ELECTROMAGNETIC BASED CMOS-MEMS ENERGY HARVESTING SYSTEM

By

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FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfilment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(ELECTRICAL AND ELECTRONIC ENGINEERING)

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Tronoh, Perak

May 2011

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.

Zati Hanani binti Abdul Rahman

ABSTRACT

An Electromagnetic Based CMOS-MEMS Energy Harvesting System can convert kinetic energy which comes from vibration into electrical power. Energy harvesting technique is very promising because no changing batteries or setting cable and wires. Kinetic energy present in various form such as vibrations, random displacements also force can be harvested into electrical energy by using electromagnetic mechanisms. Electromagnetic is suitable since it is more precise, energy efficient, extremely powerful and easier to maintain. Power is generated by means of electromagnetic transduction between a moving coil construct on a CMOS-MEMS structure and a static magnet placed between it. It mainly consists of a proof mass, thin film, coil and also a permanent magnet. Simulation shows that the line width and the turns of coil influence the efficiency of the induced voltage. Acceleration also play important role because higher acceleration give higher frequency and result in increasing the change of magnetic flux rate in the coil and yield in higher output voltage according to Faraday's Law. The mechanical characteristics are being simulated by using engineering software, CoventorWare. The sensitivity of the structure achieved from the simulation is 7.938×10^{-6} V/g at 1.5 Tesla.

ACKNOWLEDGEMENT

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.

My deepest gratitude and admiration goes to my Supervisor, Dr. Mohd Haris Mohd Khir for being supportive and willing to share outstanding knowledge and expertise upon the project completion. Under his continuous supervision, the project is able to complete within the schedule.

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 this project. Hopefully, this project would be beneficial for my future undertaking and career development.

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ABBREVIATIONS AND NOMENCLATURES

CMOS : Complementary Metal-Oxide Semiconductor
MEMS : Micro-Electro-Mechanical-System

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Nowadays, in this world, we are dependent on fossil fuel as our main energy. But, we must bear in mind that fossil fuels are non-renewable sources and we will one day run out of them as our main energy. Thus, to prevent our lives from falling part, we must do something about it. Knowing that energy such as vibrations, heat, and motion are produce from the environment, we can actually harvest energy from that. That is why, energy harvesting technologies are developing and many scientists are doing deep research about it. There are many ways in implementing energy harvesting. One of it by using electromagnetic based CMOS MEMS technologies.

1.2 Objectives

The objective for this project is to study and analyze the method of using electromagnetic based CMOS-MES in energy harvesting. A clear understanding in electromagnetic fundamental is vital in order to achieve good result in the end of the research. Analysis is done based on the structure design and then compared with the existing research done. Design and simulation is done by using CoventorWare software and for analysis, Matlab software is used. The study includes the sensitivity of the device achieved from the analysis.

1.3 Scope of Study

This project will be intended to design electromagnetic based CMOS-MEMS by using CoventorWare application for finite element analysis (FEA) and follow by Matlab for analysis. It will mainly target on applications such as in medical application, remote sensors, and wireless sensor networks, automotive and also military. Such applications are impossible to achieve by using batteries because it unaffordable to recharge them in these situations, so we can eventually harvest energy from ambient energy. For example, in highways, there a lot of vibrations coming from the movement of the car, thus we can make use of these vibration input in order to produce electricity to power up street lamp through this system.

CHAPTER 2
LITERATURE REVIEW

2.1 Energy Harvesting

Energy harvesting is to harvest energy from motion, temperature differences and vibrations, in other words, produce energy from ambient energy. The advantage of energy harvesting is that the units are virtually maintenance free after installation, because there is no internal friction and no changing batteries or setting up cables and wires. The technology is especially beneficial in locations far from the ordinary power supply where it is not worthwhile to set up cables [1].

Modern electronics continue to push past boundaries of integration and functional density, towards the elusive completely autonomous self-powered microchip. As systems continue to shrink, however, less energy is available on-board, leading to short device lifetime (runtime or battery life). Research continues to develop higher energy-density batteries but the amount of energy available is not only finite but also low, limiting the system's lifespan, which is paramount in portable electronics. Extended life is also particularly advantageous in systems with limited accessibility, such as biomedical implants and structure-embedded micro-sensors. The ultimate long-lasting solution should therefore be independent of the limited energy available during start-up, which is where a self-renewing energy source comes in, continually replenishing the energy consumed by the micro-system [2].

2.2 Kinetic Energy

Kinetic energy harvesting 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. Vibration energy is best suited to inertial generators with the mechanical component attached to an inertial frame which acts as the fixed reference. The inertial frame transmits the vibrations to a suspended inertial mass producing a relative displacement between them. Such a system will possess a resonant frequency which can be designed to match the characteristic frequency of the application environment. This approach magnifies the environmental vibration amplitude by the quality factor of the resonant system and this is discussed further in the following section [3].

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 whist 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 [3].

2.3 CMOS-MEMS

CMOS (Complementary Metal-Oxide Semiconductor) is a technology constructing integrated circuits. The important characteristics of CMOS are high noise immunity and low static power [4]. The advantages of CMOS over NMOS is low to high and high to low output transitions are very fast because it having low resistance when active [5].

MEMS (Micro-Electro-Mechanical Systems) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through micro-fabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices [6].

Microelectronic integrated circuits can be thought of as the "brains" of a system and MEMS augments this decision-making capability with "eyes" and "arms", to allow microsystems to sense and control the environment. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena [6].

The advantages of using the MEMS technology are:

1) Diverse tech that could affect every applications because it is more pervasive technology [6].
2) It blurs the distinction of complex mechanical system and integrated circuit electronics [6].

2.4 Electromagnetic Theory

Electromagnetic induction, first discovered by Faraday in 1831, is the generation of electric current in a conductor located within a magnetic field. The conductor typically takes the form of a coil and the electricity is generated by either the relative movement of the magnet and coil, or because of changes in the magnetic field. In the former case, the amount of electricity generated upon the strength of the magnetic field, the velocity of the relative motion and the number of turns of the coil [3].

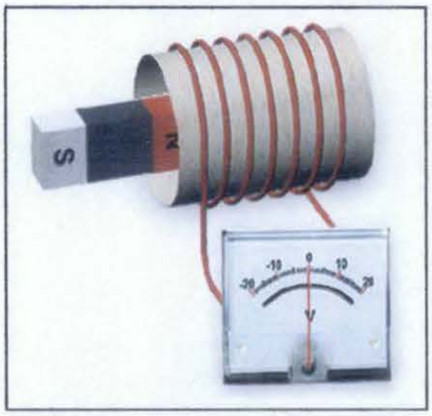

Figure 1 : Faraday Law [7]

Many electromagnetic microgenerators have been fabricated to harvest vibration energy. Sheffield University's research group first developed a micro-generator which consists of a SmCo magnet on a polyimide membrane. A maximum RMS power of 0.3 µW was obtained from this electromagnetic vibration energy harvester at a resonant frequency of 4.4 kHz. Li and co workers presented a vibration-based power generator which using a laser-micromachined copper spring as the resonating structure. This microgenerator can generate 10 µW of power with 64 Hz input excitation frequency and 100 µm input vibration amplitude. A silicon electromagnetic microgenerator with volume of about 10 mm3 was fabricated by Southampton University. It can generate a maximum power output of 104 nW for 0.4g (g = 9.8 m/s2) input acceleration at 1.615 kHz [8].

The operation principle of the electromagnetic vibration energy harvester is Faraday's Law. When any change in the magnetic flux through a coil or a closed circuit happen, an induction electromagnetic force (EMF) is generated in the coil or closed circuit. The direction of the EMF induced in the coil or closed circuit is such that it would produce current that would cause a flux opposing the original flux change which is expressed as follows:

$$U_{EMF} = -N\frac{\partial \Phi}{\partial t} = -N\frac{\partial(\vec{B}.\vec{S})}{\partial t} \tag{1}$$

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 circuit.

An electric current that is induced by a changing magnetic field will in turn induce its own magnetic field. According to Lenz's law, the induced electric current must be in such a direction that the magnetic field induced by the current opposes the original cause of the induced current. That is way the EMF induced is equal to the negative rate of change with time of magnetic flux through the circuit. Lenz's law is a consequence of the law of conservation of energy. According to the law of conservation of energy the total amount of energy in the universe must remain constant. Energy can be neither created nor destroyed. Hence it is impossible to get free energy from nothing [9].

Another equation for EMF induced is:

$$U_{EMF} = Blv \tag{2}$$

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

The design rules for electromagnetic energy harvesting system can be obtained from Eq. 2 :

(1) The number of turns of the coil should be increased as large as possible so that effective length can increase.

(2) Velocity of the structure can be varies by giving higher acceleration input to the structure.

(3) Magnetic field can be increased so that change rate of the magnetic flux can be increased. Magnet with higher magnetic energy will be used.

