VIBRATION ENERGY HARVESTER SYSTEM [VEHS]

by

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CERTIFICATION OF APPROVAL

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Approved by,

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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.

MUHAMMAD HAFIFI BIN SULAIMAN CHAN

ABSTRACT

Energy harvesting is a process in which energy is drawn from external sources. Energy harvesting device is used to convert other available form of energy, for example solar energy, wind energy, thermal energy and mechanical energy, into electrical energy. This has attracted much attention from many people to utilize the abundant natural energy from being wasted. One of the most fundamental energy available which is often neglected is vibration energy. Vibration energy subsists widely in the world and is always wasted.

The purpose of this project is to develop a working prototype, Vibration Energy Harvester System (VEHS), which will be used to convert the vibration energy created by traffic vibration on the road pavement into electrical energy. Among the technique available in converting the vibration energy into electrical energy is by using the concept of electrostatic, piezoelectric and electromagnetic induction. Since it is easy to keep a strong magnetic field using strong permanent magnet, electromagnetic induction is chosen as the suitable approach for this project. Engineering drawing tool, AutoCAD, is used to design the prototype before is it fabricated. Next, based on a presume value of identified variable, a simulation is done using MATLAB to speculate the amount of output that are able to be drawn from the actual prototype.

After that, the prototype is fabricated and the testing is carried out to observe the performance of the device. The prototype is placed on vibration generator where its frequency and acceleration can be adjusted. The result of open-loop and closed-loop test of the prototype is summarized in the graphical representation.

ACKNOWLEDGEMENT

First of all, I would like to express my greatest gratitude to God for giving me the strength, health and patience to successfully complete this project. Not to mention, to my parents and all my family members for supporting and providing fruitful advises that enable me to see this project till the end.

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ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
EH300	Energy Harvesting 300
EMF	Electromotive Force
EMI	Electromagnetic Induction
PP	Polypropylene
PVC	Polyvinyl Chloride
VEHS	Vibration Energy Harvester System

CHAPTER 1

INTRODUCTION

1.1 Background

Recently, people have started to find an alternative to the near-extinct and costly fossil fuels based energy generation for means of power supply. With the help of modern technology, energy can be harvested from the environment, which is available in the form of thermal energy, solar energy, wind energy and mechanical energy [1, 2]. Interestingly, the harvested energy can be used as an alternative energy source to supplement a primary power source and to enhance the reliability of the overall system. Energy harvesting is a process of capturing minute amounts of energy from one or more of this naturally-occurring source of energy, accumulating and storing it for later use [2].

Basically, energy harvesting consists of a set of devices capable of capturing and converting the surrounding energy, which act as a source, into electrical energy. Among common source of energy harvesting include:

i. Mechanical energy – vibration, mechanical stress and strain
ii. Thermal energy – waste heat from furnace, heaters and frictions
iii. Light energy – captured from sunlight or room light using solar panel, photodiodes or photo sensor
iv. Natural energy – wind, water flow, oceans current

Currently, solar and wind energy have emerged as the leading competitors in the field of alternative energy. The reason behind this is that, the source of energy itself is free, abundant and renewable; its usage is at our disposal [3, 4]. Both, solar and wind energy are regarded as green energy, as their operation produce no harmful emission of greenhouse gases or pollutants. In addition to that, their operating cost is also a lot less compared to the conventional power plant. Despite all that advantages, there are some shortcomings for both of this alternative energy.

Since solar energy harvester depends on the intensity of the sunlight projected onto solar panel, cloudy weather or rainy condition will interfere in the amount of sunlight that reaches the solar panel. Wind energy also has the same unreliability factor, in which the produced energy at the output depends on the speed of the wind that strikes the propeller blades. The generated power will become inefficient if the situation is unfavourable to the device [3, 4]. Moreover, the initial cost for the setup can be really expensive especially for the construction of wind turbines for wind energy and solar panel in solar energy. Solar energy and wind energy application are doubtful in time of high supply demand due to their energy source nature.

Vibration energy at the other hand, being a part of mechanical energy, posses the same advantages as in solar and wind energy. Comparing vibration energy with those two in terms of setup and maintenance cost, the total cost is fairly cheaper for vibration energy. Although often vibration creates loud sound and noise, we cannot deny the fact that the energy is abundant due to our own act such as road traffic, electrical appliances and industrial activities [5, 6, 7]. This unwanted energy can be exploited to be useful in our daily life by manipulating it in a correct way. Today, various types of vibration based energy harvester are available to suit different kind of purposes [8].

Vibration harvester seems very viable to be implemented compared to other types of alternative energy system since the source of vibration is usually optimal in busy town [5], where there is high demand for power supply. Since vibration energy harvester usually requires small installation area, unlike wind turbine and solar panel, it can be installed easily without interfering with the resident's busy routine, for example somewhere nears the road. However, the output severely depends on the amount of vibration produced and for now, most of the devices invented are for low performance appliance and electronic circuits. Further studies are needed to ensure that vibration harvester can cater the huge supply demand.

Generally, these applications are known for its ability in providing wireless system, which make it very desirable especially in remote area, since wired system are often costly and inconvenient for long transmission [1]. In other application, this harvested energy can be used in parallel (multiple energy sources) to enhance the overall efficiency and reliability of an existing system. Besides, it is also does seems viable as an alternative source of energy in the future in place of the costly and depleted fossil fuel based generation method.

1.2 Problem Statement

Nowadays, majority of equipments in our life relies on fossil fuel as source of energy. Almost all fossil fuel is used by burning or combustion which produces waste products due to the impurities in the fuel. Among those waste products are several hazardous gases such as sulphur dioxide, nitrogen oxides and other organic compound. These waste products may affect our life and our environment, in harmful ways. It has been a great concern to all, to minimize the pollution caused by the fossil fuel by researching the method on how to reduce the adverse effect of fossil fuel combustion.

On the other hand, some people have already begun to find another source of energy to reduce the dependencies on fossil fuel. Now, the attention is shifted toward finding an alternative, pollution-free source of energy scavenged from the energy available in our surroundings. In correspond to that, a device capable of harvesting this alternative energy needs to be designed, fabricated, and tested to ensure it credibility and efficiency in generating power supply.

1.3 Objective

Upon completion of this project, a few objectives are set to satisfy the scopes of study that have been underlined, which are relevant to the requirement of the project. The objectives of this project are as follows:

i. To capture minute amounts of vibration energy produced from the vehicles on the moment it go pass through the vibration energy harvester to produce electricity.
ii. To design and fabricate a vibration based energy harvester to harvest energy produced by moving vehicles on the roads. The designed prototype will be able to convert kinetic energy into electrical energy to be used to power up the electronic circuit such as sensor.
iii. To characterize, analyze and optimize the performance of the energy harvester through testing, monitoring and data acquisitioning.

1.4 Scope of Study

While the scope of study will consists of three major parts which are:

i. Investigate the causes of vibration produced by road traffic and the transmission medium of the vibration. This includes, the stress wave frequency generated when a vehicles encountered any irregularities on the pavement.
ii. Research on available method of energy harvester based on vibration-driven application and the concepts applies to it.
iii. Conduct an experimental work to optimize prototype design and reliability to the expected result.

CHAPTER 2

LITERATURE REVIEW

2.1 Traffic Vibration

Abundant vibration energy is being produced in our daily life, be it from heavy industries, road traffic or even the simple act of walking. The creation of road traffic vibration can be illustrated by a source-path-receiver scenario as in Figure 1. When a moving vehicle made contact with the road's irregularities such as potholes, crack, and uneven manhole covers, dynamic loads is induced on the pavement [5]. These loads will in turn generate stress wave, which will propagate through the soil (soil-borne) and finally reaching the foundations of adjacent structure and causing them to vibrate.

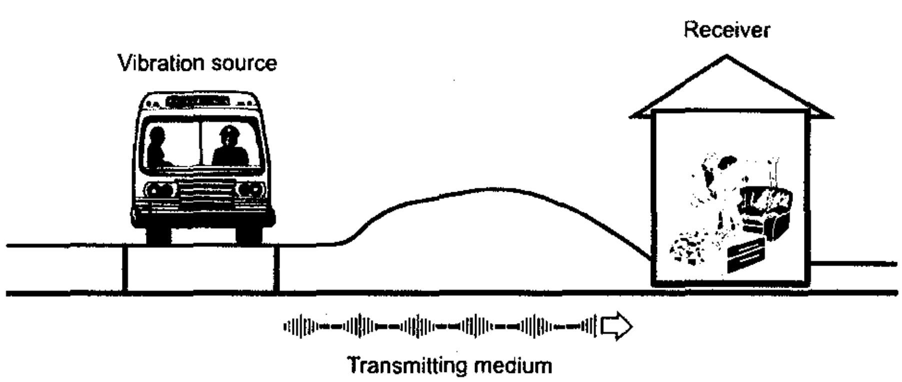


Figure 1: Road traffic vibration [5]

Traffic vibrations are mainly caused by heavy vehicles such as buses and trucks. Passenger cars and light trucks rarely induce vibrations that are noticeable to buildings and other structure from afar. When a bus or truck strikes irregularities in the pavement, it generates an impact load and an oscillating load due to the subsequent "axle hop" of the vehicle [6]. The frequencies and amplitude of the vibration depend on many factors including the condition of the road, vehicle weight, speed and suspension system, soil type and distance from the road.

In order to fully utilize this abundant vibration energy, an innovative idea, vibration driven energy harvester is being designed to convert the unused vibration energy into electrical energy [7, 8, 9]. Possible application for this device is to power up the electronic circuitry and other possible application within the same range of power specification. The kinetic energy from the road traffic is converted to electric energy by applying the electromagnetic induction principle and the vibration law. Vibration energy from the road is translated to a kinetic energy that will create a displacement in the system with respect to time causing a change in the magnetic field, which in turn produce electricity [10].

In addition to this, a booster circuit and a storage circuit will be added to the design for more efficient energy supply. Booster is used to step up the DC voltage, rectified from the output of the energy harvester, while a storage circuit is employed to store the electrical energy generated for future use. During low generation, the stored energy can be used to accommodate the supply shortage from the main power supply. This energy harvester also promotes usage of green technology as an alternative to power up electrical appliances, with nearly zero pollution emissions.

2.2 Vibration-to-Electrical Energy Harvester

Energy from ambient mechanical vibrations can be harvested by means of a magnetic field, electric field or strain on a piezoelectric material. Vibration harvesting generators consist of a seismic mass whose motion is coupled to either to an electromagnetic, a piezoelectric or an electrostatic transducer [11]. In electrostatic transducer, a polarized variable capacitor is used by means of converting the mechanical energy into electrical energy. Here, electricity is being harnessed when the plates of the charged capacitor separate in response to externally applied vibration [12]. Figure 2 shows the general overview of an electrostatic vibration energy harvester.

