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CHARACTERIZATION OF ELECTROMAGNETIC VIBRATION BASED ENERGY HARVESTING SYSTEM

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By

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FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
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CERTIFICATION OF APPROVAL

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Department of Electrical & Electronic Engineering
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Approved:

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TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Saratul Akma Bt Mohamed

ABSTRACT

This work presents the characterization of electromagnetic vibration based energy harvesting system. Energy harvesting is the process which energy is derived from external sources, captured, and stored for low power application devices. Vibration energy is an alternative energy sources beside solar, wind, and thermal energies. Energy harvesting is crucially important as it is environmental friendly and renewable sources. Overall, the electromagnetic vibration based energy harvesting converted vibration energy into electrical energy based on electromagnetic principle and second order mass spring system. It mainly consists of proof mass, vibrating membrane (spring), coil and also permanent magnet. The main objective of this project is to perform the characterization for electromagnetic vibration based energy harvester. The characterizations are divided to two parts which cover both the electrical and mechanical characterizations. Under the electrical characterization, the open loop, closed loop, impedance matching and the effect of difference gravitational acceleration to output voltage are investigated. For mechanical characterization, the resonance frequency, bandwidth frequency and damping ratio are analyzed. From the electrical and mechanical characterization, it was found that the open loop voltage produced by the device is 0.6759V, while the close loop voltage is 0.3073V at 260Ω matched impedance. Device resonance occurs at 22.7 Hz with damping ratio of 0.001862 and 10Hz operating bandwidth. From the characterization results, this device is found to be suitable for low power and autonomous applications such as the wireless sensor network, memory cell for portable electronic device and others.

ACKNOWLEDGEMENTS

In the name of Allah, the most Gracious, the Most Merciful. I give a lot of thanks and praise to God for His guidance and blessings throughout the semester to accomplish this Final Year project. It would not have been possible to write this dissertation without the help and support of the kind people around me, to only some of whom it is possible to give particular mention here.

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Besides, I would like to take this opportunity to express my deepest appreciation to my fellow colleagues and family members for continuously lend me a shoulder and helpful hands upon the completion of project. Hopefully, this project would be beneficial for my future undertaking and career development

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ABBREVIATIONS AND NOMENCLATURES

CDRGs : Coulomb-damped resonant generators

CMOS : Complementary Metal-Oxide Semiconductor

MEMS : Micro-Electromechanical-System

PV : Photovoltaic

PVC : Polyvinyl Chloride

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Over the last few years, a great advance had been developed in the electronic devices design. Usually, electronic devices used electrochemical batteries as their power supply. However, the using of electrochemical batteries has some drawbacks which are environmental pollution, limited lifetime, and large maintenance requirements. Along with the development in electronic devices, the micro power energy harvesting seems very promising. One of the ways is through vibration electromagnetic based energy harvesting. A single type of micro power energy harvesting usually can give only a small amount of output. So, the device must be characterized to match with various specifications.

1.2 Objectives

The main objective of this project is to study the characterization of vibration electromagnetic based energy harvesting system. This project is mainly focused on:

- To perform the electrical and mechanical characterization of energy harvesting.
- To find alternative solutions for micro power energy harvesting.
- To overcome the issue of extended life of batteries in low power application.
- To acquire deep understanding of electromagnetic principle and other related principle.

1.3 Scope of Study

The purpose of this project is to perform the electrical and mechanical characterization of the energy harvesting system. The target for this type of energy harvester are mainly in the fields of medical implants, embedded sensors in buildings and structures, wearable devices and recently wireless sensor networks. Basically, the scope of this project is divided into two parts:

- First semester: To build housing for vibration electromagnetic based energy harvesting system.
- Second semester: To perform the electrical and mechanical characterization of this device.

1.4 Relevancies and Feasibilities of Project

This project is very relevant for future development as the electrical energy produced is harvested from free energy source. Although, the output is very small but it can be useful for low power devices. Before this, low power devices are using electrochemical batteries as their power supply. But, electrochemical batteries had some drawbacks which are it have infinite lifetime and the disposing of batteries give harmful effect to environment. Using vibration electromagnetic based energy harvesting, is one of the solution to this problem. It is because this type of energy harvesting can minimize the maintenance and the cost for replacement of batteries. Besides that, this energy harvesting is environmental friendly. Furthermore, the size of this device is small and makes it easier to construct and to be applied for low power devices.

The facilities available in Universiti Teknologi Petronas (UTP) such as 3D-Printing, PCB Lab and Noise & Vibration Lab are one of the reasons to ensure this project feasible for further development. Other than that, the abundant of raw materials such as coil, PVC and magnet make sure this project can be achieved. Moreover, the two semester provided is sufficiently enough to completed this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Harvesting

Electrical power can be produced in many ways such as from chemical reactions, heat, light or mechanical energy. The great majority of our electrical power is produced by power plants which convert the energy produced by burning coal, oil, or natural gas, falling water, or by nuclear reactions converted into electrical energy.Unfortunately, the world energy demands depend on fossil fuels which are declining from days to days. The solution to this problem is to find the alternative source for energy supply through ambient energy harvesting.

Ambient energy harvesting is also known as energy scavenging or power harvesting, and it is the process where energy is obtained from the environment [1]. Power harvesting is very important as it output energy is environmental friendly as compared to energy produced by burning fossil fuel. Furthermore, the source of energy harvesting is virtually inexhaustible. A variety of techniques are available for energy scavenging, including solar and wind powers, geothermal energy and also kinetic energy as shown in Figure 1.

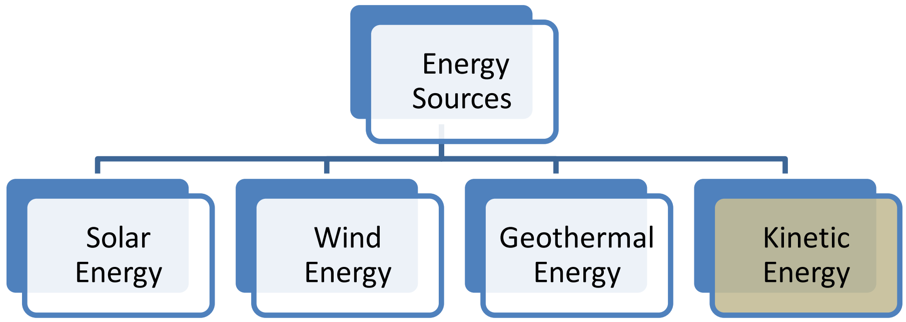

Figure 1: Type of Energy Sources

The first type of energy sources is solar energy. Solar energy is a renewable resource that is inexhaustible and is locally available. It is a clean energy source that allows for local energy independence. The sun's power flow reaching the earth is typically about 1,000 Watts per square meter (W/m^2), although availability varies with location and time of year. Capturing solar energy typically requires equipment with a relatively high initial capital cost. However, over the lifetime of the solar equipment, these systems can prove to be cost-competitive, as compared to conventional energy technologies. Electricity can alternatively be produced from sunlight through a process called photovoltaic (PV). The PV cell is the component responsible for converting light to electricity. Some materials (e.g., silicon) produce a photovoltaic effect, where sunlight frees electrons striking the silicon material. The freed electrons cannot return to the positively charge (holes) without flowing through an external circuit, thus generating current. Solar cells are designed to absorb as much light as possible and are interconnected in series and parallel electrical connections to produce desired voltages and currents [2].

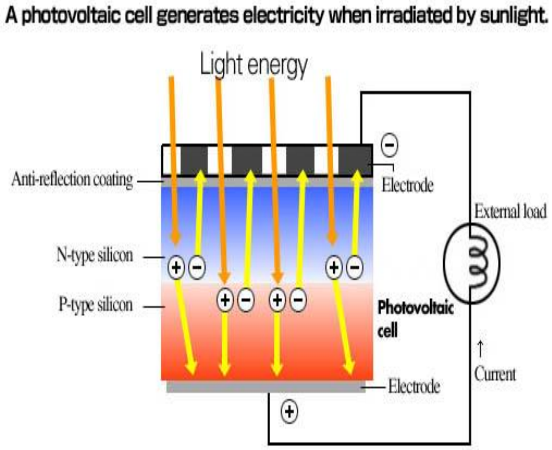

Figure 2: Principle of PV Cell [3]

Wind is simply air in motion and produced by uneven heating of the earth's surface by energy from the sun. Majority of wind energy today is converted into electricity using wind turbines as shown in Figure 3. The amount of electricity is that a turbine produces depends on its size and speed of the wind. Most of wind turbines have the some basic parts which are blades, a tower and gearbox. These parts work together to convert the wind's kinetic energy into mechanical energy that generates electricity. A wind turbine extracts energy from moving air by slowing the wind down, and transferring this energy into a spinning shaft, which usually turns a generator to produce electricity. The power in the wind that's available for harvest depends on both the wind speed and the area that's swept by the turbine blades [4].

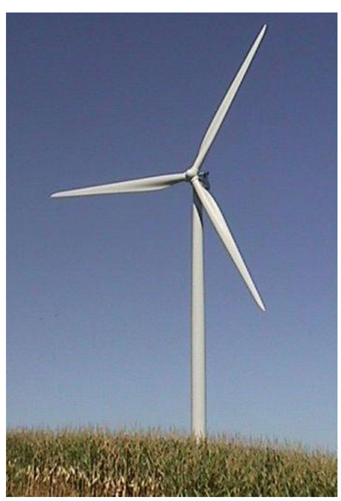

Figure 3: Wind Turbines [5]

The next type of energy sources is geothermal energy. Heat emanating from the Earth's interior and crust generates magma (molten rock).Because magma is less dense than surrounding rock, it rises but generally does not reach the surface, heating the water contained in rock pores and fractures. Wells are drilled into this natural collection of hot water or steam, called a geothermal reservoir, in order to bring it to the surface and use it for electricity production. The three basic types of geothermal electrical generation facilities are binary, dry steam (referred to as steam), and flash steam (referred to as flash). Electricity production from each type depends on reservoir temperatures and pressures, and each type produces somewhat different environmental impacts. The most common type of power plant used in geothermal energy is a flash power plant with a water cooling system, where a mixture of water and steam is produced from the wells. The steam is separated in a surface vessel (steam separator) and delivered to the turbine, and the turbine powers a generator. Figure 4 shows the operational principle of a flash plant [6].

