CMOS-MEMS PIEZOELECTRIC ENERGY HARVESTING SYSTEM

By

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FINAL REPORT

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CERTIFICATION OF APPROVAL

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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.

Siti Nurhakmi bt Suhaidin

ABSTRACT

This paper reports a low-cost, high-sensitivity CMOS-MEMS piezoelectric energy harvester with large proof mass. Piezoelectric has known to be the best in harvesting ambient vibration energy. Its simple theory to produce voltage with stress and vibration has come to many optimization researches to produce the best structure with low natural frequency and high yield strength. Four common materials have been compared to see the performance of generating the voltage output. Zinc Oxide, ZnO thin film was utilized as the best piezoelectric material and device was designed using the infamous cantilevered-beam structure which known as the best structure to produce high sensitivity of vibration and has the highest stress effect at the beam tip attached to the stator comb or fixed end. This structure is indeed compatible with CMOS-MEMS fabrication. The structure has been designed and simulated. The device has a sensitivity of 113.4 μV/g and the structure has been carefully optimized to avoid structured damage due to undesired mode by incorporating the parallel beam to the cantilever-based structure.

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ABBREVIATIONS AND NOMENCLATURE

CMOS	Complementary Metal-Oxide-Semiconductor
NMOS	Negative-Channel Metal-Oxide Semiconductor
IC	Integrated Circuit
SiO_2	Silicon Dioxide
AlN	Aluminium Nitride
ZnO	Zinc Oxide
PZT	Lead zirconate titanate
PVDF	Polyvinylidene fluoride
σ_{max}	Maximum Stress
F	Force
I	Total Inertia
i_{can}	Inertia of cantilever
t_{beam}	Thickness of the Beam
E_3	Electromagnetic
ε_r	Relative Permittivity
ε_0	Absolute dielectric constant (8.85 x 10-12 farad / meter)
d_{31}	Piezoelectric Constant
m	Mass
a	Acceleration
k	Stiffness Coefficient
E	Young's Modulus
L	Length of the Beam
w	Width
f	Resonant Frequency
ρ	Density
l_{can}	Length of the Cantilever
S_{max}	Maximum Strain

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Energy harvesting has received huge attention in the last few years [18]. Energy harvesting relates to the practice of scavenging small amounts of energy from ambient environmental sources example like wind, water, heat and vibration in order to power either some small, low power electronic system directly, or to charge an electrical storage reservoir; usually a rechargeable battery or capacitor that can be used to power a higher power application at time intervals. Micro-power technologies that use their environment for an input energy as opposed on fuel provide benefits of longer operational lifetimes. Systems that combust fuels necessitate greater quantities of fuel from the significant energy transformation losses, thus negatively impact operational lifetimes. Therefore, best alternative must be taken for a safest energy harvesting system. Basically, the energy conversion can be divided by four main focuses throughout the whole world:

a) Photo energy – electrical energy
b) Heat energy – electrical energy
c) Vibration energy – electrical energy
d) Kinetic energy (water flow) – electrical energy

The photo energy represents the solar system, heat energy represents the thermal, kinetic energy represents the water flow and vibration energy represents the electromagnetic, electrostatic and piezoelectric. The inhabitants of planet earth have been using energy from the sun since the beginning of their existence. Conversion methods are usually based on photovoltaic cells [26]. Different materials have been used for photovoltaic cells throughout the history. Photovoltaic can be known as 'matured' energy harvesting system for its well establishment since a very long time ago. It is an abundant energy source and quite inexpensive. It provides voltage and current levels that can be easily matched with microelectronics. It has relatively consistent efficiency over a broad range of wavelengths and the cells last for decades. The problem with solar is, it has limitations on placement because of the need to be correctly-oriented and well-lit locations to place the whole device. It is not suitable for small-scale harvesters because the power output directly linked to surface area. As obvious as it seems, the energy can only be delivered for only part of the day and even so, it is still depend on latitude and atmospheric conditions.

Thermal energy harvesting develops an electric charge in response to a change in temperature. It needs no moving parts and the constructions are quite simple. The disadvantages are the efficiency of conversion is limited. The available energy is affected by the thermal resistance of the source and sink of the thermal energy. The temperature differences tend to be small over miniature size scales and this energy harvesting system is indeed needs a relatively high cost.

Vibration energy represents the most abundant source and is less dependent on the time and place [23]. Vibrations can be found in a wide variety of natural, industrial, commercial and transport environments, including: vehicle engine compartments, trains, ships, helicopters and bicycles, speakers, window panes, walls, bridges, household appliances like fridges, washing machines, microwave ovens, pumps and machinery, and humans. Human movement, or course, is not necessarily directly related to vibrations. Other forms of mechanical energy come into play, particularly those that result from the bending of joints like knees and elbows or those that result from impact during walking or running, or typing on a keyboard.There are three methods of converting mechanical into electrical energy: electromagnetic, electrostatic and piezoelectric [26].

Electromagnetic conversion involves the construction of an assembly that facilitates relative movement between an electrical conductor and a magnetic field, hence the device makes use of Faraday's law of induction [26]. The conductor is usually wound in a coil in order to maximize the area of conductor that is cut by the lines of magnetic flux. A major problem concerning the use of electromagnetic converters is that the output voltage level is usually fairly. Consequently, these types of converters tend to require some form of voltage up conversion, such as a standard capacitor-diode voltage multiplier circuit. The construction of electromagnetic is also quite complicated to be fabricated.

Electrostatic conversion of vibration energy is basically the variable capacitor. A capacitor is charged by some external source and the charge is then held constant. Voltage will change in the changes of capacitance value by the changes in distance between capacitor plates. A plate of the capacitor will be fixed to the vibration source. It will then undergo acceleration in phase with vibration source. The other plate will be fixed to an inertial mass. The initial mass is suspended by spring mechanism to produce the inertia. With this, the second plate will move out of phase with the plate fixed to the vibration source. There are some problems with electrostatic vibration energy harvester. First, it needs external voltage source to charge the capacitor. Second, in maintaining the movement of two conductors in a very small separation, it needs to be in specific state without letting those plates to make contact. Third, it is depending on the mode used whether constant voltage or constant charge the extraction of energy has to be accurately synchronized to the vibration [26].

Piezoelectric conversion involves a very simple theory involving stress upon certain materials and results to a voltage output [1]. Certain materials, which can be either naturally occurring such as quartz, cane sugar, human bone, Rochelle salt or ceramic such as barium titanate, lead titanate, and lithium niobate, are piezoelectric [3]. This will produce an electric charge when subjected to mechanical pressure or conversely, they will physically deform in the presence of an electric field.

Piezoelectric will produce an electric charge when subjected to mechanical pressure and this is called direct effect. Direct effect is where a pair of point charges with equal magnitude but opposite sign, pre-exist within arrangement of material is said to possess 'spontaneous polarization' and point charges move apart or closer together and create results in a voltage. Piezoelectric thin-film will be placed at the highest stress effect of the structure which is at the tip beam connected to the fixed structure.

Micro-Electro-Mechanical Systems (MEMS) is a technology that can be defined as miniaturized mechanical and electro-mechanical elements like devices and structures that are made using the micro-fabrication techniques. The physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters [1]. MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move.

The functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable and interesting elements are the microsensors and microactuators. Microsensors and microactuators are categorized as transducers, which are defined as devices that convert energy from one form to another. For this project, the element used is microsensors. In the case of microsensors, the device converts a measured mechanical signal into an electrical signal. The performance of MEMS devices are exceptional and the method of production leverages the same batch fabrication techniques used in the integrated circuit industry which can translate into low per-device production costs, as well as many other benefits. MEMS devices are able to achieve performance at a relatively low cost level [1]. They are also very compatible to be merged onto a common silicon substrate along with integrated circuits, such as microelectronics. MEMS is undeniably one of the most important technological breakthroughs of the future. 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.

CMOS technology is the semiconductor technology used for microprocessors and applications specific integrated circuits. The incredible growth of the CMOS market has caused rapid development of CMOS technology which has led to advanced CMOS linear devices [2].There are a number of factors that will cause the CMOS linear market to continue to grow rapidly and become a very important part of linear technology. Compared with other microtechnology, CMOS technology is simpler. It does not need the three dimensional parameters like base depth, base thickness and base and collector doping [3]. CMOS technology leads to a better controlled process with less variation in crucial device parameters. The advances in processing techniques and equipment are more applicable to CMOS ICs. CMOS linear devices use the same fabrication process as CMOS digital devices which make integration of analog and digital devices simple. This capability is referred to as mixed mode integration where most components of an electronic system are implemented in a single monolithic IC chip.

The major advantages of silicon gate CMOS compared to metal gate linear ICs are their higher speed and lower power consumption.This lessens the dependence of timing accuracy on expensive components, increasing the accuracy and reducing the cost of the timing function [3]. A faster chip widens the scope of possible applications and increases signal quality and reliability. For a given frequency response, power can be reduced. All of these qualities give wider signal frequency range and operating and design margin providing increased accuracy and gain bandwidth at reduced voltages and power requirement over broad operating conditions.

1.2 Problem Statement

Much of what has been learnt about energy harvesting has been learnt in the past years or so, and can be said that many electronic systems can have built-in energy harvesting functionality in the future. However, low amounts of power delivered from energy harvesting device is giving a barrier to the technology.

Most vibrations energy harvesting devices developed are resonant structures by nature [21]. This needs to match the resonant frequency of the structure with the frequency of the vibration energy harvesting as a feasible power source. Many interesting variety of methods have been employed to achieve frequency tuning. The sources can be varied considerably in amplitude and dominant frequency [14].

As known, most vibration devices are resonant structures and ambient environmental vibrations tend to have higher acceleration values at lower frequencies. The smaller the devices, the more difficult it is to achieve a low resonant frequency.

Constructing a fair comparison of the technologies in terms of achievable power output is a difficult task: a wide variety of methods and device sizes have been employed and a wide variety of environmental conditions have been simulated [12]. In addition, the information required for comparison purposes is not always recorded.

However, it might be possible to observe the general trends of the technologies. There are many potential avenues of exploration that might have been considered include: geometric variations of the harvesters, wearable or implantable harvesters, tuned harvesters and durability of the harvesters.

The problem with piezoelectric is the voltage output is quite small. This is normal without the harvesting circuit. For further research, the device can be added with external circuit to keep the charge [4]. But this problem can be encountered by optimizing the device structure or specifically the geometric parameters. Challenges have emerged when certain objectives of the measurements are needed. Many researchers have incorporated piezoelectric systems including stress sensitivity and power charging elements into MEMS sensors to achieve higher output.

Device optimization is one way in which the power density of a harvesting device can be significantly improved. To design the piezoelectric, many parameters should be taken into account. Basically, the input and output of the device need to be considered when designing the piezoelectric and the process will be explained further in the Methodology. For the process in designing the piezoelectric, the material type needs to be chosen very wisely, counting the CMOS compatibility and amount of voltage that can be produced. Apart from materials, the shape control of the structure can be achieved through optimally selecting the shapes and sizes of the piezoelectric sensor attached to the structure and choosing the force or vibration applied to the sensor.

1.3 Aims and Objectives

The main aim of this project is to enhance the voltage output of a piezoelectric vibration energy harvesting device, by two means: computationally optimizing the geometric parameters of the device by using the basic cantilever beam structure because of the highest stress that can be produced and highest moment of inertia to ensure the constant vibration of the beam. Such that the best use is made of the volume the device may utilize in an application, thereby resulting in an increase in the sensitivity of the device (mV/g).

The main objective for this project is to expose on the basic concept of Piezoelectric and understand the conceptual design and how effective it is in harvesting the energy. Other than that is to improve MATLAB and Coventor Software skills by performing more simulation and this will prove the concept of the piezoelectric theory.

