, other low frequency seismic vibration and acoustic noise. Other than that, the piezoelectric effect operates in alternating current, requiring input time varying at mechanical resonances. It is consider as the most capable at generating energy. Most piezoelectricity produces larger voltage while the current produce is very small, generating the power that exists in the microwatts arrangements. In addition, the generating source for energy harvesting electronics is an ideal way but it is a bit too small for most system application.

1.2 Problem Statement

Lately, energy and global warming had drawn a lot of awareness in dissimilar kind of the world. Automobile is one of the largest consumers generated for movement wasted through heat and vibration. The use of capacitors as a way to store energy has been considered due to the past research on the power energy harvesting as well as can overcome the problem of traditionally battery that as limited power.

Initially, the concept and characteristic of piezoelectric that used in the energy harvesting will discuss. Those piezoelectric are use to generate the mechanical movement due to electric charges. In addition, this material can generate electrical charges by mechanical motion. However, it is need to future study which components of automotive is most suitable and capable for energy harvesting. In this study, the output voltage produces by three components will be comparing and characteristic of piezoelectric in mechanical vibration is investigated. Therefore, the piezoelectric energy harvesting circuits for circuit application design were studied.

1.3 Objectives

The objectives of this study embark:

I. To study the principle of piezoelectric circuit.

II. To study the characteristic of piezoelectric system.

III. To compare the output voltage produces by three automotive components when the sensor is connecting.

1.4 Scope of project

There are several parameters that can be discussed and varied in order to study the characteristic and performances of energy harvesting using piezoelectric. Piezoelectric is use as the sensor for harvesting design, where the main design is to harness the vibration energy. It is because piezoelectric can generate electrical charges by mechanical vibration or mechanical motion. In this study, the output voltage produce by three components will be compare and characteristic of piezoelectric will be the parameters studied.

1.5 Thesis Outline

In this thesis, there are consist of 5 main chapters. First and foremost, it is Chapter 1. This chapter will discuss briefly about the project introduction consists of background of the case study, problem statements, objectives, scope of project and thesis outline in order to conduct the project. Next, the thesis is continued with Chapter 2. This chapter contains the literature review which it is consists of a study about the past research and some theoretical concepts that related to this project study. This study referred from various sources such as books, journals, thesis and internet. While in Chapter 3 it is more focusing on the methodology used in order to complete this project. It is provides a flowchart including the process of identifies the flow of circuit, identify the sensor use and which automotive components produce a high vibration. In Chapter 4, consists of the discussion from the result obtained and the comparison between three automotive components that related to energy harvesting using piezoelectricity is investigated. Last but not least, in Chapter 5 a conclusion and recommendation is provided for future work about of this project study.

CHAPTER 2

LITERATURE REVIEW

In this section, it will discuss about the facts and information of the works involving energy harvesting before proceed to the project. This part also will study about energy harvesting devices use.

2.0 Introduction

With current improvements in the development of low power electronics such as microelectronics as well as microelectronics as well as wireless sensor nodes, and the importance of the world in the idea of "green" engineering, the subject of energy harvesting has gained considerable attention before decades. The power requirements of low power electronic components can be reduced progressively with an increase in the efficient circuit so that the energy harvesting system can be seen as a method that can be achieved in supplying energy to self-powered devices. Given that the wearable electronic device evolves and breed, there will be a growing need for more power transmission to circulate around the environment and human body. Nowadays, most of the storage is provided by the battery and power transmission through the wires (Kymissis et.al, 1998). The current approach to power distribution is clearly problematic when more tools are brought; the small use batteries require replacements everywhere or run wires through our clothes to supply tools from central power sources. Both are unacceptable.

Furthermore, conventional low-power electronic devices, such as wireless indicator nodes, rely on batteries to power the device. Battery use sometimes presents many negatives such as battery costs with changes along with the limitations imposed by appropriate access requirements for devices for battery conversion purposes. Wireless indicator nodes are usually found in remote destinations or incorporated into structures which cause access to tool can be difficult or impossible. By saving ambient energy around electronic devices, energy saving methods can offer long-term energy sources that do not require periodic replacements. Such systems may run in their own autonomous way, minimizing costs associated with battery replacement. It is obviously to generate power where it is used, by passing storage and distribution problems altogether. As a collapse of power requirement for most wearable devices, it is no longer easy to harvest some useful energy from the environment.

2.1 Energy Harvesting System

Energy harvesting has become more popular and the most popular technique is energy harvesting from surroundings. The past or background of energy harvesting started since the windmill and the waterwheel. Over decades, there are a lot of techniques to accumulate the power from heat and ambiance. The main purpose behind the look for a latest energy harvesting system is the need to master the energy of sensor network also moveable devices exclusive of batteries. Over the past few years, energy harvesting had experienced important growth required to increasing need as to create moveable devices and wireless network. Besides that, the energy recruitment and opportunities they make to use components continuously, out of the grid and for long periods, have gained considerable attention in trading and military use. Therefore, leveraging energy harvesting networks will enable to develop new medical, environmental, monitoring and security applications (IEEE, 2015).

Energy harvesting is a technique to accumulate energy from ambient sources including sunlight, vibrations, heat, and etc (Gibran Ali et.al, 2015). Besides that, energy harvesting is a process which a device associated with capturing residual energy. It is allowed to accumulate and manage amounts of natural energy and converts them into electrical energy, so that it can supply low power devices or use it later (Liew Hui Fang et.al, 2016). Wind turbine, water turbine, ocean wave and many more are example of system which can convert motion into electrical energy.

Nowadays, different energy sources has its own method to harvest the energy have been founded. Vibration energy harvesting is the most popular technique that can be used to convert mechanical energy into electrical energy. The example mechanisms to convert mechanical vibration into electrical energy can be found in electrostatic, electromagnetic and piezoelectric transducer.

2.1 Vibration Energy Harvesting based on different forms of sources

There are many variety of method or technique conversion mechanisms that can be used to convert the vibration based energy as mechanical energy to useful electrical energy as well as the vibration conversion can be implemented through piezoelectric, electromagnetic and electrostatic (Maheshwari et.al, 2013). This harvested energy can be stored into energy devices or it can be used directly. It is based on to the magnitude of output power also impedance.

2.1.1 Piezoelectric Energy Harvester

Vibration energy harvesting is an attractive solution to replace or to charge the battery which is commonly used in application. Monitoring sensors or wireless communication devices are example of application. This energy harvesting can convert waste vibration energy into useful electrical energy (Syahrul et.al, 2015). This study discuss about linear assumptions and stationary excitation characteristic that had been used in earlier analysis. The challenge by using vibration is that linear oscillator which it is well suited for stationary and narrow band excitation near their natural frequency. Furthermore, the vibration energy becomes less efficiency when it is distributed over wide spectrum.

In recent years, the piezoelectric energy harvester had received comprehensive attention. Instead of rotating, the piezoelectric materials are well suited to the reciprocating material. Among the vibration found on MEMS piezoelectric energy harvester, a structure of cantilever beam can develop the maximum and deflection and compliance constant which is the cantilever beam is the comprehensive used (Gongbo Zhou et.al, 2014). The longitudinal vibration frequency and torsional vibration frequency are higher than the bending vibration frequency. Commonly, because of simple process and relatively high efficiency, the rectangle shaped cantilever structures are widely used as shown in Figure 2.1.

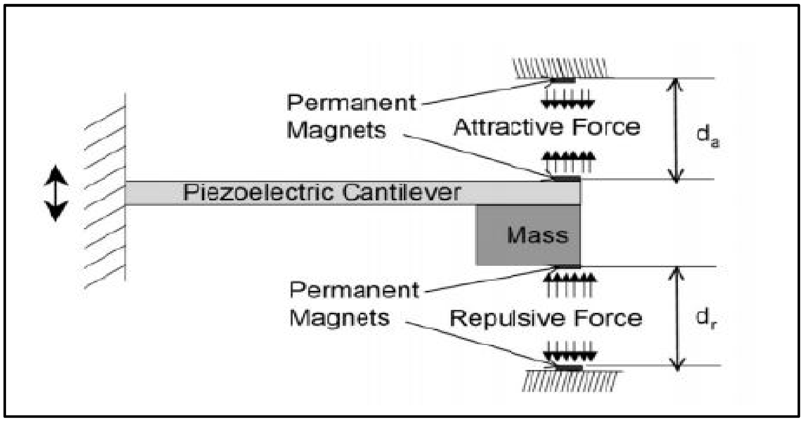


Figure 2.1: The schematic diagram of cantilever beam energy harvesting devices.

(Source: Challa et.al, 2008)

The cantilever beam is having a free small end which it is a trigon-shaped cantilever beam. It is will produce a higher output power for the higher strain. Besides that, it will produce maximum deflection than the rectangular beam which are the breadth and extent are equivalent to the bottom and elevation of the triangular beam. The example application for piezoelectric energy harvesting is the tuneable energy harvesting. These applications describe a cantilever beam consisting of piezoelectric material with a mass tip. The device is attached with four magnets as shown in the Figure 2.1 which it is used to apply attractive and repulsive forces.

2.1.2 Electrostatic (Capacitive) Energy Harvester

The electrostatic energy harvester can be defined as the system that can produce voltage via altering the capacitance. Before the energy is generating via the scheme, the initial voltage was applied toward the system. The amount of charge accumulate in the capacitor was changed by the external vibration. The circuit will generate the charge flow so that it will provide the electrical power produces by the sensor. This energy harvesting device has a great similarity among IC and MEMS technology. There are many advantages of this energy harvesting such as low noise, small size, low quality and it is most suitable in wireless sensors.

The electrets as an electrostatic guiding can be dividing into two category such as $Si0_2$ based on inorganic electrets and polymer based organic electrets. A major investigation on electrets based energy harvester with single silicon has been managed. $Si0_2$ is electrets for energy harvesting system, which it can be functional in a method that can be simulated and stable via ion implantation (U Mescheder et.al, 2009). The fabricated counter electrode for the grid electrode is used to charge the electrets after the fabrication. The harvester is fabricated with unidirectional elastic Si spring that is appropriate for converting small frequency vibrations. Figure 2.2 below show the example of electrostatic energy harvester.

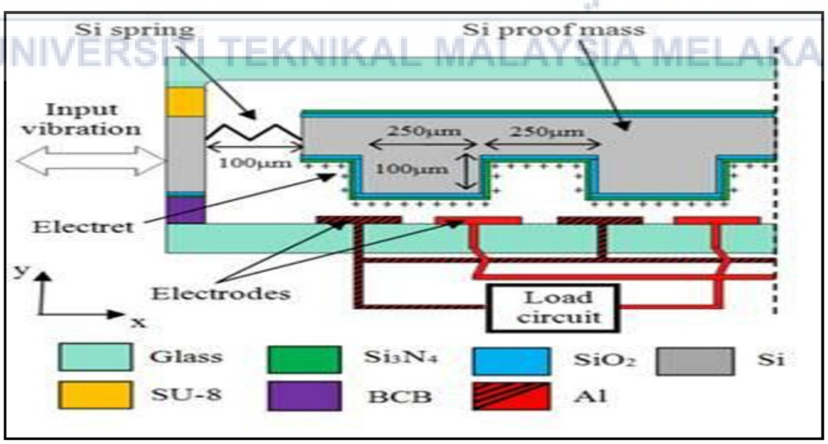


Figure 2.2: Example of schematic diagram of Electrostatic Energy Harvester

(Source: IMEC et.al, 2013)

In recent years, the electrets materials have been integrated into numerous MEMS devices with the development of MEMS technology. It is widely used dielectric medium with electricity storage function. The advantages of this energy harvesting are it has poor stability and low surface potential (Stefan Bosse et.al, 2011). Overall, the electrostatic energy harvesting is focusing on reducing the frequency. In order to further its output power, it is need to improve the electromechanical coupling performance of electrostatic vibration energy harvester.

2.1.3 Electromagnetic Energy Harvester

According to Maheshwari (2013), the concept of electromagnetic induction is discovered by Faraday in year 1813. The magnetic field was contain a generation of electric current in the conductor. The conductor usually takes the form of coil and the electric is generated by relative motion of magnetism and coil, or due to change in the magnetic field. Electromagnetic energy harvester or known as electromagnetic induction is refer to once there be a changing in magnetic flux, the induced electromotive strength will generate in a conductor around the system. To reduce risk of corrosion, electromagnetic vibration energy harvesting can be simply packaged and it can eliminate the temperature limit.

There are some relevant parameters about harvester which are magnetic induction, magnetic flux density and coercive force. Ceramic, Alnico, SmCo and NdFeB are an example of available magnet. In recent years, NdFeB is the most common magnet that had been used as permanent magnet because it had the biggest magnetic field intensity, elevated coercive strength, and no demagnetization due to vibration generator. Figure 2.3 shows the electromagnetic energy harvester using NdFeb magnet.

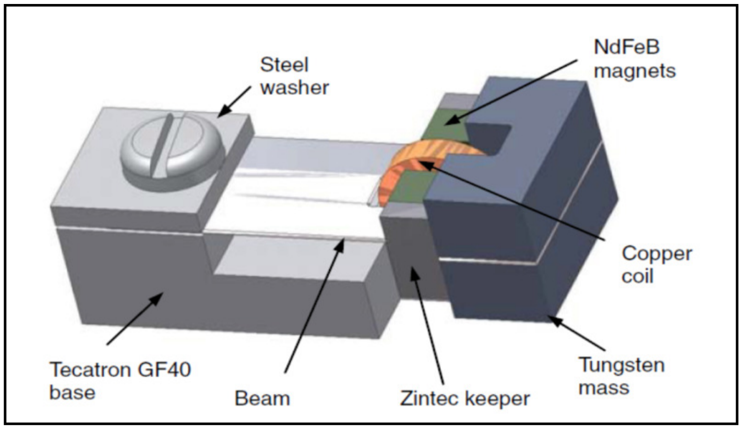


Figure 2.3: The electromagnetic energy harvester using NdFeb magnet

(Sources: Karim El-Rayes et.al, 2013)

Beeby et.al (2007) stated that the art of vibration electromagnetic powered generators using moving NdFeB magnets on the beryllium-copper beam which it is placed on the wire-wound coil. It is silicon-based micro fabricated generator. The result show that the maximum power obtains from the devices is 46μW and the load is 4kΩ. The maximum power result is from 0.59 m/s^2 of acceleration and the resonance frequency is 52Hz. While in previous research, El Hami et.al (2001), show the results gain from the electromagnetic power generator consisting of a cantilever beam with a pair of NdFeb magnets with fixed wire wound coils between the poles of magnet which it is discretely assembled generators. The present results stated that 1mW of power is obtained from 0.24cm^3 of volume and the frequency is at 320Hz. As conclusion, the centerpiece of a silicon-based micro generator has a low coil turning over a discretely fitted generator (Kulkarni et.al, 2008).

