COMPARISON OF MECHANICAL AND PIEZOELECTRIC POWER
EXTRACTION FROM A SPEED BUMP

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DEDICATION

I would like to dedicate this master’s thesis to my parents, Anand Phalke and Sunanda Phalke.
ABSTRACT OF THE THESIS

Comparison of Mechanical and Piezoelectric Power Extraction from a Speed Bump
by
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San Diego State University, 2011

The ability to capture yet untapped resources is critical to the future of energy supply. There were many motivations behind energy harvesting, and the most important is the issue of climate change and global warming. The goal of this research is to theoretically and experimentally investigate the behaviors of an energy harvesting system constructed with a bimorph cantilever built of Lead Zirconate titanate (Pb[ZrxTi1-x]O3) and tungsten proof mass to convert vibration energy into electrical energy and a mechanical system built on a gear reduction mechanism to convert the translational motion into rotational and further into electrical energy. Gear reduction is used in order to maximize the rotational motion out of translational. Based on simulation, it was found that the piezoelectric bimorph cantilever generator can produce up to 8V with the frequency range of 150 Hz and the mechanical system built on a gear reduction mechanism can produce up to 6V.
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CHAPTER 1

INTRODUCTION

This study is a theoretical and experimental comparison of a piezoelectric generator and a mechanical system built of a gear reduction mechanism. Piezoelectric generator is used to harvest the vibrational energy from a speed bump and its surroundings whereas the mechanical system is used to harvest the kinetic energy of a vehicle when it strikes the speed bump.

There is an increasing interest in the development of energy harvesting over the past few years. There are a number of different ways to capture energy, and the working condition of the harvesting plant dictate the optimum way. Apart from the mechanical systems, the processes that look promising for the energy harvesting are solar, vibration and thermoelectric. This research focuses on comparison of vibration energy harvesting using piezoelectric generator and energy harvesting from the mechanical system applying a gear reduction mechanism. To create useable energy from the vibrations, a bimorph cantilever consisting of PZT-5H and a tungsten proof mass will be modeled. The cantilever structure is efficient in converting vibration into mechanical strain [1], which, using piezoelectric materials is then converted into some electricity. To harvest the kinetic energy of a vehicle, a gear reduction mechanism will be used. Basic approach of this mechanical system is to convert the translational motion of a speed bump into the rotational motion and the gear reduction is applied to increase the revolution per minute of the system.

There are several limiting factors while considering the harvesting mechanism for the speed bump. The speed bumps are designed to hold the weight of the car, thus the speed bumps are not necessarily hollow. Some of them do have “hollow” pockets in the underside to reduce the weight of the speed bump and for easier installation. So, one of the approaches would be to build a speed bump tilted at a certain angle above the ground and to install the harvesting mechanism beneath the surface of the bump. When a moving vehicle strikes the bump, it pushes the bump to the ground and this push or the kinetic energy from the car is further converted into some useful work.
Another approach is to use those hollow pockets, where available, for harvesting energy. For that a piezoelectric cantilever generator is proposed. This piezoelectric generator can sense the vibrations when the vehicle rolls over the surface of the bump, thereby converting it into some useful work. One of the advantages of this mechanism is that potentially it can sense the ambient vibrations; therefore, it can still generate power when a vehicle does not roll over the bump.
CHAPTER 2

LITERATURE REVIEW AND BACKGROUND

2.1 BACKGROUND

Some of the primitive ways of energy harvesting are windmill and water wheel. The first windmills were developed to automate the tasks of grain grinding and water pumping, and the earliest known design is the vertical axis system developed in Persia about 500-900 A.D. Vertical axis windmills were also used in ancient China, which is often claimed as their birthplace. While the belief that the windmill was invented in China more than 2000 years ago is widespread and may be accurate, the earliest actual documentation of a Chinese windmill was in 1219 A.D. by the Chinese statesman Yehlu Chhu-Tshai. Here also, the primary applications were apparently grain grinding and water pumping [2].