There are other ways to generate electricity by using kinetic energy which is by piezoelectric and also electrostatic. For piezoelectricity, the word *piezoelectricity* means electricity resulting from pressure [10]. The compression – elongation of the piezoelectric layer creates electric charges that are collected by the electrodes and transferred to the load [11]. Piezoelectric materials produce a voltage in response to an applied force, usually a uniaxial compressive force. Current research by using piezoelectric is a piezoelectric harvesting device fabricated by MEMS technology generates a record of 85μW electrical power from vibrations. A wafer level packaging method was developed for robustness. The packaged MEMS-based harvester is used to power a wireless sensor node. Within the Holst Centre program on Micropower Generation and Storage, Imec researchers developed a temperature sensor that can wirelessly transmit data in a fully autonomous way [12].

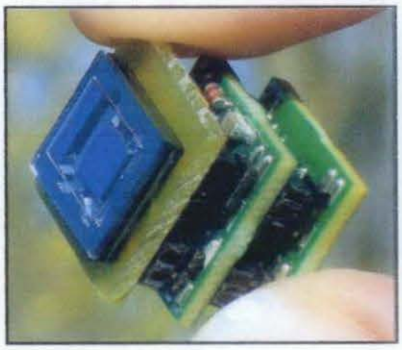

Figure 2 : Piezoelectric device [12]

For electrostatic energy harvester the principle of it is that the moving part of the transducer moves against an electrical field, thus generating energy. Meninger of MIT presented an electrostatic generator that employs a variable micro machined 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 [13]. Curent research regarding this type of energy harvesting is A 2-DOF electrostatic energy harvester. The 2D resonator can extract ultrasonic energy from all directions in the device plane as well as broaden the bandwidth, increasing the efficiency of the energy scavenging. In the first prototype, 0.1 nW power was harvested with a 10 mV peak-to-peak voltage [14].

This Waite and Bartlett Co. electrostatic generator was used as an electrotherapy device and also to power early X-ray tubes, 1890. (M-736-00508)

Figure 3 : Electrostatic generator [14]

The electromagnetic ones are typical of more stable for high force and large gap applications, very robust in harsh environment (dust, humidity) and can be driven by common low-cost, low voltage controllers, as compared with the others [15].

One of the most efficient 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. The generalized schematic diagram depicted in Figure 4 is applicable to describe the operation of electromagnetic generators. The damper, *c*, effectively represents the electromagnetic transduction mechanism, i.e. the magnet and coil arrangement.

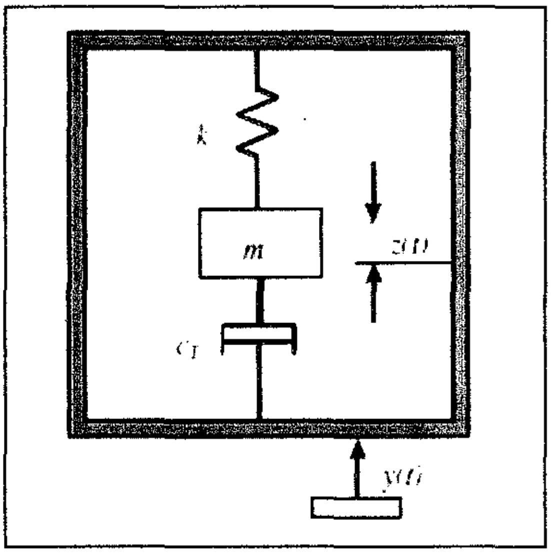

Figure 4 : Model of a vibration energy harvester

Inertial-based generators are essentially second-order, spring-mass systems. Figure 4 shows a general example of such a system based on a seismic mass, *m*, on a spring of stiffness, *k*. Energy losses within the system (comprising parasitic 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. 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:

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{y}(t) \quad (3)$$

According to Newton's second law of motion, force equal to mass time with acceleration given by this equation:

$$F = ma \quad (4)$$

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:

$$v^2 = u^2 + 2as \quad (5)$$

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 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:

$$F = -kx \quad (6)$$

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:

$$k = \frac{Ewt^3}{4l^3} \quad (7)$$

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 author used multiple springs attached in parallel. Thus the equivalent equation for the spring constant, k is:

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

The author also must be careful in designing the structure, to make sure driving frequencies do not match the natural frequency of vibration of the structure, lest the vibrations 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:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{9}$$

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

Second order systems are important for a number of reasons. They are the simplest systems that exhibit oscillations and overshoot.

1) Many important systems exhibit second order system behavior.
2) Second order behavior is part of the behavior of higher order systems and understanding second order systems helps you to understand higher order systems [16].

The following design rules for electromagnetic vibration energy harvester can be obtained if the frequency and the amplitude of the input vibration are given:

1) The mass-spring system should be designed reasonably so that its natural frequency is equal to the frequency of input vibration, that means the harvester should be at resonance when it is working;
2) The mass should be as large as possible;

3) The damping coefficient (especially the parasitic damping) should be decreased as small as possible [17].

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

The project is carried out according to the process flow as shown in Figure 5. It is started with defining problems or issues related to energy harvesting. Then, study on electromagnetic based CMOS-MEMS energy harvesting system is done by gathering information from internet resources, technical papers and also books. During this phase, electromagnetic fundamental also must be studied in order to achieve great result at the end of the research. Current technology also must be taken into account so that clear understanding on this research can be obtained.

In addition, type of electromagnetic based vibration structure based on CMOS-MEMS also need to be studied to get better understanding and what application can be used on each structure. Hybrid structure also was studied to enhance knowledge of this type of energy harvesting. Thus, the objectives of the project can be achieved and improvement can be made. Next, comparison of the existing research must be done in order to know what structure gives the best output voltage.

After all the studies, the next phase is designing the structure. During this phase, the type and structure used need to been identified. Parameters for the structure need to be stated in order to do modelling. After that, Cadence software is used to create a 2D layout for fabrication and CoventorWare software is to create 3D model and also for finite element analysis (FEA). After doing all the simulation and achieve data for every parameter needed, analysis is done by using Matlab to obtained the output voltage. Finally, the sensitivity of the device can be achieved through the analysis.

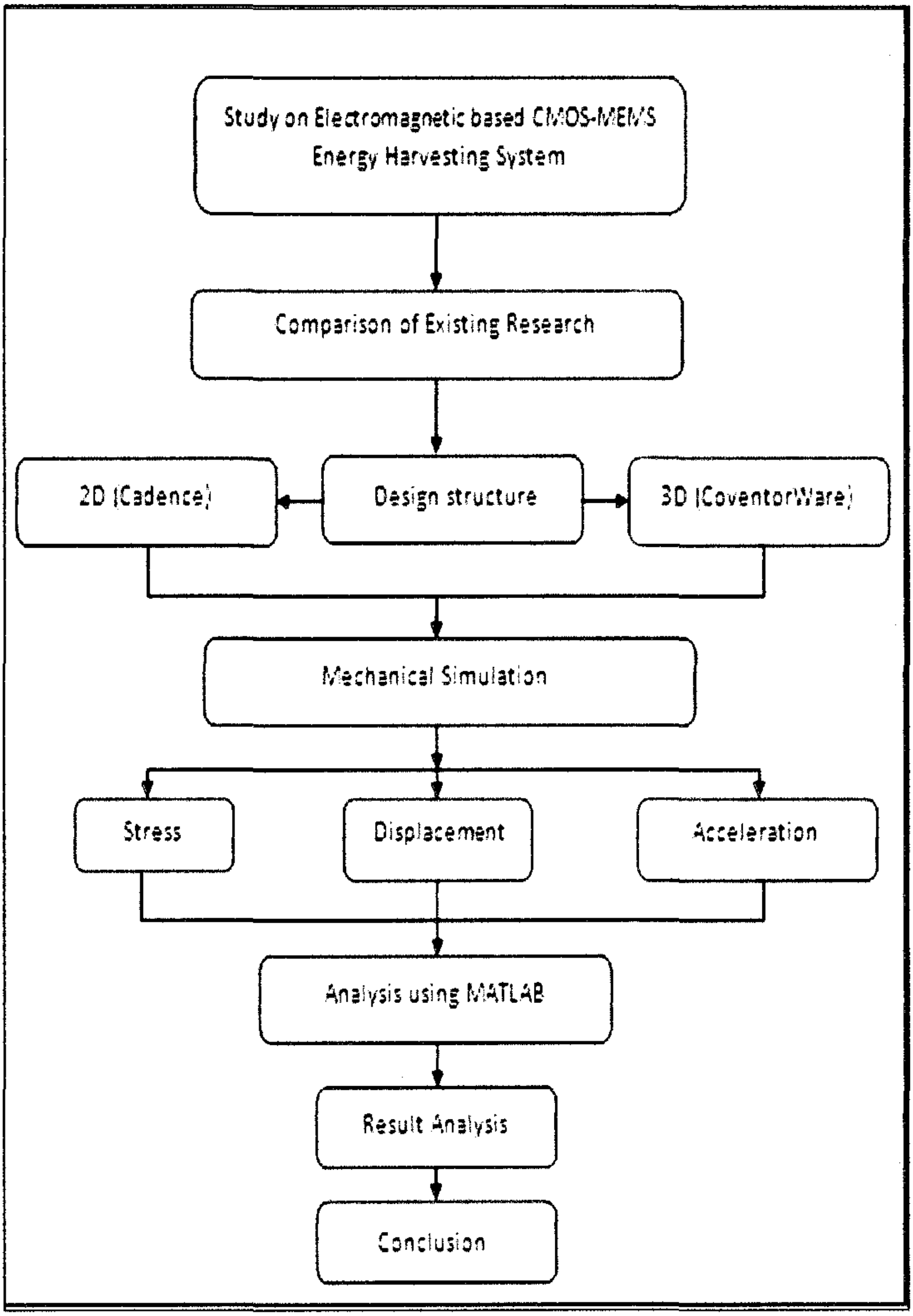

Figure 5 : Flow Diagram for Project Work

3.2 Tools and Equipment Used

For the accomplishment of the project, there are needs for a certain software application to do simulation and also analysis from the simulation result. For design structure, Cadence and also CoventorWare software is used. Cadence basically to provide 2D layout of the structure and also for fabrication purposes. Meanwhile, CoventorWare is used to do mechanical simulation from 3D model. After getting all the data needed, analysis is done by using Matlab software in order to obtain the sensitivity of the device.