Towards optimising the harvesting device, two models have been used in this research; analytical model and finite element method model. For the analytical model, in order to optimise the geometric parameters, the model must produce an expression for the voltage output of the piezoelectric device. In order to enable the design and development of the device, the model must be capable of predicting other electrical outputs of the device, namely: resonant frequency and yield stress.

From this, the piezoelectric nergy harvesting system needs to be more sensitive to the input of the vibrations, which stress a lot on the acceleration. The relationship between the acceleration and the voltage output must be directly proportional and linear with higher sensitivity.

1.4 Scope of Project

This project is intended to design an alternative to harvest the energy by using piezoelectric concept to generate the electrical energy. This project targets mainly the rural population where electricity is not available or it is unreliable. Piezoelectric effect is actually a new thing to be learnt out of all syllabuses taken. Therefore, it took more hard work to finish the task.

It can be considered that there are three main points to a typical, complete, energy harvesting system: the harvesting device energy transducer, the harvesting circuitry and the end application system. There are some works that concentrate on all three blocks of the system, so that a full system is realized and analyzed at project conclusion. However, this project focuses only on one point only, which is the harvesting device.

This project investigates the relationship between the geometric optimization of the piezoelectric generator itself that leads to the change of resonant frequency and how the stress and acceleration affects the voltage output generated.

CHAPTER 2

LITERATURE REVIEW

2.1 A Brief History of Piezoelectric

The piezoelectric effect was first demonstrated conclusively by the brothers Pierre and Jaques Curie in 1880. The word *piezoelectricity* means electricity resulting from pressure [3]. The compression – elongation of the piezoelectric layer creates electric charges that are collected by the electrodes and transferred to the load. [4] Piezoelectric materials produce a voltage in response to an applied force, usually a uniaxial compressive force. The borthers chose specific crystal cuts from crystalline solids like tourmaline, quartz, topaz, cane sugar and Rochelle salt for use in their experiments and were able to prove the appearance of a surface charge on the crystals when the crystals were subjected to mechanical stress. This later known as the piezoelectric 'direct' effect. In 1893 Lord Kelvin, a British mathematical physicist and engineer, develop an atomic model to describe the effect.

2.2 Contribution from Other Researches

There are numerous studies involving piezoelectric energy harvesting in variety of demonstration and applications has been employed. Demir et al reported the strain, deflection and generated output power for a power generator with a PZT membrane. They investigated the residual stress and compositional function of PZT thick film [20]. Lu et al [21] proposed the mdoeling of 21 mode power generators with films of PZT crystals [21]. Marzencki et al [22] Fabricated a cantilever based energy harvester with Si proof mass. Their energy harvester generated a relative low power of 0.038μW due to low piezoelectric properties of AlN film [22]. Fang et al [23] aligned a proof mass at the end tip of the PZT cantilever for a larger displacement. The PZT material used generated 2.16 μW at 1 g and 609 Hz conditions. Elfrink et al [24] generated 2V under 2g acceleration force and 572 Hz of resonant frequency. Shen et al [25] generated 160 mV under 2 g acceleration force and 456 Hz with power level of 2.15 μW.

2.3 Basic Description of the Piezoelectric Effect

To understand the piezoelectric effect, the internal structure of the solids that exhibit must first be understood. The word *piezoelectricity* means electricity resulting from pressure [3]. The compression – elongation of the piezoelectric layer creates electric charges that are collected by the electrodes and transferred to the load. [4] Piezoelectric materials produce a voltage in response to an applied force, usually a uniaxial compressive force.

In this project, the application concept to be used is sensor. The principle of operation of a piezoelectric sensor is the transformation of a physical dimension into a force, acts on two opposing faces of the sensing element [5]. Due to the intrinsic characteristics of piezoelectric materials, there are numerous applications that benefit from their use.

As for example, when a sound of a particular frequency hit the microphone transducer used in electromechanical device, it will result in a strain in the material, which will then induces an electric field. Other than that, piezoelectric sensors are also used with high frequency sound in ultrasonic transducers for medical imaging and industrial non-destructive testing.

2.4 Piezoelectric Dipole Moment

Applying pressure to the material alters the dipoles by the following process: as pressure is applied to a unit cell with no centre of symmetry [7], the cell physical distorts, resulting in a change in the distance between the positions of average positive and average negative charge, thus altering the 'moment' of the dipole. This alteration results in a change of polarisation density of the crystal, which correlates directly with a charge per unit area developed on the external face of the crystal.

Materials which are centrosymmetric, when placed under stress, experience symmetrical movement of ions, meaning there isn't a net polarization. Dipoles near each other tend to be aligned in regions called Weiss domains. The domains are usually randomly oriented or can also be aligned through process by which a strong electric field is applied across the material at suitable temperature [8, 9].

2.5 Piezoelectric Concept

Piezoelectric concerned with two properties:

a) electrical
b) mechanical

The piezoelectric effect is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials and stand in two concepts [5]:

a) Direct concept – generation of electrical charge resulting from an applied mechanical force
b) Inverse concept – generation of a mechanical force resulting from an applied electrical field

2.6 Piezoelectric Parameters

Piezoelectricity directly couples a mechanical elastic property which is stress or strain, to an electrical property which is dielectric displacement (polarisation) or electric field, and the piezoelectric coefficients are used to connect either of the two mechanical variables with either of the electrical variables. In this project, the mechanical elastic property used is stress and it needs to produce the electric field within the material.

The choice of variables determines the particular piezoelectric constant to be used. The piezoelectric coefficient is given with superscripts and subscripts depending on theory of this project, which is harvesting energy out of piezoelectric or in short, direct effect. Superscripts denote the quality held constant, for example ε^{σ} denotes that this coefficient was determined while stress was held constant. The subscripts denote the directional conditions under which the coefficient was determined. The axes sense is as shown in Figure 2-23, where the Cartesian "x" corresponds to "1", "y" corresponds to "2" and "z" corresponds to "3".

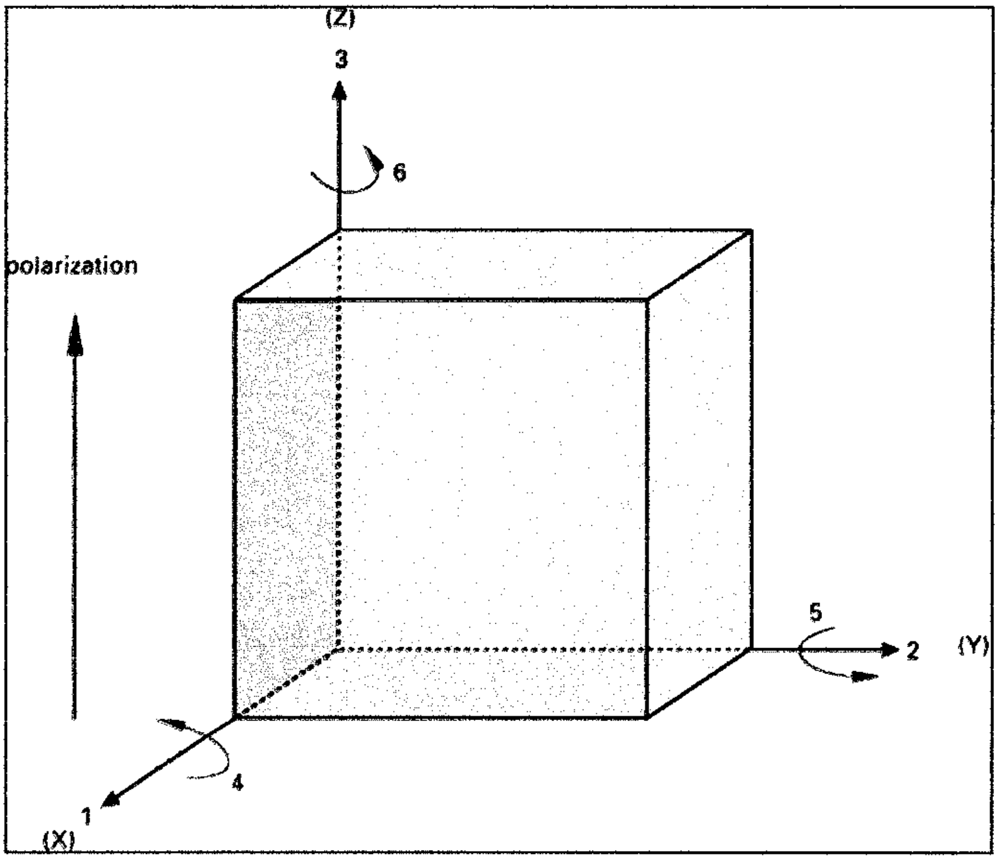

Figure 1: Labeling of Reference Axes and Planes. [7]

Piezoelectric coefficients with double subscripts (i and j) link electrical and mechanical quantities. The first subscript (i) gives the direction of the electric field or can be said as the direction of polarization generated in the material when the electric field, E, is zero. The second subscript (j) gives the direction of the mechanical stress.

To design the piezoelectric, the parameters that need to be considered such as vibration or force excitation, stress needed, permittivity, elastic compliance and voltage and current output [10]. The main thing that needs to be achieved is how much stress needs to be applied in order to generate the highest voltage as possible by using the material chosen. After the coefficient has been captured, the next step is to proceed to the simulation process.

In this project, the concept used is the Direct Concept, parallel with the main objective of this project which is to find the alternative of energy harvesting or in other words it can be called as piezoelectricity technology. The properties can be cascaded into two equations of electrical ($[\varepsilon_i][E_j]$) and mechanical properties ($[d_{ij}][\sigma_j]$) as in Equation 1 and 2.

$$D_1 = [\varepsilon_1][E_3] \tag{1}$$

$$D_3 = [d_{31}][\sigma_1] \tag{2}$$

The interaction of electrical (1) and mechanical (2) properties can be described by linear relationships [6]:

$$D_i = d_{ij}\sigma_j + \varepsilon_i E_j \tag{3}$$

These linear relationships are derived using D_i for electrical displacement, piezoelectric constant d_{ij} for the material, σ_j as stress applied, permittivity ε_i and electric field E_j. Because they depend on the anisotropy [12,13] of the piezoelectric material, these physical quantities can only be defined in terms of tensors which reflect the directionality of the electric field, the mechanical stresses, etc.

2.6.1 Piezoelectric Charge Coefficient

The piezoelectric charge coefficient, d_{31}, describes the generation of polarisation int the "3" direction (z-axis) per unit mechanical stress applied in the "1" direction. Based on research, the higher the value of d_{31} is the better.

2.6.2 Permittivity

The *permittivity*, or *dielectric constant*, ε, for a piezoelectric ceramic material is the dielectric displacement per unit electric field. ε^{σ} is the permittivity at constant stress. Below shows the equation for dielectric constant:

$$\varepsilon = \frac{permittivity\ of\ material}{dielectric\ constant\ (free\ space)} = \frac{\varepsilon_r}{\varepsilon_0} \tag{4}$$

where relative dielectric constant, ε, is the ratio of the amount of charge that an element constructed from the ceramic material can store, relative to the absolute dielectric constant, ε_0, the charge that can be stored by the same electrodes when separated by a vacuum, at equal voltage (ε_0 = 8.85 x 10-12 farad / meter).

2.6.3 Young's Modulus

As with all solids, piezoelectric ceramics have mechanical stiffness properties described as Young's Modulus, *Y*. Young's Modulus can be yielded from Equation 5 stated below with the ratio of stress (force per unit area) to strain (change in length per unit length). For this project, the Young's Modulus used is Silicon Dioxide's.

$$Y = \frac{stress}{strain} = \frac{T}{S} \tag{5}$$

2.6.4 Insersia and Moment of Inersia

The width, w_{can} and thickness t_{can} of beam will effect the inersia (6). For a beam that will vibrate at z-axis, the equation is as shown below:

$$i_{can} = \frac{w_{can}\ x\ t_{can}^{3}}{12\ x\ 2} \tag{6}$$

and this equation is of course, depend on the quantity of beam used. Equation stated is for 1 cantilever beam used.