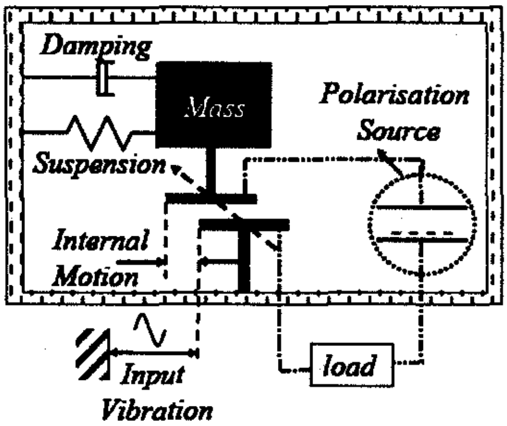


Figure 2: Schematic of an electrostatic harvester for vibration energy [12]

In contrast to electrostatic harvester, a piezoelectric energy harvester harness electrical energy when a mechanical stress is applied upon a piezoelectric material [13, 14]. When pressure is applied to an object (which has piezoelectric effect) a negative charge is produced on the expanded side and a positive charge on the compressed side. Once the pressure is removed, electrical current flows across the material. The piezoelectric effect is a reversible process [14, 15]; if a voltage applied to a strained piezo material, the shape of the solid will slightly change. Figure 3 shows a piezoelectric effect on piezoceramic.

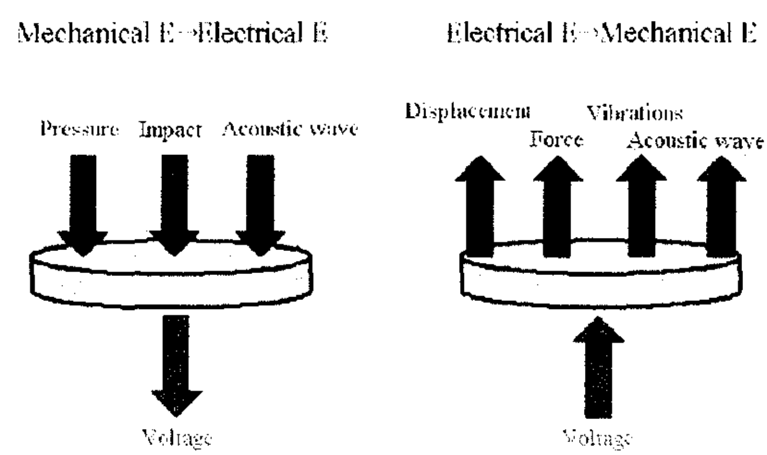


Figure 3: Reversible effect of piezoelectric [15]

Meanwhile, electromagnetic based energy harvester uses magnetic field to convert mechanical energy into electrical energy [7-10]. A coil attached to the oscillating mass traverses through a magnetic field that is established by a stationary magnet. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. Figure 4 shows an electromagnetic energy harvesting system consisting of a coil, permanent magnet and a spring.

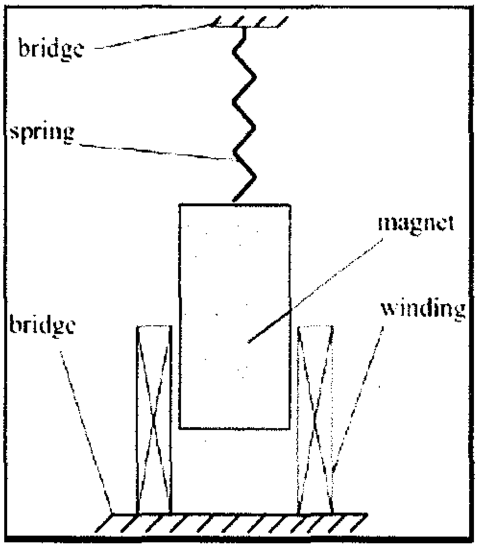


Figure 4: An electromagnetic energy harvester attached to a bridge [16]

After some evaluation, Electromagnetic is chosen as method of electrical energy generation due to the following advantages:

i. Since it is quite easy to keep a strong magnetic field with a permanent magnet and the system is quite robust, electromagnetic vibration-power generators are preferred in many applications.
ii. The system also required less maintenance and part replacement.
iii. Ease of fabrication and implementation compare to piezoelectric material and electrostatic transducer.

2.3 Concept of Operation of Electromagnetic Vibration Energy Harvester

2.3.1 Vibration Law

Vibration can be described by means of conservation of energy theory [17]. For example, consider the system in the Figure 5. When the spring is extended by a value of x, a potential energy $\left(\frac{1}{2}kx^2\right)$ is stored in the spring. Once the spring is stretched, it will try to return to its un-stretched state and in the process accelerate the mass. Once the spring has reached its un-stretched state all the potential energy that are supplied by stretching it has been transformed into kinetic energy $\left(\frac{1}{2}mv^2\right)$.

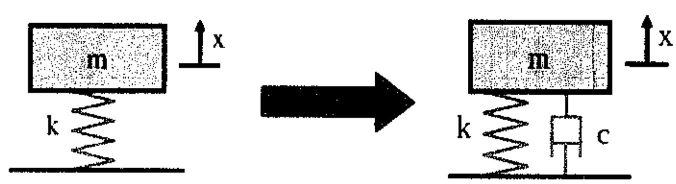


Figure 5: Mass-spring-damper models [17]

The mass will then begins to decelerate because it is now compressing the spring and in the process transferring the kinetic energy back to potential energy. In simple way, the oscillation of the spring is the act of transferring back and forth the kinetic energy and potential energy. Ideally, the system will continue to oscillate forever at the same magnitude, but in real system there is always damping element (denoted as "c") which functioned as energy absorber to dissipate the energy, thus bringing the system to rest.

This project also applies the same concept as mentioned above, where the base of the prototype will be exerted to external force (road vibration) to instigate the spring's oscillation that is attached to a mass. This device will be put under forced harmonic excitation and the response of the system is called harmonic response [18]. The designed system is assumed to be damped system under harmonic motion at the base.

Consider the system shown in Figure 6, a system where its base is subjected to harmonic force having atmospheric air as a damping element, where $y(t)$ denotes the displacement of the base and $x(t)$ is the displacement of the mass from its static equilibrium position at time t.

Figure 6: Simplified prototype spring-mass-damper model [17]

The equation of motion of such system are given as follow [18]

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \tag{1}$$

If $y(t) = Y \sin \omega t$, the above equation becomes

$$\begin{aligned} m\ddot{x} + c\dot{x} + kx = c\dot{y} + ky &= kY \sin \omega t + c\omega Y \cos \omega t \\ &= A \sin (\omega t - a) \end{aligned} \tag{2}$$

where $A = Y\sqrt{k^2 + (c\omega)^2}$ and $a = \tan^{-1}(-\ {}^{c\omega}/_{k})$. This shows that giving excitation to the base is equivalent to applying a harmonic force of magnitude A to the mass. By using solution of Eq. (3), the steady-state response of the mass $x_p(t)$, can be expressed as in Eq. (4)

$$x_p(t) = \frac{F_0}{\left[(k - m\omega^2)^2 + c\omega^2\right]^{\frac{1}{2}}} \sin(\omega t - \Phi)$$

$$= Im\left[\frac{F_0}{k}|H(i\omega)|e^{i(\omega t - \Phi)}\right] \quad (3)$$

$$x_p(t) = \frac{Y\sqrt{k^2 + (c\omega)^2}}{[(k - m\omega^2)^2 + c\omega^2]^{1/2}} \sin(\omega t - \Phi_1 - a) \quad (4)$$

$$\Phi_1 = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right)$$

where $\omega_n = \sqrt{\frac{k}{m}}$, is the natural frequency of the system and ω is the frequency of the excitation signal. Using trigonometric identities, Eq. (4) can be rewritten as

$$x_p(t) = X\sin(\omega t - \Phi) \quad (5)$$

where X and Φ is given by

$$\frac{X}{Y} = \left[\frac{k^2 + (c\omega)^2}{(k - m\omega^2)^2 + (c\omega)^2}\right]^{\frac{1}{2}} = \left[\frac{1 + (2\xi r)^2}{(1 - r^2)^2 + (2\xi r)^2}\right]^{\frac{1}{2}} \quad (6)$$

$$\Phi = \tan^{-1}\left[\frac{mc\omega^3}{k(k - m\omega)^2 + \omega c^2}\right] = \tan^{-1}\left[\frac{2\xi r^3}{1 + (4\xi^2 - 1)r^2}\right] \quad (7)$$

The frequency ratio $r = \omega/\omega_n$, must be kept to within $0 < \omega/\omega_n < 1$, to avoid having the response of the system deviate 180° (when $\omega/\omega_n > 1$) from the normal condition.

2.3.2 Electromagnetic Induction Law

A current carrying conductor produces a magnetic field around them and the reverse is also true. A changing magnetic field can also induce a current in a conductor and the current is called an induced current because it comes about by the changing magnetic field. This phenomenon is illustrated in Figure 7 and Figure 8, where a magnet is held near a coil of wire, but nothing happens. But, once the magnet is moved back and forth respectively of the coil, a voltage and a current is induced [19].

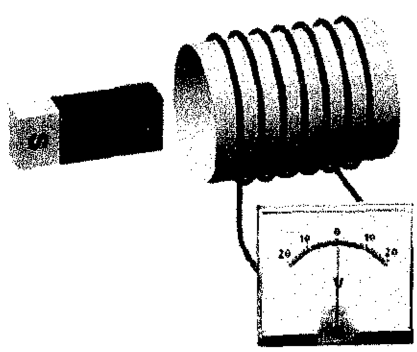


Figure 7: A magnets is held near a coil of wire [19]

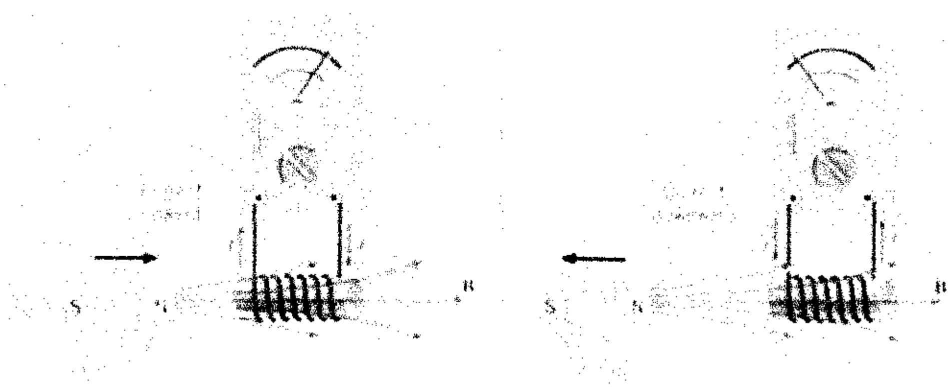


Figure 8: Magnet is moved back and forth [19]

When the magnet is moved towards the coil, the magnetic field through the coil increased, thus inducing a current. When it is moved away, the field decreases, creating a current, but in the opposite direction. Since a source of EMF (voltage) is needed to produce a current (Ohm's Law: V = IR), the moving magnet acts like a source of EMF. In other word, the moving magnet induces an EMF in the coil, which in turn produces an induced current. Another way to describe this induced EMF is in terms of something called magnetic flux. Magnetic flux is a measure of the quantity of magnetism and it deals with the magnetic field and the surface area through which it passes. Magnetic flux, Φ_B, is given as follow [20]

$$\Phi_B = \vec{B}.\vec{A} = (B)(A_{perp}) \qquad (8)$$

The flux only depends on the portion of the magnetic field that is perpendicular to the area in which it passes through. So, when the magnetic field direction is not perpendicular to the area, the equation for flux becomes

$$\Phi_B = BA\cos\theta \qquad (9)$$

The resulting induced EMF, ε, is given as the ratio of change in magnetic flux with respect to the changes of time multiplied by N (number of conductor)

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} = NBlv \qquad (10)$$

where

N = Number of conductor

B = Strength of magnetic field

l = Length of conductor

v = Velocity

Figure 9 shows a simplified drawing of the designed prototype of this project. Here the mass, which is a permanent magnet, is attached to a spring and made to oscillate under external vibration source. The changes of magnetic flux while the mass oscillates will induced an EMF at the end of the coil [19, 20].