The deposition and enhance of the magnet can be attain by micro processing technologies. Furthermore, the micro magnet can be fabricated by sputtering and electroplating and other deposition technologies have been used. The advantages of this electromagnetic energy harvester are it can improve reliability and can reduced mechanical damping so that there is no mechanical contact with other parts.

The parameters of electromagnetic damping such as flux gradient, coil turns, coil impedance and load impedance are connected in one size which it can extracted electric power. Magnet and coil are the main factor that affects the efficiency of energy harvesting. The points of this study are to reduce the devices size under the premise of not affecting energy harvesting energy, produce good toughness and develop high-performance tiny magnet. In addition, to upgrade the effectiveness of energy harvesting, electromagnetic energy harvester resonance frequency need to be adjusting according to the change of external vibration sources.

2.2 Types of Energy Harvesting Materials (Sensors)

The energy harvesting materials is such an important thing so that the power of energy harvesting can be done. The need for energy harvesting motivates the discovery to found new materials also design the latest device structure. There are numerous sensors with different materials that use in energy harvesting.

2.2.1 Thermoelectric Material

Firstly, thermoelectric material is one of the materials that use in energy harvesting which it can generate electricity from heat exchanger and it can play an important role in the solution of global sustainable energy (Snyder et.al, 2008). It is a material that are solid state energy exchanger whose electrical, thermal and semiconductor properties allow used to change waste heat into electrical energy directly for cooling or heating in niche application (Bell & Lon E, 2008). Besides that, thermoelectric material had drawn attention because it is allow direct transfer among thermal and electrical power (Xiao Zhang & Li-Dong Zhao, 2015).

Moreover, it is provide an option for power generation along with refrigeration. Furthermore, every material illustrate thermoelectric effects however the name thermoelectric material was used to illustrate the materials that are good at transform heat into electricity (Jan Willem Bos, 2012). According to Figure 2.4, it is the example of thermoelectric material which it has the free electrons and holes in a thermoelectric conductor act as a gas of charged particles while the free electron or holes in thermoelectric material carry both charges and heat.

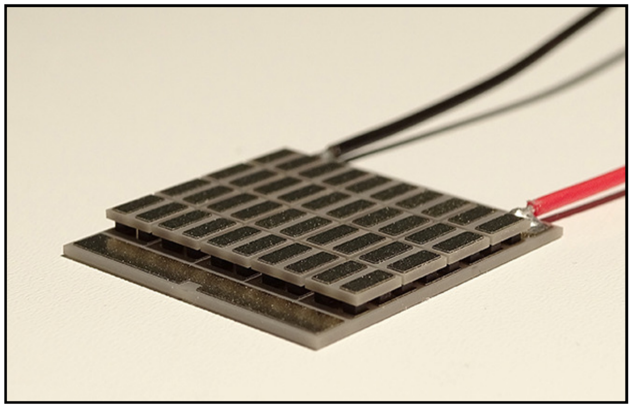


Figure 2.4: An example of thermoelectric generator use in Energy Harvesting

(Source: Charles Morries, 2017)

2.2.2 Piezoelectric material

Next, piezoelectricity is the effect of electromechanical relationship that allows certain material such as crystals and synthetic ceramics to produce an output voltage power that derived from mechanical stress or vibration. For example the acoustic transducer, mechanical actuator and electrical energy harvesting system are application that is widely used the piezoelectric material. Commonly piezoelectric materials are made of ceramic such as lead zirconate-titanate or PZT and bimorph such as polyvinylidene fluoride or PVDF. The advantages of bimorph element are soft and flexible, but it has low ceramic dielectric and piezoelectric constant (Swallow et.al, 2008).

As shown in Figure 2.5, the ceramic disc is one of the piezoelectric materials which are able to be use as a method of converting mechanical vibration energy into electrical power. These piezoelectric materials are able to be store energy and use to move different devices (R. C. Garimella et.al, 2005). Piezoelectric ceramics is referred to polycrystalline made by maxed oxide (zirconia, lead oxide, titanate, etc.) encountered by high rays and solid state reaction, then through high voltage direct current polarization, it has a general term piezoelectric effect of ceramic ferroelectric (Tianze et.al, 2009).

The charges get stored in solid materials due to application of mechanical strain (Nayan HR, 2015). Piezoelectric materials have its own criteria or specific properties of producing electric voltage in response to the power used. Commonly, crystalline or ceramic, piezoelectric materials contain a variety of uses such as sonar, sound recognition and high electrical energy generating as well as daily life, such as sources of ignition and barbecue sparks.

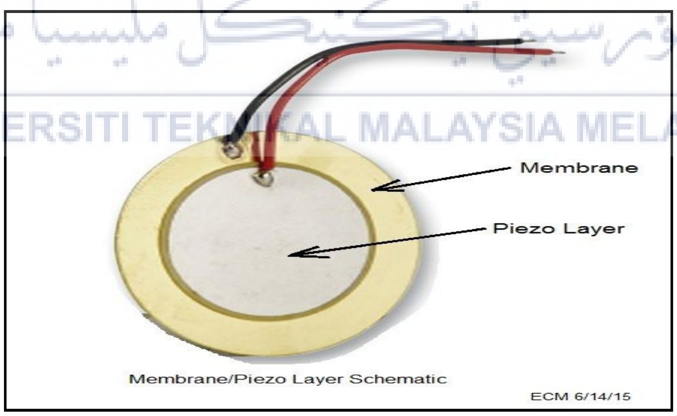


Figure 2.5: The piezoelectric material use in Energy Harvesting

(Source: Nayan HR, 2015)

2.2.3 Pyroelectric Material

Pyroelectric material is a certain crystalline properties that are naturally electrically polarized and the result is a large electric field. The gallium nitride semiconductor is the example of pyroelectric material. The large electrical field in this material is undesirable for light-emitting diodes (LEDs), but it is particularly useful for the manufacture of power transistor. In preference, pyrpelectric is clarified as the capability of certain materials which it is used to generate a provisional voltage when it is cooled or heated (Charles, 2016). It is very sensitive to rapid temperature.

This material has the possibility to produce electricity from thermal fluctuations and is a poor use of heat energy from a thermoelectric system. An electric charge of pyroelectric crystal is produced when there is temperature changes occur. The charge is only produced when the material temperature changes. The example of pyroelectric material is shown in Figure 2.6. Some remarkable introductions to existing pyroelectric materials, most of which focus on their heat sensing, infra-red relationships, heat imaging, gas movements, gas analyzers and pollutant monitoring (C.R.Bowen et.al, 2014).

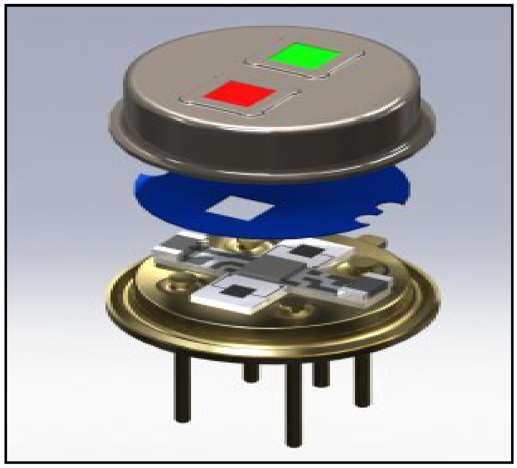


Figure 2.6: Example of Pyroelectric detector used in Energy Harvesting

(Sources: Celina Lawson, 2017)

2.3 Sensor used in Energy Harvesting

In this study, piezoelectric material is choose as the sensor for energy harvesting because it is suitable to convert mechanical energy into electrical energy by using vibration energy.

2.3.1 Piezoelectric as Energy Harvesting

All of the ambient environment sources need a transducer or energy harvesting devices to convert mechanical energy into electric electrical energy, all. The vibration energy is one of the ambient environment sources that become more popular among researchers which it is the best way attractive solution for powering autonomous system (Yildiz & Faruk, 2009). This is because vibration-based energy is an ambient source that can have everywhere and high power density.

In order to produce high electrical output density, piezoelectric is most suitable as vibration based energy conversion mechanism which it can make simple structure which easy to fabricate. The piezoelectric material has a special characteristic to develop an electrical voltage in response to the influence force. Piezoelectric materials can be used as a way to transform the vibration around into electricity which is able to store and use for other device power (Parul Dhingra et.al, 2012). Normally, piezoelectric materials contain a variety of uses such as sonar, sound recognition and high electrical energy.

Throughout World War II, new classes of man-made material have been found by research groups in the United States, Russia and Japan. The first application is for sonar used to notice submarines through sound waves. When subjected to a high polarizing voltage, a process similar to magnetization of ferrous materials, ceramics materials can be made by piezoelectric. In addition, it is called ferroelectrics which exhibit continuous piezoelectricity much higher than the natural piezoelectric material. The first piezoelectric material exploited commercially is a quartz crystals and it is still use in sonar detection application.

The piezoelectric materials can be defined as the materials that can create electricity when subjected to a mechanical stress (Parul Dhingra et.al, 2013). The mechanical energy is derived from the compression stress created during the vibration of automotive component occur. There are various types of natural and man-made materials that showcase various piezoelectric materials. The materials including Berlinite which are the same as quartz, sugar cane, Rochelle quartz salt, topaz and vice versa. The lead zicornate titanate and barium titanate are example of man-made materials in piezoelectric.

Piezoelectric effect is use to measure pressure, acceleration, temperature, tension, or strength by converting it to electrical charge by using piezoelectric sensor. The piezoelectric sensor working principle is a physical dimension which transformed into power and acting on two faces that opposed the sensing element. In the form of sound, it is the most common sensor application used to detect pressure variations such as piezoelectric microphones and for electric-powered guitars (Chris Woodford, 2017). For example, the medical imaging and industrial nondestructive testing had used this sensor piezoelectricity with high frequency sound in ultrasonic transducers.

CHAPTER 3

METHODOLOGY

3.1 Introduction of Methodology

This section describes the method use herein project to obtain energy harvesting from mechanical vibration by using piezoelectric material. The flow chart of the project is shown in Figure 3.1. These projects are start by studying the concept of energy harvesting and understand the principle working of energy harvesting. In this project, one sensor is choosing as the sensor to test the principle working of energy harvesting. The three mechanical vibrations from automotive components is verify so that the energy harvesting can be done by using the propose sensor.

3.2 Identify the sensor

Energy harvesting is a process which a device associated with capturing residual energy. It is also a system which it convert mechanical energy to electrical energy and accumulate it, so that it can supply low power devices and use it later (Liew Hui Fang et.al, 2016). To further investigate about this study, a suitable sensor needs to identify so that the project can achieve the objective to obtain energy harvesting of mechanical vibration from automotive component. In this study project, piezoelectric material is choosing as the most suitable sensor for energy harvesting which it is use vibration energy to convert to electrical energy.

Based on preview research (Minazara et.al, 2014) had developed the vibrations energy harvesting principle which it is use piezoelectric materials as a sensor into designing piezoelectric generator. It is used to install the piezoelectric generator on a bicycle handle in order to supply portable electrical energy. Based on observations, this experiment has been conducted has shown that some of the power (mW) generated by piezoelectric generators capable of turning on LED bicycle lamp. This observation proves that piezoelectric material can transform electricity in the form of targeted mobile application.