Density ρ is obtained from the ratio of the mass to volume in the material, expressed in kg/m^3 in Equation 7. Total volume of cantilever beams and proof mass also taken into consideration in Equation 8. This is very important to choose the mass of the proof mass and beam. Density of the Silicon and the total volume will produce the mass that needed in Equation 9. This will indirectly affect the moment of inersia which is as stated in Equation 10. Lastly, inersia and moment of inersia equation will be used in calculating the strain as in Equation 11.

$$\rho = \frac{mass\ volume}{volume} \left(\frac{kg}{m^3}\right) \tag{7}$$

$$V_T = (L_{pm} \times t_{pm} \times w_{pm}) + (L_{can} \times t_{can} \times w_{can}) \tag{8}$$

$$m = \rho_{SI} \times V_T \tag{9}$$

$$M = F \times \left(l_{can} + \frac{L_{pm}}{2}\right) \tag{10}$$

$$S_{max} = \frac{M \times t_{can}}{Y_{SiO2} \times i_{can}} \tag{11}$$

2.7 Resonant Frequency of Piezoelectric

Two Variables which are vital in obtaining reliable predictions for the generated voltage output are the natural frequencies and mode shapes of the structure. The change in geometric structures might change the movement of the beam.

Most properties of a piezoelectric ceramic element erode gradually, in a logarithmic relationship with time after polarization. Exact rates of aging depend on the composition of the ceramic element [15] and the manufacturing process used to prepare it. Mishandling the element by exceeding its electrical, mechanical, or thermal limitations can accelerate this inherent process. Therefore in this project, it is very important to consider the mechanical limitations for dynamic operation especially the resonant frequency.

The resonant frequency of a material is changed by mechanically loading it, and this principle is used for very accurate measurements of very small mass changes in the quartz crystal microbalance and in thin-film thickness monitors. Such a narrow resonant leads to highly stable piezoelectric [16] and a high accuracy in the determination of the resonant frequency.

In this project, resonant frequency must be kept constant to produce a sensitive energy harvester to the environment. The ambient frequency is 50-200 Hz [2] but the frequency is different at windy environment. In Malaysia, the windy climate at frequency more than 200 Hz might break the device. Therefore, the frequency aim is at 500 to 600 Hz. The required inputs to the optimization problem are the resonant frequency for the device and constraints for the volume of the device as stated in resonant frequency Equation 12 below:

$$freq = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{12}$$

where k is the spring constant and m is the mass consisting aluminum, silica and silicon dioxide. Mass (Equation 9) of piezoelectric material is neglected because it is too small. The spring constant in Equation 13 tells why geometric design affects the resonant frequency a lot.

$$k = \frac{2Ewt^3}{L^3} \tag{13}$$

L is the length of cantilever beam, w is the width of cantilever beam, t is the thickness and E is the Young's Modulus. The equation proves that the frequency of material is dependent on the geometric of the device.

When resonant frequency is low, the device sensitivity to vibrate is higher. The vibration of the beam is described by its acceleration a, which can be converted into force applied to beam's tip by Newton's Law as shown:

$$f = ma \tag{14}$$

where f is force, m is mass and a *is acceleration.* Theoretically, high piezoelectric potential would be generated when a large external force is applied onto the thin-film with smaller thickness, because large relative displacement is produced [2]. However in real case, the relative displacement of nanostructure is restricted by the mechanical strength and flexibility.

2.8 Piezoelectric Materials

There are many materials, both natural and man-made, that exhibit a range of piezoelectric effects. Piezoelectric materials can be divided by two main groups; piezoelectric ceramics and single crystal materials. Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices [7].

2.8.1 Piezoelectric Crystals

Piezoelectricity is the property of nearly all materials that have a non-centrosymetric crystal structure. Some naturally occurring crystalline materials possessing these properties are quartz and tourmaline. Some artificially produced piezoelectric crystals are Rochelle salt, ammonium dihydrogen phosphate and lithium sulphate.

2.8.2 Piezoelectric Ceramics

Approximately, the ceramic materials have a piezoelectric constant sensitivity that is two orders of magnitude higher than those of single crystal materials and can be produced by an inexpensive sintering process [10]. Unfortunately, their high sensitivity is always combined with a lack of long term stability. Therefore, piezoelectric ceramics are very often used wherever the requirements for measuring precision are not too high.

Piezoceramic components are the all-important part of electromechanical transducers [26]. Piezoceramic has special and proactive properties and already tapped many applications and have a firm footing in modern engineering [17]. Piezoceramic requires only very little energy and their shape potential are almost unlimited. And that's why this material is used in widely-ranging equipment and mechanical engineering applications.

2.9 Piezoelectric Design Shape

In [26], the author suggested to use cantilever beam for higher stress point to be generated on the piezoelectric thin-film at ambient acceleration and natural frequency. Similar stress sensitivity can be achieved by optimizing the geometric parameters of the structure [4]. In [11], magnetic coupling of a piezoelectric cantilever has been used for the same reason. A number of CMOS-MEMS piezoelectric energy harvesters have been demonstrated, in most of which only CMOS thin film micro-cantilever structures were used as proof mass [22, 23, 24, 26]. The residual stress in CMOS thin films often causes large structure curling. Thus, the area and mass of the proof mass structure is also limited.

The basic structure used is called cantilever beam and has been modified to enhance the performance. Two beams are attached to the proof mass to convert the external stress applied to each of the beam tip to relative displacement between the beam and the stator comb drives and produce the vibrations which will induce strain within piezoelectric material [2].To avoid different modes of vibration which may surely damage the device, the dimension of the structure must be carefully design so that it will be compatible with CMOS-MEMS fabrication, vibrate only at z-plane which is below the yield strength of the materials, constantly move at a suitable resonant frequency and hence produce higher voltage.

The equation to be used in calculating the voltage output is based on the shape design. Sodano et al. (2004b) formulated a model of a power harvesting system that consisted of a cantilever beam with piezoelectric patches attached. There are many other researches came out with the cantilever design and compared to other structure, cantilever gives a lot of impact on the vibration characteristic and result to better output for the device. The shape that will be used is based on cantilever beam shape. Cantilever beams are a main structural element receiving bending forces. Bending of the cantilever induces the potential difference on opposite sides of the piezoelectric layer providing an information signal about the detected chemicals [18]. The choice of cantilever is based on the "Beam Theory".

The simplification of the linear theory of elasticity provides a means of calculating the load-carrying and deflection characteristics of beams. It covers the case for small deflections of a beam which is subjected to lateral loads only [18]. The maximum principal stress in the beam may be neither at the surface nor at the center but in some general area [19].

The material film will be vertically sandwiched between two conducting films. Cantilever beam is divided into two parts:

1) Overlapped with piezoelectric material
2) Not overlapped with piezoelectric material.

This is because the difference of thickness for each part will yield to difference inertia. The stress along the length is not uniform and changes with the position (Equation 15). The relationship between the applied force and the induced voltage was calculated using Equation 16.

Equation for the applied stress:

$$\sigma_{max} = \frac{Mt}{2I} = \frac{Flt_{beam}}{2I_{beam}} \tag{15}$$

$$V = E_3 t_{piezo} = \frac{D_3 t_{piezo}}{\varepsilon} = \frac{d_{31_{piezo}} \mathrm{x}\ \sigma_{max} \mathrm{x}\ t_{piezo}}{\varepsilon_{piezo}} \tag{16}$$

and using Equation **15** and **16** for voltage output yielded to Equation 17:

$$V = E_3 t_{piezo} = \left(\frac{d_{31}}{\varepsilon_{Zno}}\right)(\sigma)\left(t_{piezo}\right) = \frac{Flt_{beam}t_{piezo}d_{31}}{2\varepsilon I_{beam}} \tag{17}$$

and F is the force manipulated, l is the length of the beam, t_{beam} is the thickness of the beam, t_{piezo} is the thickness of the piezoelectric material, ε_r is the dielectric constant of the beam and I_{beam} is the inertia of the beam.

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Procedure and Identification

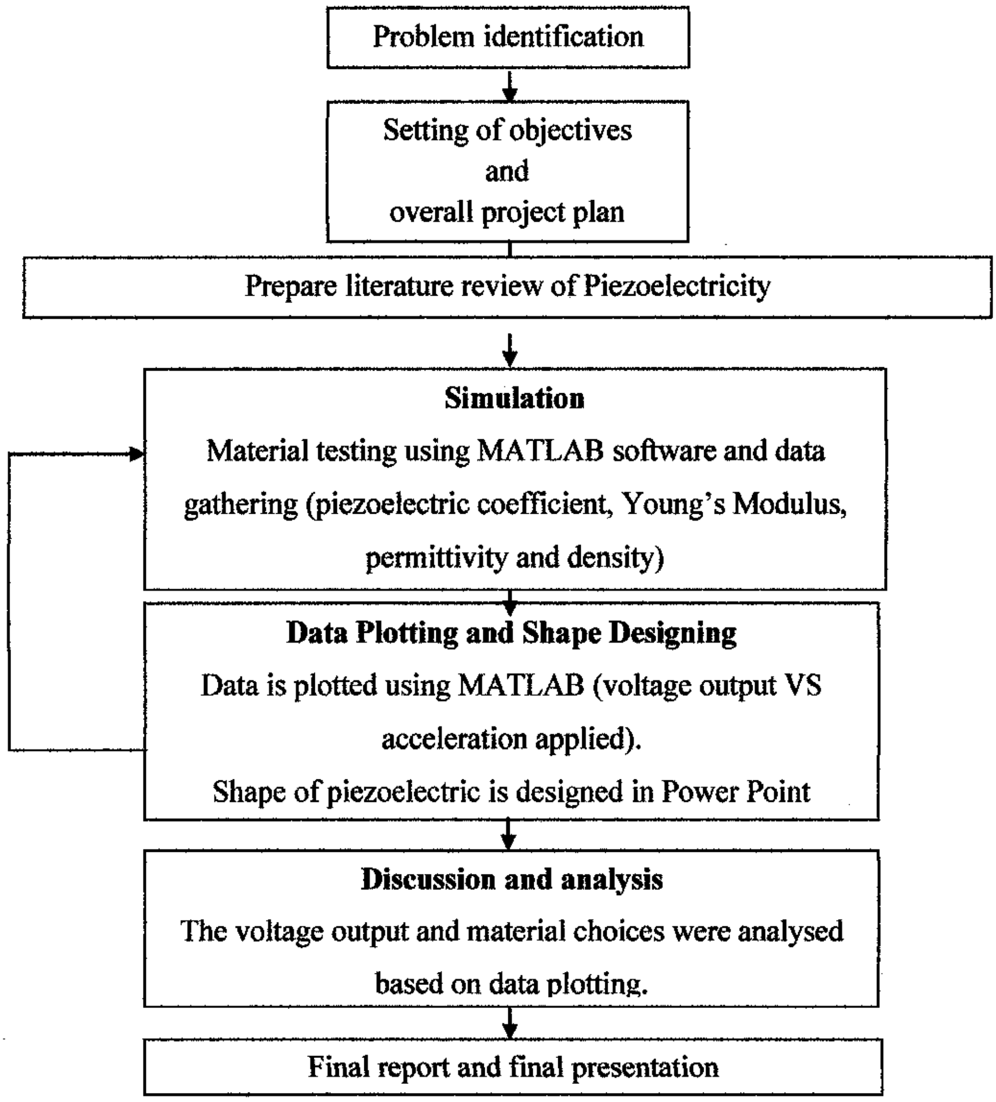

Figure 2: Flow Chart of Methodology

3.2 Methodology

3.2.1 Background Research

As a start, some researches were done to understand the literature of piezoelectric. For the Piezoelectric Principle, the tasks will be divided into two parts; Theoretical and Device and Structure Design. For the theoretical, the main focus will be on the parameters involved in the piezoelectric and how the effect goes. There are many materials can be used to design the piezoelectric sensor. This comes parallel with the explanation which will be included with some related formula and calculations.