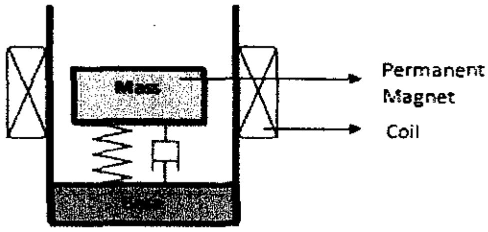


Figure 9: Simplified prototype design

2.4 Existing Electromagnetic Energy Harvester Design

Before proceeding with the construction and fabrication of the real prototype, a lot of studies must be done to investigate the existing design of electromagnetic energy harvester to get a rough idea about the system design. Among the existing design found during the researches are shown in Figure 10, 11 and 12.

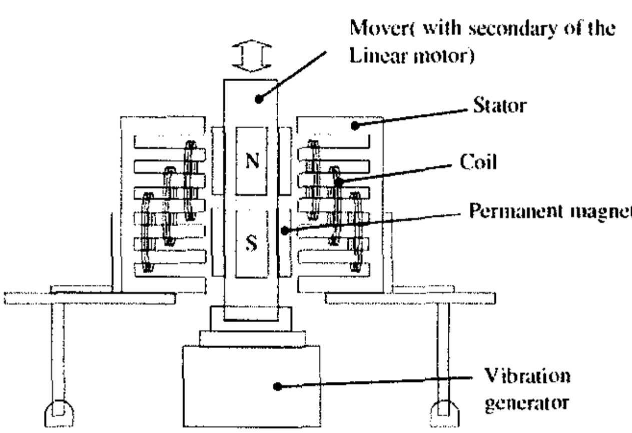


Figure 10: Linear generator tested using vibration generator [7]

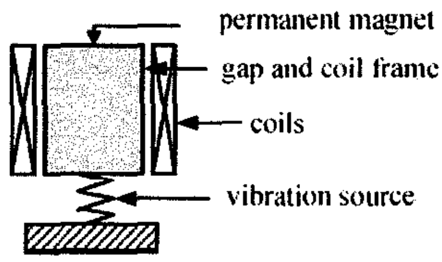


Figure 11: Basic construction of vibration driven energy harvester [8]

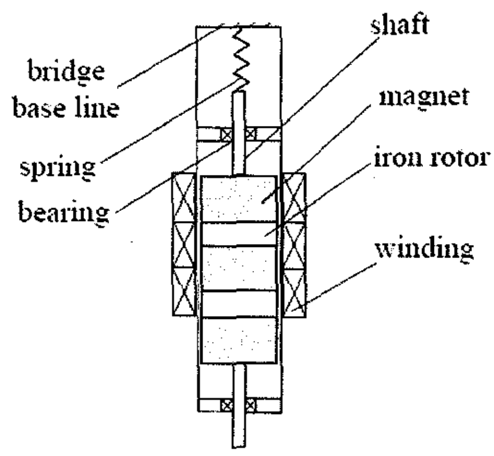


Figure 12: A linear generators with iron-permanent magnet rotor [9]

CHAPTER 3

METHODOLOGY

3.1 Flow Chart

Figure 13 shows a flow chart consisting of the planned process workflow for this project.

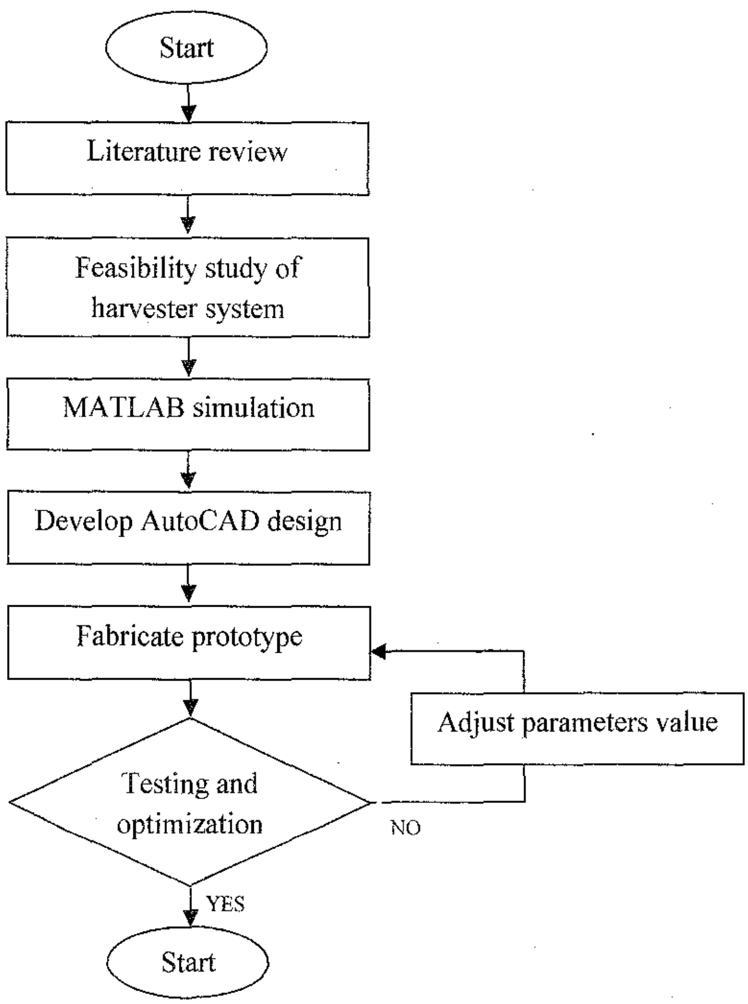


Figure 13: Process of designing and fabricating a vibration driven energy harvester

3.2 Project Workflow

To have a desired prototype with a high performance rate, the process of designing and fabricating the prototype must be done precisely. The basic steps and procedures involved in this project are specified in a chart in Appendix A. The relevant steps for this project are as follow:

i. Identify need

To come up with a design and a prototype that can harvest the vibration energy produced by the running vehicles on the roads which can be used to power up electrical appliances.

ii. Define problem

The increase number of vehicle on the road and the rough surface of the road itself have generated abundant vibration energy. Although, vibration energy seems very annoying for causing all sort of noise and damage, but due to our daily activities it will still exists. This project brings about an innovation to exploit the vibration energy by converting it into useful electrical energy.

iii. Research

A lot of researches are conducted by surfing the internet, journals, conference papers and science webpage about the concept of electricity generation from mechanical vibration. The mechanism used to covert vibration energy to electrical energy need to be studied.

iv. Set constraint

The target of this project is to complete the fabrication and testing of the prototype within the time given. The budget allocated for a project is RM500 and this should be enough to cover all the expenses for this project.

v. Set criteria

Among the criteria set for this project include, cost effective, efficient and reliable, practical and safe for usage.

vi. Analysis

All pros and cons of the proposed ideas are considered. The performance of the prototype must be monitored to inspect for any error and to monitor the product performance. Alternative ideas are considered as back-up plans if problems would arise unexpectedly in the future.

vii. Decision

A final decision is made by choosing the most practical design considering the objective and other constraint that has been set to ensure the project can be realized.

viii. Specification

The specification of the design must be set beforehand as it represent the desired outcome expected from the project. Among the specification of this project includes:

Design → Reliable

Quality →Prototype performance in term of output generated

Material → Affordable

Performance → Efficiency of the prototype

3.3 Prototype Design

Prior to fabrication of the prototype, AutoCAD, engineering software is used to design the structure of the device base on the concept and idea that have been identified earlier. The top view, side view and overall view of the prototype's drawing is shown in Figure 14.

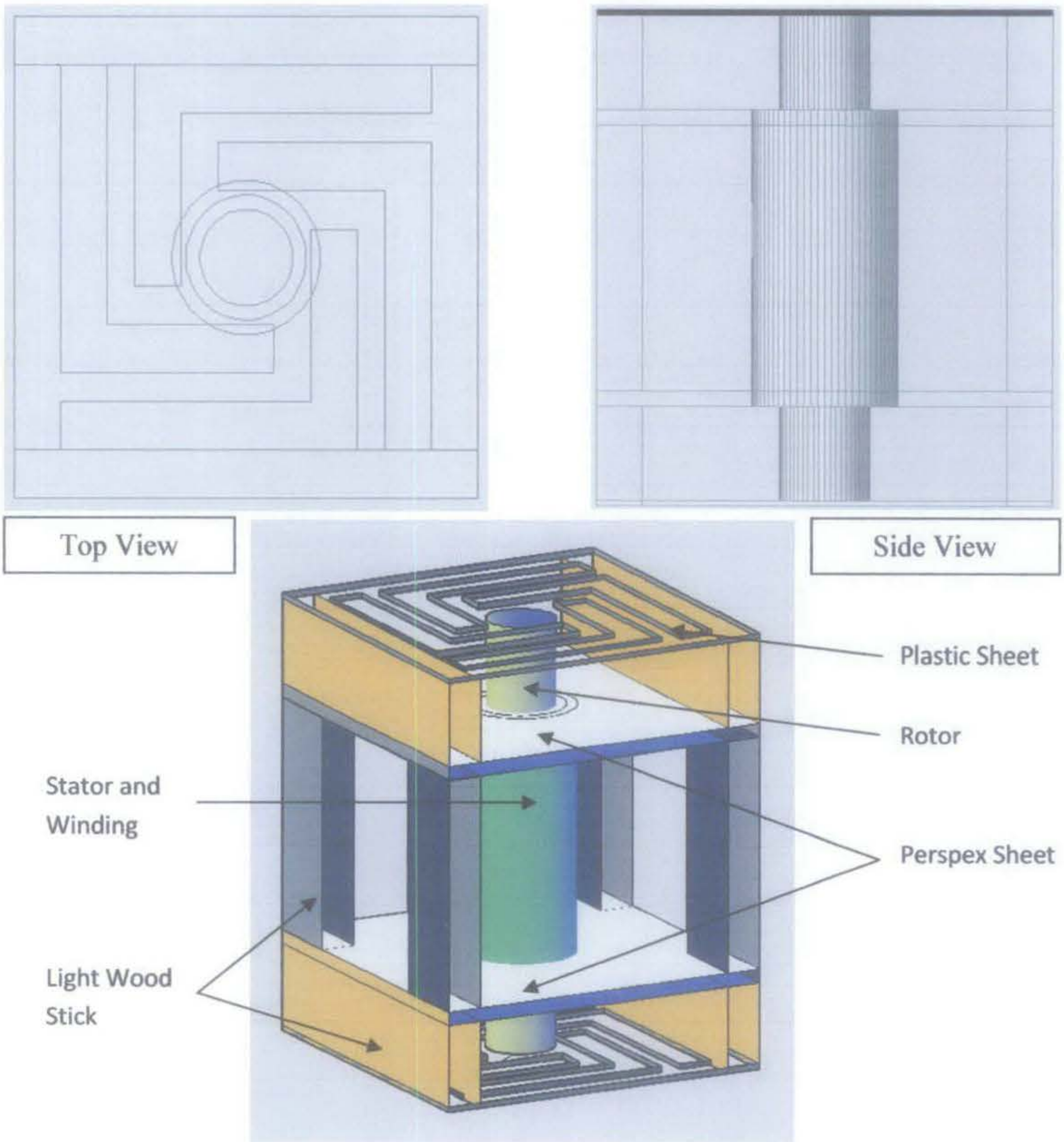


Figure 14: AutoCAD drawing of the proposed prototype

Similar to the other generator, this Vibration Energy Harvester System (VEHS), consist of three main parts namely stator, rotor and body. The prototype use some simple material including Polyvinyl Chloride (PVC) pipe, light wood stick, aluminium rod, perspex sheet, neodymium magnet and Polypropylene (PP) food container. The main parts of this prototype will be further explained in the following section.