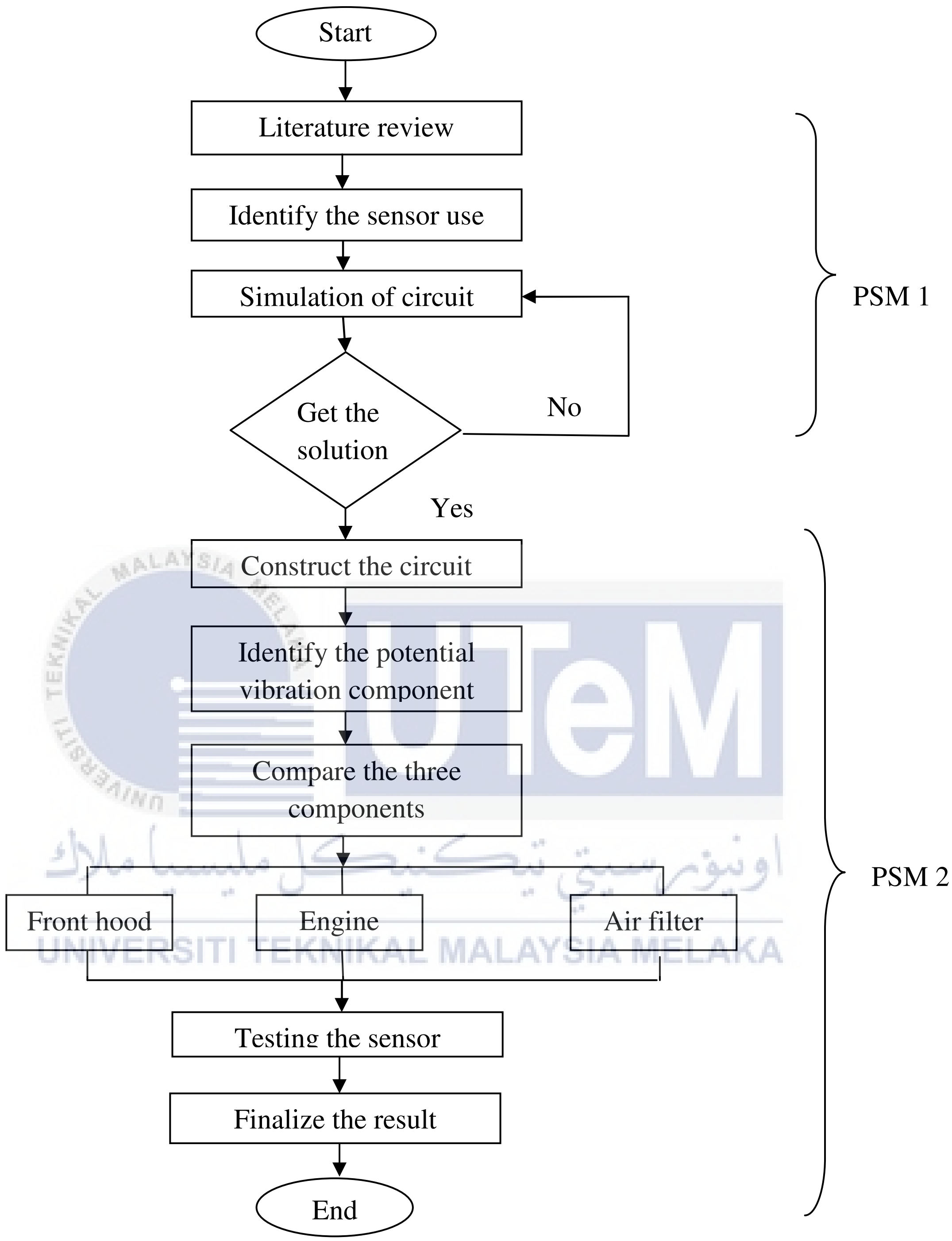


Figure 3.1: Flow chart of the methodology

3.3 Simulation of circuit

Before the piezoelectric circuit is build, the simulation of circuit is needed in order to know the flow of circuit. NI Multisim software or recognized as MultiSIM is an electronic diagram for capturing and simulation program that are part of the circuit design program corresponding to NI Utiboard. Multisim design helps to accumulate the prototype iterations and optimize printed circuit board (PCB) design before the process runs. This software was used to test the circuit before a piezoelectric circuit is build. In addition, simulation of circuit can helps to understand the flow of circuit and can determine what suitable components can be used in order to construct a real circuit. If the simulation circuit is running smoothly, the piezoelectric circuit can be build easily. Figure 3.2 shows the simulation of piezoelectric circuit for energy harvesting in this project.

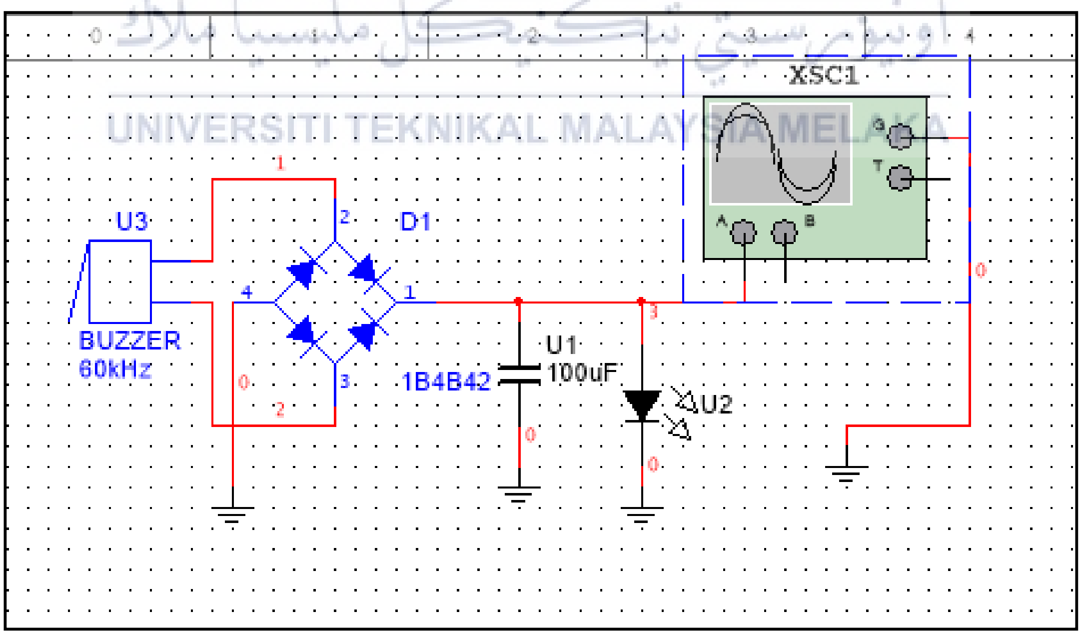
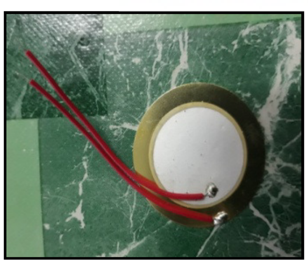


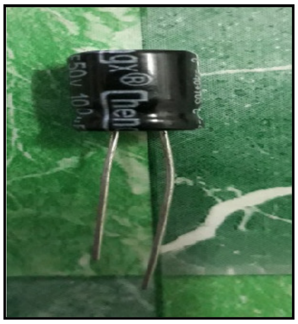
Figure 3.2: The simulation of the piezoelectric circuit

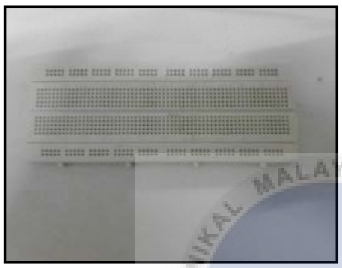
3.4 Construct the piezoelectric circuit

The piezoelectric circuit is build after the simulation of piezoelectric circuit is done and to test the principle working of piezoelectric material on energy harvesting. A piezoelectric element is a system which converts movements of mechanical vibration energy to the electrical energy, which it is store inside a capacitor. The first step to design the piezoelectric circuit is needed to know what electrical components are uses in circuit. The simulation of circuit can help to determine what electrical components are suitable to use before the piezoelectric circuit is build. Based on preview research, the basic components that always use in order to test the working principle of the circuit are breadboard, LED lamp, jumper wire, capacitor and piezoelectric plate. In this project, Table 4.2 below shows the components that used in order to construct a piezoelectric circuit.

Table 3.1: Types of components use to build a piezoelectric circuit

Types of components	Description
	• Known as ceramic disc • It is a polycrystalline made by maxed oxide (zirconia, lead oxide, titanate, etc.) which it has high sintering and solid state reaction through high-voltage direct current polarized. • It has the term of the piezoelectric effect of ferroelectric ceramics.

	• The capacitor is use to store the energy that generated by the piezoelectric and it is able to recharge and discharge faster. • The power use in capacitor is 100Ω and 50V. • It can accumulates electrical energy charge in an electrical field which it is similar to a battery
	• The type of diode use is 1N4007. • It is use to allow the current flowing through the diode which it is called forward current.
	• LED Light is the main function to help circuit creators check the functionality of a circuit to ensure it is successfully running. • It is detachable and placed on the side of the circuit to make sure that the power supply or electric current is successively in the right direction.

	• Wire jumper which it is known as electrical wire. • It is use to connect the components of a breadboard or to test the circuit, internally with other electrical components without soldering.
	• Breadboard • It is used as a construction in developing an electronic circuit and it can be solderless which it is made of plastic and contain with numerous holes. • It is a multiple function to build a variety of products using electricity.

According to Table 4.2 above, the electrical component is the basic element or an electronic part which is usually packaged in discrete form with two or more connectors. Each electric component has its own function to complete the piezoelectric circuit. The first is piezoelectric plate which it is a main component in energy harvesting and it is passive components that use piezoelectric effect. It acts as a sensor which its function is to convert mechanical system into electrical system and accumulate it so the power can be using later and can supply low power devices. Next, breadboard component is used as a construction in developing an electronic circuit and it can be solder less which it is made of plastic and contain with numerous holes. A bread board is a multiple function to build a variety of products using electricity.

Another component is wire jumper and it is used with a breadboard to build a functioning circuit. LED lamp is another component which it helps circuit creators check the functionality of a circuit to ensure it is successfully running. The LED light is detachable and placed on the side of the circuit to make sure that the power supply or electric current is successively in the right direction. Meanwhile, capacitor is a device that accumulates electrical energy charge in an electrical field which it is similar to a battery. The advantage of capacitor is it is able to recharge and discharge faster. The last part is diode, acts as the full wave rectifier which it is used to convert alternating current (AC) from piezoelectric output to direct current (DC).

In addition, all electrical components have their own characteristic and function. These electrical components are use to complete the piezoelectric circuit. All the components are connected together according to the simulation of circuit, so that the piezoelectric circuit is function well.

3.4 Identify the potential vibration components

In this project, the several potential vibration components is identifying by using a vibration meter device. In order to verify the best car components point for the placement of the piezoelectric based on the vibration produce, the average vibration for each of the chosen component is studied. In this project, the vibration meter device is used to verify the ambiance and oscillations which its dimensions provide parameter such as vibration for acceleration, velocity and displacement. Figure 3.3 shows the vibration meter devices use in this study to compare the average vibration at several points of car components.

Figure 3.3: The vibration meter devices

3.5 Compare the three components

Next, in order to determine the placement of piezoelectric based on vibration, the average vibration produced by each component is studied. The vibration is produced when there is a motion occurring from the object and there is unbalance force generation because of that the vehicles start shaking. The suitable components is identifying by refer to its average vibration. The components from automotive components are identified by doing some preview research related to the components which has a higher, medium and low vibration to test the energy harvesting using piezoelectric system by compare its output voltage. In this project, the front hood, engine and air filter is choosing as the suitable components to make a comparison for a suitable energy harvesting.

The first component is front hood which it is one of automotive component. Figure 3.4 below shows the front hood of the car. The front hood systems are one of key components in mechanical system. In addition, front hood of the car is referring to the hinged cover over the engine of motor vehicles that allow access to the engine compartment for maintenance and repair. The front hood is choosing as one the component to install the piezoelectric because it is produce the smallest vibration among the other components. So, the output voltage from the front hood can be compare whether it is suitable for energy harvesting or not.

Figure 3.4: The front hood of the car

Next component is engine which it acts as the vehicle's main source of power and it has a chemical energy which it is converted into mechanical energy. Figure 3.5 below shows the engine component inside the car. The engine uses fuel and burns it to develop mechanical power. Besides that, the pressure creates when there is a heat produce by the combustion and it is used to drive a mechanical devices. By refer to preview research, car engine is a second high vibration which it can generate energy by transforming mechanical energy into electrical energy. Preview research stated that the output voltage generate via the car engine increase significantly starting with initial time to 1st minute (Mohammad et.al, 2015). In addition, the vibration produced at the highest once the car engine was being started up. A piezoelectric system is connected at engine in order to produce energy from the vibration of car engine when the engine is switch on.

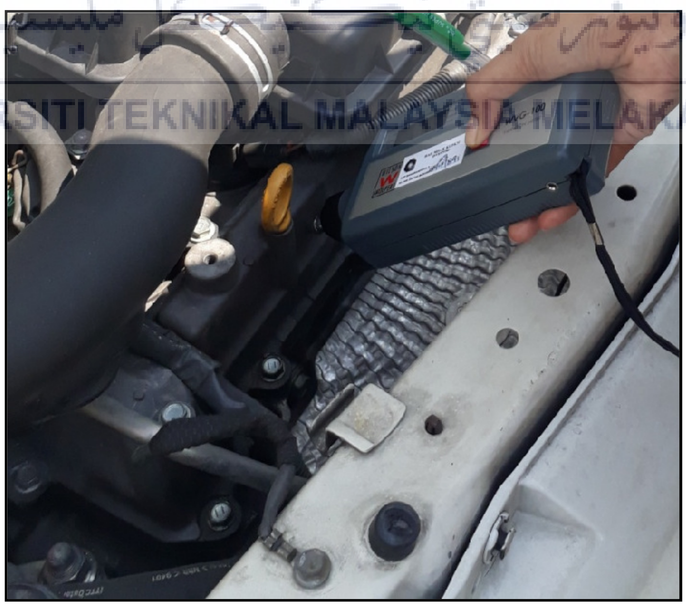


Figure 3.5: The engine in a car component

Lastly, another component is air filter. Air filter is one of the automotive components which are a necessary to proper engine operation. In this project, Figure 3.6 below shows the air filter inside the car component which it produce the highest vibration. According to Mohammad et.al, (2015) stated that the output voltage generated produce at air filter is increase linearly with time. The air filter will allow air-intake when car engine was just starting to run, which it is resulting in increasingly output voltage. The air filter will produces a higher vibration at that point and it is good component because it can generate energy continuously.

Figure 3.6: The air filter in a car component

3.7 Testing the components

Subsequently, the piezoelectric generation system is connected to the selected components to study the potency of piezoelectric energy harvesting in automotive component which vibrate more. All these components are investigated whether it is produce a suitable vibration needed for the piezoelectric generation system or not. In addition, the output voltage generate from the circuit depending on the vibration formed by the component. The higher vibration of the components will result in the better performance of piezoelectric to generate mechanical energy into electricity. In this project, the digital multimeter devices are used to know the output voltage produce at each component.