3.2.2 Materials Option

For the first step of choosing the right materials, the main point to be taken into account is the material compatibility with the CMOS. Based on some research from the media, the most common used materials in MEMS for the piezoelectric are Zinc oxide (ZnO), Lead zirconate titanate (PZT), Polyvinylidene fluoride (PVDF) and Aluminum Nitride (AlN). These materials are very common material used in piezoelectric applications. The simulations will be done to all four materials to observe which material is the best in generating voltages.

3.3 Structure Design

For the Device and Structure Design, the process required Power Point to build the shape according to the design. At this point, the shape and the materials used will be the main concern to produce the best power at the output of the device. The MATLAB was used to simulate the graph based on parameters used. For this case, all parameters and coefficients used were taken from the reference book to ensure the condition of which the coefficients were gathered is equal.

3.4 Tools and Equipment

3.4.1 MATLAB

After research for the materials type, the voltage equation and material coefficients gathered were defined in MATLAB – M-file coding to test which material results to the highest voltage output and then that material will be chosen as the piezoelectric material.

3.4.2 Power Point

Power point was used to dimensioning the 3D drawing of the shape designed in Wings 3D. It was also used to design the shape for some simple angle.

3.4.3 Conventor Software

Coventor Software is a computer-based analysis for the advanced numerical modelling method that is very reliable in producing accurate results when simulating the structure design. It enables detailed visualisation of the design.

3.5 Model and Analysis

In regard to the piezoelectric vibration energy harvesting device, an analytical model has been constructed that considers the effect each geometric parameter has on the power output of the device. By relating each dimension of the device to the power output, the model results in an expression for the power output whose arguments include every dimension of the piezoelectric generator.

CHAPTER 4

RESULTS AND DISCUSSION

Designing a harvester for a particular situation is difficult because all of the parameters interact. To gain some insight a number of simplifying assumptions will be made for the system without considering the damping factors and inductor. For this chapter, the aim is to produce the scenario where the vibration characteristics and constraints are dictated by a particular application and the optimum dimensions for maximum power output are required. This section is split into sub-sections as follows:

1) Section 4.1: Data Gathering
2) Section 4.2: Discussion of the vibration characteristic (Acceleration, Displacement and Stress.)
3) Section 4.3: Material characteristics as inputs

4.1 Data Gathering

The developed analytical model was used to determine the effects of various parameters on the generated voltage. In the following analysis Aluminum is used for the substrate layer and ZnO, PZT, PVDF and AlN for the piezoelectric layer; the structures dimensions and material properties are provided in Table 1 and Table 2 respectively. All the results presented in paper are calculated at the final resonant frequency of the structure and only the first vibrational mode. At resonant frequency, the contribution of other modes on the displacement is negligible.

The properties considered in the comparison process are relative permittivity (ε_r), Young's modulus or hardness (GPa), Density (kg/m^3), Coupling factor (k), Curie temperature ('c) and Relative permittivity or dielectric constant (ε_0). Permittivity of space used is, 8.85 x 10^{-12} F/m. For each material, the structure and type are different.

Table 1: Physical Properties of Each Material.

Segment	Material	Thickness (μm)	Width (μm)	Length (μm)
Thin-film	Piezo Material	1	10	10
Proof Mass	SiO_2	65	500	500
Beam	SiO_2	10	10	200

Table 2: Mechanical and Electrical Properties of Each Material.

Material	Young's Modulus (GPa)	Density (kg/m^3)	Relative Permittivity ε_r	Material Permittivity (p)	Piezoelectric Coefficient, d_{31} $(\rho C/N)$
ZnO	210	5600	8.5	75.23	5.43
PZT	135	7750	1730	15310.05	93.4
AlN	340	3187	9	79.65	1.65
PVDF	3	1880	13	115.05	20
SiO_2	107	2650	4.52	40	-

The material will be doped on a beam, which is SiO2 with relative permittivity or dielectric constant of 4.52. The parameters were used to calculate the voltage generated by using the Equation 17.

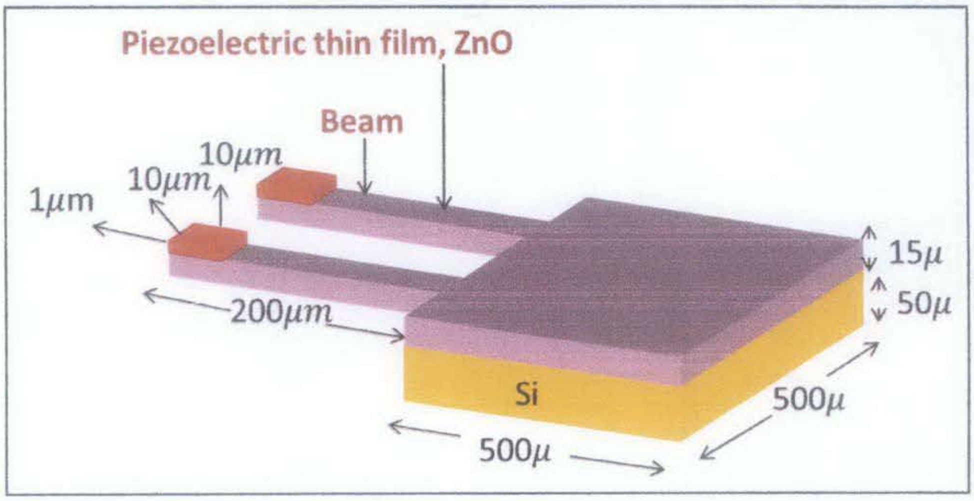

Figure 3: 3D Diagram for the Cantilever Shape and Parameters

Many experiments were conducted to obtain the right geometric parameters. This is very important to prove the characteristic of the resonant frequency in Equation 12. The design which was based on final scale in Figure 3 and resulted in Figure 4 and 5 after exported to Coventor Software. The device was covered with fixed mass to enhance the dynamic structure of the device. The design was then meshed into many parts (of the device) for more accuracy in calculation on the stress (Figure 6).

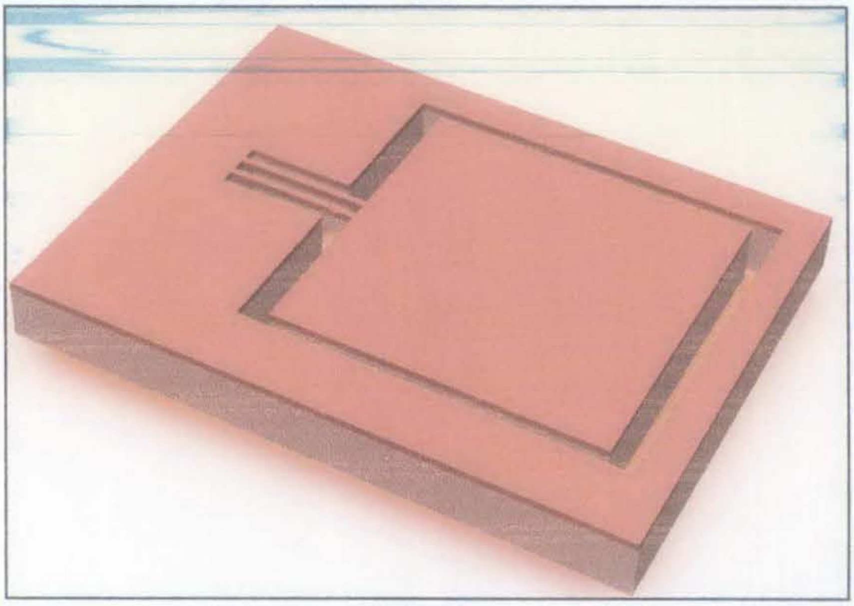

Figure 4: Surface of The Modelling Using Coventor Software Simulation.

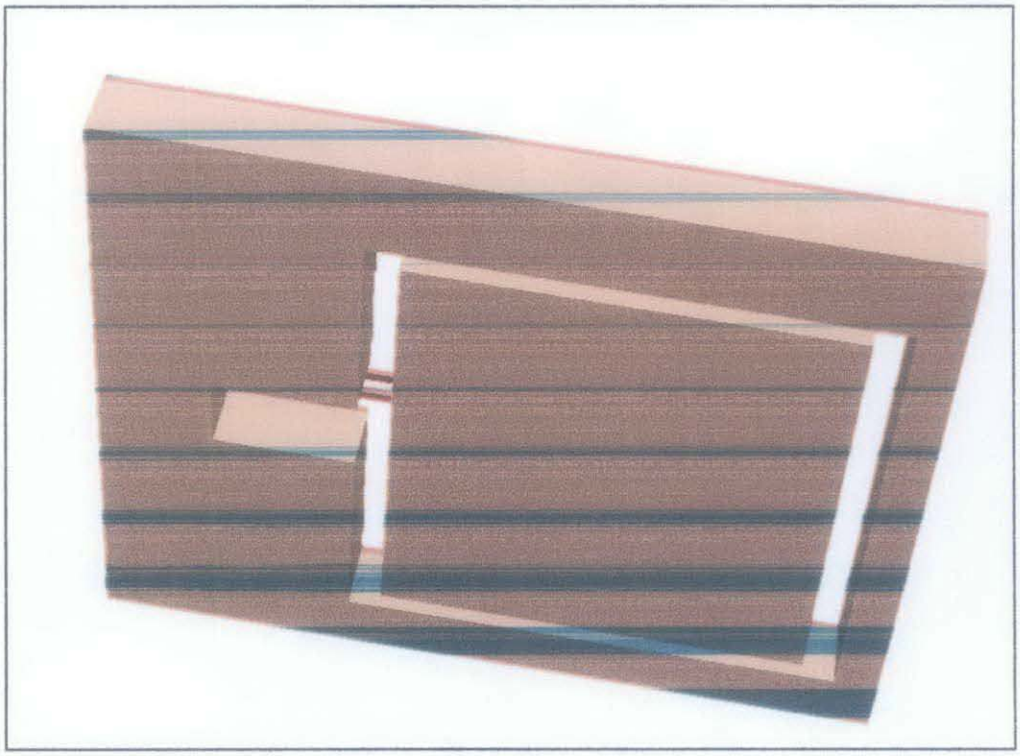

Figure 5: Bottom of The Modelling Using Coventor Software Simulation

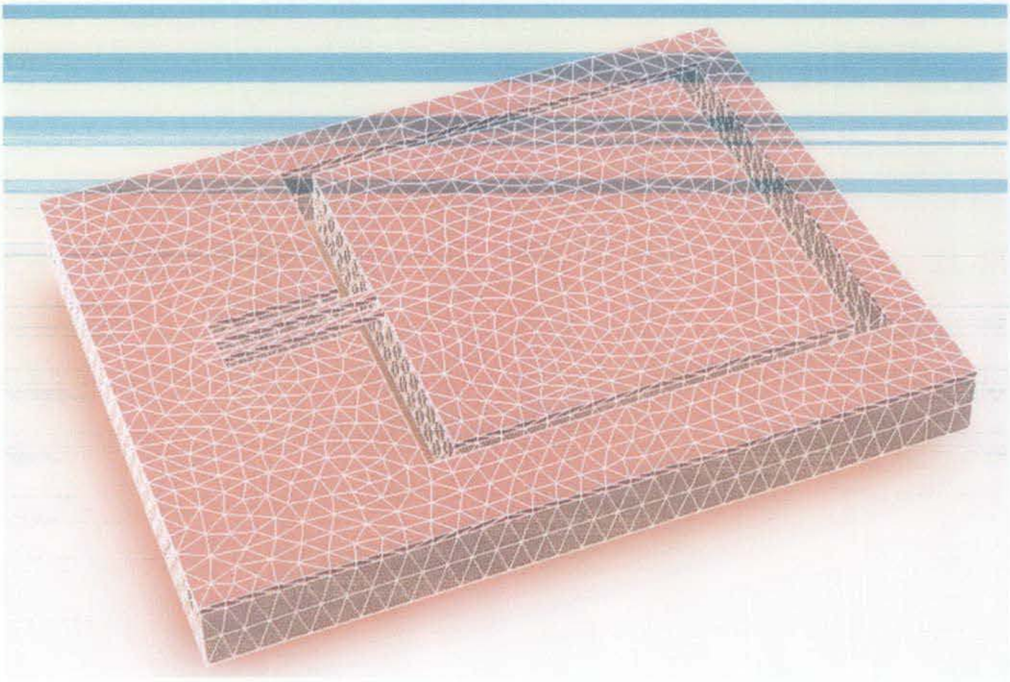

Figure 6: Meshed Process on Device in Coventor Software.