For hundreds of years, the most important application of windmills at the subsistence level has been mechanical water pumping using relatively small systems with rotor diameters of one to several meters. These systems were perfected in the United States during the 19th century, beginning with the Halladay windmill in 1854 and continuing to the Aermotor and Dempster designs, which are still in use today [2].

Between 1850 and 1970, over six million mostly small (1 hp or less) mechanical output wind machines were installed in the United States alone. The primary use was water pumping and the main applications were stock watering and farm home water needs. Very large windmills with rotors up to 18 meters in diameter were used to pump water for the steam railroad trains that provided the primary source of commercial transportation in areas where there were no navigable rivers. Whereas in the late 19th century, the successful “American” multiblade windmill design was used in the first large windmill to generate electricity [2].

2.2 ENERGY HARVESTING

Energy conversion is inherently associated with waste which results in reduced efficiency. Energy harvesting is the extraction of energy that would be otherwise wasted
from one system to power another [3]. There are many processes which lose efficiency due to light, heat or vibrations. Energy harvesting is a way to recover these unavoidable losses in the form of electricity. Energy harvesters do not produce significant amount of power, but can produce an amount sufficient for low energy electronics and control systems with little capital cost. The “fuel” for energy harvesters is naturally present and is therefore considered renewable. For this reason energy harvesting devices have attracted much interest in the military as well the commercial sector.

The first use of a large windmill to generate electricity was a system built in Cleveland, Ohio, in 1888 by Charles F. Brush. The Brush machine was a postmill with a multiplebladed “picket-fence” rotor 17 meters in diameter, featuring a large tail hinged to turn the rotor out of the wind. It was a first windmill to incorporate a step up gear box with a ratio of 50:1 in order to turn a direct current generator at its required operation speed [4].

2.3 WATER TURBINES

The idea of using naturally moving water or air to help do work is an ancient one. The most ancient of these methods was the undershot wheel or paddle wheel. On these old waterwheels, only the very lowest part of the wheel was submerged beneath a moving body of water, and the entire wheel was turned as the river flows past it, pushing against its paddles. This was the prototype for what came to be called an impulse turbine, which one driven by the force of a fluid directly is striking it. The undershot waterwheel was followed during medieval time by the overshot wheel. This first made its appearance in Germany around the middle of the twelfth century and became the prototype for the modern reaction turbine. Contrasted to the impulse turbine whose energy source is kinetic energy, the energy source for an overshot wheel is potential energy [5].

In the waterwheel, the action of water on a wheel with blades would be much more effective if the entire wheel were somehow enclosed in a kind of chamber. However, only the small amount of water pushing or falling on a wheel blade or paddle actually strikes it, and much of the energy contained in the onrushing water is lost or never actually captured. Enclosing the wheel and channeling the water through this chamber would result in a machine of greater efficiency and power. The main challenges were lack of any theoretical understanding of hydraulics as well as the absence of precision machine tools to manufacture
them. Both of these problems were resolved to some degree in the 18th century, and one of the earliest examples of reaction turbine was built in 1750 by the German mathematician and naturalist Johann Andres Von Segner (1704-1777) [5]. In this system, the moving water entered a cylindrical box containing a shaft of a runner or rotor and flows out through tangential openings, acting with its weight on the inclined vanes of the wheel.

A really efficient water turbine was now within reach it appeared and a prize was offered in France by the Societe d’Encouragement Pour l’Industrie Nationale. The prize was won by the French mining engineer Claude Burdin (1778-1873), who published these results in 1828. It was in this publication that Burdin coined the word “turbine” which he took from the Latin “turbo” meaning a whirling or spinning top [5].

2.4 ACOUSTIC NOISE

Acoustic noise is a pressure wave produced by a vibration source. Generally, a sinusoidal wave is referred to as a tone, a combination of several tones is called a sound, and an irregular vibration is referred as noise. The human ear can perceive frequencies between 20 Hz to 20000 Hz. Acoustic pressure and acoustic power are types of acoustic noise. The total amount of sound energy radiated by a sound source over a given period of time is acoustic power and is usually expressed in watts. For acoustic pressure, the reference is the hearing threshold of the human ear which is taken as 20 µPa [6].