3.3 Gantt Chart

The Gantt chart is provided together with the report in the Appendices section (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

RESULT AND DISCUSSION

4.1 Data Gathering and Analysis

In this section, data from the mechanical simulation is gather and being analyzed. First of all, before designing the structure, the material need to be chose. The best material will give the optimum output voltage. After much consideration and research done, Table 1 will show materials chose for each part and advantages for using such material in the structure.

Table 1 : List of Materials

Part	Material	Advantages
Proof Mass	Silicon substrate	1) Compatible with IC integration. 2) Smaller Young Modulus thus easier to move and lower resonant frequency.
Thin Film	Aluminium(Al), Silicon Dioxide(SiO2)	1) Very low resistivity and its adhesion compatibility with SiO2. 2) Inhibit problems like electromigration and junction spiking.
Coil	Aluminium	1) Cheaper. 2) Good conductivity 3) Easy to fabricate into the thin films.
Permanent magnet	Neodymium (NdFeb) magnet	1) Powerful magnet. 2) High magnetization.

Next part is to design the structure with the parameter that had been assigned in order for the device to work properly. Figure 6 below shows the design of the structure.

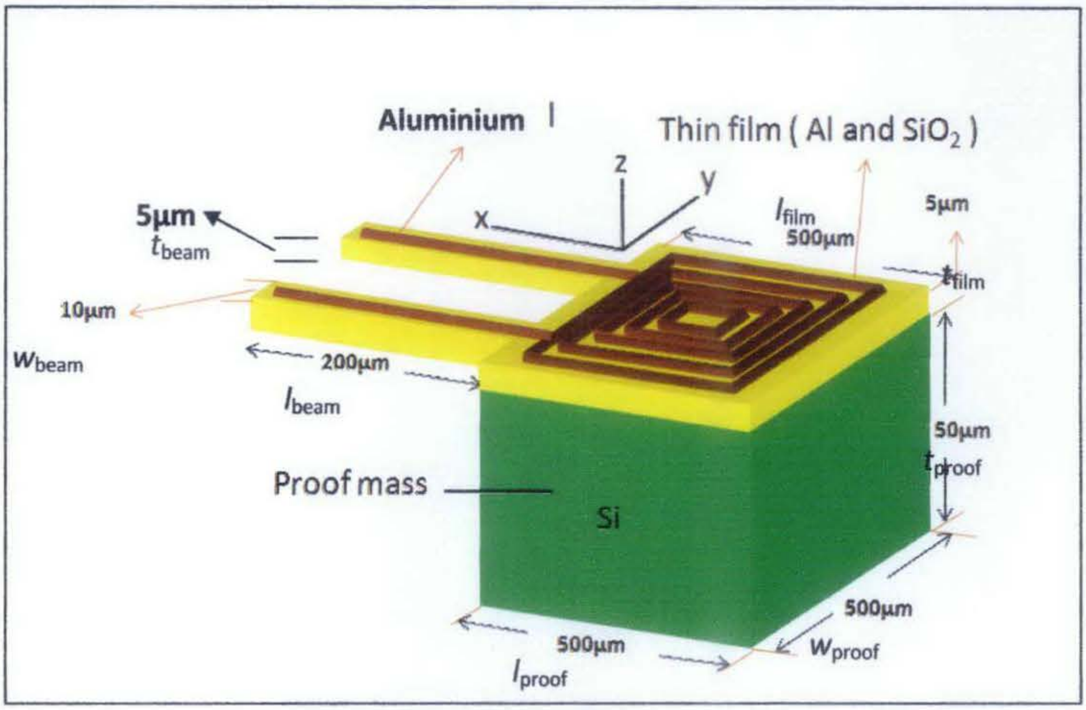

Figure 6 : Structure design of the device

The parameter of the structure is shown in Table 2 below.

Table 2 : Structure parameter

Properties	l (µm)	w (µm)	t (µm)
Proof Mass	500	500	50
Beam	200	10	5
Thin film	500	500	5

For the coil, the parameter is given in the Table 3 below.

Table 3 : Coil Parameter

Properties	N (turns)	w_{coil} (μm)	Gap between two turns (μm)	$l_{effective}$ (μm)
Coil	49	1	2	13096

The device structure consists of a proof mass contains 49 turns of aluminium coil, with a pair of beam. The structure is placed between a pair of a permanent magnet. When the proof mass substrate is excited by outside vertical vibration, it will move up and down. Thus, the aluminium coil will then cut the magnetic field exist between it which results in change of magnetic flux. As a result, induced voltage and current will be generated in the coil according to Faraday's Law of induction.

A very high magnetic energy magnet is selected which is NdFeb permanent magnet. The surface area of the magnet is to be made larger thus many same like structure can be put in between of it in order to produce higher output voltage. The distance between the structure and the permanent magnet is nearer to each other to avoid losing magnetic field density.

When the magnetic flux through a closed circuit changes, an induction electromagnetic force (EMF) is generated. The change could be produced by changing the magnetic field strength, the direction of the moving magnet, the changing area in magnetic field and also the number of turns. But in this design, one design rules must be follow which is:

"The change of rate of the magnetic flux through the coil. But since the device going to vibrate at resonant frequency and below, so the only thing we can change is the magnetic field density or also known as the strength of the magnet. Therefore, only magnetic field density can be increased in order to increase the change rate of the

magnetic flux. So kind of magnet with high magnetic energy product should be selected."

The expression of Faraday's Law is expressed as follows in Eq.1 and Eq.2 can actually describe the design rule of the structure. So, rather than changing the magnetic field density and also the changing of area in the magnetic field, type of material also used also play a vital role to obtained optimum output from the device. That is why the best material need to be chose. Parameters of the structure also need to be optimized to create a structure that can give optimum output voltage and sensitivity level at the end of the research.

4.2 Experimentation and Modelling

In this section, experimentation and modeling part are explained. First, 3D model is being constructed using CoventorWare software. Figure below show the 3D model of the structure.

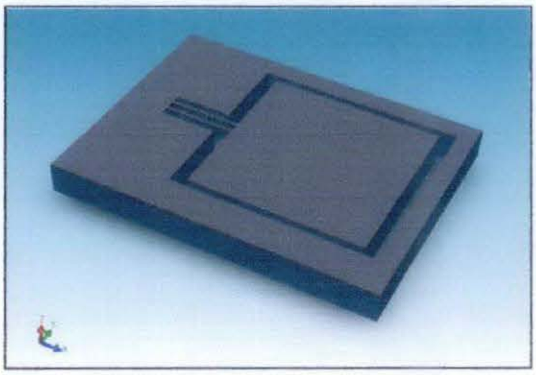

Figure 7: 3D model

After done with the 3D model, meshing is done. Figure below shows the meshing model.

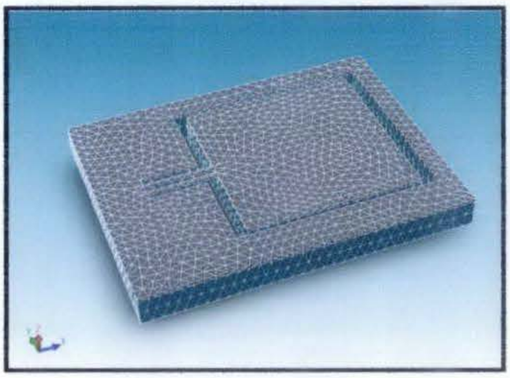

Figure 8: 3D meshing

After finishing up the meshing part, next is to do simulation. During this simulation, first phase is to see the resonant frequency of the device and also see Mode 2 and Mode 3 frequency. Figures below show the state of the device during resonant frequency, Mode 1 and Mode 2.