4.2 Discussion of Vibration Characteristics

There are three pieces of information regarding the vibration environment that need to be taken into account in order to optimise the device: the target frequency, the acceleration of the or displacement and the stress to the device. Vibration environments have been previously researched and measured and reported in [12] and [14] for the purpose of vibration energy harvesting. For the second information required, the acceleration level, a value of ±2.25m/s2 is the minimum acceleration because this is representative of real-world vibration environments [3]. Another input left, which is stress is not yet announced for the official world wide minimum ambient stress from the environment, but it is being widely researched from various scholars.

The next result from Coventor Software is shown as below figures. The structure from analytical analysis was being designed in the Coventor Software and experiment to calculate the displacement (Figure 7) and stress (Figure 8) of the moving beam towards z-axis. The acceleration was varied 1 to 10g. Results were shown in Table 3.

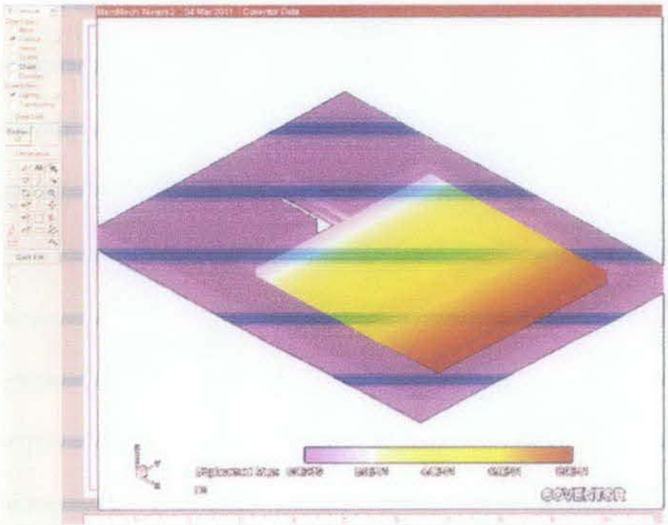

Figure 7: Displacement Magnitude based on Coventor

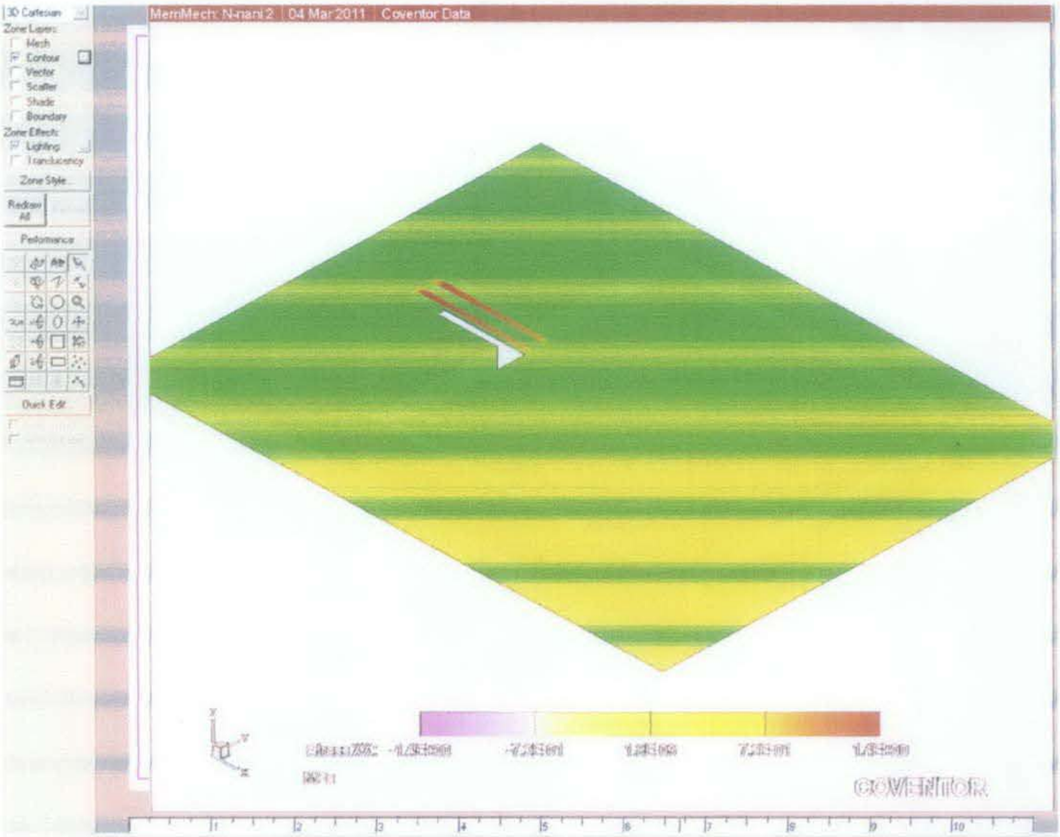

Figure 8: Stress magnitude based on Coventor.

From Figure 8, the highest stress level is at the beam which produce 1.4Mpa at acceleration 1g. This means, the piezoelectric material thin-film should be placed at that part of area to produce higher voltage output. After some simulations, results are observed. Table 3 is the result captured from the Coventor Software. The result is basically involving the properties of substrate which is Aluminum because of its higher Young's Modulus which of course, can bear higher stress and frequency It is based on the acceleration of 1g to 10g.

Table 3: Displacement and Stress vs Acceleration based on Coventor

Acceleration, (g)	Displacement (μm)	Stress (MPa)
1	0.8	1.4
2	1.6	2.9
3	2.4	4.3
4	3.2	5.8
5	4	7.2
6	4.8	8.6
7	5.6	10
8	6.5	12
9	7.2	13
10	8	14

In practice that is quite impossible for the device to hold the stress level especialy at megapascal. But this is just basically calculated from the acceleration. This means, for the device to vibrate, it requires less than 1g of acceleration. Based on researches [2,4] it basically needs around 300mg and above to vibrate the device. Even the average acceleration of air is approximately 230mg.

Table 4 shows the analysis of result after going through some calculations. The acceleration range is chosen between 10mg to 200mg because that is the range of piezoelectric acceleration requirement. The displacement is kept constant at 1.1μm because that is the highest (based on Coventor Software) displacement the proof mass can take at 1g. The stress obtained and the frequency is the analysis result from first simulation from Coventor Software. The voltages for all materials are calculated using Equation 17.

Table 4: Full Results based on analysis from Coventor Software

Acceleration	Stress	Displacement	Frequency	Voltage (μV)			
(g)	(Pa)	(um)	(Hz)	PZT	PVDF	ZnO	AlN
0.01	18	1.10	298.48	9.51	2.03	0.55	0.37
0.02	36	1.10	422.12	19.02	4.07	1.10	0.74
0.03	54	1.10	516.98	28.53	6.10	1.66	1.11
0.04	72	1.10	596.96	38.03	8.14	2.21	1.48
0.05	90	1.10	667.42	47.54	10.20	2.76	1.86
0.06	108	1.10	731.13	57.05	12.20	3.31	2.23
0.07	126	1.10	789.71	66.56	14.20	3.87	2.60
0.08	144	1.10	844.23	76.07	16.30	4.42	2.97
0.09	162	1.10	895.44	85.58	18.30	4.97	3.34
0.10	180	1.10	943.88	95.08	20.30	5.52	3.71
0.20	360	1.10	1334.85	190.20	40.70	11.00	7.42
0.30	540	1.10	1634.85	285.30	61.00	16.60	11.10
0.40	720	1.10	1887.76	380.30	81.40	22.10	14.80
0.50	900	1.10	2110.58	475.40	102.00	27.60	18.60
0.60	1080	1.10	2312.02	569.60	122.00	33.10	22.20
0.70	1260	1.10	2497.27	665.60	142.00	38.70	26.00
0.80	1440	1.10	2669.70	760.60	163.00	44.20	29.70
0.90	1620	1.10	2831.64	855.80	183.00	49.70	33.40
1.00	1800	1.10	2984.81	950.80	203.00	55.22	37.10
2.00	3600	1.10	4221.16	1907.40	407.00	110.40	74.20

4.2.1 Resonant Frequency

According to Roundy et al. [11] for 'low level' ambient vibrations, a common frequency magnitude is below 200 Hz and out of several vibration sources they examined the frequency peak centred somewhere close to 120 Hz. That frequency is very much suitable for environment acceleration which might not be constant and less efficiency and extremely fragile. Other than the environment, the vibrational energy waste also occured to many other applications which mostly require higher output power like transformer, medical treatment [3] generators, car vibration and many more. For this project, the target frequency is 400 Hz – 1000 Hz, suitable for many applications.

After doing the simulation in the Coventor Software by varying the geometric parameters, final result of resonant frequency yielded is 647.3 Hz. This means, the geometric parameters effect on the structure (cantilever)'s natural or resonant frequency. The effect of external force with higher frequency range of the cantilever will change the mode of beam movement. The device has been varied to 3 different mode which shown in Figure 9, 10 and 11 to observe the higher frequency and stress it can take.

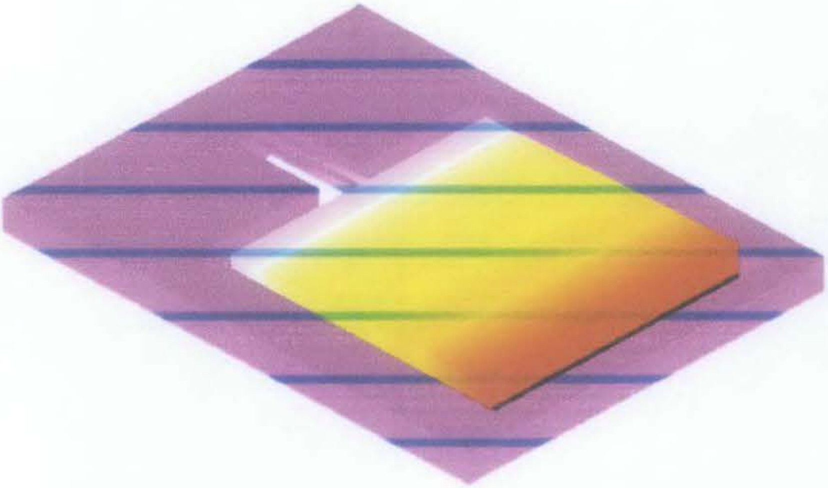

Figure 9: "Z" Mode

Figure 7 is resulted from frequency of 647.3 Hz occured in Z-mode. This is the desired mode. The beam is vibrating at z-axis or 3-axis direction. The problems occured if the mode changes to "See-Saw" mode and "X-Y" mode as in Figure 8 and 9.