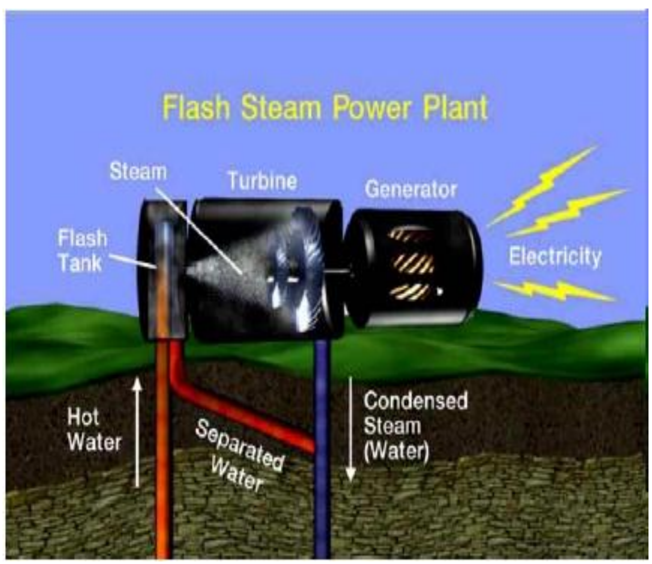

Figure 4: Flash Steam Power Plant [7]

Other than that kinetic energy is also another type of energy sources. It requires a transduction mechanism to generate electrical energy from motion and the generator will require a mechanical system that couples environmental displacements to the transduction mechanism. The design of the mechanical system should maximize the coupling between the kinetic energy source and the transduction mechanism and will depend entirely upon the characteristics of the environmental motion. The transduction mechanism itself can generate electricity by exploiting the mechanical strain or relative displacement occurring within the system. The strain effect utilizes the deformation within the mechanical system and typically employs active materials (e.g., piezoelectric). In the case of relative displacement, either the velocity or position can be coupled to a transduction mechanism. Velocity is typically associated with electromagnetic transduction based relative position is associated with electrostatic transduction. Each transduction mechanism exhibits different damping characteristics and this should be taken into consideration while modeling the generators. The mechanical system can be increased in complexity, for example, by including a hydraulic system to magnify amplitudes or forces, or couple linear displacements into rotary generators [8].

Solar energy had produced largest power densities among ambient energy resources. However, solar energy is not suitable for indoor energy scavenging or places with limited sunlight. Wind energy then also had some issues with the weather variations and absolutely not suitable for indoor energy harvesting application. Although geothermal energy is available everyday which means it consistently available but it is very difficult to find potential places to construct the plant. The most potential ambient energy resources to be develop for future is kinetic energy. It is because kinetic energy is available everywhere. It also provides higher power density than other systems and very suitable for low power application.

2.1.1 Vibrations

One example of kinetic energy is vibration. Vibration can be produced through rotational of electrical machine, heel strike and many more. Energy withdrawal from vibrations could be based on the movement of a spring-mounted mass relative to its support frame. Mechanical acceleration is produced by vibrations that, in turn, cause the mass component to move and oscillate. This relative dislocation causes opposing frictional and damping forces to be applied against the mass, thereby reducing and eventually extinguishing the oscillations. The damping force energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic), or strain on a piezoelectric material as shown in Figure 5[1].

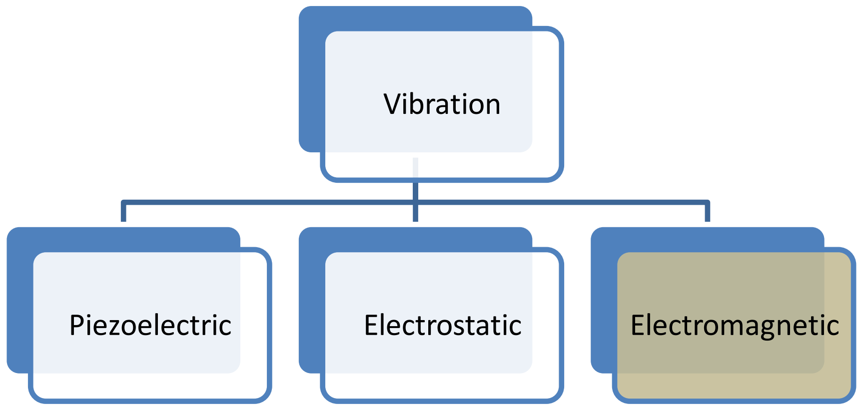

Figure 5: Ambient Energy Sources from Vibration

The piezoelectric effect was discovered by J and P Curie in 1880. They found that if certain crystals were subjected to mechanical strain, they became electrically polarized and the degree of polarization was proportional to the applied strain. This method alters mechanical energy into electrical energy by straining a piezoelectric material [8]. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, which provides higher strain for a given input force [9]. The voltage produced varies with time and strain, effectively producing an irregular AC signal on the average. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system. Moreover, piezoelectricity has the ability of some elements, such as crystals and some types of ceramics, to generate an electric potential from a mechanical stress [10]. This process takes the form of separation of electric charge within a crystal lattice. If the piezoelectric material is not short circuited, the applied mechanical stress induces a voltage across the material. There are many applications based on piezoelectric materials, one of which is the electric cigarette lighter. In this system, pushing the button causes a spring-loaded hammer to hit a piezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumps across a small spark gap. Following the same idea, portable sparkers used to light gas grills, gas stoves, and a variety of gas burners have been built-in piezoelectric based ignition systems [8].

The basis of electrostatic energy conversion is the variable capacitor. If the charge on the capacitor is constrained, the voltage will increase as the capacitance decreases. If the voltage across the capacitor is constrained, charge will move from the capacitor as the capacitance decreases. In either case, mechanical kinetic energy is converted to electrical energy [11]. Constant voltage or constant current achieves the conversion through two different mechanisms. For example, the voltage across a variable capacitor is kept steady as its capacitance alters after a primary charge. As a result, the plates split and the capacitance is reduced, until the charge is driven out of the device. The driven energy then can be stored in an energy pool or used to charge a battery, generating the needed voltage source. The most striking feature of this method is its IC-compatible nature, given that MEMS (Micro-electromechanical system) variable capacitors are fabricated through relatively well-known silicon micro-machining techniques. This scheme produces higher and more practical output voltage levels than the electromagnetic method, with moderate power density [8]. A research had been done to an electrostatic generator that employs a variable micro machine capacitor. Two different designs were studied: a parallel capacitor operated with a constant charge and a comb capacitor operated with a constant voltage. These generators are also called Coulomb-damped resonant generators (CDRGs) because they are based on electrostatic damping. If the charge on the capacitor is maintained constant while the capacitance decreases (e.g. reducing the overlap area of the plates or increasing the distance between them), the voltage will increase. If the voltage on the capacitor is maintained constant while the capacitance decreases, the charge will decrease [12].

This technique uses a magnetic field to convert mechanical energy to electrical energy [13]. A coil attached to the oscillating mass is made to pass through a magnetic field, which is established by a stationary magnet, to produce electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and therefore must be increased to become a viable source of energy [14]. Techniques to increase the induced voltage include using a transformer, increasing the number of turns of the coil, or increasing the permanent magnetic field [12].One of the most effective methods for energy harvesting is to produce electromagnetic induction by means of permanent magnets, a coil and a resonating cantilever beam. In principle, either the magnets or the coil can be chosen to be mounted on the beam while the other remains fixed. It is generally preferable, however, to have the magnets attached to the beam as these can act as the inertial mass [8].

A study of comparison between these three vibration sources (piezoelectric, electrostatic and electromagnetic) had been done by Marzenchki (2005) [15]. These three sources are compared between their energy density, current size and their problems.

Table 1: Comparison of Vibration Energy Harvesting Techniques [14]

	Piezoelectric	Electrostatic	Electromagnetic
Energy Density	4 mJ cm^{-3}	24.8 mJ cm^{-3}	35.4 mJ cm^{-3}
Problems	Very high voltage and need of adding charge source	Very low output voltages	Low output voltages

After comparison had been done, in order to harvest energy by electrostatic, an external power supply is required. Piezoelectric energy generators have higher power densities, however, thin films have very poor coupling coefficient and their fabrication technique is not compatible with the CMOS technology. Moreover, both electrostatic and piezoelectric energy converters have an aspect of high output voltage and very low output current, which may put a constraint on these types if the powered application draw high current (like multi-phase electromagnetic micromotors). Electromagnetic converters seem to be a very attractive option as generators have very simple and well-known operating theory, they are self sustained micro generators (no external power source is needed), and most of their parts can be fabricated by the modern MEMS micromachining techniques [16].