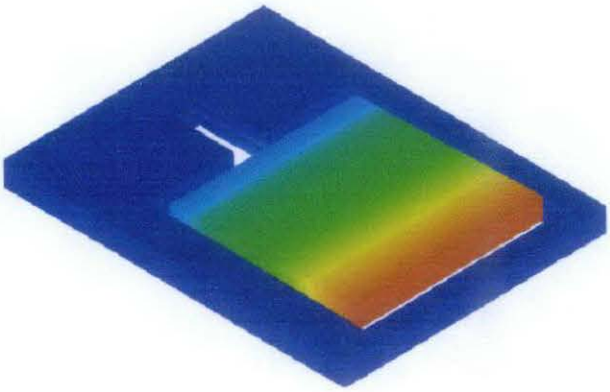

Figure 9 : Mode 1

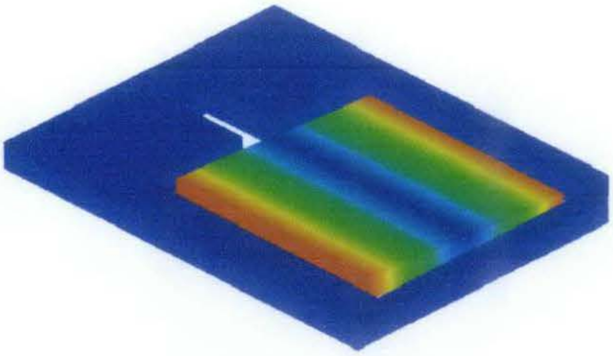

Figure 10 : Mode 2

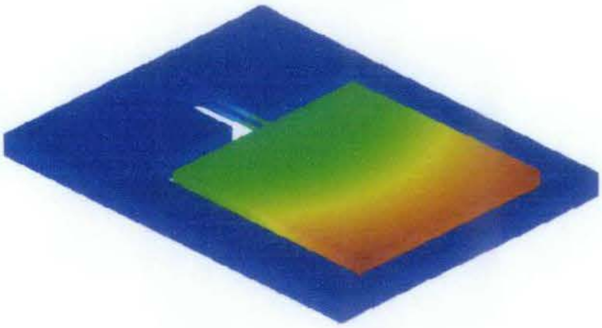

Figure 11 : Mode 3

Table 4 below will show frequency at each mode.

Table 4 : Frequency at each mode

Properties	Frequency (Hz)	Motion
Mode 1	674.317	Up and Down
Mode 2	2130.47	See-saw
Mode 3	6550.07	Along X-Y plane

For this device to work properly, it must works at mode 1. Mode 1 is the resonant frequency. During this resonant frequency, this device will move at higher amplitude. This structure also can work below the resonant frequency. So, it gives the higher output voltage. In addition, this device moves up and down in order to cut magnetic flux. Mode 2 and mode 3 must be avoided because it might break the structure and also the motion is not same as in mode 1.

400 – 1 kHz frequency is the range of frequency for CMOS-MEMS structure. It can be used in wireless sensor application, medical application and also military. If this structure works at ambient frequency which is 50 - 200Hz, it cannot withstand higher frequency and can only works for dedicated application only. So, higher resonant frequency will allow device to works for many application and not fragile as structure at ambient frequency.

Next, simulation is done by varying acceleration parameter. Acceleration is varied from 1 – 10 g. From the simulation, data of displacement and also stress are obtained. From the data and Eq.5, result of velocity is displayed in Table 5 below.

Table 5 : Data from Simulation and Result

Acceleration (ms^{-2})	**Stress (MPa)**	**Displacement (μm)**	**v^2 ($\times 10^{-6}$ m^2s^{-2})**	**v ($\times 10^{-3}ms^{-1}$)**
1g	1.4	0.8	15.68	3.96
2g	2.9	1.6	62.72	7.92
3g	4.3	2.4	141.12	11.88
4g	5.8	3.2	250.88	15.84
5g	7.2	4.0	392	19.8
6g	8.6	4.8	564.48	23.76
7g	10	5.6	768.32	27.72
8g	12	6.4	1003.52	31.68
9g	13	7.2	1270.08	35.64
10g	14	8.0	1568	39.6

From the data obtained from the simulation, the stress at the beam at 10g acceleration is 14 MPa. It do not exceed the yield strength of aluminum which is 15.4 GPa. This must taken into account to make sure the structure will not break if higher acceleration is given. In addition, higher acceleration, gives higher displacement, thus the change of magnetic flux increase and lead to higher output voltage.

After obtained the velocity of each structure for each acceleration, next sensitivity of the device can be obtained by using Eq.2. From Eq.2, the magnetic field density, B need to be varies from 0.1 – 1.5 Tesla. Sensitivity of the device is obtained from the slope of the graph voltage versus acceleration at certain magnetic field density. Figures below show result of the sensitivity of the device at different magnetic field density.