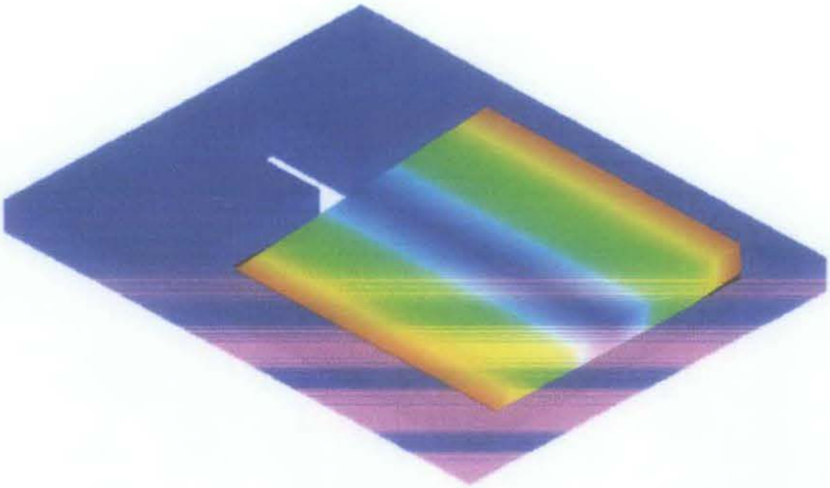

Figure 10: "See-Saw" Mode.

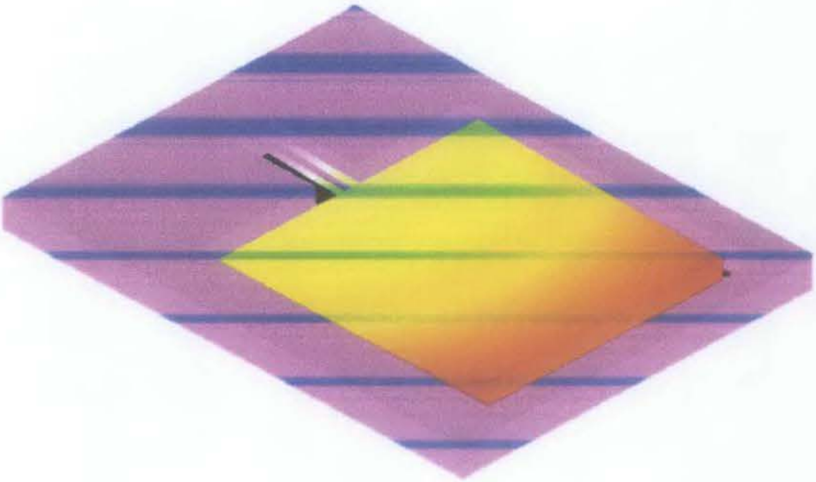

Figure 11: "X-Y" Mode.

Figure 10 with 2130 Hz in "See Saw" mode and Figure 11 with 5550 Hz in "X-Y" mode. Different modes of the device operation is one of the factors to break the device. Other factor will be shown afterwards. Using data captured from the Coventor Software (Table 4) a graph has been plotted to observe the range of all the three modes in Figure 12. Mass of proof mass attached on the beam is calculated using Equation 12. Mass of the beam is ignored because the value is too small.

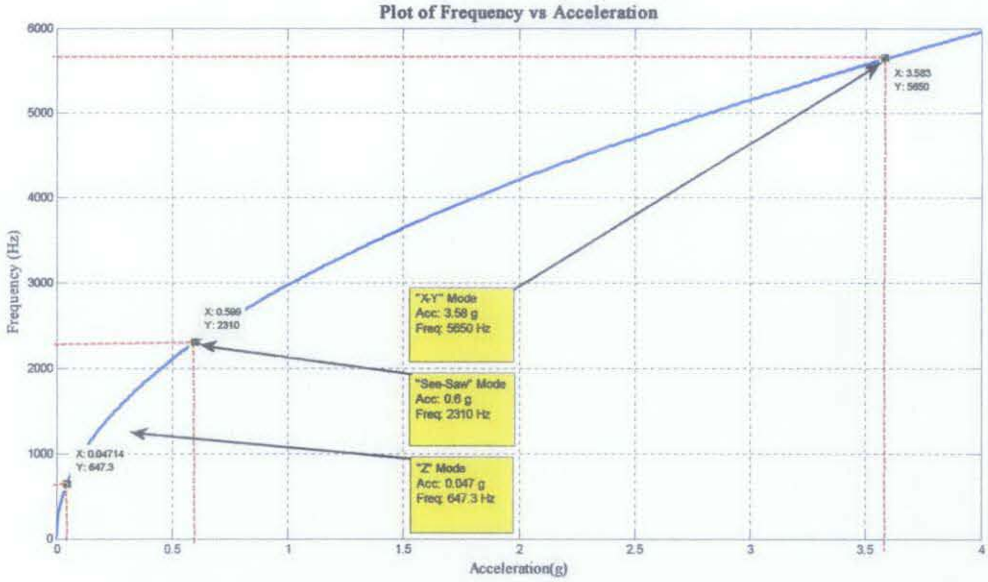

Figure 12: Frequency vs Acceleration for all 3 Modes

The results of frequency range in Figure 12 show that "Z" mode has the smallest range while "See Saw" mode has the highest frequency range which is starting at 5650 Hz. There is an early assumption from the simulation results. There is a high possibility of the device to break starting at frequency of 2130 Hz which means, starting at the first mode change.

Figure 13 focus on the range of "Z" mode. The value might be smaller if other condition of the device is considered, which is the yield strength. If the displacement of the vibrating device is too high that it reaches the point of deformation, this device will easily break.

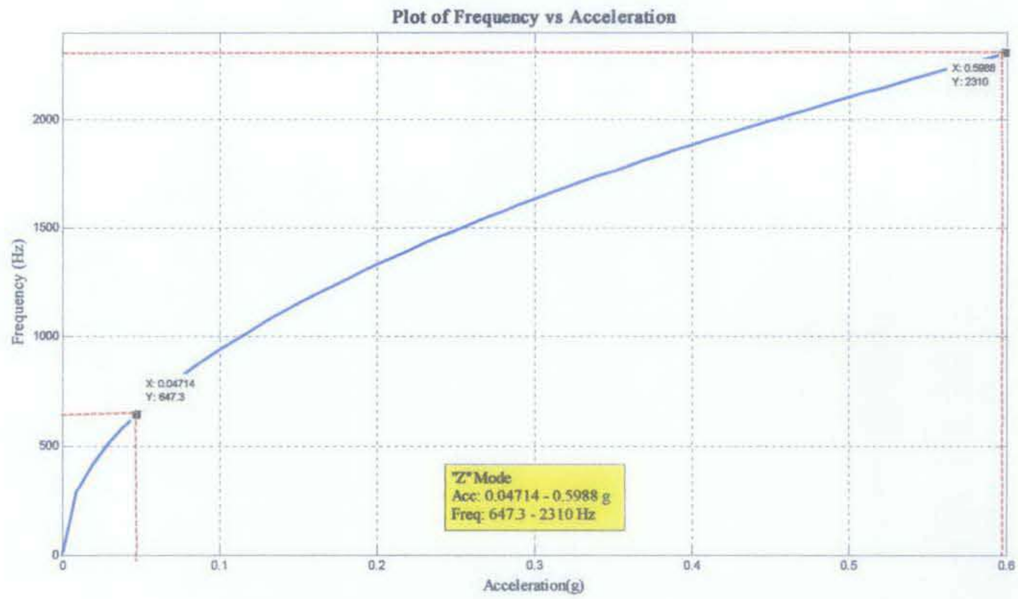

Figure 13: Frequency Range for Z-Mode

The range of "Z" mode vibration is 647.3 to 2310 Hz. The curve line of "Z" mode (red line) range is almost linear. The range of acceleration to move beam is 0.0471 to 0.5988 g. This is normal value for Piezoelectric device especially nanostructure geometric parameters. This resonant frequency of the device can be changed to gain better output result, but it must still within the range of "Z" mode.

For this project, the geometric parameters should be compatible with CMOS-MEMS technique and suitable to be fabricated as microchip device and placed in the environment. The target as stated is the ambient vibration.Since from a small deviation from the resonant frequency induces a large reduction of output signals due to narrow resonant peak of MEMS devices, the energy harvester requires precise modeling to determine their dimensions for the expected resonant frequency (Equation 12).

Simulations have been done in MATLAB to see the relationship between the geometric parameters and the frequency of the device. Figure 14 shows that the trend between resonant frequency (Hz) and beam length (m) varies with constant displacement at 1.1μm and acceleration varies from 10mg to 10g.

The graph is labeled with the range of frequency which is below the yield strength to see the whole idea of characteristic. The width and thickness is kept constant at 500μm and 65μm respectively. The range of frequency obtained according to the first graph (Figure 13) is 353.7 to 2133 Hertz. From the graph, the length of the device can still be changed within range of 284.45μm to 772.3μm.

According to Rupesh Patel et al in [19], the magnitude of the inverse time constant is mainly responsible for the varying trend. As shown in the graph, increment of the beam length reduces the magnitude of inverse time constant thereby benefiting the generated voltage.

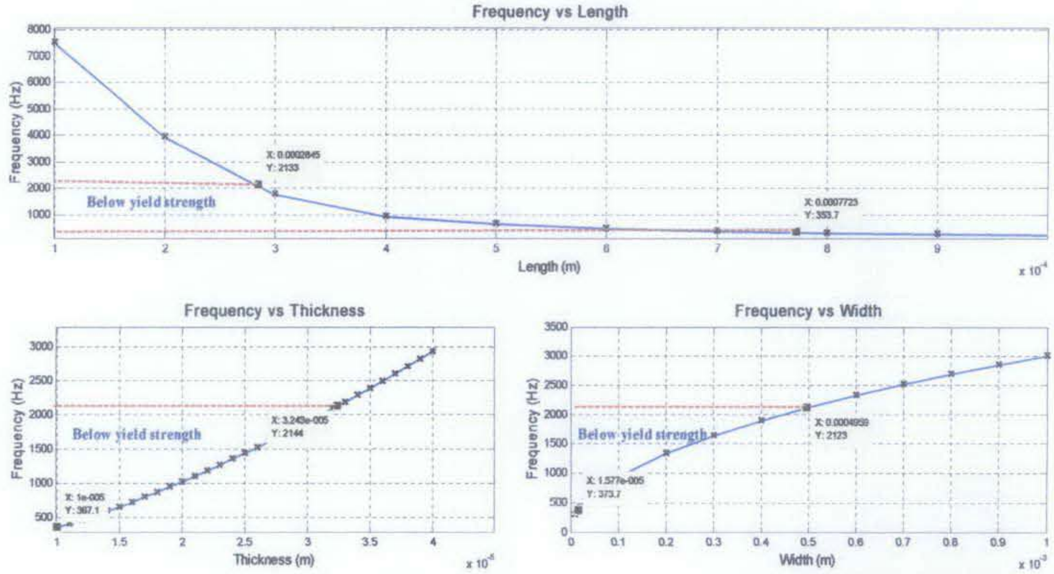

Figure 14: Relationship Geometric Parameters of Device and Frequency.

Other trend is observed from the graph. Graph Frequency vs Width is observed and the results show that it is better to use wider beam. Below the yield strength, range of beam width with the constant of length and thickness is 15.5μm to 500μm.

This results show that, the current beam used now is the highest beam and can still be changed to lower beam width. With the sensitivity (slope) of the graph and considering the stiffness (Equation 13) it is better to use multiple narrower beams rather than one wide beam.

One issue with altering the geometrical parameters is that the resonant frequency of the system will be changing too [26]. This problem can be catered down by altering the parameters simultaneously. Theorytically, for the same value of resonant frequency, higher voltage will be generated for higher thickness of the thin-film. Then the length of the beam can be reduced at the right scale depending on the sensivity of the graph.

4.2.1 Acceleration, Displacement and Stress

Apart from the resonant frequency of the device, there is one other thing that must also be taken into consideration; the yield strength of the device. The piezoelectric layer will not be taken into account because it is too thin that it will be neglected, because it is the cantilever's strength that will confront the stress [26]. By using the data in Table 3, a graph is plotted to see the relationship between Displacement and Stress in the manipulation of Acceleration upon the device.