Figure 3.6: The Digital MultiMeter

The Figure 3.6 above shows the digital multi meter device use in this project. Digital Multimeter is a test tool that is used to measure two or more electrical values such as voltage (volts), current (amperes) and resistance (ohms). Figure 4.2 above shows that when the digital multimeter is connected at polarity of each component which it is cathode and anode, the output voltage reading of each component will produce.

3.8 Finalize the result

The last method is the result of energy harvesting gain when using piezoelectric generating system is finalized. It is means that result and discussion are included in this method. The characteristic of piezoelectric that affect on each component is investigated. The comparison of output voltage gain from the vibration by each component to converts mechanical energy into electrical energy when connected to piezoelectric circuit is studying. In addition, with reference to the preview study, the output voltage generated by the circuit depends on the resulting vibration.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter will discuss about the result gain from the case studies. The average vibrations produced at each point of the car and the types of components use to build a circuit are discussed.

4.2 Vibration produced

Vibration is produced when there is a motion occurring from the object and there is unbalance force generation because of that the vehicles start shaking. In this study, the several car components are identified by doing some preview research related to the components which has a higher and lower vibration so that the comparison to test the energy harvesting using piezoelectric system can be determined. This data was obtained to investigate the most significant piezoelectric placement on the car components of car. The result is obtained from measuring the vibration at some point on the car component by using the vibration meter device. To determine the best position for piezoelectric placement based on the vibration, the measurement is takes on three readings to determine the average vibration for each chosen selected point. The data obtain is recorded in Table 4.1.

Table 4.1: Vibration produced at each point of the car

Location	Vibration produce (km/h)			
	1^{st}	2^{nd}	3^{rd}	Average
Exhaust	2.01	2.10	2.33	2.15
Air Filter	1.96	2.08	2.01	2.02
Engine	0.81	0.78	081	0.80
Car battery	0.18	0.16	0.16	0.17
Front hood	0.16	0.14	0.15	0.15

According to Table 4.1, the point selected at each of the car components are exhaust, air filter, engine, car battery and front hood. It is shown that the three readings of each selected point at car were recorded in order to determine the average of the vibration produced. The average vibrations generated for each selected point are as shown in Figure 4.1.

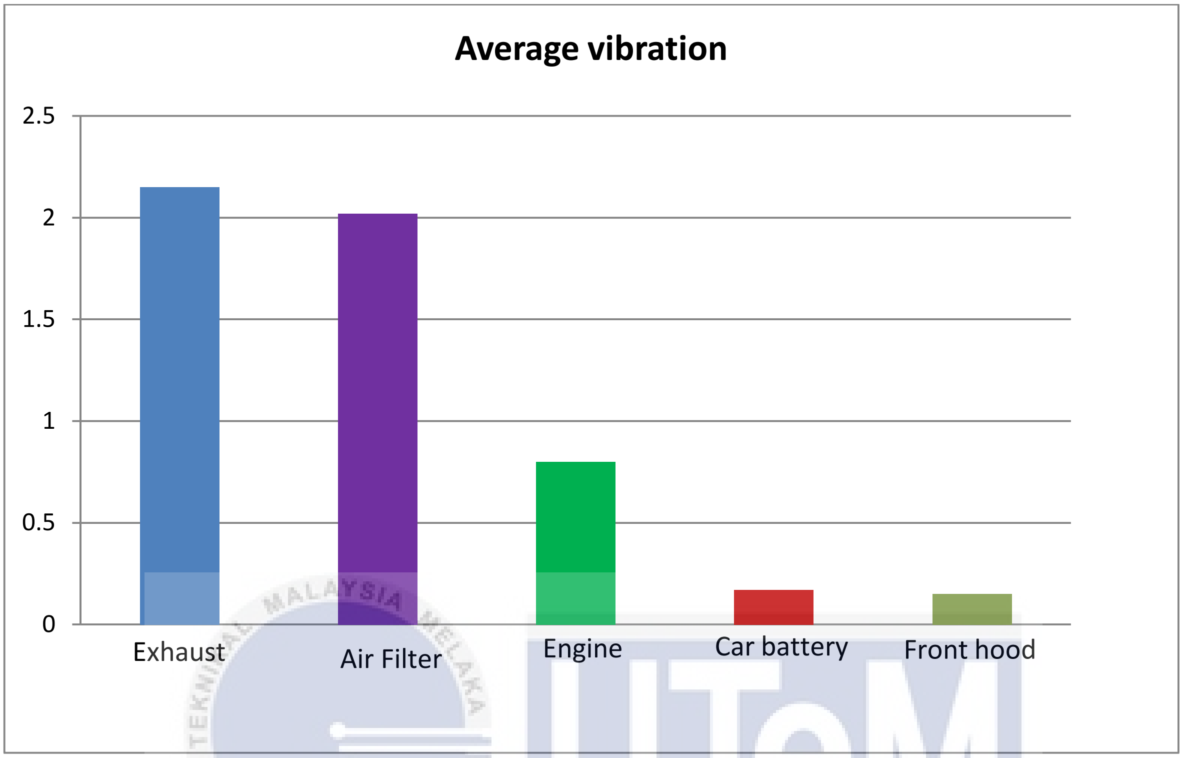


Figure 4.1: Average vibration produced at different point

According to Figure 4.1, it shows the average vibration at the selected point. The highest point is the exhaust which is 2.15 km/h .The second highest vibration produce is air filter and follow by the engine which respectively 2.02 km/h and 0.80 km/h. Next, the average vibration produce at car battery is 0.17 km/h. The last selected point is at the front hood of the car which 0.15 km/h.

Based on this average vibration, even though the exhaust system gives the highest average vibration, but because of the emitted heat and the exposed state of this point exhaust system has been neglected as a piezoelectric point installation. Next, the condition points was selected as the experimental point for the piezoelectric are air filter and engine because it is the second and third highest average vibration produced. The car battery and the front hood point only give the minimum output vibration, however the front hood is choose as the experimental point for the piezoelectric so that the comparison between the highest and lowest vibration produce of each components selected point can be determined.

4.3 Schematic Diagram of Piezoelectric Energy Harvesting Circuit

In this project, schematic diagram of piezoelectric was illustrated by using Ni Multisim 13.0 software. . It is used to determine the accuracy and design efficiency before the system is built. It is use to explore the advantages of alternative designs without physically building the system. By investigating the effects of certain design decisions during the design phase rather than the construction phase, the overall construction cost of the system diminishes significantly. Furthermore, it is use to show the schematic diagram of circuit before the circuit is build and to know the output voltage produce. According to Figure 4.2 shows the schematic diagram of piezoelectric circuit and Figure 4.3 shows the output voltage obtained using this software. According to Figure 4.3, the maximum output voltage produce by the simulation of circuit is 4.178nV.

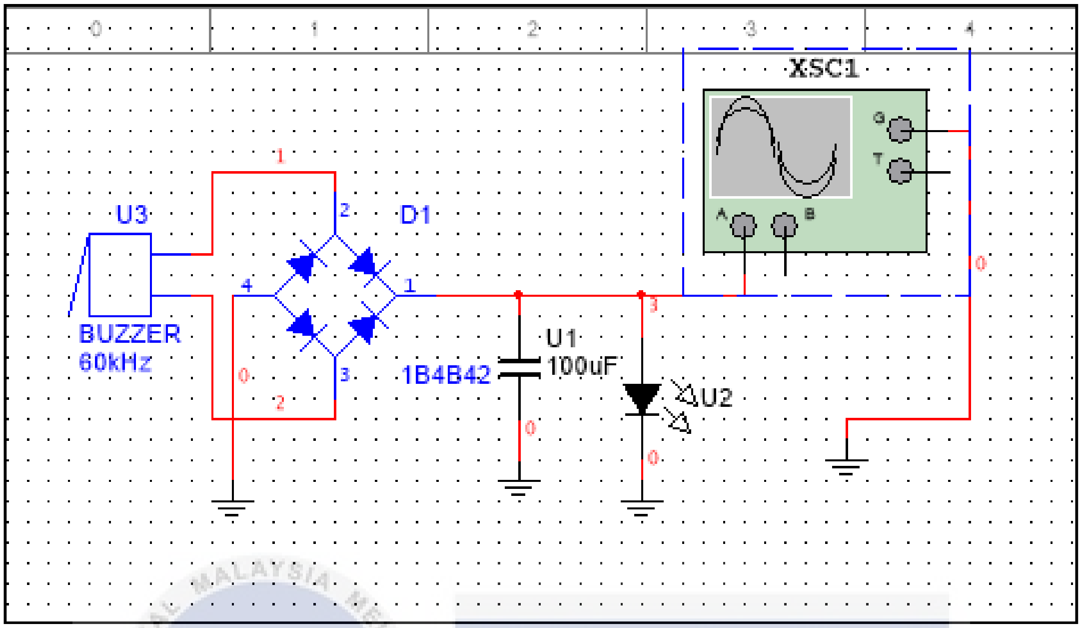


Figure 4.2: The schematic diagram of piezoelectric circuit.

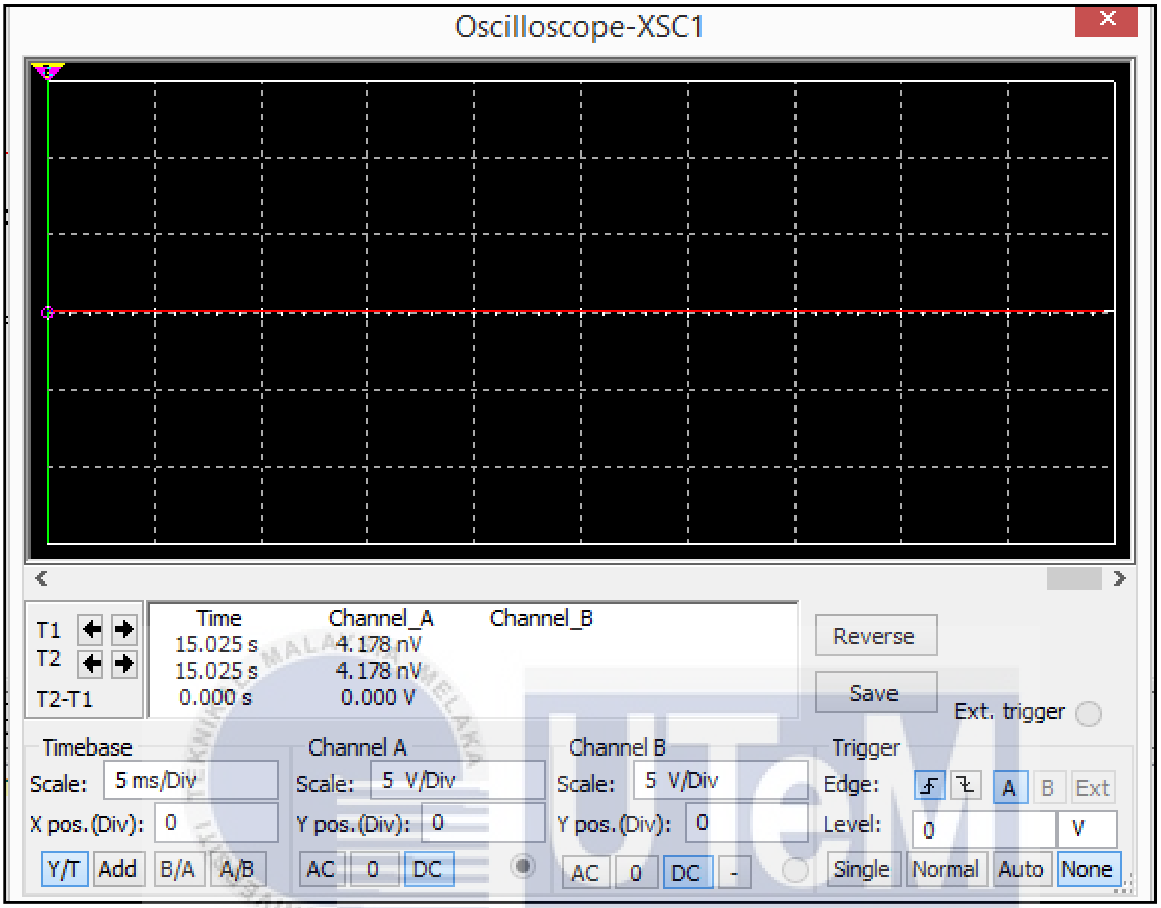


Figure 4.3: The output voltage of schematic diagram

4.4 Piezoelectric circuit

The piezoelectric circuit is done by follow the schematic diagram of circuit. This circuit consists of a full wave rectifier and capacitor to store energy. The full wave rectifier is used to convert alternating current (AC) from piezoelectric output to direct current (DC). Figure 4.4 shows the circuit diagram. As can seen, the circuit consists of 20 piezoelectric, wire jumper, 4 schottky diode as full wave rectifier, capacitor 100µF 50V to store energy and LED light as a load. In Figure 4.5, shows the detail component solder on the PCB Board.