2.1.2 Micropower Energy Harvesting

With the development of electronic production process, consumer electronic devices have become smaller and more portable. Since power is an important issue for electronic devices, micro generator can be applied to provide additional power. The function of micro generators can be applied in electronic devices providing additional power. The function of micro generators is not only to produce additional power but also to recycle and reuse waste energy. Earlier, vibration-based electromagnetic power generator had been chosen to convert electromagnetic field into electrical power [12]. The first electromagnetic MPG capable of generating 0.3 µW at an excitation of 4 MHz was developed in [17, 18], however, the induced voltage (8 mV) was far too low to be practically implemented. The structure used a fixed planar which contains micro machined coil of 13 turns and a magnet of 2.4 mg weight and 1 x 1 x 0.3 mm^3 dimensions that was attached to a micro machined membrane using a polymide solution. Micro power energy harvesting is also essential for wireless communication. Application areas include surveillance spaces in industrial equipment such as manufacturing or automated assembly floors, certain locations in buildings such as the heating and cooling ducts, small appliances, large exterior windows, automobiles, aircraft, etc. [19].

2.2 Principle of Electromagnetic Generator

2.2.1 Electromagnetic Principle (Faradays Law)

The basic principle of the electromagnetic vibration energy harvester is Faradays Law. Michael Faraday $formula$ted that electromotive force (EMF) produced around a closed path is proportional to the rate of change of the magnetic flux through any surface bounded by that path. In practice, this means that an electric current will be induced in any closed circuit when the magnetic flux through a surface bounded by the conductor changes. This applies whether the field itself changes in strength or the conductor is moved through it.

In mathematical form, Faraday's law states that:

$$U_{EMF} = -N\frac{\partial \phi}{\partial t} = -N\frac{\partial(\overrightarrow{B}.\overrightarrow{S})}{\partial t} \quad (1)$$

Where N is number of turns of the closed circuit, U_{EMF} is magnetic flux in every turn, $\vec{B}$ is magnetic flux density and $\vec{S}$ is area vector of closed circuits.

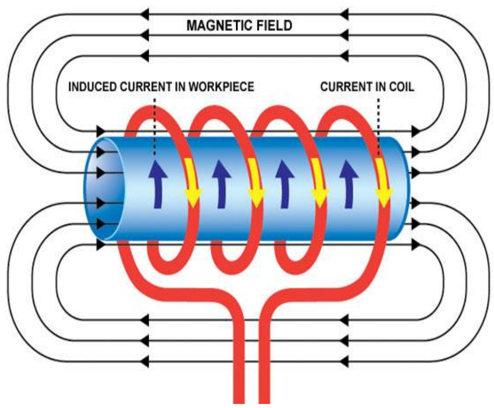

Figure 6: Principle of Faradays Law [28]

An electric current that is induced by a changing magnetic field will in turn induce its own magnetic field. Lenz’s Law stated that an induced electromotive force (emf) always gives rise to a current whose magnetic field opposes the original change in magnetic flux. That is way the EMF induced is equal to the negative rate of change with time of magnetic flux through the circuit.

Another equation for EMF induced is:

$$U_{EMF} = Blv \quad (2)$$

Where B is magnetic flux density, l is effective length of the wire and v is velocity of the wire.

2.2.2 Vibration Energy Harvester

Basically, the electromagnetic generators of vibration are using second-order spring mass systems as shows in Figure 8. Assuming that the mass of the vibration source is significantly greater than that of the seismic mass and therefore not affected by its presence and also that the external excitation is harmonic, then the differential equation of motion is described as:

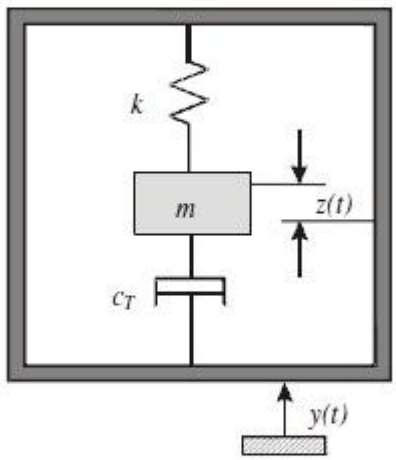

Figure 7: Second-order mass spring [8]

$$mz(t) + cz(t) + kz(t) = -my(t) \qquad (3)$$

where m is seismic mass on a spring of stiffness, k. Energy losses within the system (comprising practical losses, c_p, and electrical energy extracted by the transduction mechanism, c_e) are represented by the damping coefficient, c_T. These components are located within the inertial frame which is being excited by an external sinusoidal vibration of the form $y(t) = Y \sin(\omega t)$. This external vibration moves out of phase with the mass when the structure is vibrated at resonance resulting in a net displacement, $z(t)$, between the mass and the frame.

According to Newton's second law of motion, force equal to mass time with acceleration

$$F = ma \tag{4}$$

where F equal to force exerted, m equal to the mass and a is equal to acceleration. Thus we can get the equation of motion which is

$$v^2 = u^2 + 2as \tag{5}$$

where v is final velocity of the structure, u is the initial velocity, a is the acceleration and s is the displacement of the structure. Mass spring system is based on Hooke's Law. Hooke's Law stated that the extension of a spring is in direct proportion with the load added to it as long as this load does not exceed the elastic limit. Hooke's Law is

$$F = -kx \tag{6}$$

where F is the force exerted, x is the displacement of the mass and k is the spring constant. To calculate the spring constant, the equation is

$$k = \frac{Ewt^3}{4l^3} \tag{7}$$

where E is equal to Young Modulus elasticity, w is width, t is height and l is the length of the structure itself. Since in the design, the device used multiple springs attached in series by equation (8) and parallel given by equation (9) as

$$k_{total} = k_1 + k_2 \tag{8}$$

$$\frac{1}{k_{total}} = \frac{1}{k_1} + \frac{1}{k_2} \tag{9}$$

To make sure driving frequencies do not match the natural frequency of vibration of the structure less vibration increase to dangerous amplitudes. Natural frequency is when the mass is attached to the end of such spring and oscillates under free vibration. It is also known as resonance frequency. The equation given is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{10}$$

where k is the stiffness of the beam and m is the mass of structure.

CHAPTER 3
METHODOLOGY

3.1 Research Methodology & Project Activities

The project is carried out according to the process flow as shown in Figure 9. Firstly, the problems related to energy harvesting is being identify and defined. Next, all the information and material from internet, journal, technical papers and also books had been gathered. The study about electromagnetic based energy harvesting being done based on material gathered before. During this phase, electromagnetic fundamentals be emphasized as it is the most important principle for this study. Some applications had been included to relate the importance of this energy harvester to current scenario.

Besides that, as the objective of this study is to review about energy harvester, type of macro scale energy harvester also need to be studied. Then, comparison between the types of energy sources had been done and the suitable type of energy sources for this study had been chosen is kinetic energy. Since the vibration is one of the examples of kinetic energy, a deep study about vibration is being done. A solid research about three type of vibration-based micro generator had been done to choose the best type of micro generator that gives the suitable output voltage. In addition, some characteristics of electromagnetic energy harvester are being investigated to achieve deep understanding for this study.

After all the studies, the next step is designing the test jig for this study. During this phase, a detailed design is presented before building the package. After that, Autocad software is used to create a 3D layout.

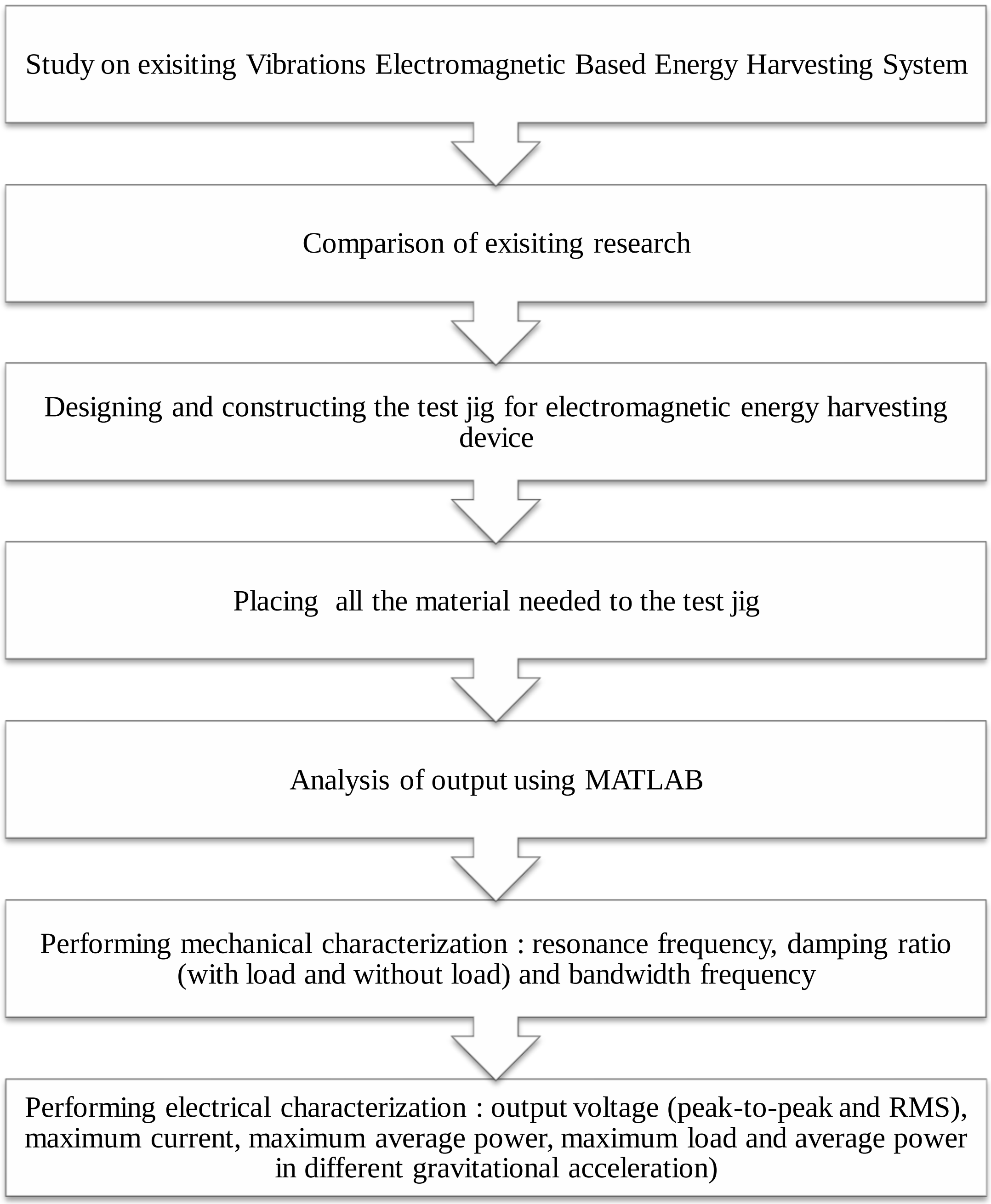

Figure 8: Flowchart Diagram for Project

Then, the PVCs being shaped according to the measurement designed earlier. All the needed material will be placed to the test jig. The data then is simulated using MATLAB to check the deviation of value of characterization to the theoretical value.