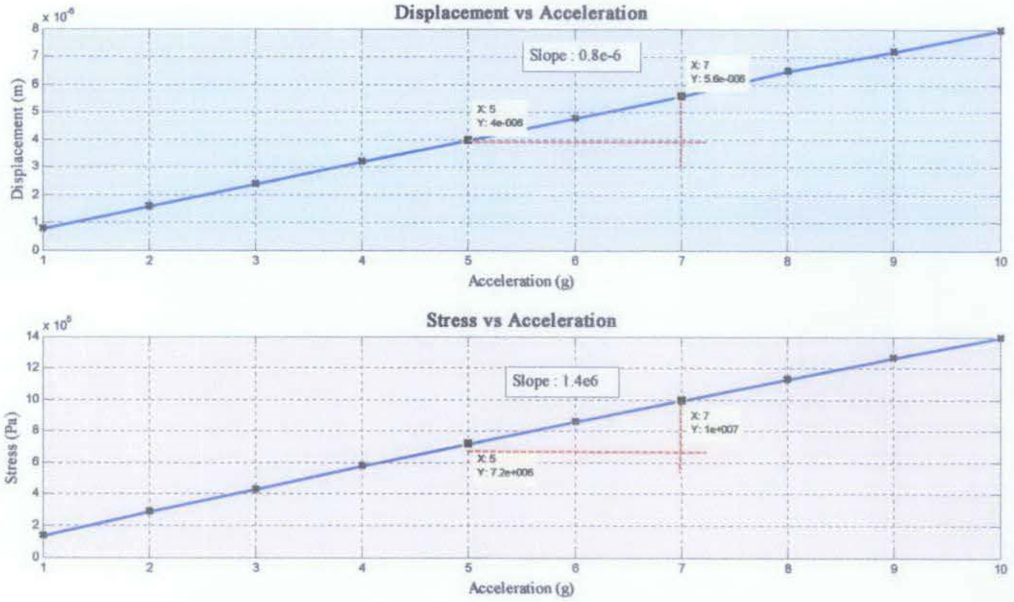

Figure 15: Displacement and Stress vs Acceleration based on Coventor.

Both graphs in Figure 15 are linear. Displacement changes every 0.8μ while stress change 1.4M. This means all the changes of both graphs are uniform. Same thing goes with Displacement vs Acceleration graph. In short, as acceleration increase, the value of displacement and stress also increase. Therefore, stress and displacement is proportional to acceleration.

For this project, all pieces of layers involved in fabricating the device [26] should be taken into account to calculate the sensitivity, the stress level it can bear until its yield strength.

For this device, aluminum is used as reference to the maximum strength the device can take. A graph of stress-strain characteristic had been plotted in Figure 16 by using data in Table 5. The data is calculated based on the observation from Coventor Software result and analysis in Table 4.

Table 5 : Strain-Stress from the Variation of Acceleration and Displacement

Acceleration (g)	Displacement (m)	Strain (m)	Stress (Pa)
0.05	0.04	0.08	17.67
0.06	0.05	0.10	36.73
0.07	0.06	0.11	55.76
0.08	0.06	0.13	74.77
0.09	0.07	0.14	93.74
0.10	0.08	0.16	112.70
0.20	0.16	0.32	300.79
0.30	0.24	0.48	486.30
0.40	0.32	0.64	669.22
0.50	0.40	0.80	849.57
0.60	0.48	0.96	1027.36
0.70	0.56	1.12	1202.59
0.80	0.64	1.28	1375.29
0.90	0.72	1.44	1545.45
1.00	0.80	1.60	1713.08
2.00	1.60	3.20	3252.87
3.00	2.40	4.80	4551.20
4.00	3.20	6.40	5617.90
5.00	4.00	8.00	6462.80
6.00	4.80	9.60	7095.73
7.00	5.60	11.20	7526.53
8.00	6.50	13.00	7781.80
9.00	7.20	14.40	7821.03

Figure 16: Stress-Strain Characteristic of Al Thin-Film Based on Coventor

From graph shown above, true elastic limit of aluminum substrate is 17.72 Pa. It is defined as the lowest stress at which the beam move. Since the beam moves at very low stresses so detecting its true elastic limit is very difficult. But this is basic assumption based on calculations and trend observation. At its proportional limit, the stress is already proportional to strain. The yield strength is the one that has been explained before that will effect the elasticity of the beam and very easily break. As long as the stress exert to the beam is lower than the yield strength (2993 Pa) of the substrate material (Aluminum) the beam is still able to vibrate.

4.3 Discussion of Materials Characteristics

In addition to the vibration characteristics, a further consideration is the characteristics of the materials that the cantilever comprises. These material characteristics can be categorized as inputs to the objective function. There are many types of piezoelectric ceramic available commercially. As we already understood, the piezoelectric effect consists of the ability of certain crystalline materials to generate an electrical charge in proportion of an externally applied force (direct piezoelectric effect) [4].

The concept of utilizing piezoelectric material for energy generation has been studied by many researchers over the past few decades. In order to ensure or prove the optimum design of these results, some sensitivity analysis is required. A research was done on commercial piezoelectric thin films that are currently available. A difficulty in finding out about the piezoelectric properties was that quite often not all of the data required was provided by the manufacturers and it changes with several conditions. But what most important in a material is the piezoelectric charge constant; a high piezoelectric charge constant which imply a high conversion of mechanical energy to electrical energy.

The piezoelectric constants in Table 2 are the values of films measured for less than 1μm under a given force of cantilever; the stress on the surface of the structure is different depending on the Young's modulus of the materials. For example, polymer PVDF has a low Young's modulus and makes larger displacement on the structures as compared to others. Materials used in this simulation are PZT, Zinc Oxide (ZnO), Aluminum Nitride (AlN) and PVDF.

According to previous researches [21, 22, 23, 24, 25, 26], the best material that generates voltage is PZT. This is due to its higher piezoelectric constant d_{31} and following it is PVDF, ZnO and AlN. There are many type of PZT that has been used in the industry, but the fabrication process is quite complicated than other materials.

Voltages generated by of all four materials were being analytically calculated by using Equation 17 based on variables used in Table 2 and produce results in Table 5 and Figure 17, 18 and 19 shows the comparison between the four materials. The acceleration is varied from 0.01 to 2 g. Stress is obtained based on the analysis from Coventor Software simulations. Displacement is kept constant with 1.1μm. Frequency yielded also based on Graphs below shows the voltage output vs acceleration to both materials used:

Figure 17: Voltage vs Stress for PZT, PVDF, ZnO and AlN

From Figure 17 above, at stress applied is 1.8kPa, the voltage output is generated by PZT is highest with 951.7 μV, followed by material PVDF, ZnO and AlN. The voltage generated is linear and proportional to the stress exerted.

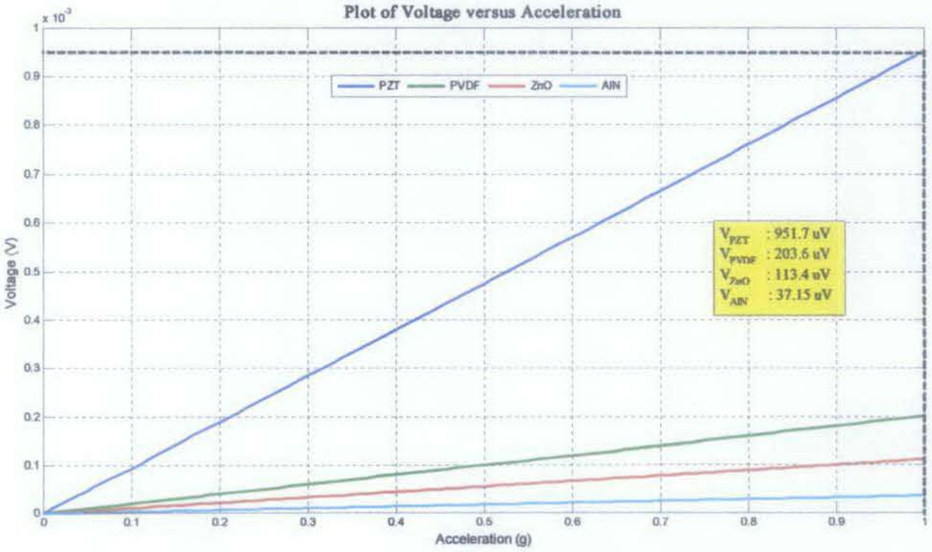

Figure 18: Voltage vs Acceleration for PZT, PVDF, ZnO and AlN

As expected, the graph of Voltage vs Acceleration in Figure 18 above is also linear and the voltage output generated is also proportional to the acceleration, since the stress is proportional to the acceleration.

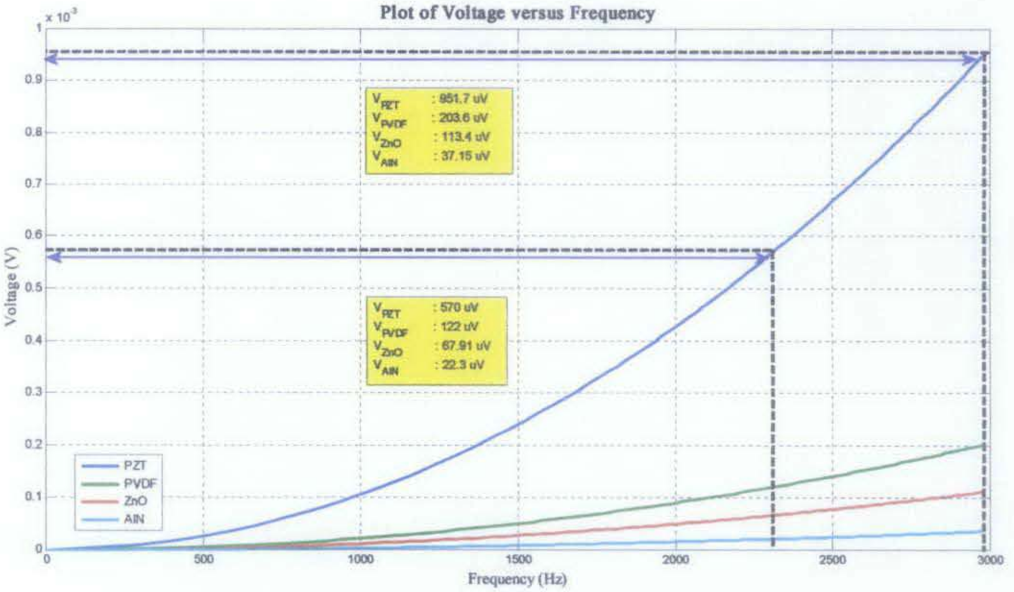

Figure 19: Voltage vs Frequency for PZT, PVDF, ZnO and AlN.

In Figure 19, the graph of Voltage vs Frequency is not linear. It is a polynomial shape. But unlike the graphs in Figure 17 and 18, this graph shows that the maximum frequency before the mode change is effect on the voltage output too. The highest voltage this device can generate within the "Z" mode at 0.599g is 570μV for PZT, 122μV for PVDF, 67.91μV for ZnO and 22.3μV for AlN.

Table 6: Comparison of PZT, PVDF, ZnO and AlN Results

	PZT	**PVDF**	**ZnO**	**AlN**
Voltage Sensitivity (μV/g)	951.7	203.6	113.4	37.15
CMOS-compatibility	Complex	Compatible	Compatible	Compatible
Strength	Very High	Very low	High	High
Frequency Band	Narrow	Narrow	Very wide	wide
Availability	Rare	Common	Common	Common

The Table 6 above shows the properties and results from simulations and research [2, 3, 5, 8, 9]. The PZT is obviously the best in generating voltage compared to other materials, but compared to other materials, the fabrication of PZT is way more complicated and complex. PZT has the highest strength while PVDF comes to the lowest. Of all materials, ZnO has the widest frequency band, which is up to Giga Hertz. This is very advantageous as it can be used in many applications that require high frequency. Of all materials, PZT is quite new and not very common compared to other materials.