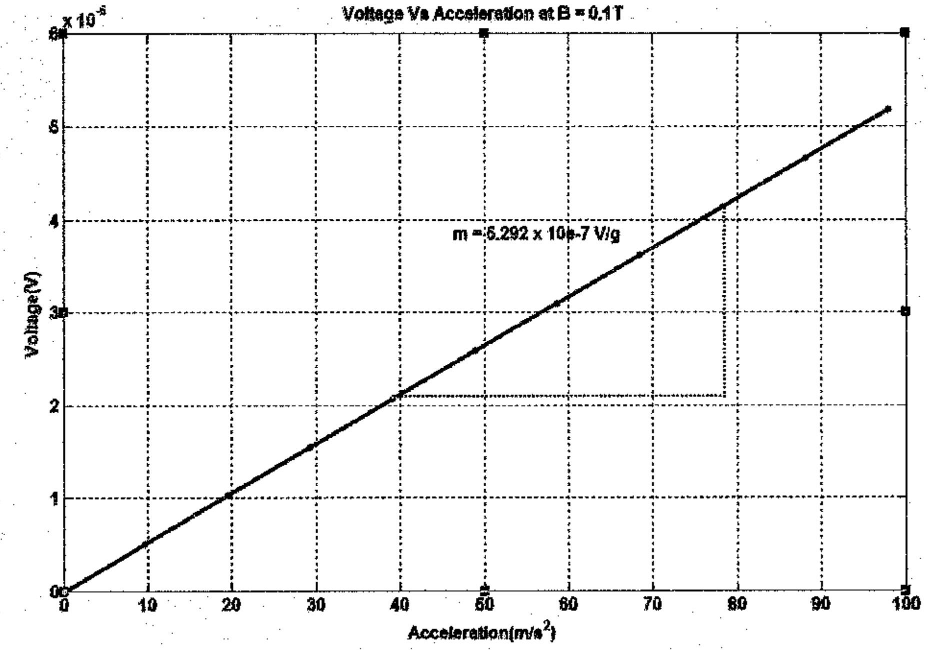

Figure 12 : Voltage Versus Acceleration at B = 0.1 T

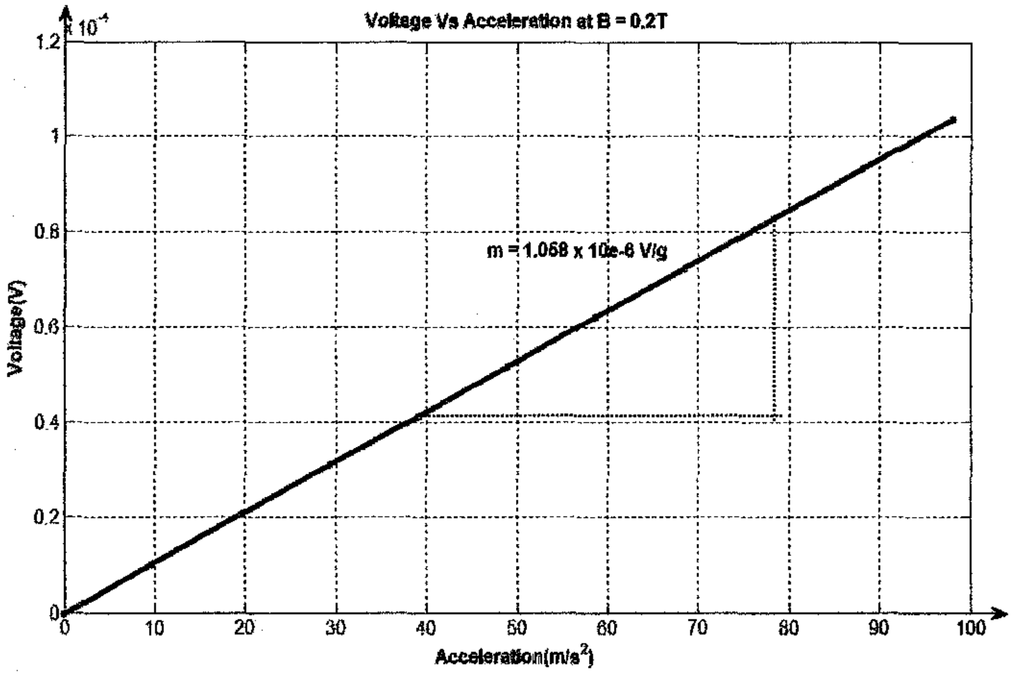

Figure 13 : Voltage Versus Acceleration at B = 0.2 T

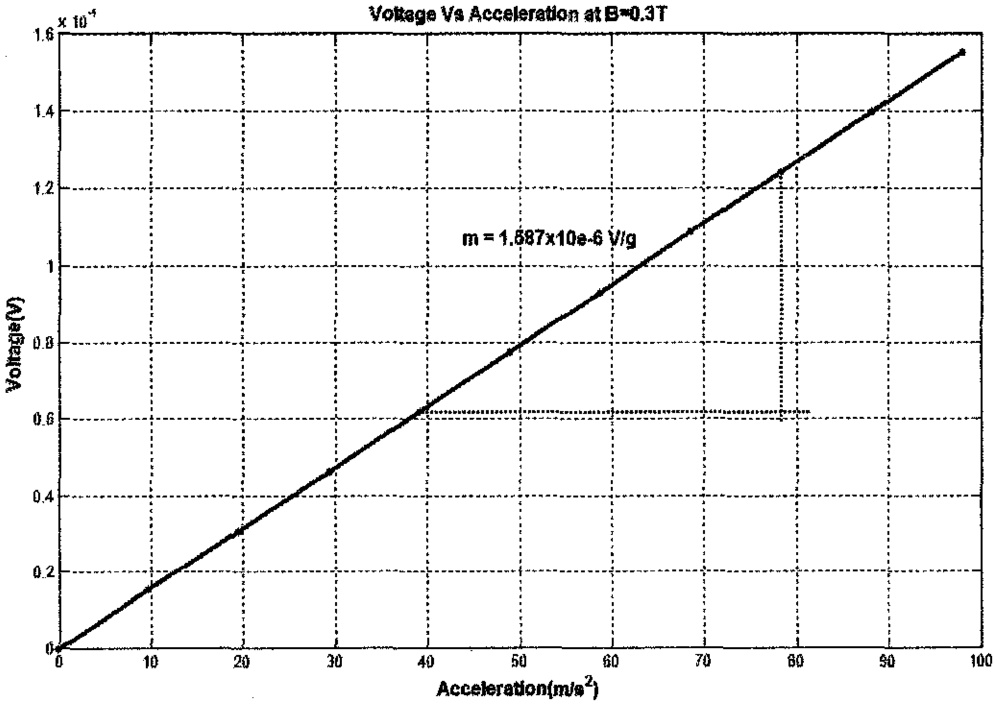

Figure 14 : Voltage Versus Acceleration at B = 0.3 T

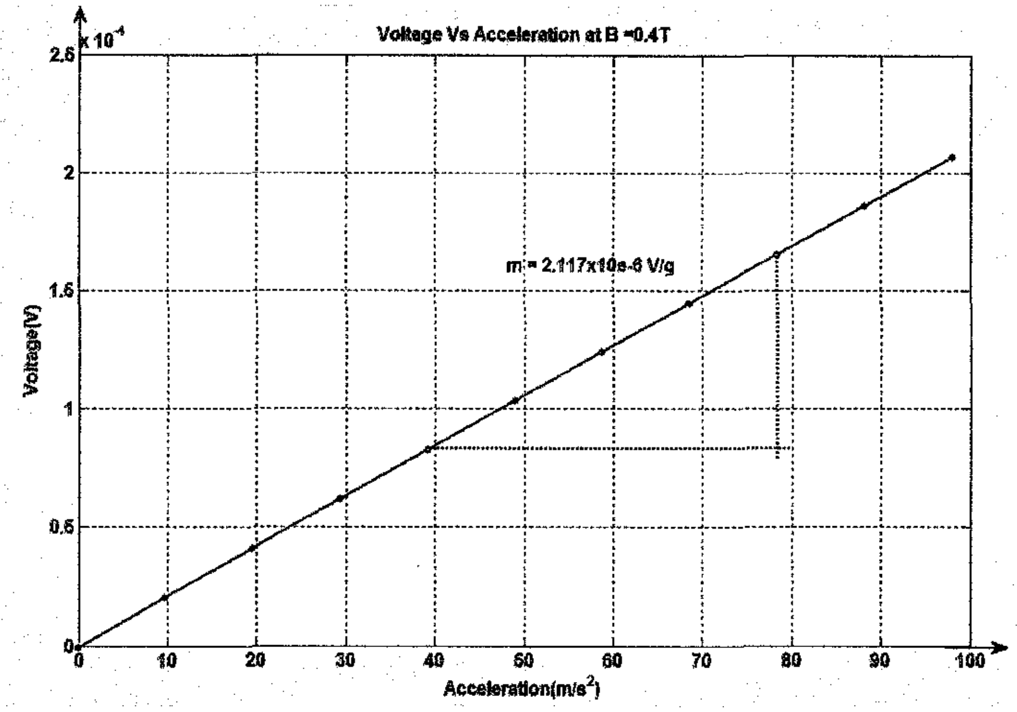

Figure 15 : Voltage Versus Acceleration at B = 0.4 T

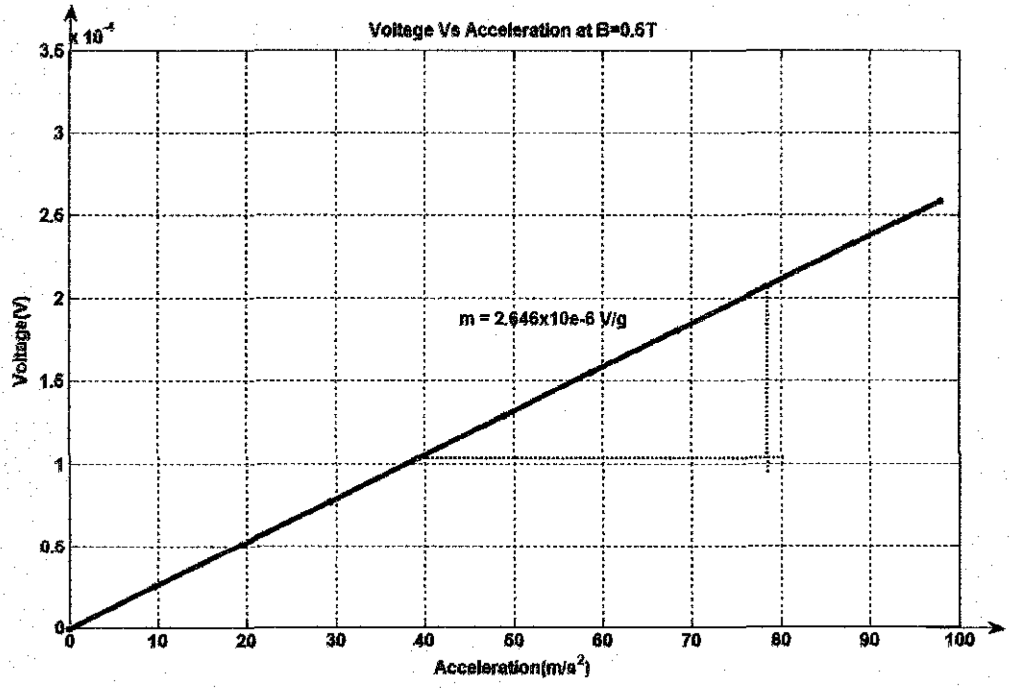

Figure 16 : Voltage Versus Acceleration at B = 0.5 T

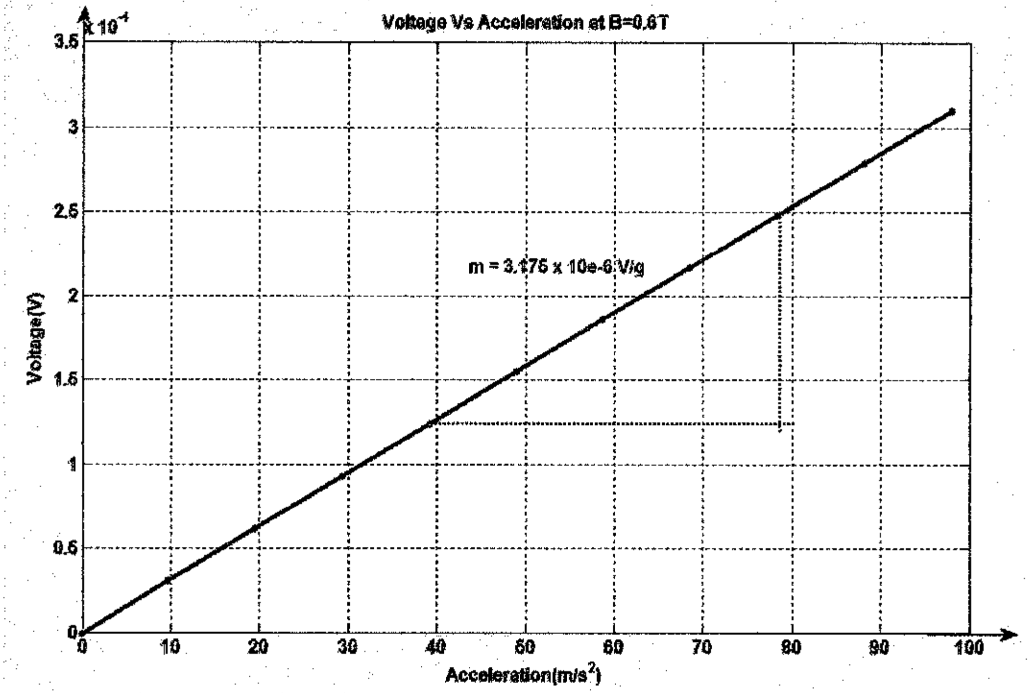

Figure 17 : Voltage Versus Acceleration at B = 0.6 T

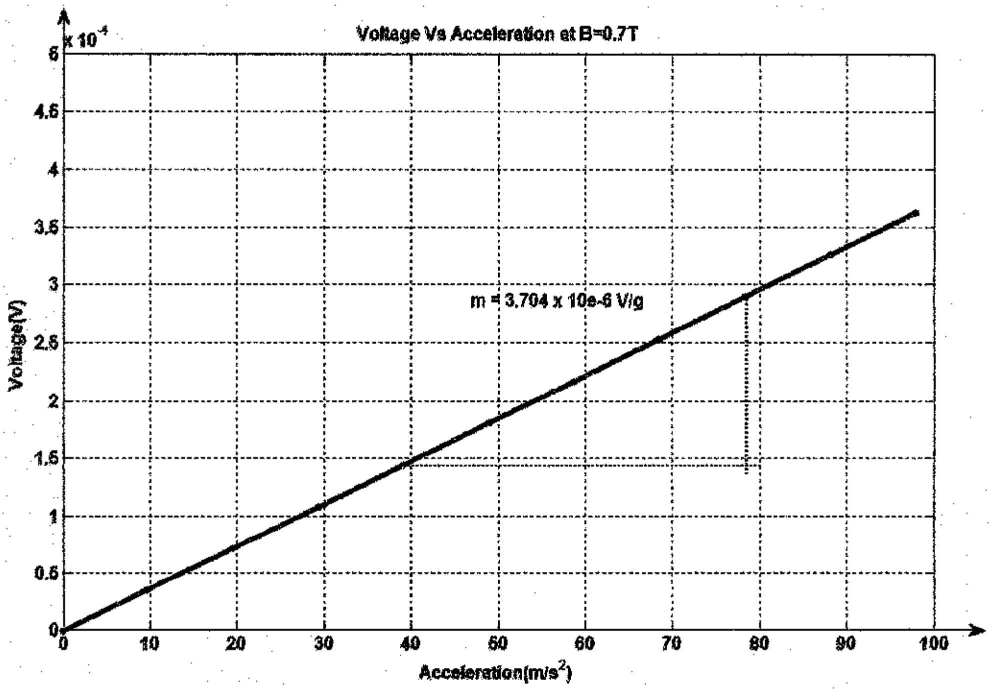

Figure 18 : Voltage Versus Acceleration at B = 0.7 T

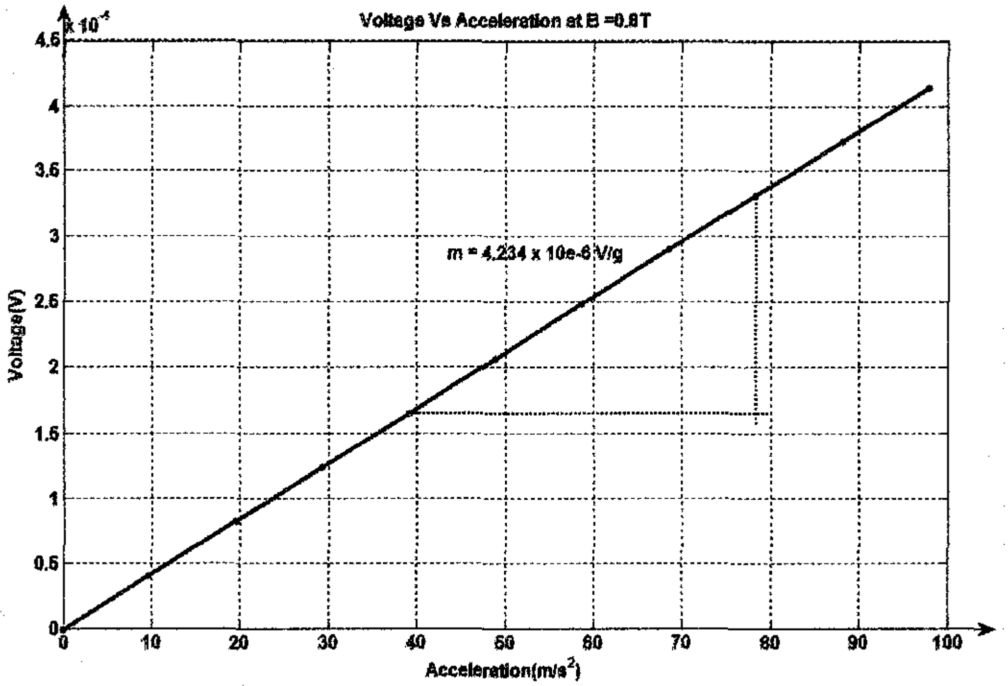

Figure 19 : Voltage Versus Acceleration at B = 0.8 T

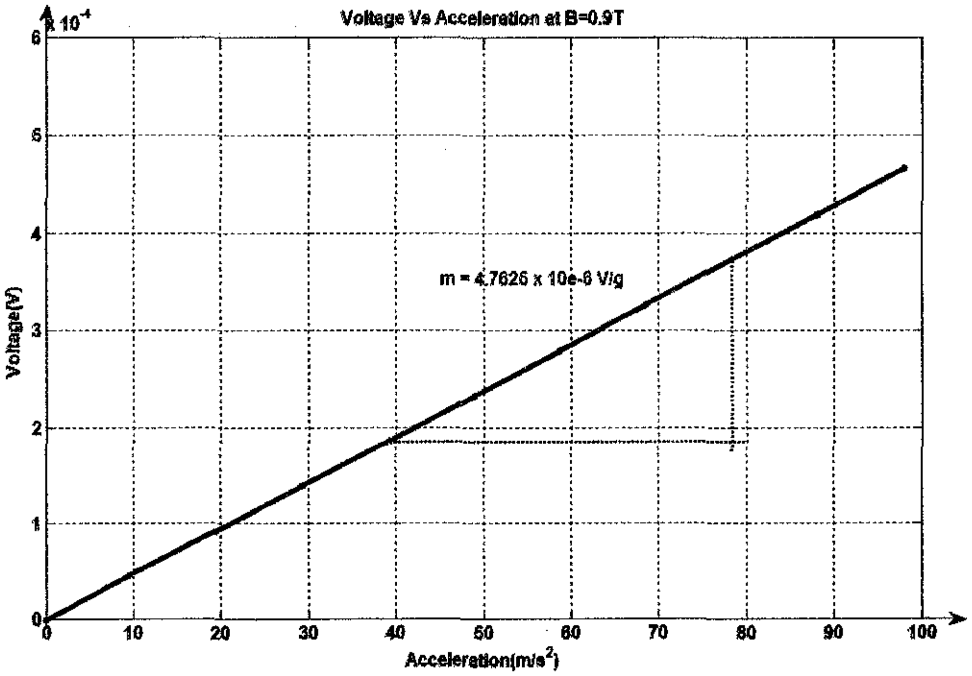

Figure 20 : Voltage Versus Acceleration at B = 0.9 T

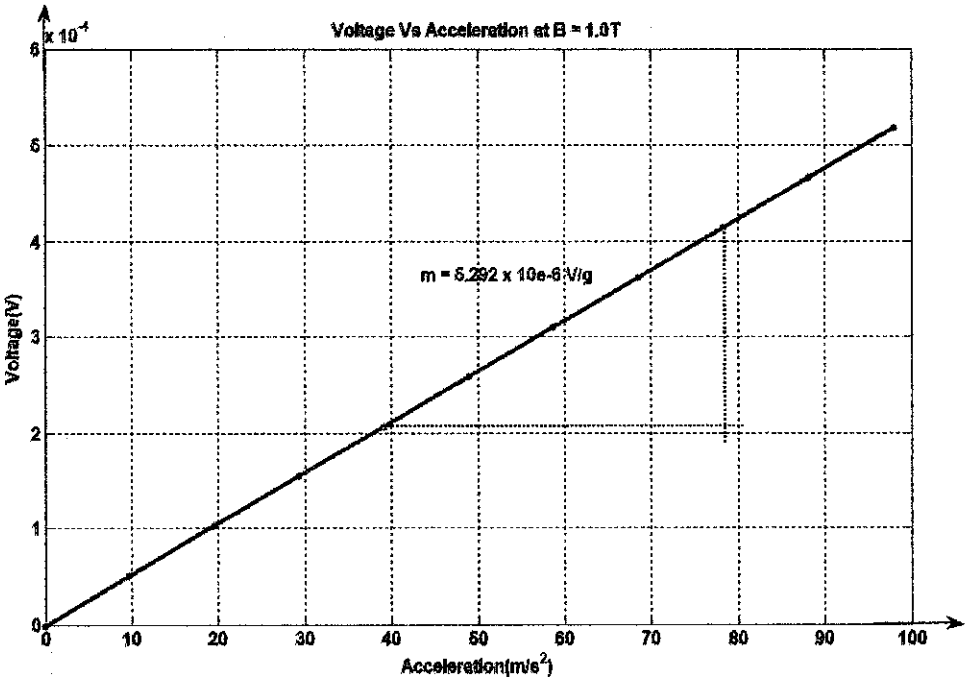

Figure 21 : Voltage Versus Acceleration at B = 1.0 T

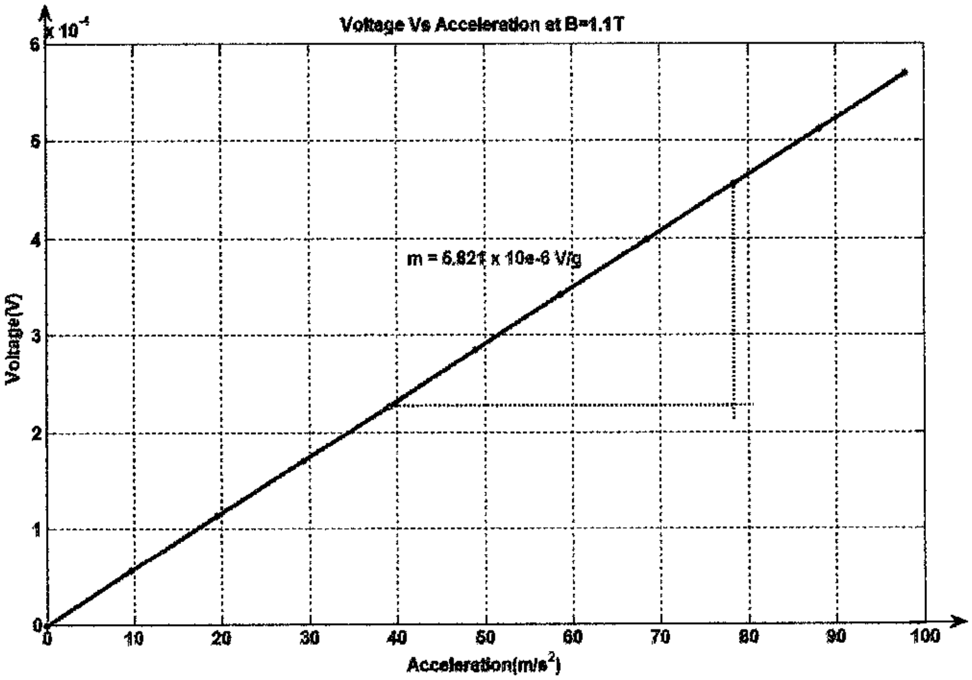

Figure 22 : Voltage Versus Acceleration at B = 1.1 T

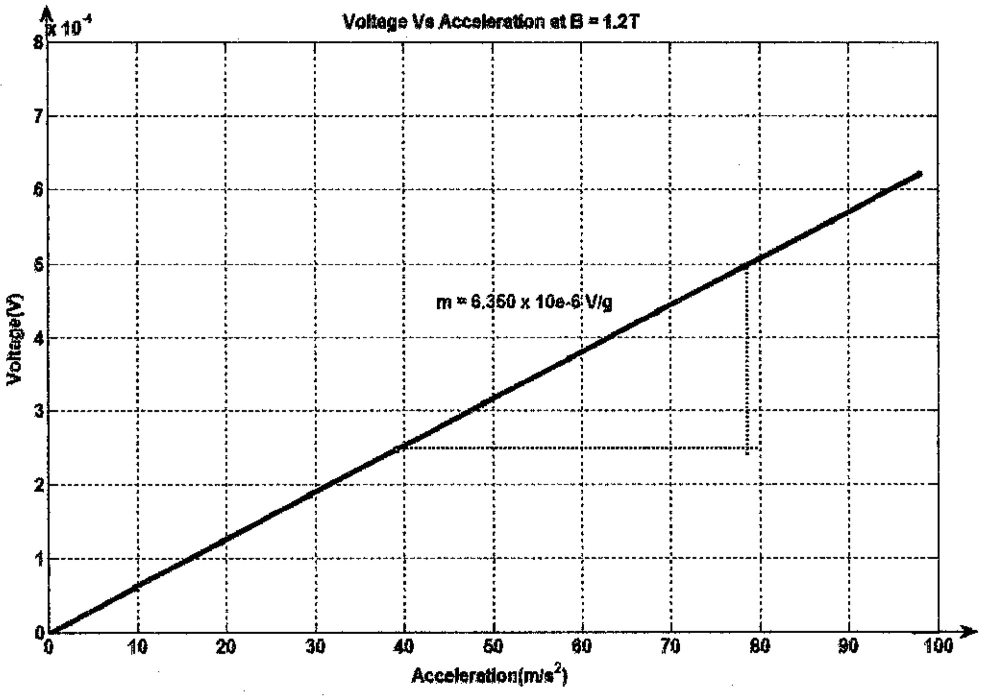

Figure 23 : Voltage Versus Acceleration at B = 1.2 T

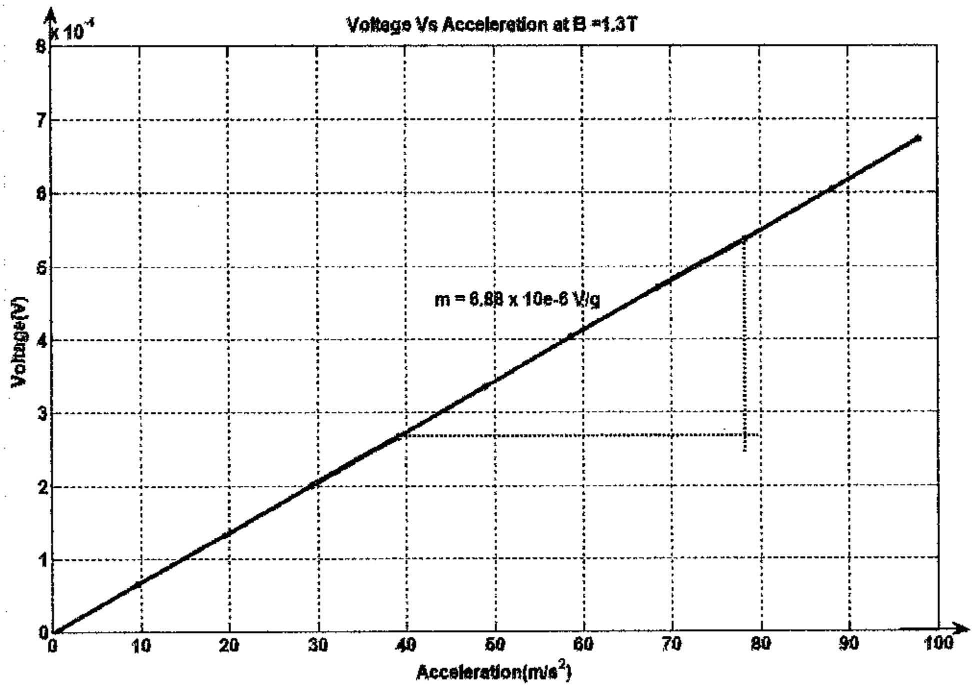

Figure 24 : Voltage Versus Acceleration at B = 1.3 T

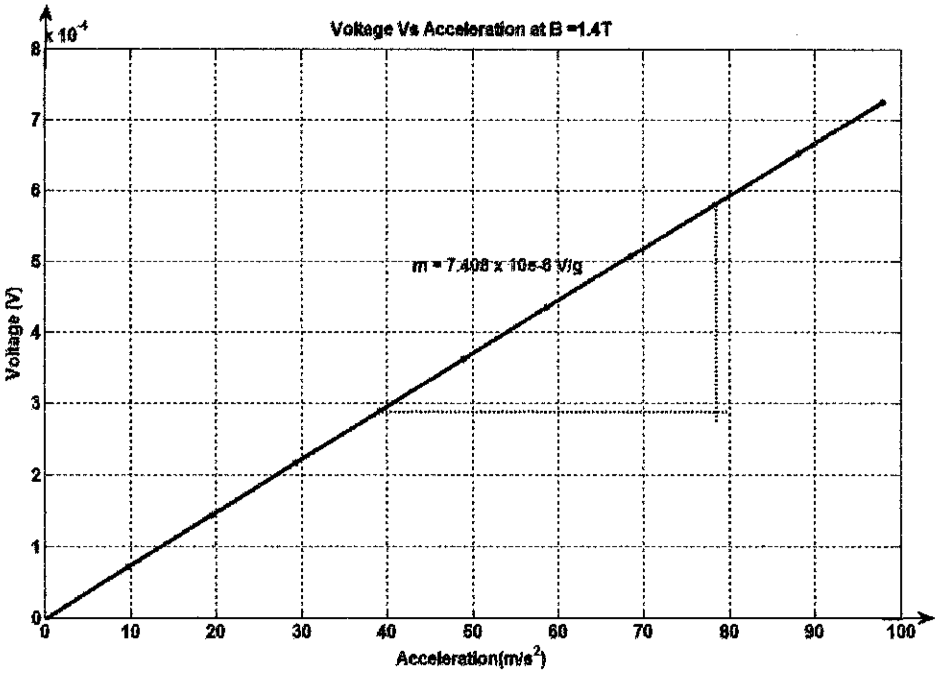

Figure 25 : Voltage Versus Acceleration at B = 1.4 T

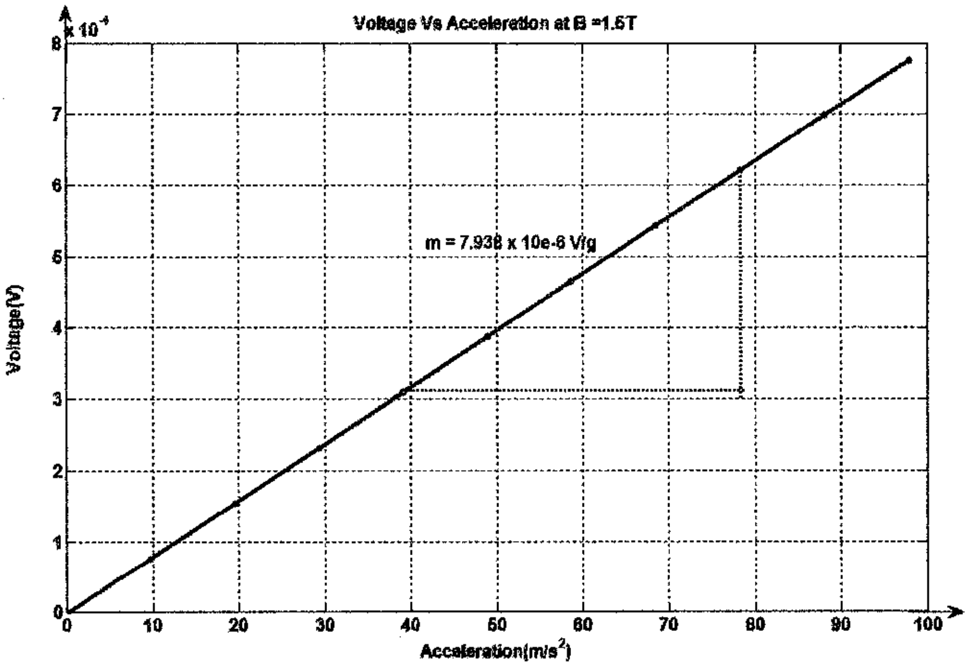