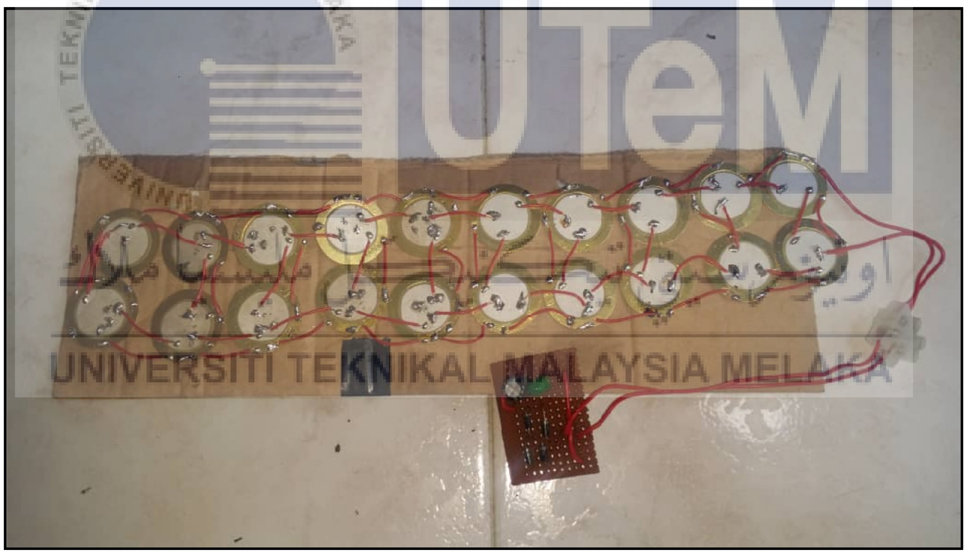


Figure 4.4: The circuit diagram

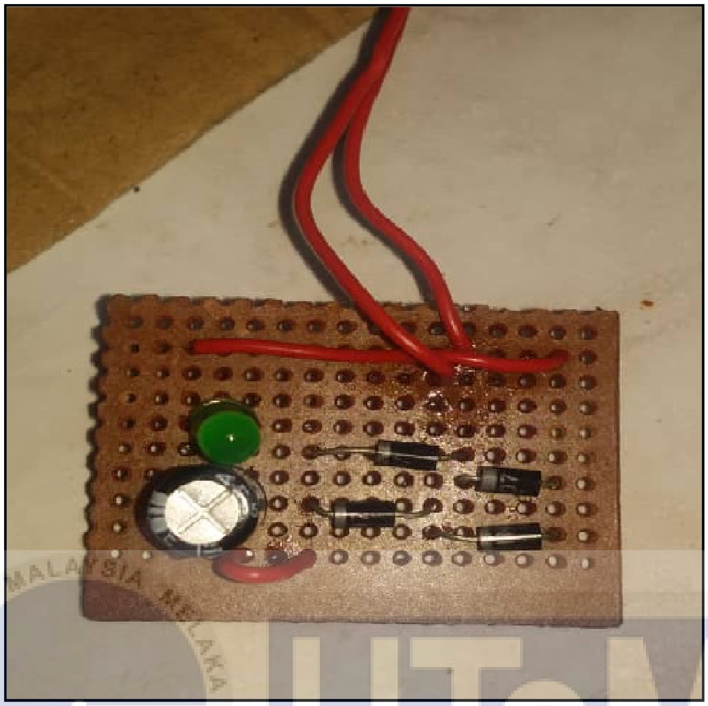


Figure 4.5: The components use to build a piezoelectric circuit

4.5 Output voltage of Piezoelectric in three components

The testing of circuit is done at three components to compare the output voltage of each component. The engine, air filter and front hood are used in this project. It is use to determine whether the vibration produce at each components is suitable or not for energy harvesting. This is due to the output voltage generated from the circuit is depends on the vibration produced.

In this project, the first component that been tested on the piezoelectric output is that engine of the car. The graph in Figure 4.6 shows the resultant of the output. It is shown that the output voltage was generated by the system increase drastically from initial time to 1st minute. This is due to the engine is being started up and vibration produced by the engine is at the highest. By referring to the graph, the output voltage produce by the engine is increasing slightly and it starting to decrease at 4th minutes onwards.

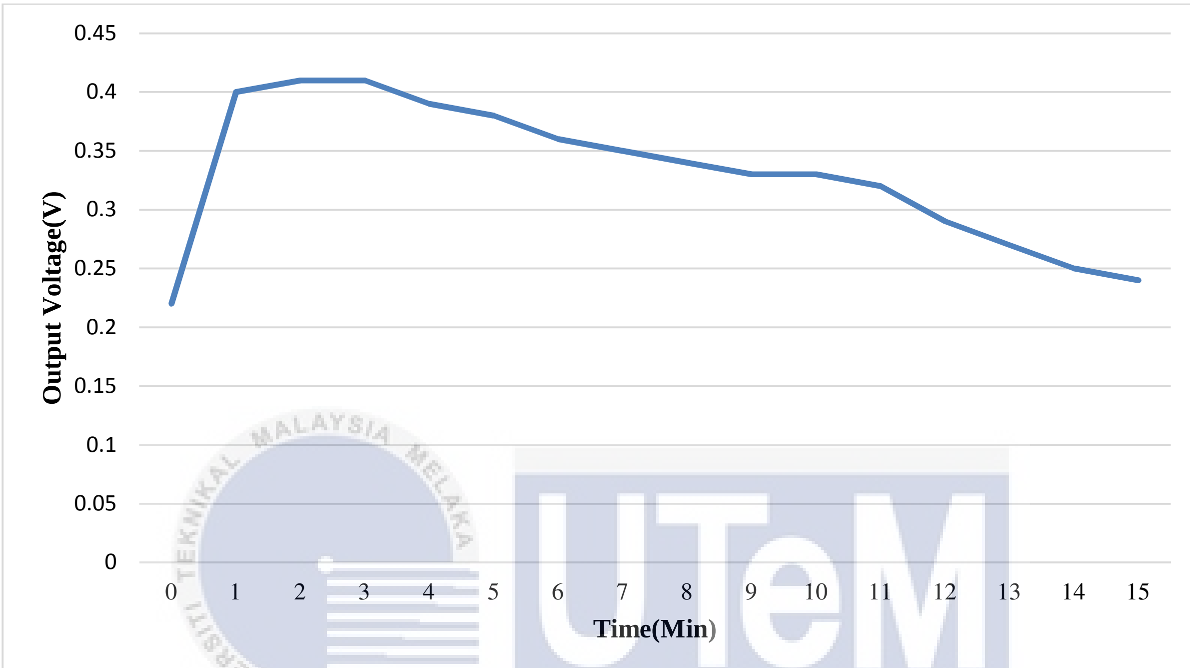


Figure 4.6: The output voltage of Piezoelectric in engine against time

This is because the engine produces a stable vibration when the car is static and it produce low amount of vibration. In energy harvesting, the system is not suitable because it does not utilized enough vibration from the car engine. In addition, for a car in static condition, the engine component is not a suitable point to install the piezoelectric circuit. This is because the engine only utilized the vibration generated at the moment when the engine of car started and it cannot produce enough energy after the engine has been steady and onwards.

The second point of the piezoelectric placement is at front hood of the car. As know, the front hood produces the small vibrations. So, the vibration produced at front hood is not enough for energy harvesting. The graph in Figure 4.7 shows the output voltage produce at the front hood. As can seen, the 1st minute of output voltage shows the highest value 0.32V until it continuously drop the output voltage. Moreover, for the car in static condition the front hood is not suitable for the piezoelectric placement because the energy produce is too low for the energy harvesting.

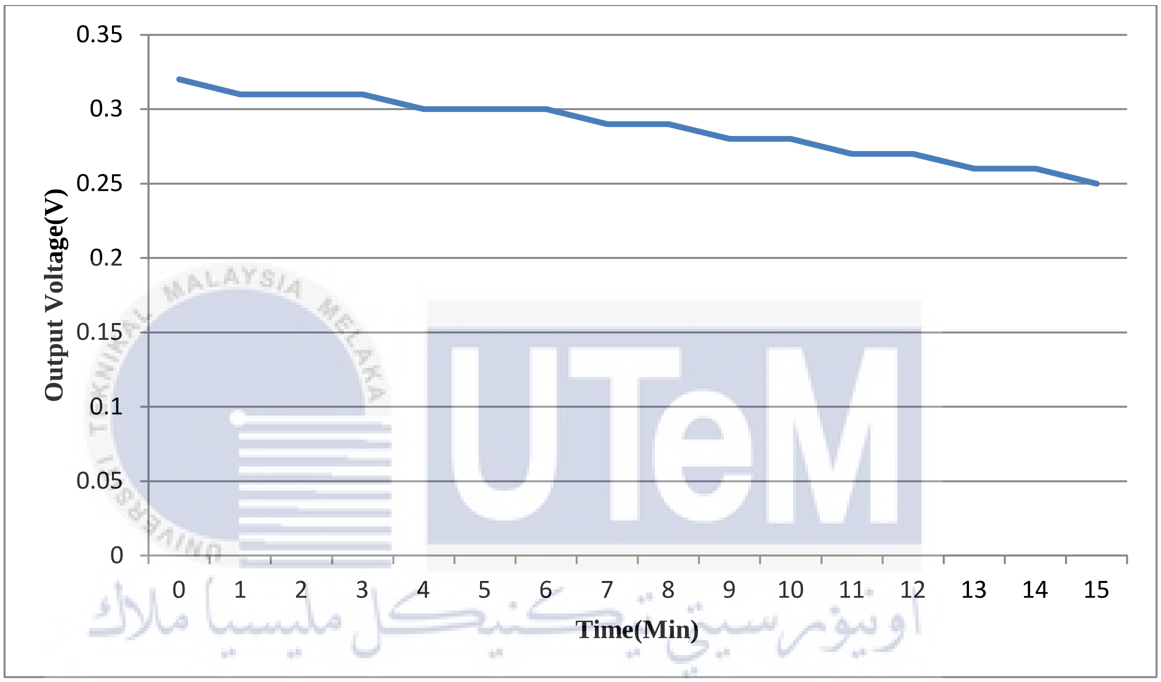


Figure 4.7: The output voltage of front hood against time

Next, the last point of the piezoelectric placement to test is at the air filter. As can seen in this point, the graph in Figure 4.8 shows the output voltage is produced increase linearly with time from the starting of experiment until 6th minutes. This is because the air filters begin to allow air-intake when the car was just starting and it resulting in drastic increase in the output voltage generated. This is the period in which the vibration is generated on the highest air filter. However, the output voltage generated continuously after the 6th minutes because the engine is starting stable and the air intake is in the air filter for non-moving car is the same as before. In addition, the vibration produced is still the same. Therefore, the output voltage is generated continuously.

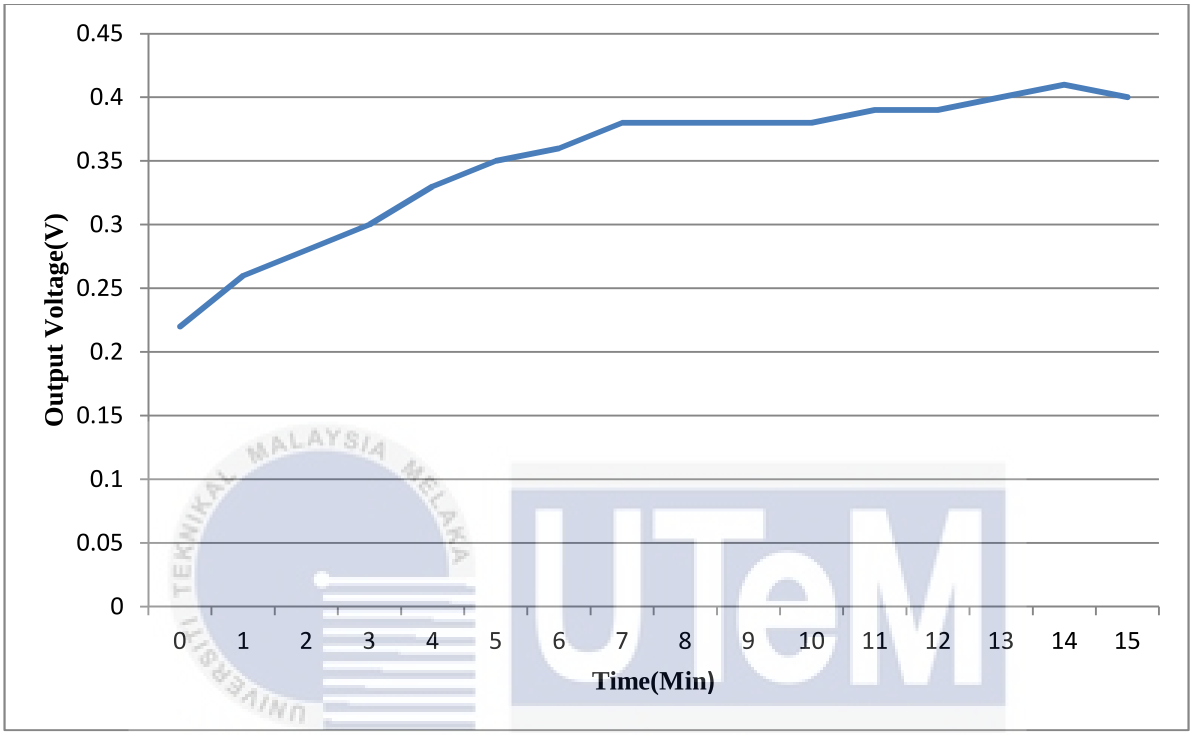


Figure 4.8: The output voltage of Air Filter against time

4.6 Comparison output voltage of three components

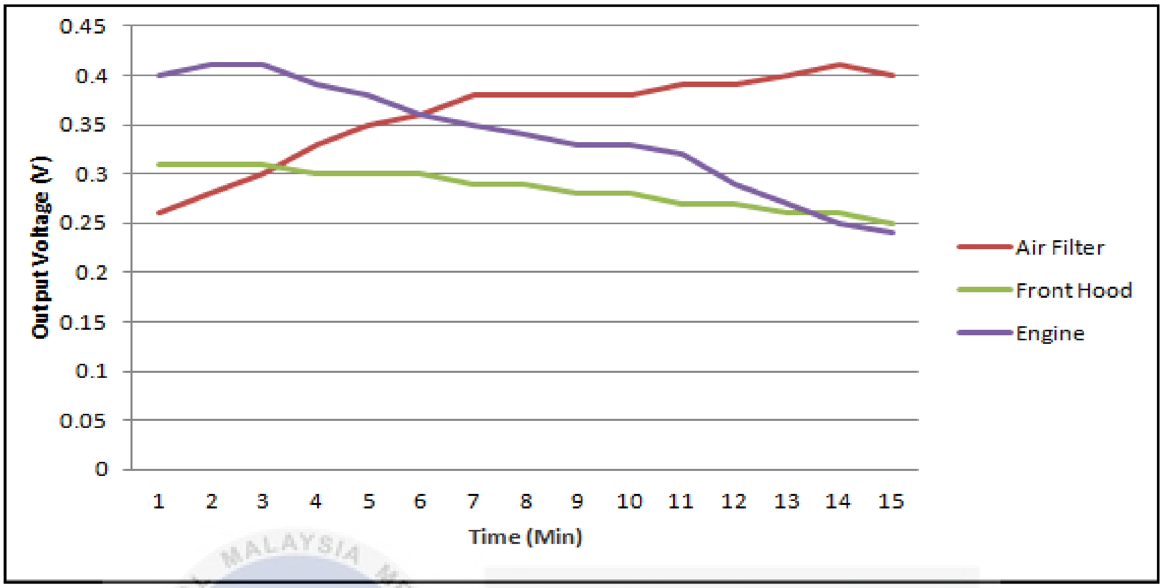


Figure 4.9: The comparison output voltage of three components

By refer to the figure above, after all the components are being testing the result shows that the best point to install this system for cars that are not moving is air filter. This is because of the generating system energy at the moment the car starts and after the car is stable, the output voltage remains the same and there is no significant increase for the importance of this project. For the Air filter, the highest output voltage is 0.41V and it increase linearly with time from the starting of experiment until 6th minutes.