Then, the devices will be test on vibration shaker that will act as source of vibrations. The mechanical characterization such as mechanical noise, strain and resonant frequency will be tested to the device. Then, electrical characterization (output voltage, current and electrical noise) testing will be performed.

3.2 Tools and Equipment Used

For design structure, AutoCAD software had been used to simulate 3D view of test jig and to get the exact measurement of test jig. There are some materials needed to construct housing which are one pieces of magnet, a vibrating membrane (spring) and copper wire. Meanwhile, below are the lists of equipment needed to perform mechanical and electrical characterization for electromagnetic based energy harvesting system.

- Vibration Shaker

Figure 9: Vibration Shaker

- Controller for Vibration Shaker

Figure 10: Controller for Vibration Shaker

- Dynamic Analyzer

Figure 11: Dynamic Analyzer

3.3 Gantt Chart

The Gant Chart is provided together with the report in the Appendix A. The Gantt chart is a guideline for the project timeline. It can be changed from time to time depending on certain circumstances.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

Chapter 4 is dedicated to gather and elaborate the results obtained from characterizing the energy harvester system. There are two types of characterization that has been conducted which is the electrical and mechanical characterizations. For mechanical characterization, several important parameters have been extracted such as the resonant frequency and damping ratio. For electrical characterization, the open loop voltage, impedance matching, closed loop voltage and effect of varying gravitational acceleration the output voltage have been conducted. Both characterizations are required prior to overall determination of energy harvester system performance.

4.2 Prototype Development

The construction of the electromagnetic vibration energy harvester is very simple. It consist the vibrating membrane, magnet, housing and the copper coil as shown from Figure 12 to Figure 15.

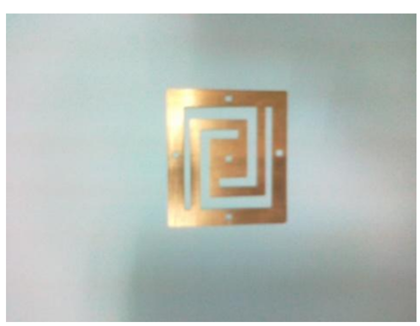

Figure 12: Vibrating Membrane

Figure 13: Magnet

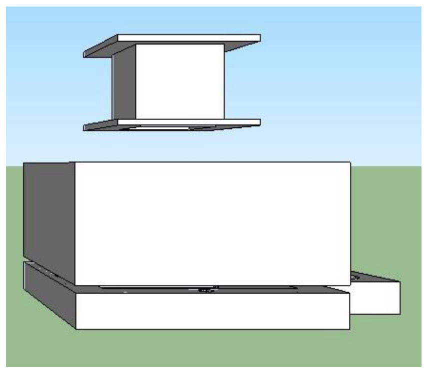

Figure 14: Housing

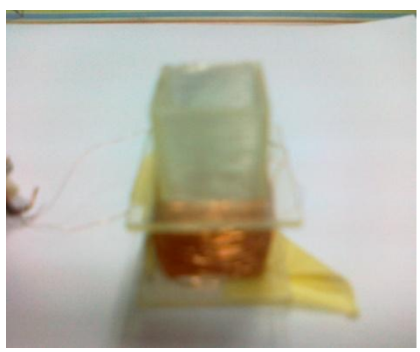

Figure 15: Copper Coil

The vibrating membrane is Copper Layer of dimension 38mm x 41mm x 250μm thick. Copper materials are chosen since it provides good spring constant coefficient, *k* for low vibration application. The vibrating membrane is etched to produce a crab-leg shape using Ferric Chloride ($FeCl_3.6H_2O$) chemical in UTP PCB-Lab. A unit of Neodymium (NdFeb) magnet which has magnetic field strength of 1.2Tesla is glued to the vibrating membrane to act as seismic mass, *m* and generating the source of magnetic field. This device structure contains 1707 turns of copper coil. The coil housing then had been placed on top of the magnet. Each coil has a diameter of 100µm and internal resistance of ≈ 234 Ω. Table 2 below summarized the prototype's properties.

Table 2: Prototype's Properties

Properties	**Value**
Magnet	**Magnetic Field Strength:** 1.2 T **Dimension:** 10 mm x 10 mm x 10 mm **Weight:** 1.2 g
Housing	**Dimension:** 39 mm x 42 mm x 21 mm
Vibrating Membrane (Spring)	**Dimension:** 38 mm x 41 mm **Stiffness Coefficient, *k* :** 13.82 N/m
Coil	**Number of turns:** 1707 **Length of copper coil** : 0.95 m

After the material is placed onto it housing as shown in Figure 16, the prototype are ready for the testing.

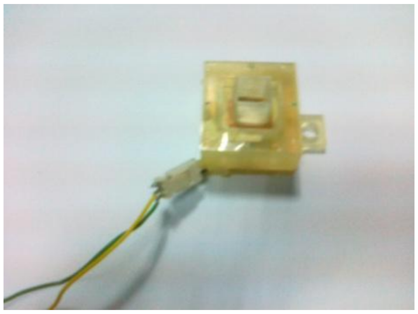

Figure 16: Prototype

In order to perform the testing, the equipement is being setup as shown in Figure 17. Then, the prototype is screwed to the vibration shaker.

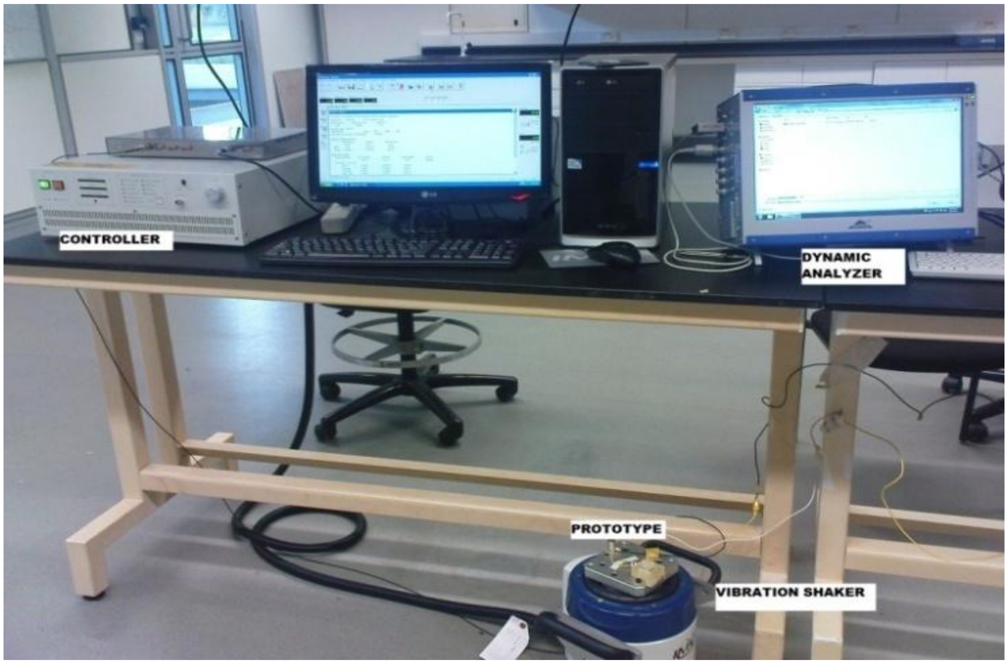

Figure 17: Characterization Setup

There two monitor used for the experiment. First monitor is connected to controller. Controller function is to control the value of vibration to the shaker. The software K2/Sine is used as interface between the controller and the vibration shaker. Using this software, there are two options available which are manual reference and sweep test difference. For manual reference, the value of the frequency and gravitational acceleration is inserted manually. Then, the value of frequency also can be varied using the increment button in the software. Meanwhile, for sweep test difference, only the range of frequency and gravitational acceleration is inserted. After the frequency reach the upper range, the controller will stop giving input to the vibration shaker.

The vibration shaker's role is to excite the prototype according to the input signal from the controller. When some value of vibration is being excited by an external sinusoidal vibration form y (t), the movement of the spring and magnet in the housing's coil will cut the magnetic field which results in change of magnetic flux. When the magnetic flux through a closed circuit changed, an induction electromagnetic force (EMF) is generated in the coil. The wire then is connected to the other monitor which is the Dynamic Analyzer. It is used to saved, monitor and analysis the output from the prototype in the form of sinusoidal wave.