i. **Rotor**

Rotor is the moving part of the device and it comprise of five Neodymium cylindrical magnets, each heights about 0.5 cm with a diameter of 1.0 cm. The magnet has a remanence of 1.2 T and weighs 2.86 g each. The magnet is stacked together and at each ends of the stack, 1.7 cm long aluminium rod having similar diameter with the magnet is attached. Aluminium rod and cylindrical magnet made a 6.2 cm long and 21 g rotor for this prototype. Figure 15 shows the magnets and aluminium rod used in this project.

Figure 15: Magnets and aluminium rod for the rotor

Then, the rotor is connected to a centre of a plastic sheet at both ends. Polypropylene (PP) food container's cap is used to produced 0.7 mm thick, 5.0 cm wide and 5.0 cm long crab-legs designed plastic sheet. The plastic sheet is designed and cut in such a way to allow it to oscillate up and down when an appropriate mass is applied to it. Here, the plastic sheet is used to provide support and help the rotor to oscillate as well as to replace the use of traditional mechanical spring. The design of the plastic sheet can be seen in Figure 16.

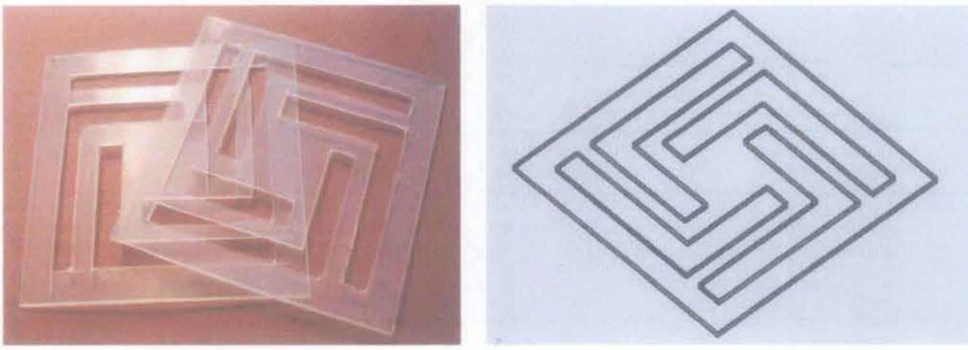


Figure 16: Plastic sheet

The mass ratio mass ratio between aluminium rod and magnet plays an important role in producing optimum oscillation. Since the aluminium is light, more magnets can be used in the rotor to produce more magnetic fields.

ii. Stator

Stator is the stationary part of the generator. Here, the stator consists of 3.4 cm long Polyvinyl Chloride (PVC) pipe and winding. PVC is chosen as the stator since ferromagnetic material like steel will attract the rotor. The rotor is made of magnets and aluminium rod, thus ferromagnetic material is not suitable to be used as the stator since it will attract the rotor and hinder the rotor oscillation. As for the winding, enamelled copper wire with a diameter of 0.10 mm is used to make the coils. The higher number of the turns in the winding, the more magnetic fields it can capture. The following Figure 17 shows the stator with winding around it.

Figure 17: Stator and winding

With the inner diameter of the pipe being 1.3 cm and the rotor diameter is 1.0 cm; this creates a 0.15 cm air gap between stator and rotor. The gap allows the rotor to move freely within its range of movement and helps avoid the rotor from hitting the inside wall of the stator.

iii. Body

The body of the prototype is comprised of wooden stick and two 5.0 cm × 5.0 cm perspex sheet with a 1.65 cm hole at the centre as shown in Figure 18. The body made the outer part of the device which is used to hold the stator and rotor. It also acts as a transmission medium for the vibration from the road to the plastic sheet which will instigate the rotor movement. Wooden stick is primarily used in this project due to its light weight and soft nature that enable it to absorb vibration more efficiently thus making the rotor easier to oscillate if external force is applied to the structure. Moreover, heavier material will increase the overall mass of the device that will reduce it capability to vibrate properly. Figure 19 shows how the structure looks like when the stator is added to the body while Figure 20 shows the top view of the structure when the plastic sheet is attached to the prototype.

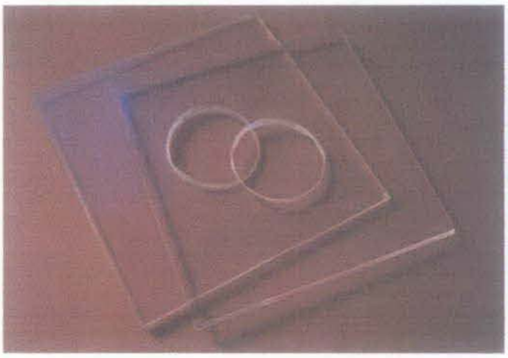


Figure 18: Perspex sheet

Figure 19: Stator and winding attached to the perspex sheet

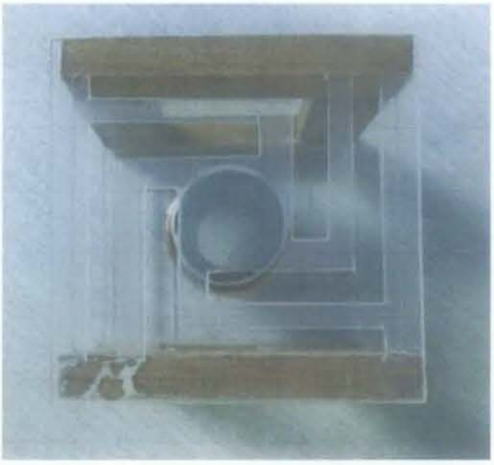


Figure 20: Top view of prototype with plastic sheet attached

Figure 21 shows the completed prototype with the additional of four 2.0 cm long wooden stick used as the legs that is connected to the aluminium base to create a space for the rotor to oscillate. The overall height of the prototype is 8.5 cm and weighs around 60 g.

Figure 21: Completed prototype

iv. Other

Additionally, Energy Harvesting 300 (EH300) module as shown in Figure 22 is used to produce stable DC output. Since the output from the device is a varying sinusoidal AC signal which entirely depend on the amount of vibration on the road, a rectifier is used to convert the AC signal into DC output. EH300 module is also equipped with an Ultra-capacitor which can store up to 3.6 V. The DC output is stored in the Ultra-capacitor for later use and during low power generation.

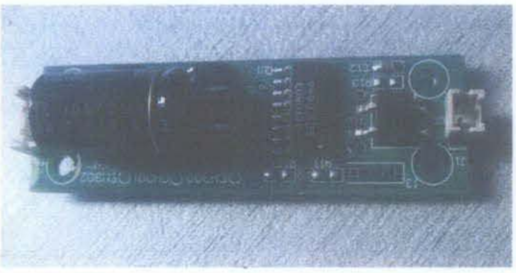


Figure 22: Energy Harvesting 300 (EH300) module

3.4 Prototype Testing

After the fabrication of the prototype is completed, the device is tested to observe its performance. The test is done in laboratory using vibration generator to simulate the vibration that existed on the road due to traffic. The prototype is bolted to the vibration generator and the test condition is defined from the PC through the vibration generator interface. After that a signal is send to the vibration controller unit to produce the predefined signal according to the setup from the PC. The controller is also responsible for test control and data acquisition. Next, the control signal from controller will go to the amplifier before the signal is further forwarded to the vibration generator. The vibration generator will produce a vibration according to the test condition defined earlier. Digital oscilloscope is also use to monitor the test results. The process is repeated until a appropriate results are obtained. The setup for the testing equipment is illustrated in Figure 23.

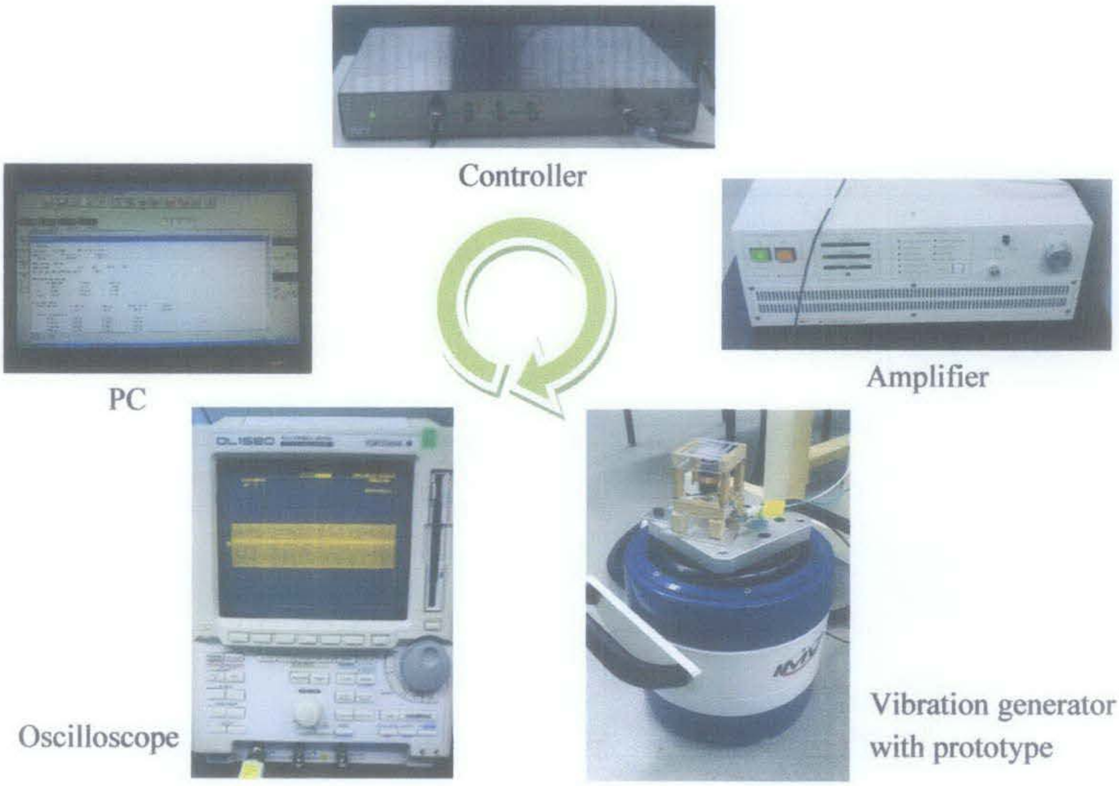
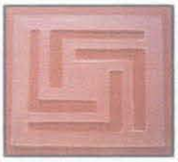