Meanwhile for the engine the highest output voltage is 0.41V but it start decrease at 4th minute. The engine is not suitable because the engine only utilized the vibration generated at the moment when the engine of car started and it cannot produce enough energy after the engine has been steady and onwards. Lastly, for the front hood the highest output voltage is 0.32V and it start decrease. The front hood is not suitable for the piezoelectric placement because for the car in static condition the energy produce is too low for the energy harvesting.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Several decades ago, the project of energy harvesting from clean environmental energy has become well known. The enhancement of technology in the energy-capture capabilities around encourages people to learn more about piezoelectric effects. Energy harvesting is the system which it captures and accumulates energy until it becomes obtainable, saving the energy for the duration of time and conditioning it into usable form later. There are many of renewable energy sources which can be harvested by the environment. Energy harvesting is not to replace batteries but it is use to reduce some of the weakness associated with the maintenance issues. It is related with the advantages to a new different, effectiveness, and renewable resource with many of possible applications.

Piezoelectricity with mean vibrations is one of the most conventional since vibration sources are almost everywhere. Piezoelectric material has the ability to capture the energy of an automotive component pressure which usually wastes energy and converts it into electricity can be used. Moreover, it is does not contaminate the environment because it is environmental friendly. The characteristic of this piezoelectric material are it cannot withstand the high temperature. Next, to produce a high voltage many piezoelectric need to be used. So that it can produce high maximum output frequency. Furthermore, it has a many type of piezoelectric.

In addition, a full wave rectifier which is diode is used to build a circuit in this project and the capacitor is used to store the energy. A full wave rectifier is used to convert intermittent current (AC) from piezoelectric output to direct current (DC). Next, the capacitor is used to accumulate the energy produce from the circuit for future use. The circuit are install at three components so that the output voltage of each components are compared whether it suitable for energy harvesting or not.

In this study, the three components from the car are choosing as source of vibration. The components are engine, air filter and front hood. The experiment was conducted at each component to obtain various result of energy harvesting. But due to several limitations, not all levels of vibration can be used as a source. As conclusion, the air filter is the best part to install piezoelectric for energy harvesting because the system can produce continual energy. It is because at air filter the vibrations generated are sufficient even when the car is in a static state. According to the first discovery of piezoelectric, it shows that the piezoelectricity has the potential to generate micro energy especially for hybrid car electronics.

5.2 Recommendation

There are several areas that need to be addressed in future work. Better physical impedance in designing piezoelectric generators for power sources. Furthermore, changing a more suitable transistor for the piezoelectric source signal should be designed. Next, the output energy generated from piezoelectric energy capture can be increased by using piezoelectric materials for example bimorph materials and polymer film.

Additionally, output power can also be enhanced using the piezoelectric energy supply module. The modules such as LTC3588-1 from Linear Technology is one of the example integrated with the lost full wave bridge rectifiers with high efficiency buck converters to develop a complete power optimization solution optimized for high impedance power sources such as piezoelectric transducers.

Next improvement for high power output is the drive design for piezoelectric discs. The actuating function is to move the piezoelectric disc from the mechanical vibration of the automotive component. The exact design of the drive for piezoelectric discs can increase the highest power that the piezoelectric disk element can produce.

REFERENCES

Amos Kingatua. (2016, June 23). The How and Why of Energy Harvesting for Low-Power Applications. Retrieved from https://www.allaboutcircuits.com/technical-articles/how-why-of-energy-harvesting-for-low-power-applications/.

B. Lafarge, C. Delebarre, S. Grondel, O. Curea and A. Hacala. (2015). Analysis and Optimization of a Piezoelectric Harvester on a Car Damper. *Journal from ScienceDirect*, Vol 70, 970-973.

Basagni, S., Naderi, M. Y., Petrioli, C., & Spenza, D. (2013). Wireless sensor networks with energy harvesting. *Mobile Ad Hoc Networking: Cutting Edge Directions, Second Edition,* 1–36.

Carmen Emily Yang. (2016, September 16). *What is the Piezoelectric Effect?* Retrieved from http://www.electronicdesign.com/power/what-piezoelectric-effect.

Celina Lawson. (2017, August 22). Pyroelectric Detector Market Research Report 2017 to 2022. Retrieved from http://www.donohuereport.com/pyroelectric-detector-market/.

Charles Morris. (2017, March 1). Thermoelectric generators convert waste heat from an ICE to electricity. Retrieved from https://chargedevs.com/newswire/thermoelectric-generators-convert-waste-heat-from-an-ice-to-electricity/.

Chris Woodford. (2017, August 11). Piezoelectricity. Retrieved from http://www.explainthatstuff.com/piezoelectricity.html.

Challa,V. R., M.G. Prased, Y. Shi, and F. T. Fisher. (2008). A vibration energy harvesting devices with bidirectional resonance frequency tenability. Journal of *Smart Mater*, Vol 17, 1-10.

C.R.Bowen, H.A.Kim, P.M.Weaver and S.Dunn. (2014). Piezoelectric and ferroelectric materials and structures for energy harvesting applications. *Journal of Energy & Environmental Science*, Vol (7), 25-44.

Caliò, R., Rongala, U., Camboni, D., Milazzo, M., Stefanini, C., de Petris, G., & Oddo, C. (2014). Piezoelectric Energy Harvesting Solutions. *Sensors*, *14*(3), 4755–4790.

Camarda, A., Romani, A., & Tartagni, M. (2014). Piezoelectric transformers for ultra-low voltage energy harvesting applications. *Procedia Engineering*, *87*, 1521–1524.

Dikshit, T., & Shrivastava, D. (2010). Energy Harvesting via Piezoelectricity. *BVICAM's*, *2*(2), 265–270.

Esteves, G., Fancher, C. M., Röhrig, S., Maier, G. A., Jones, J. L., & Deluca, M. (2017). Electric-field-induced structural changes in multilayer piezoelectric actuators during electrical and mechanical loading. *Acta Materialia*, *132*, 96–105.

E. Minazara, D. Vasic and F. Costa. (2008). Piezoelectric Generator Harvesting Bike Vibrations Energy to Supply Portable Devices. J*ournal from Universite de Cergy-Pontoise 9503*, Vol 1(6), 508-513.

Fang, L. H., Idris, S., Hassan, S., Bin, R., Rahim, A., Fareq, M., & Malek, A. (2016). A study of vibration energy harvester. *ARPN Journal of Engineering and Applied Sciences*, *11*(8), 5028–5041.

G Altena, M Renaud, R Elfrink, M H Goedbloed, C de Noiijer and R van Schaijk. (2013). Design improvements for an electrets-based MEMS vibrational electrostatic energy harvester. *Journal of Physics*: Conferences Series 476 012078, 1-5.

Gibran Ali, John Wagner, David Moline and Todd Schweisinger. (2015). Energy harvesting from atmospheric variations – Theory and test. *Journal of Renewable Energy.* Vol 74, 528-535.

Gongbo Zhou, Linghua Huang, Wei Li and Zhencai Zhu. (2014). Harvesting Ambient Environmental Energy for Wireless Sensor Networks: A survey. *Journal of Sensor*, Vol 2014(2014), 20.

Hamid Jabbar, Hyun Jun Jung, Nan Chen, Dae Heung Cho and Tae Hyun Sung. (2017). Piezoelectric energy harvester impedance matching using a piezoelectric transformer. *Journal of Sensors and Actuators A: Physical*, Vol 264, 141-150.

Haresh Khemani. (2009, December 10). Piezoelectric Transducer. Retrieved from http://www.brighthubengineering.com/hvac/52190-piezoelectric-transducers/.

IMEC and Panasonic. (2013,June 26). High-performance electrostatic MEMS vibration energy harvester. Retrieved from https://www.energyharvestingjournal.com/articles/5559/high-performance-electrostatic-mems-vibration-energy-harvester.

IEEE. (2015). Energy Harvesting Wireless Communication: A Review of Recent Advance. *IEEE Journal on Selected Areas in Communications*, Vol 33(3), 360-381.

Jabbar, H., Jung, H. J., Chen, N., Cho, D. H., & Sung, T. H. (2017). Piezoelectric energy harvester impedance matching using a piezoelectric transformer. *Sensors and Actuators, A: Physical*, *264*, 141–150.

Jan Willem Bos. (2012, March 1). Thermoelectric materials:efficiencies found in nanocomposites. Retrieved from https://eic.rsc.org/feature/thermoelectric-materials-efficiencies-found-in-nanocomposites/2020263.article.

Karim El-Rayes and Dr. Eihab Abdel-Rahman. (2013, December 3). Vibration Based Energy Harvesting (2). Retrieved from http://www.vlsiegypt.com/home/?p=1677.

Khairulnizam Othman and Suhairi Ismail. (2016). Power Generation Piezoelectric Vibration for Sensor. *ARPN Journal of Engineering and Applied Sciences*, Vol 11(12), 7622-7627.

Khameneifar, F., & Arzanpour, S. (2008). Energy Harvesting From Pneumatic Tires Using Piezoelectric Transducers. In *Smart Materials, Adaptive Structures and Intelligent Systems, Volume 1*.

Kumar, P., Dwivedy, S. K., & Kumari, P. (2016). Dynamic Analysis of Piezoelectric Based Energy Harvester under Periodic Excitation. *Procedia Engineering*, *144*, 635–644.

Kurushin, M. I., Balyakin, V. B., & Kurushin, S. A. (2015). Methods of Vibration Control in Elastic Systems with Gears. *Procedia Engineering*, *106*, 192–201.

Lafarge, B., Delebarre, C., Grondel, S., Curea, O., & Hacala, A. (2015). Analysis and optimization of a piezoelectric harvester on a car damper. In *Physics Procedia*.

Liew Hui Fang, Syed Idris Syed Hassan, Rozemizi Bin Abdul Rahim and Mohd Fareq Abdul Malek. (2016). A Study of Vibration Energy Harvester. *ARPN Journal of Engineering and Applied Sciences,* Vol 11(8), 5028-5041.

Mikhail I. Kurushin, Valeriy B. Balyakin and Stepan A. Kurushin. (2014). Methods of Vibration Control in Elastic Systems with Gears. *Journal of Science Direct*, Vol 106(2014), 192-201.

Michele Kinman. (2010, May 5). Energy Harvesting for a Greener Environment. Retrieved from https://www.ecnmag.com/article/2010/05/energy-harvesting-greener-environment.

Nayan HR. (2015). Power Generation Using Piezoelectric Material. *Journal of Material Sciences & Engineering*, Vol 4(3).

Parul Dhingra, Jhilam Biswas, Anjushree Prasad and Sukanya S Meher. (2013). Article: Energy Harvesting using Piezoelectric Materials. IJCA *Special Issue on International Conference on Electronic Design and Signal Processing*, Vol (4), 38-42.

Raghu Chandra Garimella, Dr. V. R. Sastry and Mohammed Shoeb Mohiuddin. (2015). Piezo-Gen-Approach to Generate Electricity from Vibrations. *Journal from Science Direct*, Vol 11(2015), 445-456.

R.M. Toyabur, M. Salauddin and Jae Y. Park. (2017). Design and experiment of piezoelectric multimodal energy harvester for low frequency vibration. Journal of Ceramic International, Vol 43, S675-S681.

Sergey Shevtsov and Shun-Hsyung Chang. (2015). Modelling of vibration energy harvesting system with power PZT stack loaded on Li-Ion battery. *Journal of ScienceDirect,* Vol 41, 12618-12652.

Stefan Bosse, Dirk Lehmhus, Walter Lang, Matthias Busse. Material-integrated intelligent systems: technology and applications. Weinheim: Wiley-VCH, 2017. Print.

Siddharth Jain and Arun Yadav. (2013). Torsional Vibration of Meshed Gear System. *International Journal of Engineering Research & Technology (IJERT),* Vol 2(8), 218-222.

Syahrul Hisham Mohammad, Mohd Firdaus Thalas, Aminurrashid Noordin, Muhammad Sharil Yahya, Mohd Hanif Che Hassan and Zulkifli Ibrahim. (2015). A Potential Study of Piezoelectric Energy Harvesting in Car Vibration. *ARPN Journal of Engineering and Applied Sciences*, Vol 10(11), 8642-8647.