4.3 Data Simulation

For analysis of data, the data had been simulated using MATLAB using the code in APPENDIX B. The aim of data analysis is to check the percentage of error for output produced by this energy harvesting. Using the equation (2), the open loop voltage had been calculated to find the peak to peak induced voltage. The sine wave of 22.7 Hz frequency had been used as the input. The data simulated is shown in Figure 17.

$$U_{EMF} = Blv \qquad (2)$$

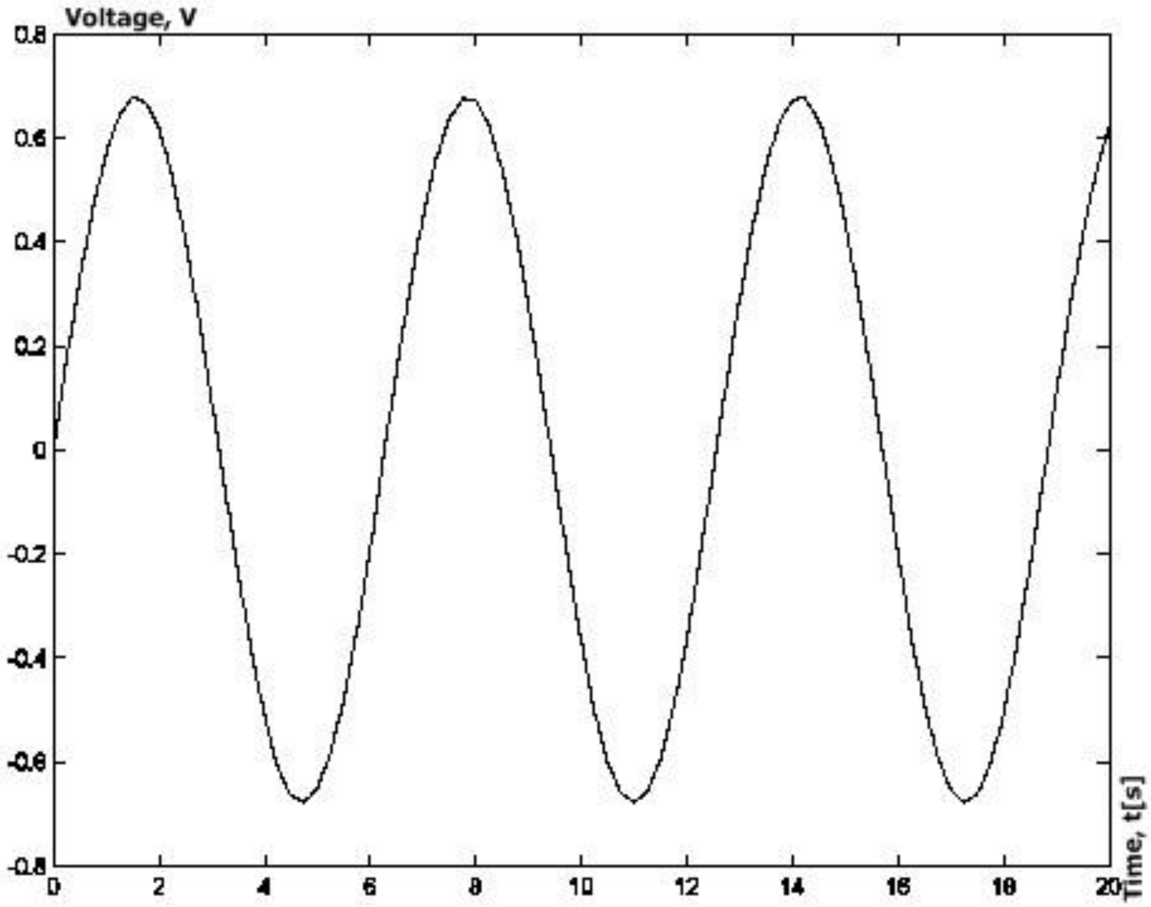

Figure 18: Simulation of Open Loop Voltage

The simulated open loop voltage is 0.6790 V. The equation (12) given is used to check the percentage of error between the simulation value and experimental value.

$$Percentage\ of\ error\ (\%) = \frac{|True\ Value - Experimental\ value|}{True\ Value} \times 100\% \qquad (10)$$

4.4 Mechanical Characterization

4.4.1 Resonance Frequency

Resonance is the tendency of a system to oscillate at greater amplitude at some frequencies than at others [20]. The objective of this test to is to find this greater amplitude by varying the frequency and at the same time observing the output voltage. Try and error methods are used initially by varying the input frequency to the shaker system from 10 Hz until 30 Hz. Simultaneously, the output from Dynamic Analyzer also observed. After the frequencies incremented for several times, the most suitable frequencies that produced highest peak to peak voltage is found to be 22.7 Hz as shown in the Figure 19.

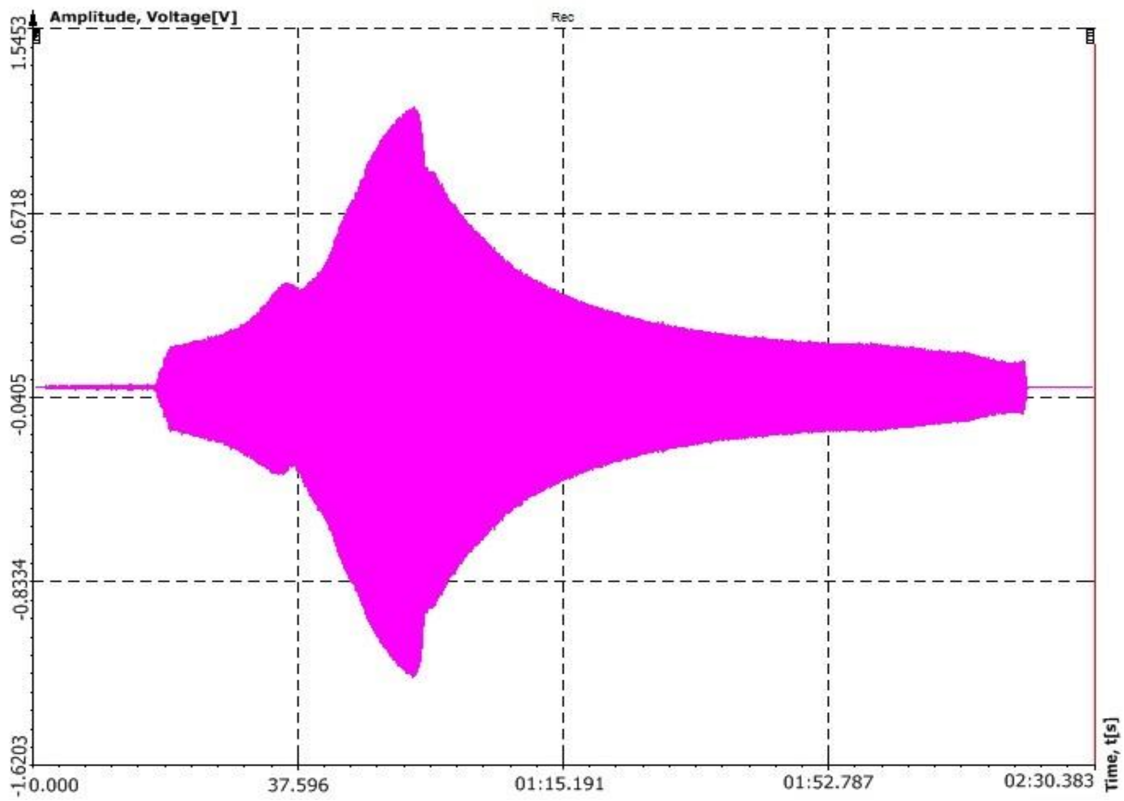

Figure 19: Resonance Frequency

Based on the Figure 19, it can be observed that the resonance only occur once at 22.7 Hz. The vibration amplitude will decrease below and above the resonance level.

4.4.2 Damping Ratio

Damping ratio is a dimensionless measure describing how oscillations in a system decay after a disturbance. It is a measure of describing how rapidly the oscillations decay from one bounce to the next [21]. From damping ratio the behavior of the system can be predicted (over-damped, under-damped, or critically-damped type of system). In order to find the Damping Ratio, the device is injected with some frequencies and left to gradually decay in amplitude towards zero as shown in Figure 20. The decaying waveform is then captured using DeweSoft Software.