Figure 23: Testing equipment setup

3.5 List of Materials

Based on the design of the prototype, the list of materials used for this project is stated below in Table 1:

Table 1: List of materials

Material	Picture	Description
1.2 T Neodymium Permanent Magnet		Neodymium is a strong permanent magnet with its remanence (magnetic field strength) range between 1.0 – 1.3 Tesla. Higher magnetic field will produce higher EMF.
Enamel Coated Copper Coil		Coated-copper coil act as a conductor to cut the magnetic field produce by permanent magnet. 0.1mm diameter of copper wire is chosen to have more number of turns of coil.
5 cm × 5 cm Plastic Membrane		Plastic membrane is used as a medium to transfer the vibration given at the base to the mass. Stiffness of the membrane plays an important role in producing maximum displacement of the mass.
1 cm Diameter Aluminium Rod		Aluminium shaft is used to support the mass while it transverse due to the vibration at the base. The shaft mass contributes to the overall mass which is critical for the device performance.
5 cm × 5 cm Perspex Sheet		Perspex sheet is used to hold the stator. This light material is suitable to be used due to its durability in harsh environment.
Light Wooden Stick		1.2 cm × 0.5 cm wooden stick is used to support the overall structure of the prototype. Light material helps the prototype to vibrate easily.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Simulation Results

In order to design a working prototype of electromagnetic energy harvester, a simulation is done to investigate the characteristics of the parameters involve with the performance of the device. Before proceeding with the simulation certain parameters value are presumed and later updated accordingly for optimum power generation. The presumed parameters value for this simulation is stated in Table 2.

Table 2: Presumed parameters value for simulation

Parameters		Value
m	Mass of rotor	0.020 kg
k	Plastic sheet stiffness	315.8273 N/m
c	Damping element	0.01593
$f_n(\omega_n)$	Natural frequency in Hz (rad/s)	20 Hz (125.6637 rad/s)
N	Number of turns of coil	2000
B	Magnet remanence	1.2 T
l	Length of conductor	0.015 m

The simulation is done in MATLAB M-file script by using the relationship between each parameter stated in the above table as well as the equation covered in previous section. Figure 24 and Figure 25 shows the excitation signal from traffic vibration on the road which is exerted to the base of the prototype and the corresponding displacement of the rotor. In this simulation, the excitation signal frequency is put to be the same as the resonance frequency, at 20 Hz (125.6637 rad/s).

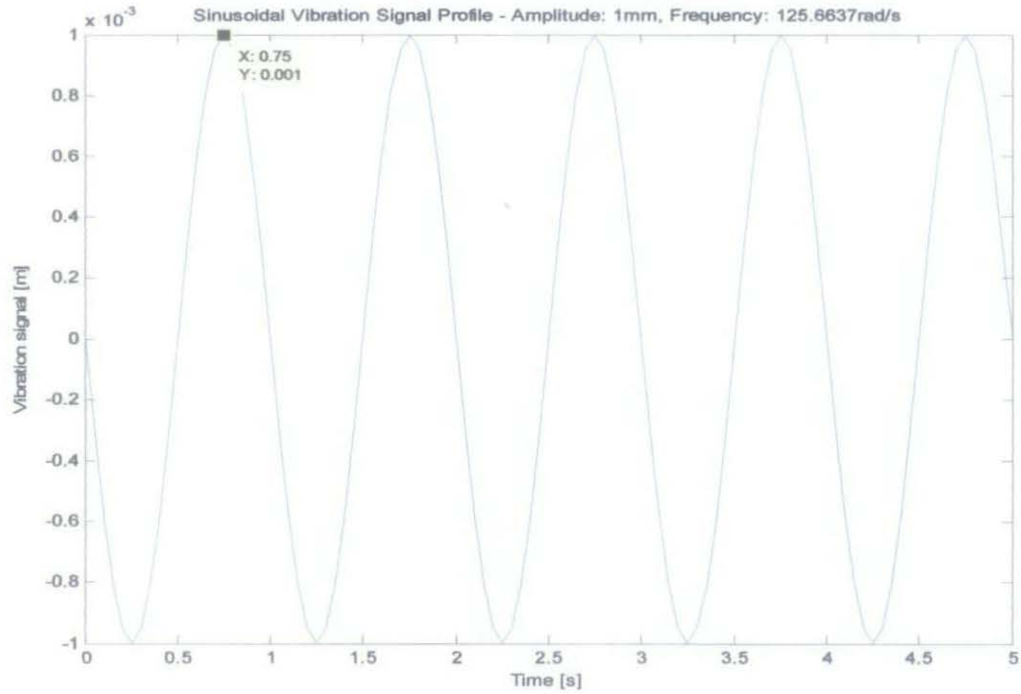


Figure 24: Excitation signal

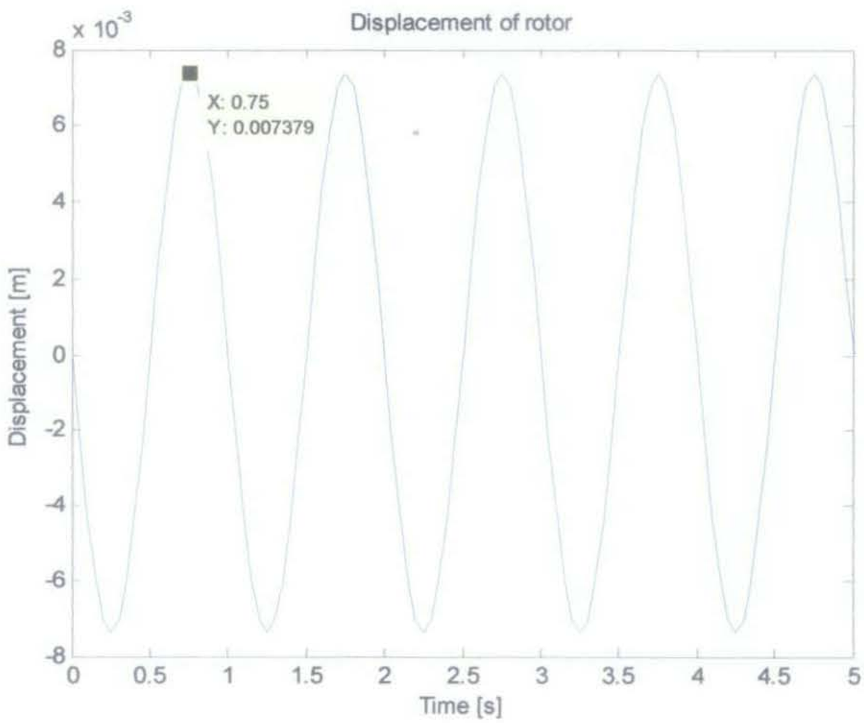


Figure 25: Displacement of the rotor

From the above graphs, it is observed that the amplitude of the rotor displacement is about seven times of the amplitude of the excitation signal. The relationship between the amplitude of the excitation signal and the displacement of rotor is given as follow:

$$\frac{X}{Y} = \left[\frac{1 + (2\xi r)^2}{(1 - r^2)^2 + (2\xi r)^2}\right]^{\frac{1}{2}} \tag{11}$$

From Eq. (11), the displacement transmissibility, T_d or the ratio between the amplitude of the rotor displacement over the amplitude of the excitation signal greatly depend upon the value of damping ratio, ξ and frequency ratio, r. For constant value of excitation signal amplitude, Y, the mass displacement, X, will decrease if the damping ratio increases. The motion of the mass is restricted with more damping element in the system. Since the frequency ratio is given as $r = \omega/\omega_n$, its value depends on the ratio of the excitation frequency, ω and the natural frequency, ω_n of the device. Increasing the frequency ratio by increasing the excitation signal frequency, while keeping the damping ratio constant, will increase the displacement transmissibility. However, that is only true when the value of $r \leq 1$, when the excitation signal frequency is less or equal to the natural frequency.

When the excitation signal frequency is increased exceeding the value of the natural frequency, the response of the system will deviate 180°. The value of the displacement transmissibility will decrease with increasing value of frequency ratio. The amplitude of the rotor's displacement is optimum when the excitation signal frequency equals to the natural frequency of the device. Thus, it is crucial to keep the frequency ratio below or equal to one. Next, the velocity of the rotor and the initial estimated induced EMF produced by the system using the initial presumed parameters value is illustrated in Figure 26 and Figure 27 respectively. For this simulation, the recorded value of rotor's velocity is 0.0947 m/s while the estimated peak-to-peak voltage produced is about 6.818 V.