Very rare research attempts were made to harvest acoustic noise from the environment. The research team at University of Florida examined acoustic energy conversion. The team reported analysis of strain energy conversion using a flyback converctor circuit [7]. The output of a vibrating PZT piezoceramic beam is connected to an AC to DC flyback converter which is estimated to provide conversion efficiency greater than 80% at an input power of 1 mW and 75% efficiency at an input power of 200 µW [8]. This is insufficient amount of power available from acoustic noise to be in the scenario being investigated, except for very rare environments with extremely high noise levels.

2.5 PYROELECTRICITY

Pyroelectric effect converts small temperature differences into electrical current or voltage [9]. It is produced by the capability of certain materials to generate an electric
potential when they are heated or cooled. Due to temperature change, negative and positive charges move to opposite end through migration, and thus an electric potential is established. It is similar to piezoelectric effect which is another type of ferroelectric behavior. Pyroelectric energy harvesting requires inputs with time varying and suffers from small power outputs in energy scavenging.

2.6 TEMPERATURE VARIATION

Thermal gradients in the environment are directly converted to electrical energy through Seebeck effect [10,11]. Temperature changes between opposite segments of a conducting material result in a heat flow and consequently charge flow since mobile, high energy carriers diffuse from high to low concentration region. The generated voltage and power is relative to the Seebeck coefficient of the thermoelectric materials and the temperature differential. Big thermal gradients are essential to produce practical voltage and power levels [12]. Thermoelectric micro device which is capable of converting 15µW/cm$^3$ at 10 ºC temperature gradient is demonstrated by Stordeur and Stark in 1997 [13]. This is promising, and with the improvement of thermoelectric materials, it could result in more than 15µW/cm$^3$.

One of the latest designs of thermoelectric energy harvester was the thermoelectric generator designed and introduced in the available technologies website of Pacific Northwest National Laboratory [14]. This energy harvesting design has diverse applications including automotive performance monitoring, biomedicine, agricultural management and security surveillance.

2.7 PASSIVE HUMAN POWER

A significant amount of work has been done on the possibility of scavenging power off the human body for use by wearable electronic devices [15,16]. The conclusion of studies at Massachusetts Institute of Technology suggests that the most energy rich and most easily available source occurs at the foot during heel strike and in the bending of the ball of the foot. This research has led to the development of the piezoelectric shoe inserts. The power density available from the shoe inserts meets the constraints of this project. Furthermore, the
The problem of how to get the energy from a person’s foot to the other places of the body has not been satisfactorily solved. The application space for such devices is extremely limited.

**2.8 ACTIVE HUMAN POWER**

The type of human powered systems investigated at Massachusetts Institute of Technology could be referred to as passive human powered systems in that the power is scavenged during common activities rather than requiring the user to perform a specific activity to generate power. Human powered systems of this second type, which require the user to perform a specific power generating motion, are common and may be referred to separately as active human powered systems. Examples are standard flash lights that are powered by squeezing a lever and the freeplay wind-up radios [15]. Active human powered devices are however not applicable to this project.

**2.9 VIBRATIONS**

Indoor operating environment may have reliable and constant mechanical vibration sources for ambient energy scavenging. Indoor machinery sensors may have plenty of mechanical vibration energy which can be monitored and used fruitfully. Energy withdrawal from vibrations could be based on the movement of a spring mounted mass relative to its support frame [17]. Mechanical acceleration is produced by vibrations that cause the mass component to oscillate and move. This relative dislocation causes opposing frictional and damping forces to be applied against the mass. This damping energy can be converted to electrical energy via an electric field (electrostatic), strain on a piezoelectric material or magnetic field (electromagnetic).