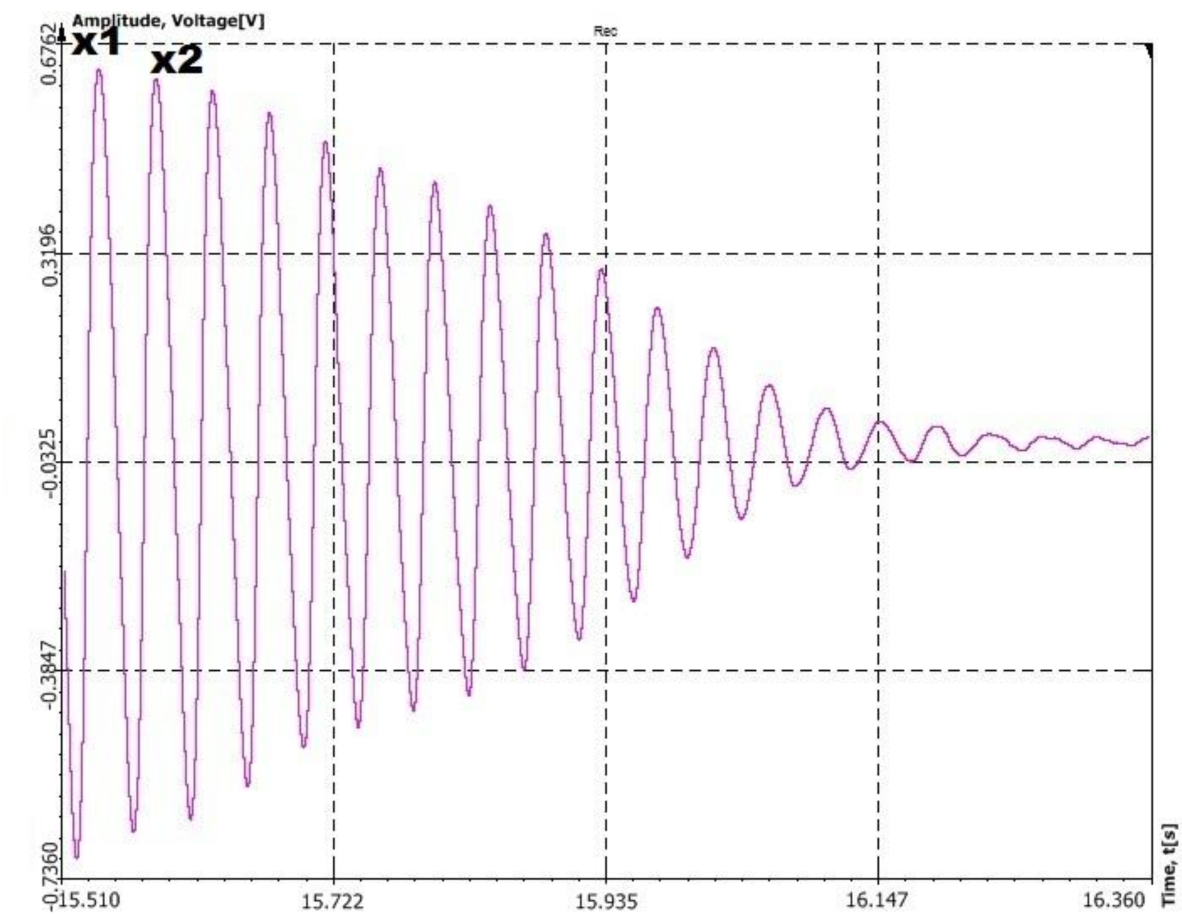

Figure 20: Damping Ratio without Load

For calculation, the ratio of x1 and x2 had been calculated using:

$$\delta = \ln\frac{x1}{x2} = \ln\frac{0.6533}{0.6457}$$

$$\delta = 0.0117$$

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} = \frac{0.0117}{\sqrt{(2\pi)^2 + (0.0117)^2}}$$

$$\zeta = 0.001862$$

Next the system with load is considered. The device is connected to the load and the plot of the waveform is shown in Figure 21.

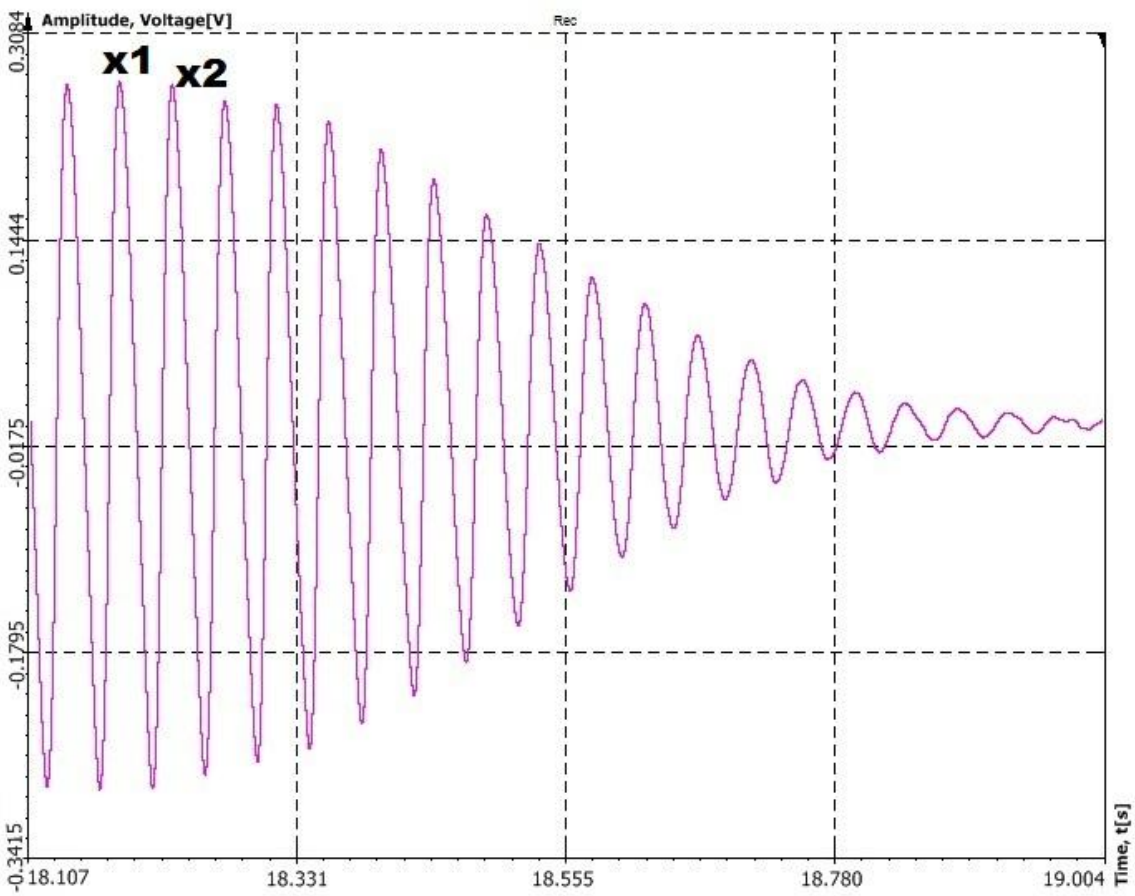

Figure 21: Damping Ratio with Load 260Ω

For calculation of the damping ratio with load of 260Ω as shown in Figure 21, similar steps are followed:

$$\delta = \ln\frac{x1}{x2} = \ln\frac{0.2727}{0.2659}$$

$$\delta = 0.02525$$

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} = \frac{0.02525}{\sqrt{(2\pi)^2 + (0.02525)^2}}$$

$$\zeta = 0.004019$$

The value of the damping ratio ζ determines the behavior of the system. A damped harmonic oscillator can be:

- *Overdamped* ($\zeta > 1$): The system returns (exponentially decays) to equilibrium without oscillating. Larger values of the damping ratio ζ return to equilibrium more slowly.
- *Critically damped* ($\zeta = 1$): The system returns to equilibrium as quickly as possible without oscillating. This is often desired for the damping of systems such as doors.
- *Underdamped* ($0 < \zeta < 1$): The system oscillates (at reduced frequency compared to the *undamped* case) with the amplitude gradually decreasing to zero.
- *Undamped* ($\zeta = 0$): The system oscillates at its natural resonant frequency (ω_o) [22].

Since the value of ζ both is in the range of $0 < \zeta < 1$, the system is categorized as under damped. It means that, when the input is injected the mass tends to overshoot from starting position, and then return, overshooting again. With each overshoot, some energy in the system is dissipated, and the oscillations die towards zero.

4.5 Electrical Characterization

4.5.1 Open Loop Voltage

Using resonance frequency of 22.7 Hz obtained from previous chapter, the greatest amplitude of the output voltage at this frequency is considered as the open loop voltage without load. Open Loop is a control system that uses only an input signal to actuate an output. Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points [23].

$$V = IR \tag{11}$$

Using the specific resonance frequency, the output voltage produced by the vibrating electromagnetic energy harvester system is a sinusoidal waveform of about 0.6759 V peak to peak as shown in Figure 22.

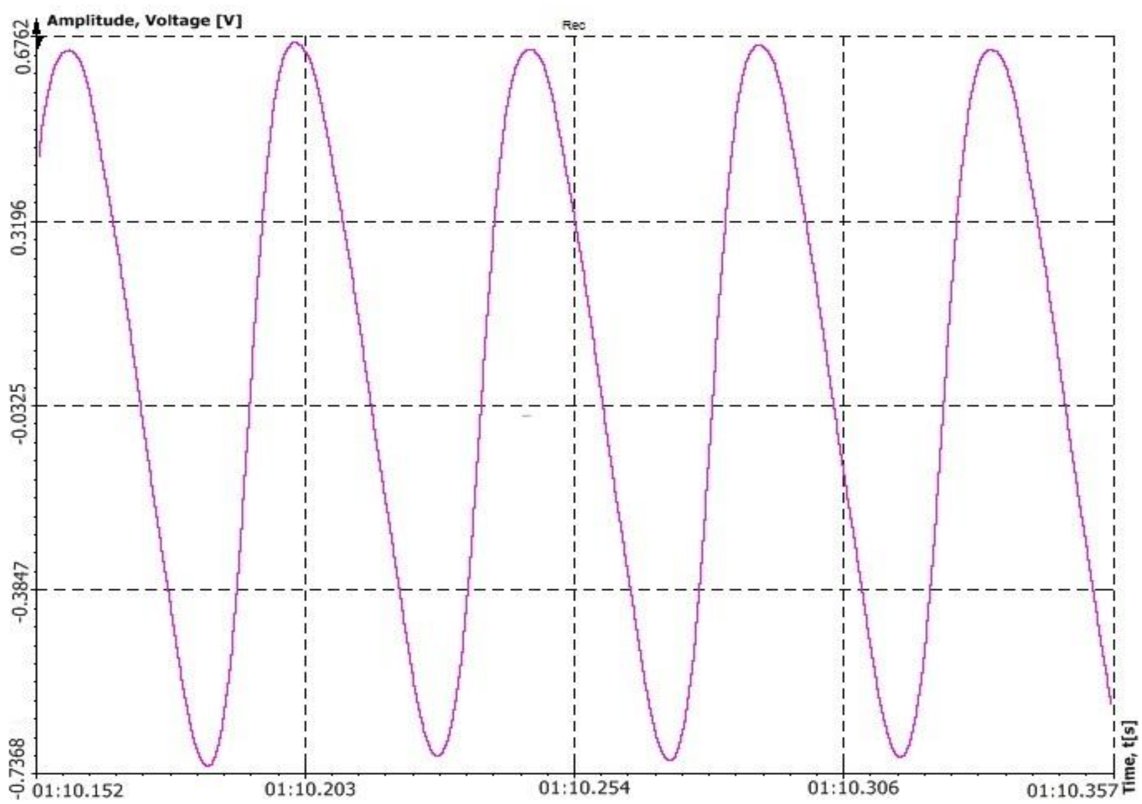

Figure 22: Open Loop Voltage

The value of an AC voltage produced by the energy harvester system is continually changing from zero up to the positive peak of 0.6759 V, through zero then to the negative peak. The RMS value is the effective value of a varying voltage and is found to be [27]:

$$V_{RMS} = 0.7 \times V_{peak} \quad (12)$$

$V_{RMS} = 0.7 \times 0.6759 = 0.4731$

4.5.2 Impedance Matching

Impedance matching is the practice of designing the input impedance of an electrical load (or the output impedance of its corresponding signal source) to maximize the power transfer or minimize reflections from the load [24]. Since the objective of Impedance matching is to find the load impedance that gives the maximum power, the range of the loads for this experiment are selected around the internal resistance of the device itself which is between 240 Ω to 290 Ω. Input frequency equivalent to the resonant frequency of the device is chosen as the input source of vibration. The output then had been connected to different value of loads. Next, from the peak to peak voltage, the power been calculated using equation (14)

$$P_{av} = \frac{V^2}{R} \quad (13)$$

From the Table, it is clearly shows that using load of 260 Ω will producing the maximum power which is 0.3632 mW.

Table 3: Impedance Matching with Resonance Frequency of 22.7 Hz

Loads	Average Power (mW)
240Ω	0.2477
250Ω	0.2894
260Ω	0.3632
270Ω	0.3552
280Ω	0.3007
290Ω	0.2872

4.5.3 Closed Loop Voltage

Closed loop voltage is the voltage drop when output is connected with the loads. For this test, the probe from Dynamic Analyzer is connected across the load to determine the voltage drop. The output voltage produced is shown in Figure 23. Since the circuit is in the closed loop condition, it will allow the current to flow in around the circuit. The closed loop is aim to find the output voltage produced when the system is connected with the load. This test is very important because the maximum output power is linearly dependant with the closed loop voltage. The effect of difference load is also investigated throughout this test. Referring to Table 3, the maximum power is when the device connected to the 260 Ω loads. So, the output voltage produced is 0.3073 V.

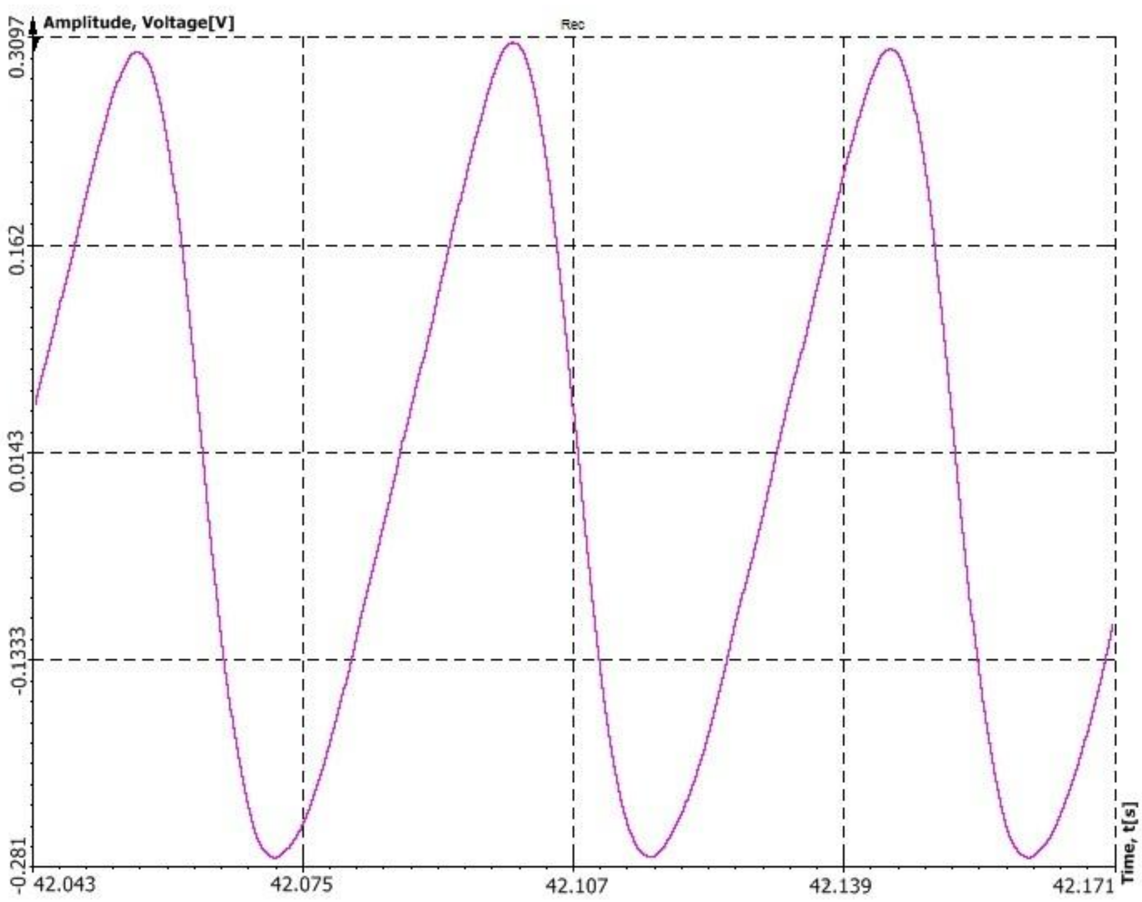

Figure 23: Closed Loop Voltage

Using equation (12),

$$V_{RMS} = 0.7 \times 0.3073 = 0.2151V$$

4.5.4 Bandwidth Frequency

Bandwidth is defined as a band containing all frequencies between upper cut-off and lower cut-off frequencies as shown in Figure 24. Upper and lower cut-off (or 3 dB) frequencies corresponds to the frequencies where the magnitude of signal's Fourier Transform is reduced to half (3 dB less than) its maximum value [25]. Meanwhile, for the characterization of the energy harvester, the bandwidth is tested to find the most suitable range of frequencies for optimum output power.

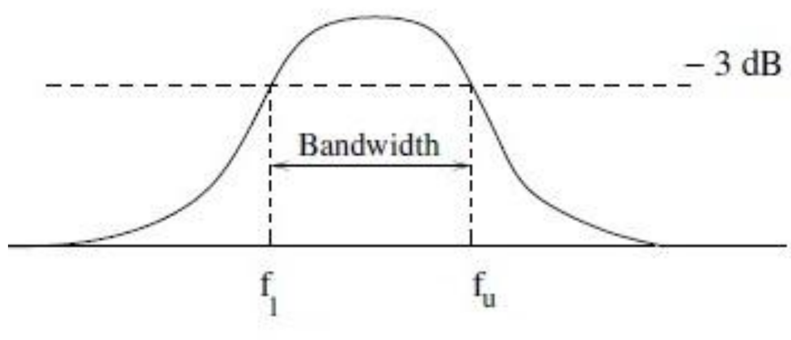

Figure 24: Upper cut-off and lower cut-off Frequencies

To determine the bandwidth, the sweep reference option is used in K2/Sine software. With reference to Figure 25, the frequency range selected is from 20 Hz to 30 Hz. Initially, when the input frequency of excitation of 20 Hz is used, the output produced is found to be quite small. The output is at maximum when the frequency approaching 22 Hz. It means that the device reach its optimum frequency. Then, if the frequency used is below or upper these range, it will not give the optimum output voltage.