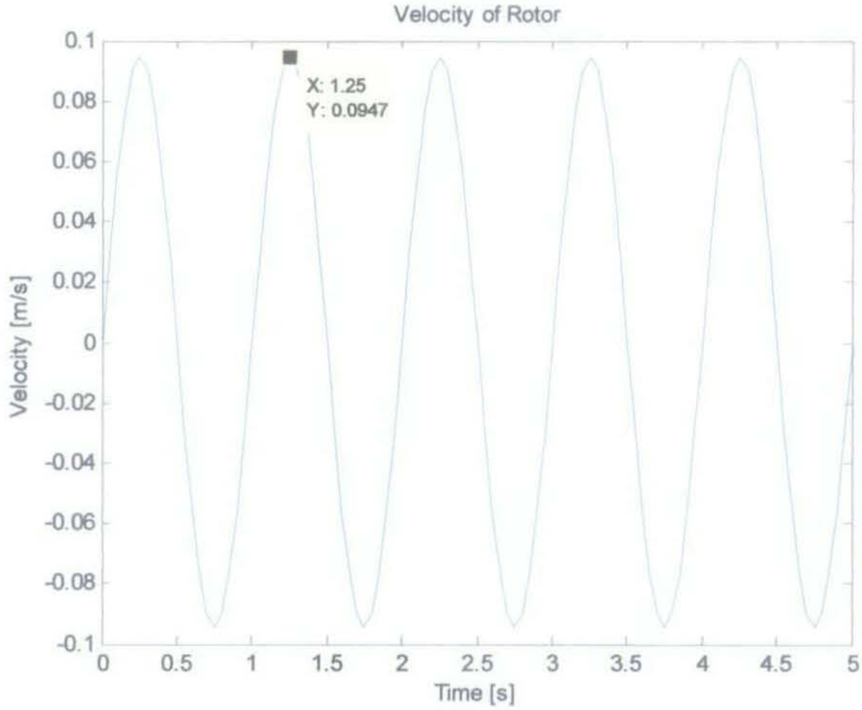


Figure 26: Velocity of the rotor

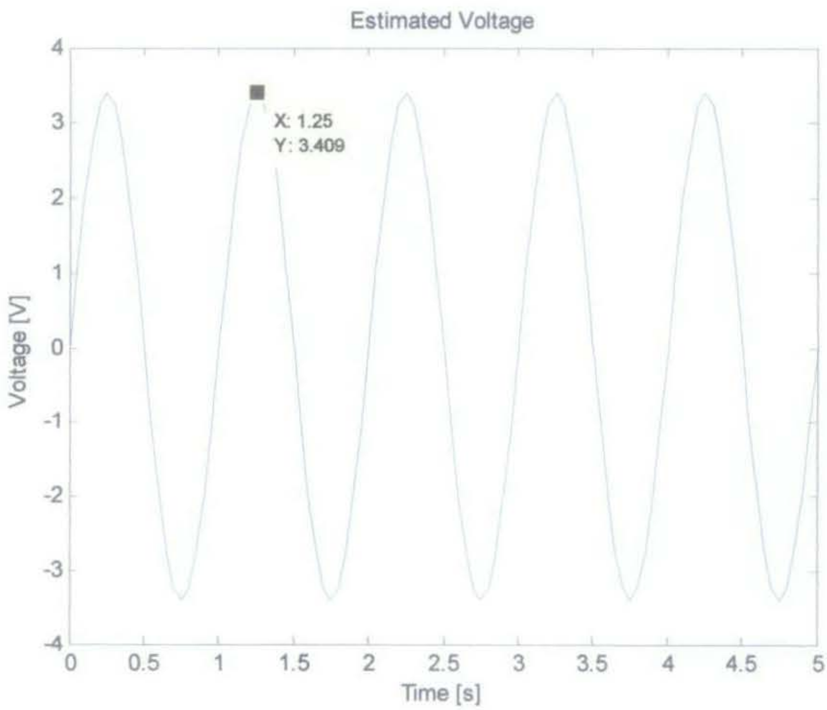


Figure 27: Estimated EMF induced

The velocity of the mass and the value of induced EMF depend upon the value of damping element, plastic sheet stiffness and mass of the rotor. Damping element put restriction on the movement of the rotor. If the value of stiffness and mass are kept constant, with the increasing value of the damping element, the velocity and the estimated induced voltage will be reduced. Here, the damping element, c, is assume to be constant at 0.01593 while other parameters, stiffness, k, and mass of rotor, m, are varied. The relationship between plastic sheet stiffness and mass of rotor with value of peak-to-peak EMF is shown in Figure 28 and Figure 29.

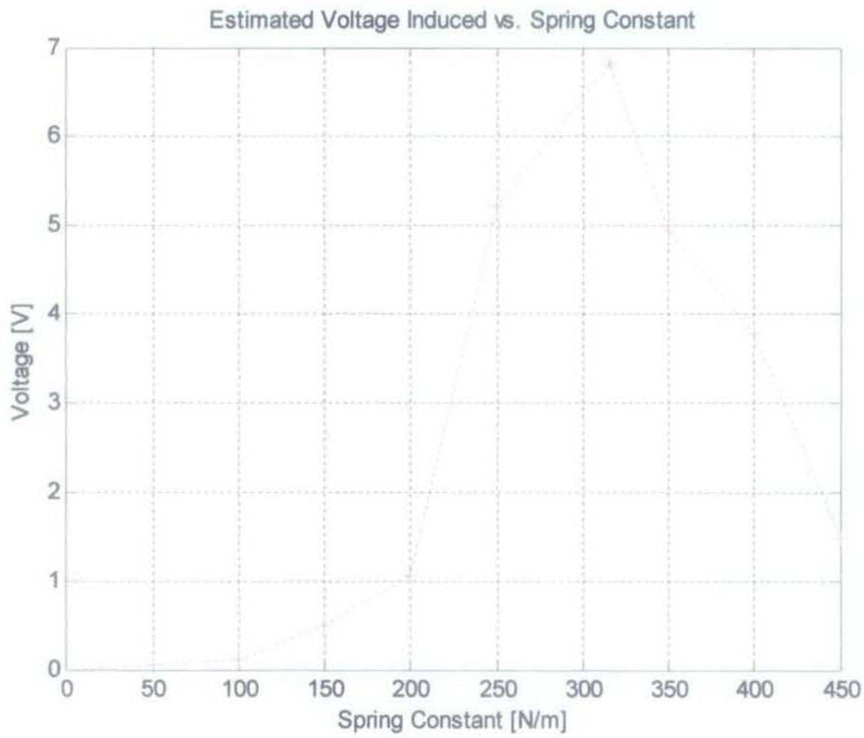


Figure 28: Effect of plastic sheet stiffness to estimated EMF value

The value of damping element and mass of the rotor are kept constant. Notice that, when the plastic sheet stiffness increases, the value of the generated EMF will also increase but only up to a certain point. When the spring constant is continued to be increased, the value of the generated EMF reduces. Maximum estimated EMF is 6.818 V with stiffness of the plastic sheet being 315.8273 N/m.

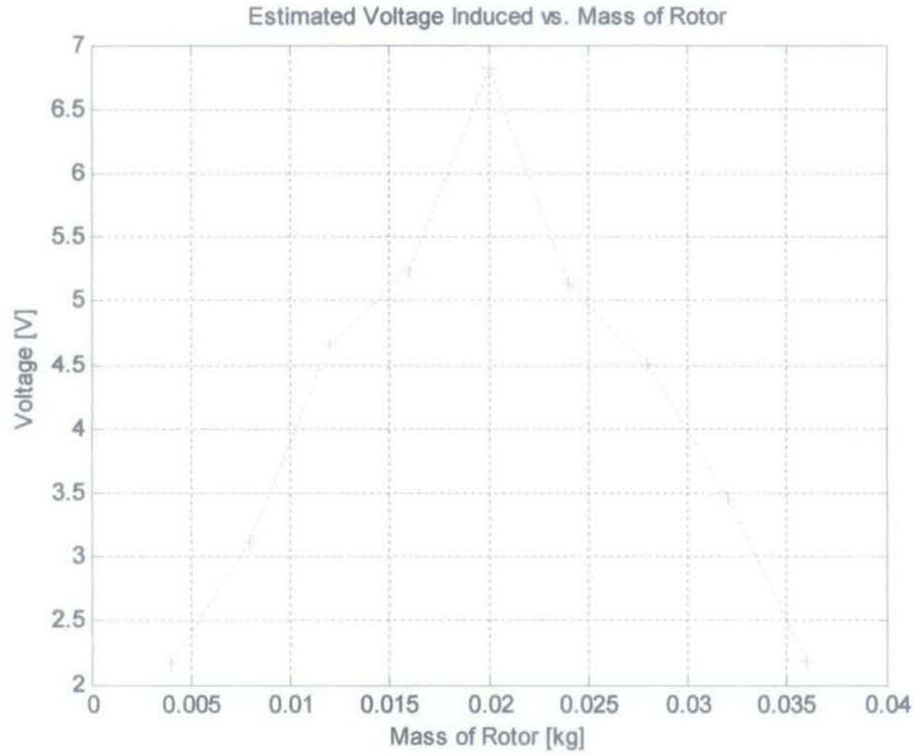


Figure 29: Effect of mass of rotor to estimated EMF value

After that, the value of damping element and plastic sheet stiffness is kept constant and the value of mass is varied to investigate its effect on generated EMF value. Clearly, as shown in Figure 29, when the value of the mass is increased, the amount of the generated EMF will also increase accordingly. Maximum EMF is produced when the mass is 0.02 kg. However, similar to the case in Figure 28, the value of the EMF will start to decrease when the mass of the rotor reached a certain point. The relationship between mass, m, plastic sheet stiffness, k and damping element, c with natural frequency, ω_n and damping ratio, ξ is given as follow:

$$\omega_n = \sqrt{\frac{k}{m}} \quad or \quad f_n = 2\pi\sqrt{\frac{k}{m}} \tag{12}$$

$$c = 2\xi m\omega_n \tag{13}$$

Referring to Figure 28 and Eq. 12, the response of the system can be divided into two parts. Firstly, the mass and excitation signal frequency is kept constant at 0.02 kg and 20 Hz (125.6637 rad/s). At stiffness value lower than 315.8273 N/m, the frequency ratio is actually exceeding one. So, with increasing value of plastic sheet stiffness, the value of the natural frequency increase, the frequency ratio decreases (but still exceed one) while the displacement transmissibility increases. The estimated EMF also increases. When the stiffness is further increased beyond 315.8273 N/m, the response of the system backs to normal since the frequency ratio is now less than one. Increasing value of stiffness will increase the natural frequency and decrease the frequency ratio and the displacement transmissibility. The estimated EMF also will decrease.

Similarly, using Eq. 12, the response of the system can also be divided into two parts for Figure 29. Now, the value of plastic sheet stiffness is kept constant at 315.8273 N/m together with the excitation signal frequency. When the mass is increased until 0.02 kg, the value of the natural frequency decreased, value of frequency ratio and displacement transmissibility increased. The estimated EMF also increased. Since the frequency ratio is lower than one at value of mass lower than 0.02 kg, the system response is normal. In contrast, when the mass is further increased, value of natural frequency drop below excitation signal frequency, making the frequency ratio exceed one. The displacement transmissibility of the system decreases together with the estimated EMF value.

Higher value of damping element and spring stiffness will make it harder for the mass to transverse through the magnetic field. Mass will have less freedom to move and this will decrease the amplitude of displacement of the mass. The resulting velocity of the mass and estimated EMF at the end of the coils will be reduced. In order to have an optimum performance of the system, those three factors must be kept balance. In addition to that, the response of the system must always be kept at normal condition by ensuring that the natural frequency value always bigger or equal to the excitation signal frequency.

Figure 30 shows the relationship between the frequency of excitation signal and the estimated peak-to-peak EMF. Increasing the value of the excitation signal frequency will increase the frequency ratio and displacement transmissibility. Subsequently, the value of the estimated EMF will also increase. This case will stay true if the value of the excitation signal frequency is lower or equal to the natural frequency of the device. The natural frequency is now set to be 20 Hz (125.6637 rad/s) by keeping the stiffness value of the plastic sheet and mass of the rotor constant at 315.8273 N/m and 0.02 kg respectively. Thus, for excitation signal frequency lower or equal to 20 Hz, the response of the system will be normal.

However, when the frequency of the excitation signal is increased higher than 20 Hz, the response of the system will diverge 180° from the normal condition. With increasing value excitation signal frequency, the frequency ratio increases but displacement transmissibility decreases. The estimated EMF produced also will decrease. The excitation signal frequency must be kept below or equal to 20 Hz to keep the response of the system in normal condition.