Figure 26 : Voltage Versus Acceleration at B = 1.5 T

From the figure above, the sensitivity of the device in summarized in Table 6 below.

Table 6 : Sensitivity of the device

Magnetic field density (Tesla)	Sensitivity (x 10^{-6} V/g)
0.1	0.529
0.2	1.058
0.3	1.587
0.4	2.117
0.5	2.646
0.6	3.175
0.7	3.704
0.8	4.234
0.9	4.723
1.0	5.292
1.1	5.821
1.2	6.350
1.3	6.88
1.4	7.408
1.5	7.938

From the summarized table, it can be said that at higher magnetic field, the sensitivity of the device is increased. The sensitivity of the device at 1.5 Tesla is 7.938 x 10^{-6} V/g. The dimensions of the coil affect the induced voltage in the coil. This is because if the structure has more number of turns, the value of $l_{effective}$ will increase. This will yield higher output voltage according to Eq. 2. Thus, it can be said that the width and gap of the turn of the coil will affect the number of turns of the coil. In this design, the width is 1μm and the gap is 2μm. The simulation can be explained from a physical view. The coil with smaller width and gap can generate higher output voltage according to Faraday's Law.

Varying the magnetic field density can easily affect the induced EMF. However, according to the design and availability and also suitability of the design, we can only use up to 1.5 Tesla.