**Electrostatic Energy Harvesting:** This method depends on the variable capacitance of vibration dependant varactors [15]. A varactor, or variable capacitor, which is initially charged, will separate its plates by vibrations, in this way mechanical energy is transformed into electrical energy. Constant voltage or constant current achieves the conversion through two different mechanisms. For example, the voltage across a variable capacitor is kept steady as its capacitance alters after a primary charge. As a result, the plates split and the capacitance is reduced, until the charge is driven out of the device. The driven energy then
can be stored in an energy pool or used to charge a battery generating the needed voltage source.

**Piezoelectric Energy Harvesting:** It alters mechanical energy into electrical energy by straining a piezoelectric material [18]. Deformation or strain causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever beam structure with a mass at the free end, as it produces higher strain for a given input force [1]. There are many applications based on piezoelectric materials, such as portable sparkers used to light gas grills and stoves and variety of burners built on piezoelectric based ignition system. This topic is discussed in detail in the next chapter.

**Electromagnetic Energy Harvesting:** This technique uses a magnetic field to convert mechanical energy to electrical energy [19]. A coil attached to the oscillating mass is made to pass through a magnetic field which is established by a stationary magnet to produce the needed electric energy. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and must therefore be increased to become a viable source of energy [20]. Techniques to increase the induced voltage include using a transformer, increasing the number of turns of the coil, or increasing the permanent magnetic field [21].

In a study conducted to test feasibility and reliability of the different ambient vibration energy sources by Marzencki in 2005 [22], three different vibration energy sources, electrostatic, electromagnetic, and piezoelectric were investigated and compared based on their complexity, energy density, size, and encountered problems. The study is summarized in Table 2.1 [22], Comparison of vibration energy harvesting techniques.

### 2.10 Summary of Energy Harvesting

Literature review indicated that ambient energy harvesting systems are fruitful area of research. A very new class of applications are being designed and developed for ambient energy harvesting systems. It seems unlikely that the systems already developed efficiently run automatically by adding an energy harvesting system. Many research efforts have been conducted on low power energy harvesting. Literature review shows that no single power
### Table 2.1. Comparison of Vibration Energy Harvesting Techniques

<table>
<thead>
<tr>
<th></th>
<th>Electrostatic</th>
<th>Electromagnetic</th>
<th>Piezoelectric</th>
</tr>
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<tbody>
<tr>
<td>Complexity of process flow</td>
<td>Low</td>
<td>Very High</td>
<td>High</td>
</tr>
<tr>
<td>Energy Density</td>
<td>4 mJ cm(^{-3})</td>
<td>24.8 mJ cm(^{-3})</td>
<td>35.4 mJ cm(^{-3})</td>
</tr>
<tr>
<td>Current size</td>
<td>Integrated</td>
<td>Macro</td>
<td>Macro</td>
</tr>
<tr>
<td>Problems</td>
<td>Very high voltage and need of adding charge source</td>
<td>Very low output voltages</td>
<td>Low output voltages</td>
</tr>
</tbody>
</table>

source is sufficient for all applications and the selection of energy source should be considered according to the characteristics and environment of the application.

For the mechanical energy harvesting, a rotation source or a waste vibration should exist in the surrounding to scavenge and convert that mechanical energy into electrical energy. The higher the rotation or waste vibration is, the higher the electrical energy would be that can be stored for the application. Vibration energy and mechanical power look promising methods to harvest energy from the environment. Therefore, it was decided to pursue vibrations and mechanical rotations for this project. Mechanical rotations are achieved by using a gear system, and for the vibrations piezoelectric cantilever structure was used. This was chosen on the basis of a study conducted by Marzencki [22], which shows that the piezoelectric has the maximum energy density from the vibration energy harvesting devices.
CHAPTER 3

PIEZOELECTRIC MATERIALS

3.1 Piezoelectricity

In 1880 Pierre and Jacques Curie, during their experimental work on crystallography, showed that some crystalline materials, such as Rochelle salt, generate electric charges when subjected to mechanical stresses, known as the direct piezoelectric effect [23]. The inverse effect, i.e., that an applied electric field induces a mechanical deformation, was mathematically predicted by Lippman in 1881 from basic thermodynamic principles and successively verified experimentally by the Curie brothers [24].