From all materials, ZnO is indeed the best material because it is CMOS-MEMS compatible, common in the industry, the price is reasonable, has high strength and has a very wide frequency band.

According to Emma Louise's report [26], "*One cannot simply change a dimensional parameter, without first considering that the volume, and the resonant frequency constraint must both be adhered to, otherwise the comparison would be meaningless.*"

4.4 Summary of Device Design, Performace, Advantages and Disadvantages

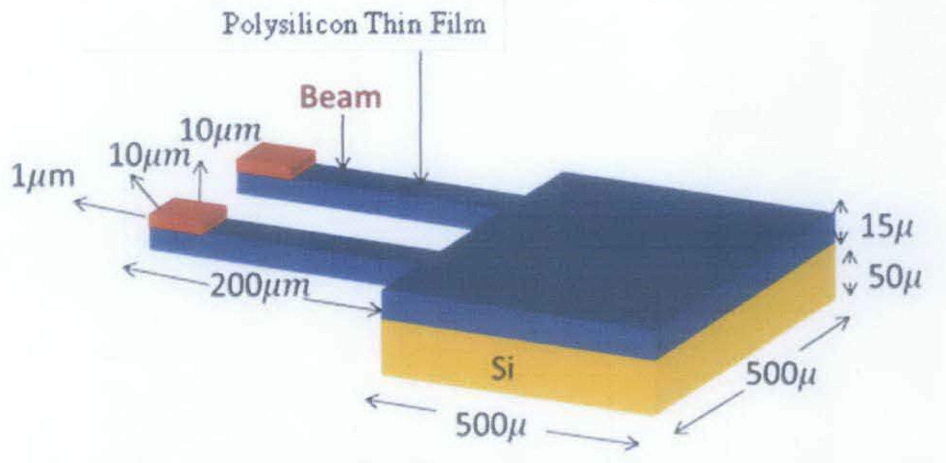

Figure 20: 3D View of Finilized Piezoelectric Energy Harvesting Design

Table 7: Finilize of Geometric Parameters

Segment	Material	Thickness (µm)	Width (µm)	Length (µm)
Thin-film	Piezo Material	1	10	10
Proof Mass	Al+Si+SiO_2	65	500	500
Beam	SiO_2	10	10	200

Table 8: Advantages and Disadvantages of the Device

Advantages	Disadvantages
CMOS-compatible	Low voltage sensitivity
Wide Frequency Band	
High Strength	
Reliable	

Figure 20 shows the 3D view of finilized design of this project. Table 7 concludes the geometric parameters after being changed in some ranges and going through number of simulations. The advantages and disadvantages of this device are stated in Table 8. The performance of the device is achieved according to the objectives for enhancing the voltage, with 113.4 µV/g but still low sensitivity and need to be improved to enhance the sensitivity of the device.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the piezoelectric energy harvester is produced. In order to use piezoelectric able to convert unused mechanical vibration energy to electrical energy such as with motor or generators. Piezoelectric cantilevers have been widely studied for energy harvesting applications, but suffer from poor output power outside of a narrow frequency range near the cantilever resonant. The cantilever length bring much effect on the structure strength. The resonant has been set to 647.3 Hz instead of using the ambient frequency, which varied from 50 – 200 Hz. This is due to the sensitivity of the device and to avoid the yield strength as possible. Resonant values were set by varying the length of cantilever. The results from Coventor Software proves that the larger the stress value, the higher the voltage output becomes. Acceleration gives effect to the stress and thus the voltage output. ZnO appears to be the best material which is very compatible and can be used in many applications.

5.2 Recommendations

The configuration of piezoelectric parameters should be optimized with higher increment in the voltage output. Since voltage levels obtained from energy harvesters are rather low and periodic, a storage capacitor is usually included in the circuitry. Future studies will be carried out on a more realistic storage.

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APPENDIX A
MATLAB CODING

```
% Piezoelectric Simulation
% FYP 2010

clear all,close all,clc,

% Piezoelectric MATERIALS : ZnO
% Piezoelectric Proof Mass : Si/SiO

%----------------------PHYSICAL PROPERTIES------ -----------------%

% Materials (from internet: value differs with physical properties)
    rho_Si = 2659;     % density of bulk silicon [kg/m3]
    E_SiO2 = 107e9;    % SiO2 Young's Modulus (GPa)[N/m^2]
    e_SiO2 = 4.52;     % SiO2 Dielectric constant [k^T]

% Piezoelectric Thin-Film, [m]
    t_piezo = 1e-6;
    w_piezo = 5e-6;
    l_piezo = 5e-6;

% Proof Mass
    L_pm = 500e-6;          % length,m
    t_pm = 2400e-6;           % thickness,m
    w_pm = 500e-6;           % width,m
    V_Si = L_pm*t_pm*w_pm;  % volume = length*thickness*width

% Cantilever : SiO2
    l_can = 200e-6;
```

```
    t_can = 5e-6;
    w_can = 5e-6;
    l_L_can = l_can + L_pm/2;


%----------------------ELECTRICAL PROPERTIES------ -------------%
% a) Relative Permittivity (Dielectric Constant), k
     %(k=permittivity material/permittivity space)
        DC_ZnO = 8.5;                          % ZnO



     % Permittivity Space, e0 [Farad/m]
        e_space = 8.85e-12;


     %  Permittivity Material, e [Farad/m]
        e_piezo = e_space*DC_ZnO;            % ZnO



 % b) Piezoelectric Coefficient Matrix [C/N]
      d31_piezo = 5.43e-12;                  %ZnO

%----------------------MECHANIAL PROPERTIES-----------------------%

% a) Young's Modulus MATERIAL (GPa)[N/m^2]
     E_piezo=210e9;     % ZnO



% b) Maximum STRAIN at the cantilever surface
     m=rho_Si*V_Si; % mass=density*volume
     %g=1:100    % range for the acceleration
     g=1:10:1000;    % range for the acceleration
     a=g*9.8;        % acceleration [1g = 9.8 m/s^2] applied = 10g
     F=m*a;          % force generated by the acceleration and mass

% c) Moment of Inertia, M
     M=F*l_L_can;                % Inertia of beam cantilever
```

```
    % Inertia Proof Mass (ignore cantilever inertia, assume too small)
    I_pm = (2*w_pm*t_pm^3)/12;  % inertia for 1 beam
    i_pm = I_pm/2;              % inertia for 2 beams

% d)STRAIN (Strain=Moment*thickness/2*Young's Modulus*Inertia)
    strain_max = (M*t_can)/(2*E_SiO2*i_pm);    % SiO2 Strain
    %strain_max = (M*t_can)/(2*E_piezo*i_can); % Piezo Strain

% e)STRESS (Stress=Strain*Young's Modulus)
    stress_max = E_SiO2*strain_max;


    %----------------------VOLTAGE OUTPUT-------------------------%


%V=2*(d31_piezo*F*1_L_can*t_can*t_piezo/(2*e_piezo*i_pm));

n = 2; % no of piezoelectric in series
D3=d31_piezo*stress_max;
E3=D3/e_piezo;
V=2*E3*t_piezo;

%------------------------GRAPH PLOTTING-------------------------%

plot (g, V)
xlabel('acceleration [m/s^2]')
ylabel('Voltage [V]')
axis ([0 100 0 1e-4]);
hold on
title('Plot of Voltage versus Acceleration')
%axis ([0 1000 0 1e-3])
```

SUBPLOT COMPARISON GRAPH for DIFFERENT MATERIAL

```
ZnO = [2.83e-07 5.66e-07 8.49e-07 1.13e-06 1.41e-06 1.70e-06 1.98e-06 2.26e-06 2.55e-06 2.83e-06];
PVDF = [2.29e-07 4.58e-07 6.86e-07 9.15e-07 1.14e-06 1.37e-06 1.60e-06 1.83e-06 2.06e-06 2.29e-06];
AlN = [4.62E-08 9.24E-08 1.39E-07 1.85E-07 2.31E-07 2.77E-07 3.24E-07 3.70E-07 4.16E-07 4.62E-07];
PZT = [4.36E-08 8.72E-08 1.31E-07 1.74E-07 2.18E-07 2.61E-07 3.05E-07 3.49E-07 3.92E-07 4.36E-07];


subplot(2,2,1); plot(ZnO)
title('ZnO')

subplot(2,2,2); plot (PVDF)
title('PVDF')

subplot(2,2,3); plot(AlN)
title('AlN')

subplot(2,2,4); plot(PZT)
title('PZT')
```

Graph Voltage vs Stress

```
d = 5.45e-12;%piezo constant ZnO
e = 7.52e-12;%epsilon ZnO
s=(0:1.4e6:14e6);%stress applied from coventor
t= (1e-6);%thickness piezomaterial film
Vo = (d/e)*s*t;
plot(s,Vo);
xlabel('Stress [MPa]')
ylabel('Voltage [V]')
title('Plot of Voltage versus Stress')
```

```
 Graph Voltage vs Acceleration
d = 5.45e-12;
e = 7.52e-11;
t= (1e-6); L = 700e-6;
a = (0:1:10);
Y = 5600;
s =(Y*L*a);
Vo = (d/e)*s*t
plot(a,Vo);
xlabel('Acceleration [g]')
ylabel('Voltage [V]')
title('Plot of Voltage versus Acceleration')
```

```
%Equation to solve the Relationship between Acceleration vs
Frequency

a = (0:1e-3:2e1); % Acceleration range from 1e-3 to 2e1
g = (a/9.8);
D = 0.53e-6; % Average (safe) displacement of the device based on
COVENTOR
f=sqrt(a/D);% Equation of to find frequency
%using formula: F=ma, a=(D/t^2)=(D*f^2)

plot (g, f)
xlabel('Acceleration [g]')
ylabel('Frequency [Hz]')
title('Acceleration vs Frequency')
```

```
 Plot of Voltage Versus Acceleration for Each Material
x = 0:1e-2:1e1;
s = (45.96e-6*x*9.8)/(500e-6*500e-6);
```

```
y = (93.5e-12*s*1e-6)/(20*8.85e-12);
y2 = (11.43e-12*s*1e-6)/(20.52*8.85e-12);
y3 = (20e-12*s*1e-6)/(20*8.85e-12);
y4 = (3.65e-12*s*1e-6)/(20*8.85e-12);

plot(x,y,x,y2,x,y3,x,y4)

xlabel('Acceleration')
ylabel('Voltage [V]')
title('Plot of Voltage versus Acceleration')
```

APPENDIX B

GANTT CHART

No.	PROJECT	JAN	FEBRUARY				MARCH				APRIL					MAY		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	13	14
		24/1 - 30/1	1/2 - 6/2	7/2 - 13/2	14/2 - 20/2	21/2 - 27/2	28/2 - 6/3	7/3 - 13/3	14/3 - 20/3	21/3 - 27/3	28/3 - 3/4	4/4- 10/4	11/4 - 17/4	18/4 - 24/4	25/4 - 29/4	2/5 - 8/5	9/5 - 15/5	16/5 - 22/5
1.0	**UTP Procedures**																	
	1.1 Progress Report								14th									
	1.2 Poster Presentation (EDX)											6th						
	1.3 Draft Report													18th				
	1.4 Final Report (Softcopy)														28th			
	1.5 Technical Report														28th			
	1.6 Viva															3rd		
	1.7 Final Report (Hardbound)																	20th
2.0	**Researches**																	
	2.1 Structure Design	🟥	🟥	🟥	🟥													
	2.2 Coventor Simulations					🟨	🟨	🟨	🟨	🟨								
	2.3 Resonant Frequency					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨			
	2.4 Optimize Design								🟨	🟨	🟨	🟨	🟨	🟨	🟨			
	2.5 Simulation Performance Using MATLAB											🟨	🟨	🟨	🟨			
	2.6 Materials Comparison								🟨	🟨	🟨	🟨	🟨	🟨	🟨			

Gant Chart : Final Year Project Semester 1