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The electromagnetic based vibration energy harvester is capable of converting vibration energy. It consists of a proof mass, and also a permanent magnet. Input vibration was given in order to move the proof mass up and down, thus the aluminium coil inside the thin film will cut the magnetic flux in order to induced voltage.

From the simulation result, the sensitivity of the device is higher when the input acceleration is higher. Furthermore, higher magnetic field density also affects the voltage induced greatly. The device has a resonant frequency of 674.317 Hz which is suitable of wireless sensor system, bio-medical and also military application.

These offer a well-established technique of electrical power generation and the effect has been used for many years in a variety of electrical generators. There is a wide variety of spring-mass configurations that can be used with various types of material that are well suited and proven in cyclically stressed applications. Comparatively high output current levels are achievable at the expense of low voltages.

5.2 Recommendation

The configuration of electromagnetic based vibration parameters should be optimized with higher increment in the voltage output. Mechanical simulations must be done from the modelling phase so that the structure achieved the desired optimum output. Improvisation must be done to the structure thus higher sensitivity can be obtained. Furthermore, research on latest technology such as nanotechnology on the energy harvesting system need to be done more to get better understanding in the project.

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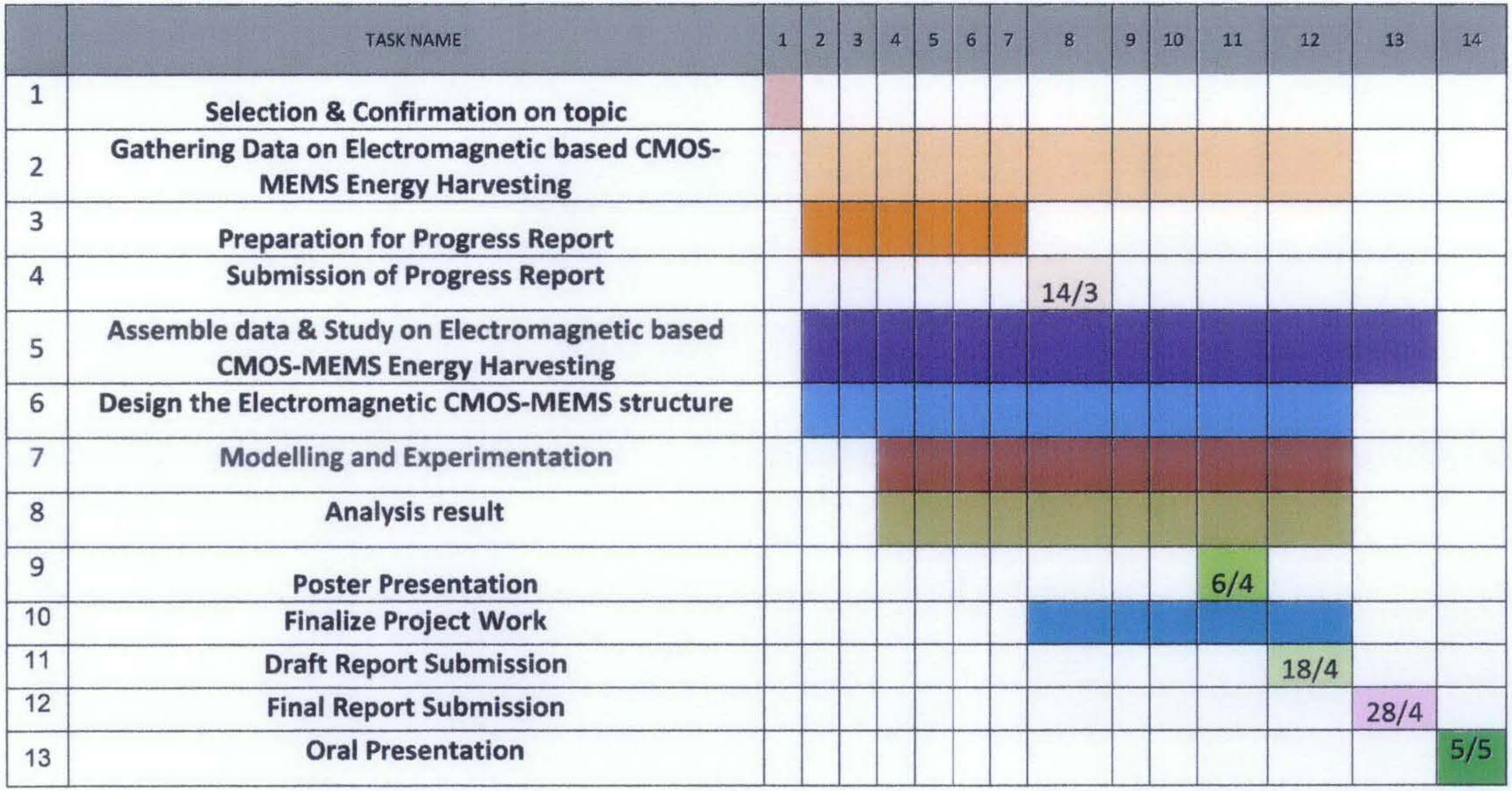
APPENDICES

APPENDIX A

Gantt Chart



	TASK NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Selection & Confirmation on topic**	■													
2	**Gathering Data on Electromagnetic based CMOS-MEMS Energy Harvesting**		■	■	■	■	■	■	■	■	■	■	■		
3	**Preparation for Progress Report**		■	■	■	■	■	■							
4	**Submission of Progress Report**								14/3						
5	**Assemble data & Study on Electromagnetic based CMOS-MEMS Energy Harvesting**		■	■	■	■	■	■	■	■	■	■	■	■	
6	**Design the Electromagnetic CMOS-MEMS structure**		■	■	■	■	■	■	■	■	■	■	■		
7	**Modelling and Experimentation**				■	■	■	■	■	■	■	■	■		
8	**Analysis result**				■	■	■	■	■	■	■	■	■		
9	**Poster Presentation**											6/4			
10	**Finalize Project Work**								■	■	■	■	■		
11	**Draft Report Submission**												18/4		
12	**Final Report Submission**													28/4	
13	**Oral Presentation**														5/5

APPENDIX B

Coding A

```
a=(0:9.8:98)';
s=(0:0.8:8)';
array = [a s];
mult=a.*s;
x= 2*mult;
v = sqrt (x);
plot(s,a);
plot(a,v);
plot(s,v);
```

APPENDIX C

Coding B

```
L = 13096e-6;
B = 1.5;
a=(0:9.8:98);
v= (0:3.96e-3:39.6e-3);
Vemf = B*L*v;
plot(a,Vemf);
```