Piezoelectricity is a result of the material properties at the microscopic level. Piezoelectric ceramics are crystalline materials whose basic cell, below the curie temperature has an asymmetric distribution of charge given a permanent polarization. A macroscopic block of crystalline material is made up of an assembly of grains and domains. Each domain has a direction prevalent polarization. However, in normal conditions, the domains are randomly oriented and the overall polarization of the block is statistically null. If a strong electric field like 2000V/m is applied for a sufficiently long time, the domains tend to statistically orient in the direction of the electric field and the net polarization is induced. The polarization remains when the polarizing field is removed. The obtained material block is a polarized piezoelectric ceramic. The coupling between deformation and electric field is due to the geometric effects related to domain reorientation caused by an applied electric field.

The piezoelectric effect is a property that exists in many materials. The name is made up of two parts; piezo which is derived from the Greek word for pressure, and electric from electricity. In a piezoelectric material, the application of a force or stress results in the development of a charge in the material. This is known as direct piezoelectric effect. Conversely, the application of a charge to the same material will result in a change in mechanical dimensions or strain. This is known as the indirect piezoelectric effect. Several ceramic materials have been identified as exhibiting a piezoelectric effect. They include lead-zirconate–titane (PZT), lead-titanate (pbTio2), lead-zirconate (pbZro3), and barium-titanate
(BaTio3). The ceramics are not actually piezoelectric but rather exhibit a polarized electrostrictive effect. A material must be formed as a single crystal to be truly piezoelectric. Ceramic is a multi crystalline structure made up of a large numbers of randomly oriented crystal grains. The random orientation of the grains results in a net cancelation of the effect. The ceramic must be polarized to align a majority of the individual grain effects. The term piezoelectric has become interchangeable with polarized electrostrictive effect in most literature.

Piezoelectric materials have been widely used for energy conversion device, for instance, single crystal quartz, ceramic PZT, screen printed thick PZt film, chemical solution deposited (CSD) or sol-gel derived PZT, non-ferroelectric ZnO and AlN thick or thin films, polymer PVDF (polyvinylidene difluoride), etc., nevertheless the majority of piezoelectric thin films is PZT because of the high piezoelectric constant and coupling coefficient at the morphotrophic phase boundary (MPB). Commercially, ceramic PZT is usually not used in its pure form, but doped acceptor or donor atoms to create vacancies and facilitate domain wall motion. Acceptor doping generates hard PZT such as PZT-5A, while donor doping generates soft PZT such as PZT-5H. In general, hard PZT domain wall is pinned by impurities thereby decreasing the losses, but at the expense of piezoelectric constant reduction. Soft PZT has higher piezoelectric constant, but larger losses due to internal friction.

### 3.2 Piezoelectric Effect

A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied. Conversely, a mechanical deformation is produced when an electric field is applied. This effect is formed in crystals that have no center of symmetry. To explain this, we have to look at the individual molecules that make up the crystal. Each molecule has a polarization, one end is more negatively charged and the other end is positively charged, and is called a dipole. This is a result of the atoms that make up the molecule and the way the molecules are shaped. The polar axis is an imaginary line that runs through the center of both charges on the molecule. In a monocrystal the polar axes of all the dipoles lie in one direction. The crystal is said to be symmetrical because if we were to cut the crystal at any point, the resultant polar axes of the two pieces would lie in the same direction as the original. In a polycrystal, there are different regions within the materials that have a different
polar axis. It is asymmetrical because there is no point at which the crystal could be cut that would leave the two remaining pieces with the same resultant polar axis.

### 3.3 Axis Nomenclature

The piezoelectric effect, as stated previously, relates mechanical effects to electrical effects. These effects, as shown above, are highly dependent upon their orientation to the poled axis. It is, therefore, essential to maintain a constant axis numbering scheme. The axis nomenclature followed is shown in Figure 3.1.