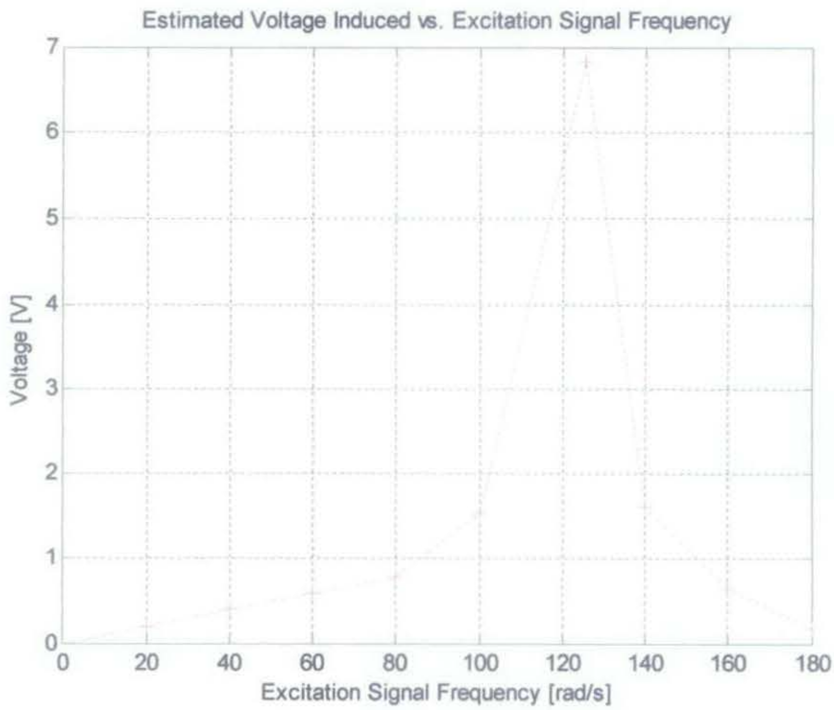


Figure 30: Effect of excitation signal frequency to estimated EMF value

The amount of generated EMF also depends on the number of turns of the coil. Figure 31 shows the effect of varying number of turns of the coil to the EMF value. Obviously, the value of the estimated EMF is directly proportional with the number of turns of the coil. Higher output will be achieved with higher number of turns.

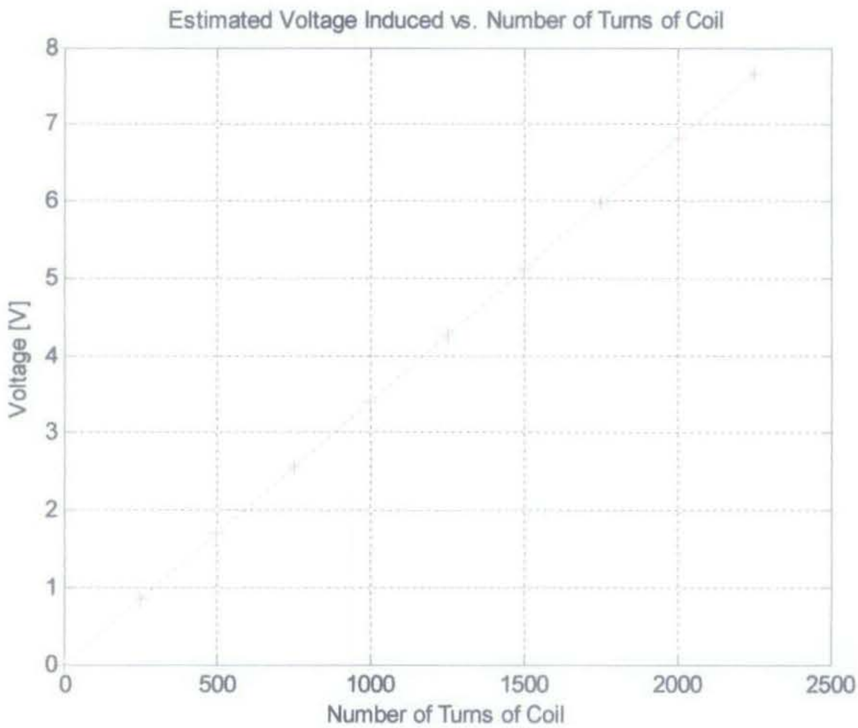


Figure 31: Effect of number of turns of the coil to estimated EMF value

4.2 Testing Results

After the prototype's fabrication is completed, a series of test is conducted to observe the performance of the device. The following Table 3 shows the parameters value involved with the prototype testing.

Table 3: Parameters value for prototype testing

Parameters		**Value**
m	Mass of rotor	0.02104 kg
k	Plastic sheet stiffness	338.9284 N/m
c	Damping element	0.01766
$f_n(\omega_n)$	Natural frequency in Hz (rad/s)	20.2 Hz (126.9203 rad/s)
N	Number of turns of coil	2000
B	Magnet remanence	1.2 T
l	Length of conductor	0.016 m

Comparing the real parameters value with the presumed value used in the simulation, there are some deviations. For example, the value of mass of rotor, plastic sheet stiffness and damping element are all slightly higher during the real testing compared to the simulation. Thus, the resulting natural frequency of the device is also different. This can be traced back to the point where the prototype was still in fabrication stage. The presumed values in simulation are ideal value chosen in order to produce maximum output. However in real implementation, those conditions are sometimes hard to fulfill due to several reason. Nevertheless, the real parameters values are kept as closely as possible to the simulation value to produce the highest output possible. The following Figure 32 and Figure 33 show the displacement and velocity of the rotor using the parameters in Table 3.

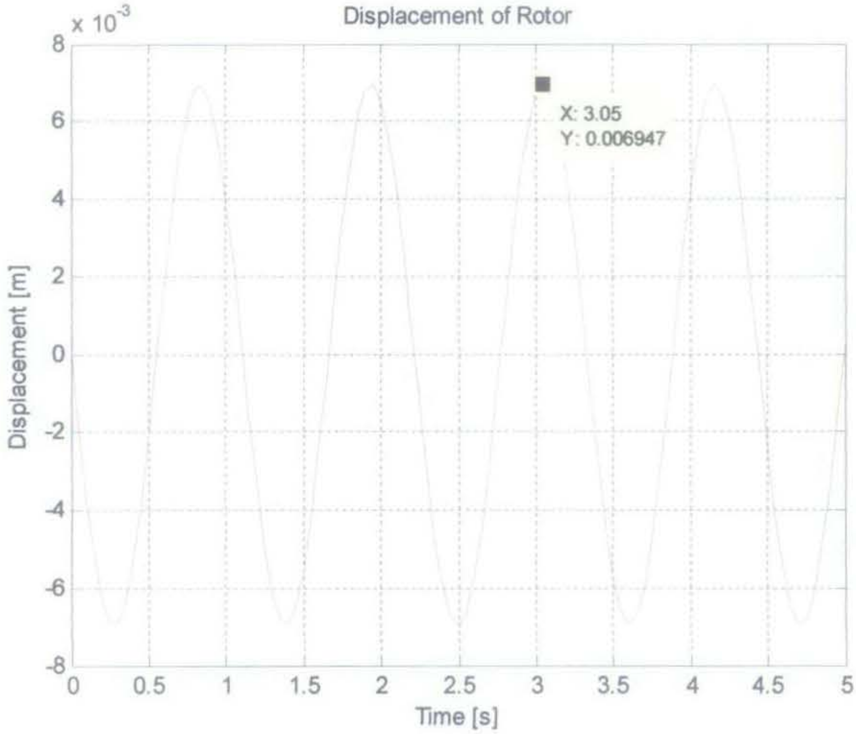


Figure 32: Displacement of the rotor

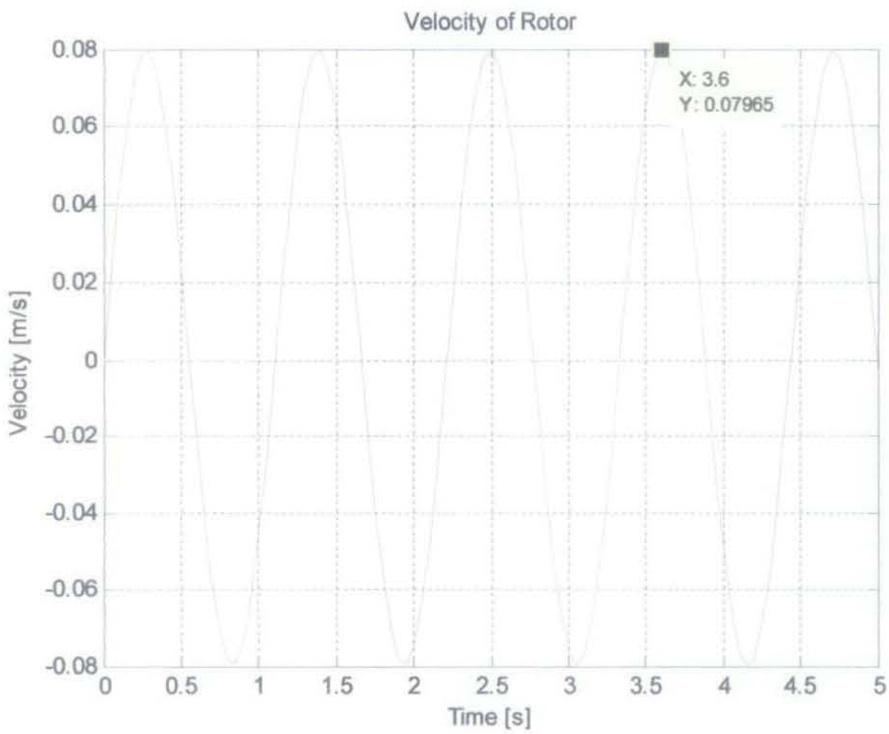


Figure 33: Velocity of the rotor

By using similar excitation signal profile as in simulation, the results for both simulation and testing are compared with each other. The test condition is predefined in the PC in order for the vibration generator to produce the vibration signal. Since the maximum output is produced when the applied excitation signal's frequency equals to the natural frequency of the device, the test is conducted at resonance frequency. The amplitude and the frequency of the excitation signal are set to 0.001 m and 20 Hz (125.6637 rad/s) and the acceleration of the excitation signal is set to 9.8 m/s^2.

However, when the test is conducted, the maximum output is obtained when the frequency of the excitation signal at 20.2 Hz (126.9203 rad/s). This indicates that the natural frequency of the device has slightly increased, from 20 Hz to 20.2 Hz, due to the value of the plastic sheet stiffness and mass of the rotor. The following Figure 34 shows the increment in the prototype natural frequency. The maximum peak-to-peak voltage produced is 5.734 V at 20.2 Hz.