Shancymol Sojan and R.K. Kulkarni. (2016). A Comprehensive Review of Energy Harvesting Techniques and its Potential Applications. *International Journal of Computer Applications,* Vol 139(3), 14-19.

Sojan, S., Student, P. G., & Kulkarni, R. K. (2016). A Comprehensive Review of Energy Harvesting Techniques and its Potential Applications. *International Journal of Computer Applications*, *139*(3), 975–8887

Shevtsov, S., & Flek, M. (2016). Random Vibration Energy Harvesting by Piezoelectric Stack Charging the Battery. *Procedia Engineering*, *144*, 645–652.

Shen, H., Ji, H., Qiu, J., Bian, Y., & Liu, D. (2015). Adaptive synchronized switch harvesting: A new piezoelectric energy harvesting scheme for wideband vibrations. *Sensors and Actuators, A: Physical*, *226*, 21–36.

Toyabur, R. M., Salauddin, M., & Park, J. Y. (2017). Design and experiment of piezoelectric multimodal energy harvester for low frequency vibration. *Ceramics International*, *43*(May), S675–S681.

Tanvi Dikshit, Dhawal Shrivastava, Abhijeet Gorey, Ashish Gupta, Parag Parandkar and Sumant Katiyal. (2010). Energy Harvesting via Piezoelectricity. *International Journal of Information Technology*, Vol 2(2), 265-270.

U Mescheder, B Muller, S Baborie and P Urbanovic. (2009). Properties of $Si0_2$ electret films charged by ion implantation for MEMS-based energy harvesting systems. *Journal of Micromechanics and Microengineering*, Vol 19, 9.

Wang, J., Lin, T. and Zuo, L. (2013). High efficiency electromagnetic energy harvester for railroad application. ASME Design Engineering Technical Conference (IDETC 2013), pp.1-10.

X. Liu, C. Li, Y.D. Deng and C.Q.Su. (2015). An energy-harvesting system using thermoelectric power generation for automotive application. *Journal of Electrical Power and Energy System*, Vol 67,510-516.

Xiao Zhang and Li-Dong Zhao. (2015). Thermoelectric materials: Energy conversion between heat and electricity. *Journal of Materiomics*, Vol 1(2), 92-105.

Yamuna. M. B and K. Shanmukha Sundar. (2014). Design of Piezoelectric Energy Harvesting and Storage Devices. *International Journal of Advanced Research in Electrical, Electronics and Instrumental Engineering,* Vol 3(8), 10945-10953.

Yamuna, M. B., & Sundar, K. S. (2014). Design of Piezoelectric Energy Harvesting and Storage Devices. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO 3297: 2007 Certified Organization)*, *3*(8), 10945–10953.

Yang, C. E. (2016). What is the Piezoelectric Effect? *Electronicdesign.Com*, 1–8.

Yang, Z., Erturk, A., & Zu, J. (2017). On the efficiency of piezoelectric energy harvesters. *Extreme Mechanics Letters*, *15*, 26–37.

Yang, Z., Wang, Y. Q., Zuo, L., & Zu, J. (2017). Introducing arc-shaped piezoelectric elements into energy harvesters. *Energy Conversion and Management*, *148*, 260–266.

Zhengbao Yang, Yan Qing Wang, Lei Zuo and Jean Zu. (2017). Introducing arc-shaped piezoelectric elements into energy harvesters. *Journal of Energy Conversion and Management,* Vol 148, 260-266.

APPENDICES

For more information, please visit the product page.

CUI INC	Part No: CEB-35D26	Date: 7/28/2008
	Description: piezo electric diaphragm	Unit: mm
		Page No: 1 of 4

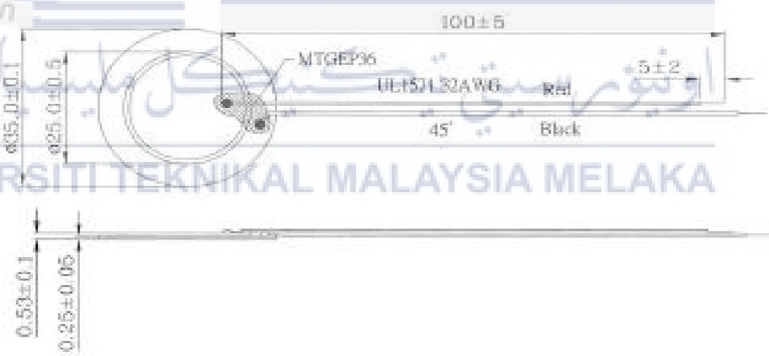
RoHS

Specifications

Maximum input voltage	30 Vp-p	
Resonant frequency	2.6 ± 0.5 KHz	see Measurement Methods
Resonant impedance	300 Ω max.	see Measurement Methods
Electrostatic capacitance	30,000 ±30% pF	at 1 KHz / 1 V
Operating temperature	-20 ~ +70° C	
Storage temperature	-30 ~ +80° C	
Dimensions	Ø35.0 x H0.53 mm	
Weight	2.0 g max.	
Material	Brass	
Terminal	Wire type	
DC resistance	20 M Ω min.	Fluke 45 rate: Fast Measurement time: 1 second (only for ≤ 20 mm test)
RoHS	yes	

Appearance Drawing

Tolerance: ±0.5



Phone: 800.275.4899 Fax: 503.612.2381 www.cui.com 20050 SW 112th Ave. Tualatin, OR 97062

A1: Piezoelectric Data Sheet

For more information, please visit the product page.

CUI INC

Part No: CEB-35D26

Description: piezo electric diaphragm

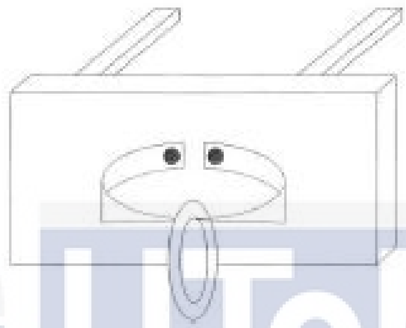
Date: 7/28/2008
Unit: mm

Measuring Methods

1) Resonant frequency / Resonant impedance

The piezo electric diaphragm should be clamped at a node point (as shown in the following figure) to be free from any mechanical stress. Measure its resonant frequency and resonant impedance by using a vector impedance analyzer or equivalent.

When the input frequency is swept within 100 Hz to 5 KHz, the resonant frequency is defined as the frequency where the impedance shows minimum value. This impedance should be the resonant impedance.



2) Static capacitance

The electrostatic capacitance should be measured at 120 Hz by using an L.C.R. meter (ex. HP4194A(H.P.)) or equivalent. The part should be clamped in the same way as the measurement or resonant frequency / resonant impedance mentioned above.

Mechanical Characteristics

Item	Test Condition	Evaluation Standard
Solderability (Connector excepted)	Stripped wires of lead wires are immersed in rosin for 5 seconds and then immersed in solder bath of 270 ±5°C for 3 ±0.5 seconds.	90% min. of the stripped wires will be wet with solder. (Except the edge of the terminal)
Lead Wire Pull Strength	The horizontal force of 3.0N (0.306kg) should be applied to the double lead wire for 30 sec.	No damage or cutting off.
Vibration	The diaphragm should be measured after applying a vibration amplitude of 1.5 mm with 10 to 55 Hz band of vibration frequency to each of the 3 perpendicular directions for 2 hours.	The value of the resonant frequency should be ±10% of the initial measurements. Electrostatic capacitance should be ±20% compared with the initial measurement. The SPL should be within ±10dB compared with the initial measurement.

Phone: 800.275.4899 Fax: 503.612.2381 www.cui.com 20050 SW 112th Ave. Tualatin, OR 97062

For more information, please visit the product page.

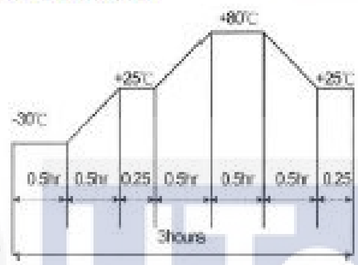
CUI INC

Part No: CEB-35D26

Description: piezo electric diaphragm

Date: 7/28/2008
Unit: mm
Page No: 3 of 4

Environment Test

Item	Test Condition	Evaluation Standard
High temp. test	After being placed in a chamber at +80°C for 240 hours.	The diaphragm will be measured after being placed at +25°C for 4 hours. The value of the resonant frequency should be ±10%, the value of the electro static capacitance should be ±20% compared to the initial measurements. The resonant impedance should be 2,000 Ω max.
Low temp. test	After being placed in a chamber at -30°C for 240 hours.	
Humidity test	After being placed in a chamber at +40°C and 90±5% relative humidity for 240 hours.	
Temp. cycle test	The part shall be subjected to 5 cycles. One cycle will consist of: 	

Test Conditions

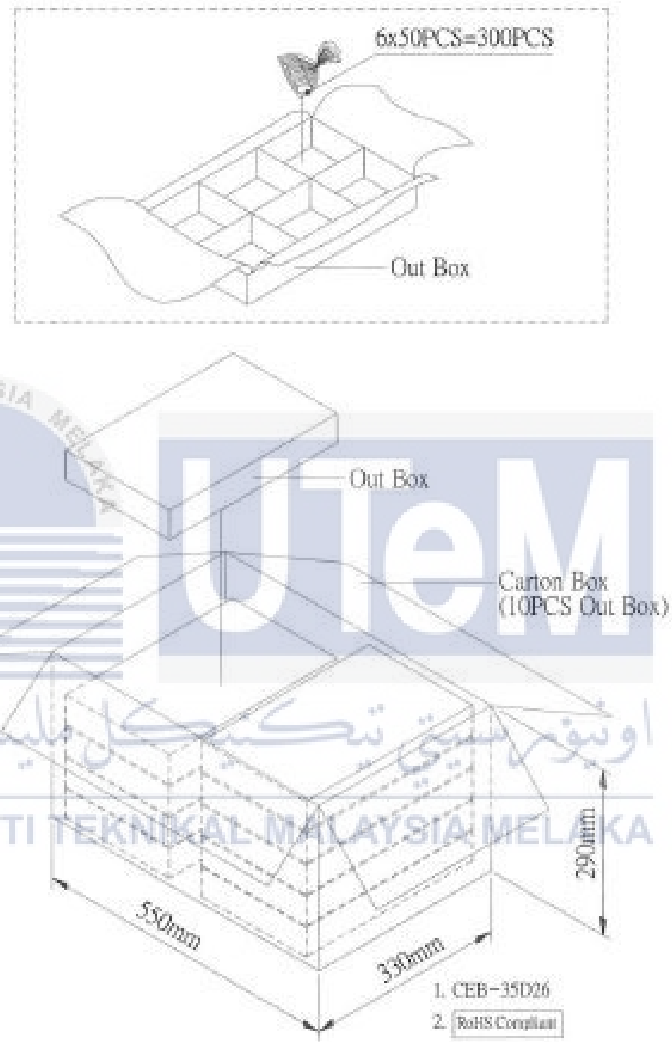
Standard Test Condition	a) Tempurature: +5 ~ +35°C	b) Humidity: 45 - 85%	c) Pressure: 860-1060 mbar
Judgement Test Condition	a) Tempurature: +25 ±2°C	b) Humidity: 60 - 70%	c) Pressure: 860-1060 mbar

Phone: 800.275.4899 Fax: 503.612.2381 www.cui.com 20050 SW 112th Ave. Tualatin, OR 97062

For more information, please visit the product page.

CUI INC | **Part No: CEB-35D26** | **Date: 7/28/2008**
Description: piezo electric diaphragm | **Unit: mm** | **Page No: 4 of 4**

Packaging



Out Box	310mmx248mmx49mm	6x50PCS=300PCS
Carton Box	550mmx330mmx290mm	300PCSX10=3,000PCS

Phone: 800.275.4899 Fax: 503.612.2381 www.cui.com 20050 SW 112th Ave. Tualatin, OR 97062

MOTOROLA
SEMICONDUCTOR TECHNICAL DATA

Order this document
by 1N4001/D

Axial Lead Standard Recovery Rectifiers

This data sheet provides information on subminiature size, axial lead mounted rectifiers for general–purpose low–power applications.

Mechanical Characteristics

- Case: Epoxy, Molded
- Weight: 0.4 gram (approximately)
- Finish: All External Surfaces Corrosion Resistant and Terminal Leads are Readily Solderable
- Lead and Mounting Surface Temperature for Soldering Purposes: 220°C Max. for 10 Seconds, 1/16" from case
- Shipped in plastic bags, 1000 per bag.
- Available Tape and Reeled, 5000 per reel, by adding a "RL" suffix to the part number
- Polarity: Cathode Indicated by Polarity Band
- Marking: 1N4001, 1N4002, 1N4003, 1N4004, 1N4005, 1N4006, 1N4007

1N4001 thru 1N4007

1N4004 and 1N4007 are Motorola Preferred Devices

LEAD MOUNTED RECTIFIERS
50–1000 VOLTS
DIFFUSED JUNCTION

CASE 59–03
DO–41

MAXIMUM RATINGS

Rating	Symbol	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	Unit
*Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	Volts
*Non–Repetitive Peak Reverse Voltage (halfwave, single phase, 60 Hz)	V_{RSM}	60	120	240	480	720	1000	1200	Volts
*RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	Volts
*Average Rectified Forward Current (single phase, resistive load, 60 Hz, see Figure 8, T_A = 75°C)	I_O	1.0							Amp
*Non–Repetitive Peak Surge Current (surge applied at rated load conditions, see Figure 2)	I_{FSM}	30 (for 1 cycle)							Amp
Operating and Storage Junction Temperature Range	T_J T_{stg}	–65 to +175							°C

ELECTRICAL CHARACTERISTICS*

Rating	Symbol	Typ	Max	Unit
Maximum Instantaneous Forward Voltage Drop (i_F = 1.0 Amp, T_J = 25°C) Figure 1	v_F	0.93	1.1	Volts
Maximum Full–Cycle Average Forward Voltage Drop (I_O = 1.0 Amp, T_L = 75°C, 1 inch leads)	$V_{F(AV)}$	—	0.8	Volts
Maximum Reverse Current (rated dc voltage) (T_J = 25°C) (T_J = 100°C)	I_R	 0.05 1.0	 10 50	µA
Maximum Full–Cycle Average Reverse Current (I_O = 1.0 Amp, T_L = 75°C, 1 inch leads)	$I_{R(AV)}$	—	30	µA

*Indicates JEDEC Registered Data

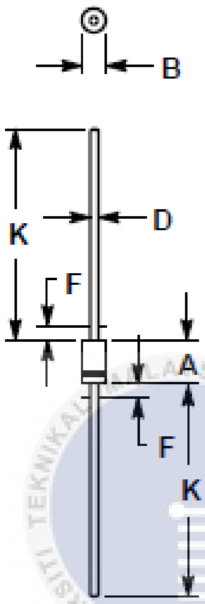
Preferred devices are Motorola recommended choices for future use and best overall value.