<table>
<thead>
<tr>
<th>#</th>
<th>Axis</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>Z</td>
</tr>
<tr>
<td>4</td>
<td>Shear Around X</td>
</tr>
<tr>
<td>5</td>
<td>Shear Around Y</td>
</tr>
<tr>
<td>6</td>
<td>Shear Around Z</td>
</tr>
</tbody>
</table>

For electromechanical constants:

\[
d_{ab},\ a = \text{electrical direction} \\
\ b = \text{mechanical direction}
\]

Figure 3.1. Axis nomenclature.

### 3.4 Electromechanical Coupling

Electromechanical coupling coefficient is an indicator of the effectiveness with which piezoelectric material converts electrical energy into mechanical energy or mechanical energy into electrical energy.

\[
K = \frac{\text{Mechanical energy converted to electrical charge}}{\text{Mechanical input energy}} \tag{3.1}
\]

Or

\[
K = \frac{\text{Electrical energy converted to mechanical displacement}}{\text{Electrical input energy}} \tag{3.2}
\]
While there are many piezoelectric materials from which to choose for a piezoelectric generator, we plan on using lead zirconate titanate (PZT).

3.5 Poling

Piezoelectric material, which is non-conductive in nature, does not have free electrons, and therefore electrons cannot pass freely through the material. Piezoelectric material is made up of crystals that have many fixed electrons. These fixed electrons can move slightly as the crystals deform by the external force. This slight movement of electrons alters the equilibrium status in the adjacent conductive materials and creates electric force. This force will push and pull the electrons in the electrodes attached to the piezoelectric crystal as shown in Figure 3.2.

Figure 3.2. Poling Process: (a) Before poling, (b) during poling, and (c) after poling.

Piezoelectric ceramic materials, as stated earlier, are not piezoelectric until the random ferroelectric domains are aligned. This alignment is accomplished through a process known as “poling”. Poling consists of inducing a D.C. voltage across the material. The ferroelectric domains align to the induced field resulting in a net piezoelectric effect. It should be noted that not all the domains become exactly aligned. Some of the domains only partially align and some do not align at all. The number of domains that align depends upon the poling voltage, temperature, and the time the voltage is held on the material. During poling the material permanently increases in dimension between the poling electrodes and decreases in dimensions parallel to the electrodes. The material can be depolarized by reversing the poling voltage, increasing the temperature beyond the materials Currie point, or by inducing a large mechanical stress.
Voltage applied to the electrodes at the same polarity, as the original poling voltage results in a further increase in dimension between the electrodes and decreases the dimensions parallel to the electrodes. Applying a voltage to the electrodes in an opposite direction decreases the dimension between the electrodes and increases the dimensions parallel to the electrodes.

Applying a compressive force in the direction of poling that is perpendicular to the poling electrodes, or a tensile force parallel to the poling direction, results in a voltage generation on the electrodes, which has the same polarity as the original poling voltage. A tensile force applied perpendicular to the electrodes or a compressive force applied parallel to the electrodes results in a voltage of opposite polarity. Removing the poling electrodes and applying a field perpendicular to the poling directions on a new set of electrodes will result in mechanical shear. Physically shearing the ceramic will produce a voltage on the new electrodes.

3.6 Stacked Piezoelectric Device, 33-Type

Generally piezoelectric devices cannot create large deformations. It is almost impossible to detect the deformation with naked eye. The small micro scale deformation with very high electric field requirement and the material’s brittle characteristics prevent popular use of the device material for strain generation. To overcome this disadvantage of piezoelectric devices, stacked piezoelectric device was introduced. The stacked device can produce same strain with a low electric field. A piezoelectric stack actuator is made of large number of these piezoelectric plates that are glued together and wired in parallel. The device actuation direction is 33-type that is, the force and poling directions are the same. So better performance can be obtained from the actuator depending on the number of the piezoelectric layers. For this reason, piezoelectric stack actuator is a more common force generating device than single actuators. The disadvantages of the stacked piezoelectric devices are that lateral force must be avoided, and they are relatively large in volume.