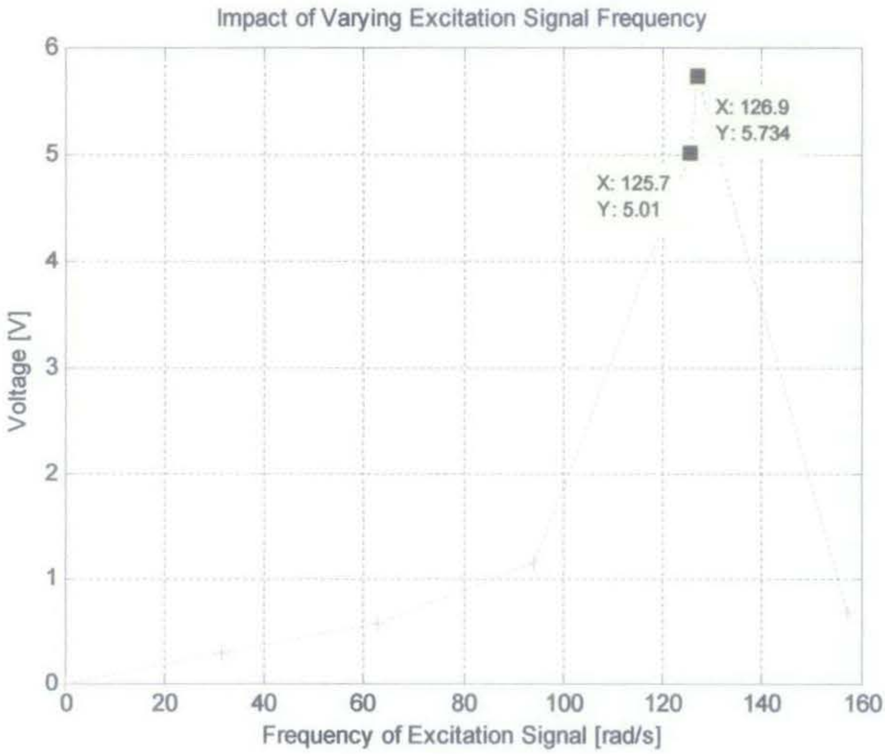


Figure 34: Increment in prototype natural frequency

The excitation signal frequency is slowly increased from 0 Hz until 25 Hz (157.0796 rad/s) to see the output produced at different frequency. From Figure 34, noticed that, the value of the peak-to-peak voltage keeps increasing with increasing value of the excitation signal frequency until the frequency reaches 20.2 Hz. After that point, the value of peak-to-peak voltage continues to drop since the excitation signal frequency exceeds the natural frequency of the device. Although the frequency ratio increases, the displacement transmissibility will decrease since the response of the system already diverge 180° from the normal condition.

The response of the system in terms of the EMF produced when driven at resonance frequency is shown in Figure 35. Meanwhile, Table 4 shows the difference between the results obtained in the simulation and during testing.

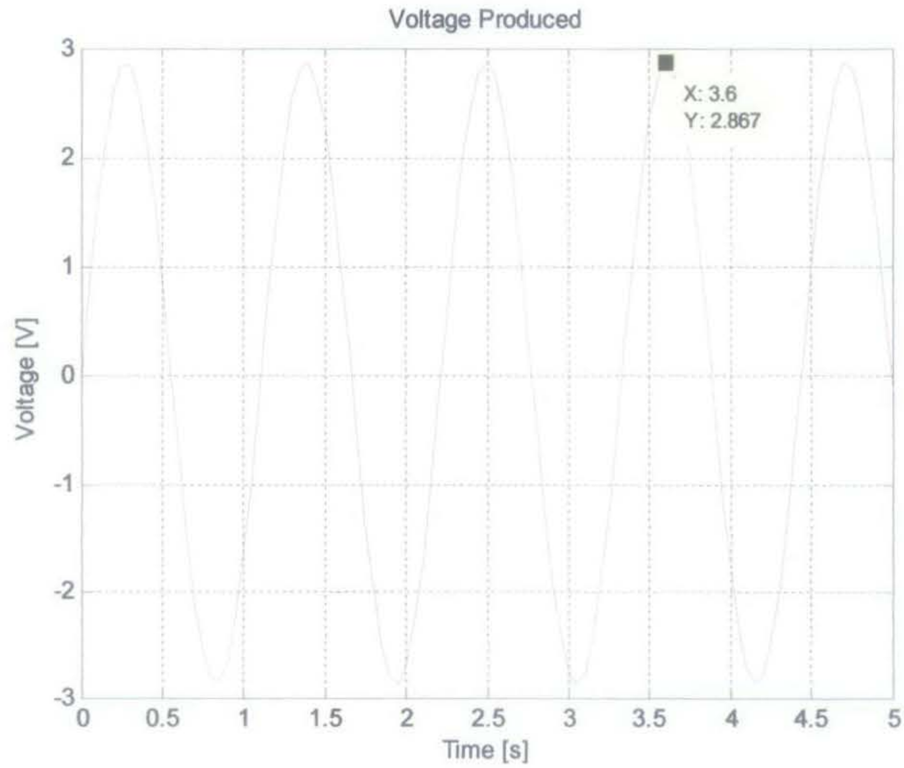


Figure 35: EMF produced

Table 4: Comparison between simulation and testing parameters value

Parameters		Simulation Value	Testing Value
m	Mass of rotor	0.02 kg	0.02104 kg
k	Plastic sheet stiffness	315.8273 N/m	338.9284 N/m
c	Damping element	0.01593	0.01766
$f_n(\omega_n)$	Natural frequency in Hz (rad/s)	20 Hz (125.6637 rad/s)	20.2 Hz (126.9203 rad/s)
N	Number of turns of coil	2000	2000
B	Magnet remanence	1.2 T	1.2 T
l	Length of conductor	0.015 m	0.016 m
X	Amplitude of rotor displacement	7.379 mm	6.947 mm
v	Amplitude of rotor velocity	0.0947 m/s	0.07965 m/s
V	Peak-to-peak voltage	6.818 V	5.734 V

From the table, it is noted that the value of displacement and velocity of the rotor as well as the peak-to-peak voltage produced during testing are all slightly lower than the expected value in simulation. This is due to the higher damping element value in the testing environment. Damping element restricts the movement of the rotor, thus producing lower output. Error analysis between the simulation and the testing value is given as Eq. 14.

$$\%\,Error = \frac{Simulation\ result - Testing\ result}{Simulation\ result}\ x\ 100\% \tag{14}$$

i. Percentage error for amplitude of rotor displacement:

$$\%\,Error = \frac{7.379 - 6.947}{7.379}\ x\ 100\% = 5.85\ \%$$

ii. Percentage error for amplitude of rotor velocity:

$$\% \, Error = \frac{0.0947 - 0.07965}{0.0947} \, x \, 100\% = 15.88 \, \%$$

iii. Percentage error for peak-to-peak voltage:

$$\% \, Error = \frac{6.818 - 5.734}{6.818} \, x \, 100\% = 15.91 \, \%$$

After that, a closed-loop test is done to investigate the power and current produced by the device when a 280 Ω resistor is put in series with the output of the prototype. Figure 36 shows the results for the closed-loop test. Peak-to-peak voltage produced is 3.072 V.

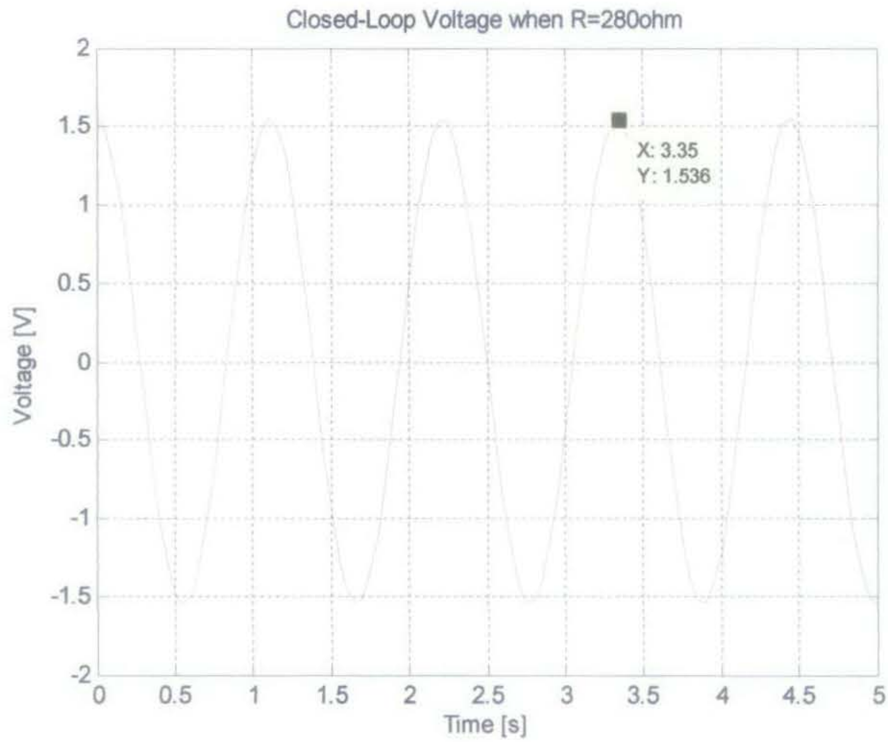


Figure 36: Closed-loop EMF

iv. Generated power:

$$P = \frac{V^2}{R} = \frac{(3.072)^2}{280} = 33.70 \, mW$$

v. Current produced:

$$I = \frac{P}{V} = \frac{33.70 \, m}{3.072} = 10.97 \, mA$$

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, a linear generator called Vibration Energy Harvester System (VEHS) has been designed and fabricated based on Vibration and Electromagnetic Induction (EMI) Law. The designed prototype is able to convert kinetic energy from the vibration from vibration generator into electrical energy to be used to power up the electronic circuit such as sensor. Basic characteristics of the device have been studied including the parameters involved. The vibration existed on the road are reproduced using vibration generator and the performance of the prototype is observed through several testing, monitoring and data acquisitioning.

From the results of the generated voltage, it is proven that the prototype is working adequately, with 15.91% deviation in the testing result peak-to-peak voltage. Table 5 below summarizes the result obtained during testing stage.

Table 5: Testing result summary

Parameters		**Value**
V_{OL}	Open-loop peak-to-peak voltage	5.734 V
V_{CL}	Closed-loop peak-to-peak voltage	3.072 V
P_G	Power generated	33.70 mW
I	Current	10.97 mA

5.2 Recommendations

There a many improvements that can be made in order to produce a more desirable output. For example, the plastic sheet, that is used in this project to help oscillate the rotor when an external force is applied to the prototype, can be replaced with a more sensitive and flexible material such as polymer. Polymer has a better elasticity characteristic than plastic sheet and more durable under tough condition. Plastic sheets are sometimes can easily lose its elasticity if it being put under high force continuously. However, polymer is very hard to get in the market and very expensive compare to the plastic sheet which can be recycled from PP food container.

More features can be added to the existing design in order to increase the product marketability. Apart from its main objective to develop an alternative and pollution-free vibration based energy harvester, this project is also intended to raise people awareness about green technology and the importance of utilizing the energy available in the surrounding. The prototype can further be improved by reducing its size while maintaining its capability to produce the same or greater amount of output. In addition to that, the application of the prototype is not limited to only placing it on the roadside. The vehicle itself produces vibration whilst it is moving and this harvester can be put in place to harvest that vibration energy.

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APPENDICES

Appendix A – FYP 1 Timeline

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■							Mid-semester break							
2	Preliminary Research Work	■	■	■	■											
3	Preliminary Design Stage			■	■	■	■									
4	Submission of Extended Proposal						■									
5	Estimation of Project Performance						■	■		■						
6	Proposal Defence									■	■					
7	Material Survey and Purchasing										■	■	■	■		
8	Preliminary Fabrication Stage													■	■	■
9	Submission of Interim Draft Report														■	
10	Submission of Interim Report															■

Appendix A – FYP 2 Timeline

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues								Mid-semester break								
2	Submission of Progress Report																
3	Project Work Continues																
4	Pre-EDX																
5	Submission of Draft Report																
6	Submission of Dissertation (soft bound)																
7	Submission of Technical Paper																
8	Oral Presentation																
9	Submission of Project Dissertation (hard bound)																