Rev 5

MOTOROLA

A2: Diode Data Sheet

PACKAGE DIMENSIONS



NOTES:
1. ALL RULES AND NOTES ASSOCIATED WITH JEDEC DO–41 OUTLINE SHALL APPLY.
2. POLARITY DENOTED BY CATHODE BAND.
3. LEAD DIAMETER NOT CONTROLLED WITHIN F DIMENSION.

	MILLIMETERS		INCHES	
DIM	MIN	MAX	MIN	MAX
A	4.07	5.20	0.160	0.205
B	2.04	2.71	0.080	0.107
D	0.71	0.86	0.028	0.034
F	—	1.27	—	0.050
K	27.94	—	1.100	—

CASE 59–03
(DO–41)
ISSUE M

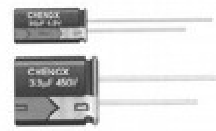
LC@SC 立创
WWW.SZLCSC.COM

KM Series

+105°C, General (普通品)

FEATURES

1. Rated working voltage range 6.3 to 100V DC/160 to 450V DC at operation temperature range -40 to +105°C/-25 to +105°C.
2. This series is for communication equipments, switching power supply, industrial measuring instruments, automotive electric products, etc.



SPECIFICATIONS

Item	Performance Charactesistics	
Operating Temperature Range	-40 to +105°C	-25 to +105°C
Reted Working Voltage Range	6.3 to 100V	160 to 450V
Nominal Capacitance Range	0.1 to 33000μF	
Capacitance Tolerance	±20% (120Hz, +20°C)	
Leakage Current	I ≤ 0.01CV or 3(μA) whichever is greater	I ≤ 0.03CV +40(μA)
	after 2 minutes application of rated working voltage at +20°C	

tan δ (120Hz, +20°C)

Working Voltage (V)	6.3	10	16	25	35	50	63	100
tan δ (max.)	0.26	0.22	0.18	0.16	0.14	0.12	0.10	0.08

Working Voltage (V)	160	200	250	250	350	400	420	450
tan δ (max.)	0.20	0.20	0.20	0.20	0.24	0.24	0.24	0.24

For capacitance value > 1000μF, add 0.02 per another 1000μF

Low Temperature Characteristics

Impedance ratio max. at 120Hz

Working Voltage (V)	6.3	10	16	25	35	50	63	100
Z-25°C / Z+20°C	5	4	3	2	2	2	2	2
Z-40°C / Z+20°C	10	8	6	4	3	3	3	3

Working Voltage (V)	160	200	220	250	350	400	420	450
Z-25°C / Z+20°C	3	3	3	4	4	6	6	15

For capacitance value > 1000μF, Add 0.5 per another 1000μF for Z-25°C / Z+20°C
Add 1.0 per another 1000μF for Z-40°C / Z+20°C

High Temperature Loading

Test conditions

Duration :	φD	≤ 6.3	≥ 8
	Load life	1000h	2000h

Ambient temp. : +105°C
Applied voltage : DC voltage with maximum permissible ripple current specified at +105°C (Sum of the DC voltage and super-imposed peak AC voltage for maximum permissible ripple current should be equal to reted DC working voltage).

Post test requirements at +20°C
Leakage current : ≤ Initial specified value
Cap. change : within ±20% of initial measured value
tan δ : ≤ 200% of initial specified value

Shelf Life

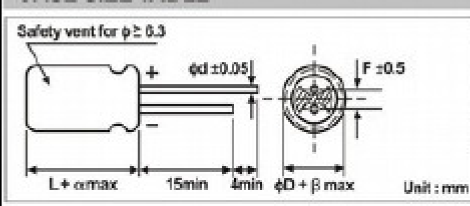
Test conditions
Duration : 1000 hours
Ambient temp. : +105°C
Applied voltage : (None)

Post test requirements at +20°C
Same limits for high temperature loading.

Others

JIS C - 5101 (IES 60384)

CASE SIZE TABLE



φD	5	6.3	8	10	12.5	16	18	22	25
F	2.0	2.5	3.5	5.0	5.0	7.5	7.5	10.0	10.0
φd	0.5			0.6		0.8			
α	(L < 20) 1.5				(L ≥ 20) 2.0				
β	(D < 20) 0.5				(D ≥ 20) 1.0				

A3: Capacitor Data Sheet

LC@SC 立创
WWW.SZLCSC.COM

KM Series

+105°C, General (普通品)

STANDARD RATINGS

Voltage (Code)		6.3V (0J)		10V (1A)		16V (1C)		25V (1E)	
Cap.(uF)	Code	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current
0.1	104								
0.15	154								
0.22	224								
0.33	334								
0.47	474								
1	105								
2.2	225								
3.3	335								
4.7	475							5 x 11	26
10	106					5 x 11	35	5 x 11	38
22	226			5 x 11	49	5 x 11	54	5 x 11	57
33	336	5 x 11	54	5 x 11	60	5 x 11	65	5 x 11	75
47	476	5 x 11	65	5 x 11	70	5 x 11	80	5 x 11	84
68	686	5 x 11	70	5 x 11	75	5 x 11	90	5 x 11	92
100	107	5 x 11	95	5 x 11	105	5 x 11	125	6.3 x 11	159
220	227	5 x 11	153	5 x 11	170	6.3 x 11	213	8 x 12	285
330	337	6.3 x 11	216	6.3 x 11	239	8 x 12	315	8 x 12	340
470	477	6.3 x 11	258	6.3 x 11	285	8 x 12	366	10 x 12.5	471
680	687	8 x 12	365	8 x 12	408	10 x 12.5	480	10 x 16	620
1000	108	8 x 12	443	10 x 12.5	571	10 x 16	680	10 x 20	821
2200	228	10 x 16	740	10 x 20	886	12.5 x 20	1108	12.5 x 20	1176
3300	338	10 x 20	1032	12.5 x 20	1205	12.5 x 25	1389	16 x 25	1646
4700	478	12.5 x 20	1280	12.5 x 25	1492	16 x 25	1740	16 x 30	2012
6800	688	12.5 x 25	1554	16 x 25	1824	16 x 30	2081	16 x 35	2308
10000	109	16 x 25	1897	16 x 30	1980	16 x 35	2379	18 x 35	2500
15000	159	16 x 30	2188	16 x 40	2180	18 x 35	2600		
22000	229	18 x 35	2400	18 x 40	2407				
33000	339	18 x 40	2555						

Maximum Allowable Ripple Current (mA rms) at 105°C 120Hz

Case Size φD x L(mm)

Voltage (Code)		35V (1V)		50V (1H)		63V (1J)		100V (2A)	
Cap.(uF)	Code	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current
0.1	104			5 x 11	1				
0.15	154			5 x 11	1.5				
0.22	224			5 x 11	3				
0.33	334			5 x 11	4				
0.47	474			5 x 11	7			5 x 11	10
1	105			5 x 11	13			5 x 11	16
2.2	225			5 x 11	20			5 x 11	23
3.3	335			5 x 11	30			5 x 11	34
4.7	475	5 x 11	28	5 x 11	37	5 x 11	40	5 x 11	40
10	106	5 x 11	41	5 x 11	54	5 x 11	59	6.3 x 11	61
22	226	5 x 11	67	5 x 11	79	5 x 11	79	6.3 x 11	92
33	336	5 x 11	80	5 x 11	101	6.3 x 11	122	8 x 12	144
47	476	5 x 11	101	6.3 x 11	133	6.3 x 11	146	10 x 12.5	199
68	686					8 x 12	155	10 x 16	240
100	107	6.3 x 11	168	8 x 12	229	10 x 12.5	251	10 x 20	349
220	227	8 x 12	294	10 x 16	509	10 x 20	504	12.5 x 25	622
330	337	10 x 12.5	419	10 x 16	589	12.5 x 20	688	12.5 x 25	860
470	477	10 x 16	547	10 x 20	707	12.5 x 20	810	16 x 25	990
680	687	10 x 20	682	12.5 x 20	923	12.5 x 25	1160	16 x 30	1289
1000	108	12.5 x 20	1023	12.5 x 25	1287	16 x 25	1448	18 x 35	2020
2200	228	16 x 25	1497	16 x 35	1884	18 x 35	1781		
3300	338	16 x 30	1808	18 x 35	2167				
4700	478	18 x 35	2335						
6800	688	18 x 40	2400						

Maximum Allowable Ripple Current (mA rms) at 105°C 120Hz

Case Size φD x L(mm)

LC@SC 立创
WWW.SZLCSC.COM

KM Series

+105°C, General (普通品)

STANDARD RATINGS

Voltage (Code)		160V (2C)		200V (2D)		220V (2N)		250V (2E)	
Cap.(μF)	Code	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current
0.47	474							6.3 x 11	8
1	105							6.3 x 11	17
2.2	225							6.3 x 11	27
3.3	335			6.3 x 11	30	6.3 x 11	30	6.3 x 11	35
4.7	475	6.3 x 11	41	6.3 x 11	40	8 x 12	40	8 x 12	45
10	106	8 x 12	60	10 x 12.5	72	10 x 12.5	70	10 x 12.5	75
22	226	10 x 16	110	10 x 16	113	10 x 20	125	10 x 20	130
33	336	10 x 20	156	10 x 20	165	12.5 x 20	165	12.5 x 20	184
47	476	10 x 20	195	10 x 20	194	12.5 x 20	220	12.5 x 25	238
68	686	12.5 x 20	250	12.5 x 25	250	12.5 x 25	245	16 x 20	246
82	826	12.5 x 25	310	10 x 30	320	12.5 x 30	280	16 x 25	351
100	107	12.5 x 25	360	16 x 25	386	16 x 25	335	16 x 25	390
150	157	12.5 x 30	380	16 x 25	525	16 x 30	365	16 x 30	440
180	187	12.5 x 35	420	12.5 x 35	560	16 x 35	500	16 x 35	469
220	227	16 x 30	680	16 x 30	643	16 x 40	615	16 x 35	485
270	277	16 x 30	728	18 x 30	740				
330	337	16 x 35	830	18x 30	808				
390	397	16 x 35	850	18 x 35	904				
470	477	16 x 40	880	18 x 40	1016				
560	567	16 x 45	925	18 x 45	1112				

Maximum Allowable Ripple Current (mA rms) at 105°C 120Hz

Case Size φD x L(mm)

Voltage (Code)		350V (2V)		400V (2G)		420V (2M)		450V (2W)	
Cap.(μF)	Code	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current	Case Size	Ripple Current
0.47	474	6.3 x 11	8						
1	105	6.3 x 11	18	6.3 x 11	19	6.3 x 11	15	6.3 x 11	16
2.2	225	6.3 x 11	25	8 x 12	30	8 x 12	29	8 x 12	24
3.3	335	8 x 12	40	8 x 12	35	8 x 12	35	8 x 12	29
4.7	475	8 x 12	43	8 x 12	40	10 x 16	52	10 x 16	42
10	106	10 x 16	73	10 x 16	78	10 x 20	85	12.5 x 25	84
18	186	12.5 x 20	100	12.5 x 20	105	12.5 x 25	124	10 x 30	108
22	226	12.5 x 20	150	12.5 x 20	148	12.5 x 25	140	12.5 x 25	131
27	276	12.5 x 25	177	10 x 30	192	12.5 x 25	170	12.5 x 30	164
33	386	12.5 x 25	200	12.5 x 25	193	16 x 25	200	16 x 25	237
39	396	12.5 x 25	258	16 x 25	251	12.5 x 30	248	12.5 x 35	256
47	476	12.5 x 25	265	12.5 x 30	266	12.5 x 35	288	16 x 30	305
56	566	16 x 30	280	12.5 x 35	336	12.5 x 40	344	16 x 30	352
68	686	16 x 30	288	16 x 30	396	16 x 30	408	16 x 30	366
82	826	18 x 30	372	18 x 30	443	16 x 35	456	18 x 30	440
100	107	18 x 35	460	18 x 30	489	18 x 35	488	18 x 35	490
120	127			18 x 35	570	18 x 40	528	18 x 40	592
150	157			18 x 40	616	18 x 45	568	18 x 45	640
180	187			18 x 50	704				

Maximum Allowable Ripple Current (mA rms) at 105°C 120Hz

Case Size φD x L(mm)

RIPPLE CURRENT MULTIPLIER

Frequency Coefficient

Rated Voltage(V)	Cap.(μF) Coefficient Freq (Hz)	50	120	300	1k	10k~
6.3 ~ 100	~ 47	0.75	1.00	1.35	1.57	2.00
	68 ~ 470	0.80	1.00	1.23	1.34	1.50
	≥ 560	0.85	1.00	1.10	1.13	1.15
160 ~ 450	0.47 ~ 220	0.80	1.00	1.25	1.40	1.60
	≥ 270	0.90	1.00	1.10	1.13	1.15