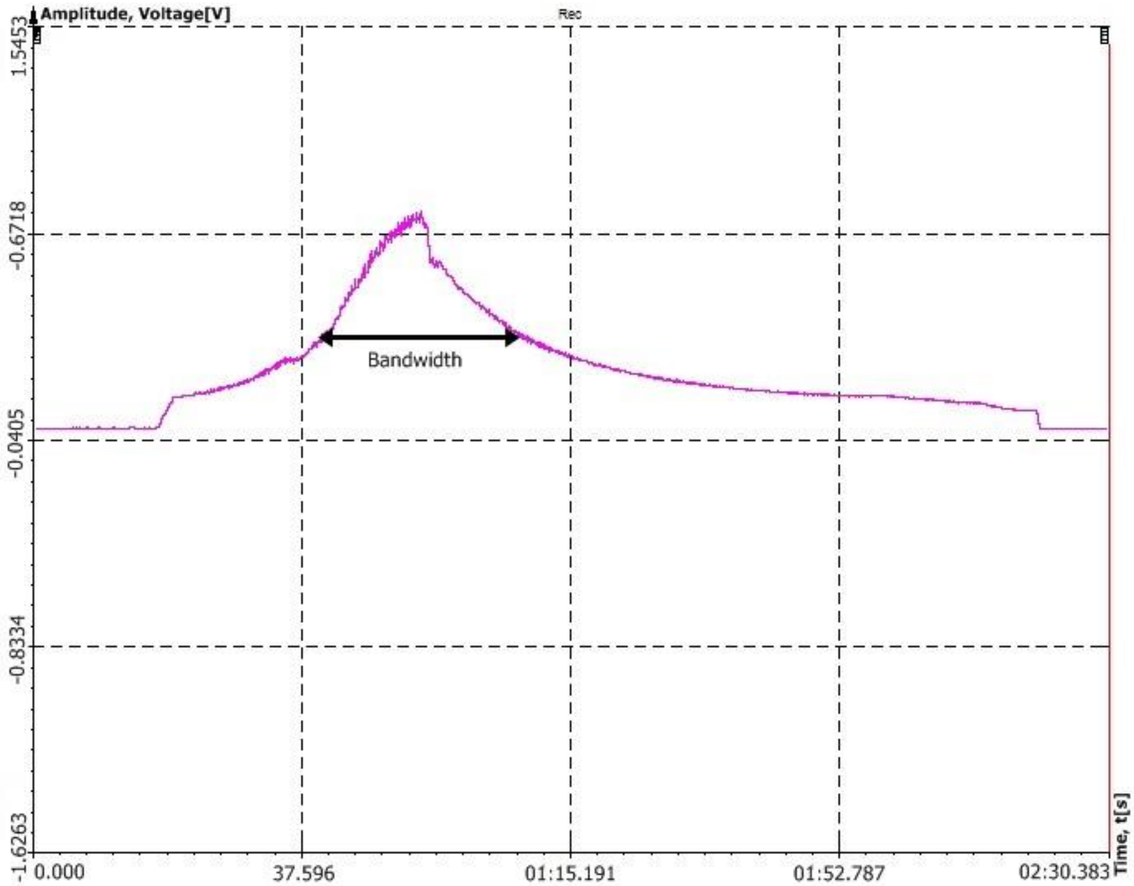

Figure 25: Bandwidth Frequency

The bandwidth frequency is calculated using the equation (14):

$$f_b = f_{upper} - f_{lower} \quad (14)$$

The bandwidth for this device is

$$f_b = 20\ Hz - 30\ Hz = 10\ Hz$$

4.5.5 Output voltage in Different Gravitational Acceleration

The gravity of earth has an approximate value of 9.81 ms^{-2} or (1 g) by ignoring the effects of air resistance [26]. Actually, this value of gravitational acceleration is varied dependent upon location. Such factor such as the latitude, altitude, depth, local topography and buoyancy forces of the object causing the differences in the acceleration. But, the most important is the latitude of the object [27]. Considering the existence of these entire factors, the effect of difference acceleration to the open loop voltage is produced. For this subtopic, the resonance frequency is set as constant. The experiment is set up by varying the input of acceleration of the vibration shaker. The purpose of this experiment is to determine different acceleration will produce different output voltage. This may simulate different acceleration which can occur from different vibration due to dynamic behavior of the motion on the road for an example as shown in Figure 26.

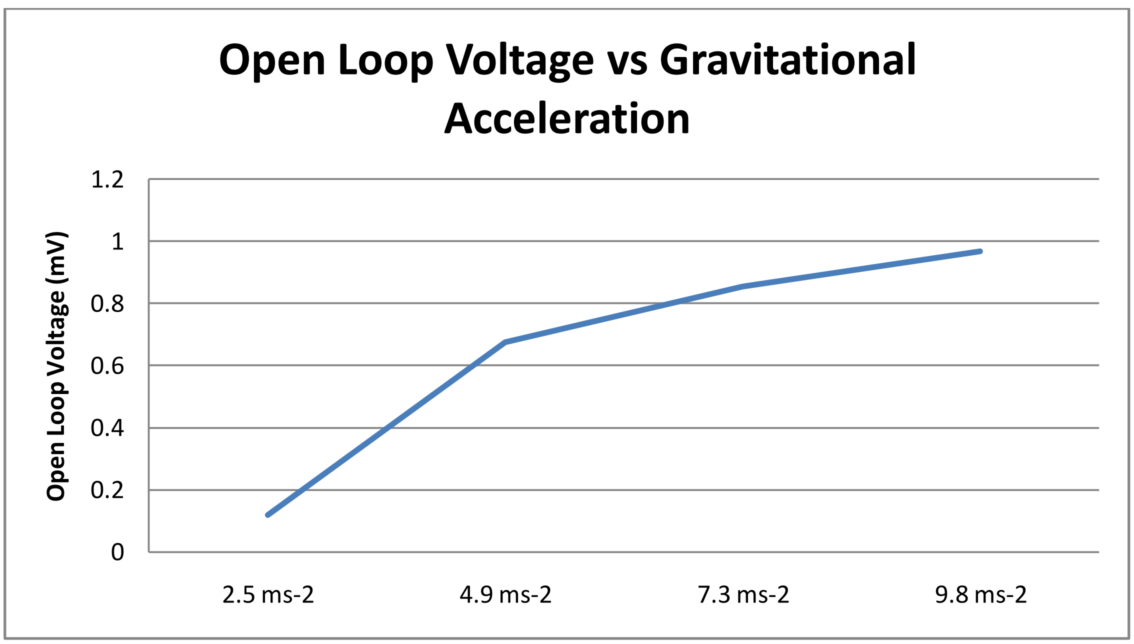

Figure 26: Graph of Open Loop Voltage vs Gravitational Acceleration

Based on Figure 26, open loop voltage produced is increased when the acceleration is being increased. When the acceleration is increased, the rate of magnet movement cutting the flux in the coil also increased. So, the induce voltage produced also increased. Since the frequency is linearly dependant with the acceleration, the application for higher frequency will produce more output compared to low frequency. But, it is very difficult to get value of 1 g, so the value of 4.9 ms^{-2} is chosen to use as constant for entire experiment.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The electrical and mechanical characterizations have been performed to investigate the performance of the energy harvesting system. From characterization process, certain parameters can be extracted. Apart from performance investigation, future system enhancement and suitable applications could also be identified and recommended from the characterization results. Table 5 summarizes the electrical and mechanical properties of the energy harvester device.

Table 4: Summary of Characterization of Device

Parameter	**Value**
Resonance Frequency	22.7 Hz
Bandwidth Frequency	10 Hz
Damping Ratio	Without Load: 0.001862 With Load (270 Ω) : 0.001419
Open Loop Voltage	$V_{Peak\text{-}to\text{-}Peak}$: 0.6759 V V_{RMS} : 0.4731 V
Closed Loop Voltage	$V_{Peak\text{-}to\text{-}Peak}$: 0.3073 V V_{RMS} : 0.2152 V
Maximum Power Average	0.3632 mW
Maximum Load	260 Ω

The theoretical value of open loop voltage is 0.6790 V and the experimental value is 0.6795 V. The percentage of error is calculated using the equation (12):

$$Percentage\ of\ error\ (\%) = \frac{|0.6790V - 0.6759V|}{0.6790V} \times 100\% = 0.46\%$$

The open loop voltage is deviated 0.46% from the theoretical value. It is due to energy loses because of the magnet is collide with the inner part of housing wall. Some energy also may lose the energy in form of heat and resulted the error to the data.

Referring to Table 4, the energy harvesting system is found to be suitable for low power applications such as the wireless sensor network devices with vibration input sources ~~as~~ in the range of 22.7 Hz. Usually, the range of frequency under 30 Hz is considered as low frequency vibration [1]. Knowing that the vibration sources such as heel strikes, rotation machines and human motions are available for free, it is such a waste if that energy are not being utilized. Mostly, low power devices are using electrochemical batteries as their power supply. Since the batteries had some constraint with the infinite lifetime, the energy harvesting seems very suitable to replace the traditional technology. Since the output from this energy harvester is very small, it can be used to charge up batteries for low power application device. For example, the Wireless Sensor Network is very impractical without energy harvesting because the replacement of batteries can be costly. Since there are free energy is ready to harvested, the electromagnetic vibration based can be solution to this problem. Portable electronic devices such as SmartTAG had batteries that go down. The movements from car can sufficiently enough to be source of vibration input for powering up this device. For military application, this energy harvester can be used to convert operational strains and vibrations of a helicopter blade into electrical energy that enable them to monitor loads on rotating components.
Considering the size of the device, it can accommodate the smaller space and very suitable for autonomous wireless device such as Wireless Sensor Network.

5.2 Recommendations

For further development there are some suggestion needed to be done in order to maximize the output. Few recommendations are suggested. Firstly, magnet with higher field magnetic must be used to maximize the output voltage. More number of coils must be used as the output voltage is increased proportional to number of coils. Next, seismic mass attached to spring also affected the output power of device. The output power produced is proportional to seismic mass of spring. The spring design also can be improved to increase the output voltage. The spring also can be designed in the larger scale compared to current design. Material for the current spring is Copper. The problem with the Copper it is very easy to bend. This may causing the spring hit the wall thus produce the signal's noise. The suggested material is Polyethylene Terephthalate (PET) because it is insulator which will not absorb the heat. So, the energy will not be wasted thus improve the output voltage. The constant spring coefficient of spring, k for PET is also as good as the constant spring of Copper.

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APPENDICES

APPENDIX A

Gantt Chart

	Task Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Designing and Constructing Test Jig for Electromagnetic Vibration based Energy Harvesting														
2	Performing electrical and mechanical characterization for Electromagnetic Vibration based Energy Harvesting														
3	Preparation of Progress Report														
4	Submission of Progress Report								16/7						
5	Design and construct test jig														
6	Modeling and Experimentation														
7	Analysis Result														
8	Poster Presentation											8/8			
9	Finalize Project Work														
10	Draft Final Report & Technical Paper Submission													15/8	
11	Oral Presentation (VIVA)														27/8
12	Final Report Submission														7/9

APPENDIX B

Coding A

```
B= 1.2;
L= 0.95;
v = 0.5956
A = B*L*v
t=0:0.25:20;
y = A*sin(2*pi*22.7*t);
plot(t,y)
```