For the piezoelectric stack as a power generator, the stacked piezoelectric system can convert only longitudinal direction compressive force to electric energy. A stack piezoelectric generator can produce charge only when pressed along the longitudinal direction. If a compressive prestress is applied to the stack to prevent fracture in both
piezoelectric and glued layer, then the applied force can be either tensile or compressive. A stack piezoelectric cannot generate electric energy with bending lateral force. In addition, small sized stacked devices are hard to fabricate. For the power generation purpose, magneto-electric generators perform better than same sized stack piezoelectric generators.

### 3.7 Piezoelectric Device, 31-Type

Another common piezoelectric actuator is the cantilever beam. Cantilever benders can generate significant deflection compared to the longitudinal direction cantilever actuators, and can be found in many applications such as microvalves etc. Cantilever benders can be good power generators because it is easier to convert force into higher strain, as compared to the 33-type stack configuration. Multilayer cantilever beams are common mechanical bending elements and are widely used. The mechanism of cantilever bender is simple. One layer is generally in tension and the other layer is in compression. They are usually called unimorph or bimorph cantilever depending on the number of layers in the bender element. Bimorph cantilever piezoelectric generator contains two piezoelectric layer bonded to a non piezoelectric material in the middle, and unimorph cantilever contains one piezoelectric layer and one non piezoelectric layer. One example of a unimorph cantilever is a thermostat. Thermostats are made of two materials with different thermal expansion coefficients. Since one side of the cantilever is more sensitive to temperature change, a unimorph cantilever will bend when temperature changes. In the piezoelectric unimorph cantilever beam, the piezoelectric layer expands or contracts. When the unimorph cantilever beam undergoes bending, electric fields are generated between the electrodes of the piezoelectric layer.

Piezoelectric benders are often used to create actuators with large displacement capabilities. The bender works in a mode which is very similar to the action of a bimetallic spring. Two separate bars or wafers of piezoelectric material are metalized and poled in the thickness expansion mode. They are then assembled in a +--+ stack and mechanically bonded. In some cases, a thin membrane is placed between the two wafers. The outer electrodes are connected together and a field is applied between the inner and outer electrodes. The result is that for one wafer the field is in the same direction as the poling voltage while the other is opposite to the poling direction, which means one wafer is increasing in thickness and decreasing in length while the other wafer is decreasing in
thickness and increasing in length, resulting in a bending moment. The PZT bender configuration and the PZT bending modes are shown in Figure 3.3 [25].

![Figure 3.3. PZT bender configuration. Source: Ajitsaria, Jyoti K. “Modeling and Analysis of PZT Micropower Generator.” PhD diss., University of Auburn, 2008. http://etd.auburn.edu/etd/bitstream/handle/10415/1489/Ajitsaria_Jyoti_50.pdf?sequence=1.](image)

General unimorph and bimorph cantilevers are made of thin bulk piezoelectric patches. The poling direction of the bulk patch is perpendicular to the surface as shown in figure, thus the characteristics for the general cantilever beam are the 31-types. The 31-type configuration has the poling direction perpendicular to the stress direction and electrodes cover the whole top and bottom surface of the piezoelectric layer.

### 3.8 General Piezoelectric Actuation

To create a useable voltage from piezoelectric materials a mechanical stress has to be applied. To apply this stress cantilever geometry can be used. The cantilever is attached to the base. When vibrations are applied to the base, the cantilever material actuates according to its modal shapes and creates stresses as shown in Figure 3.4.

The stresses in the piezoelectric cantilever create deformation in the piezoelectric crystal structure and this deformation creates a voltage potential. This voltage potential will push electrons through a conductive material, such as gold, which is applied to the surface of the piezoelectric cantilever. The movement of electrons through the conductive material creates the electrical power that can be harvested.

A vibrating piezoelectric device differs from a typical electrical power source because its internal impedance is capacitive rather than inductive. The internal impedance of the piezoelectric material is the resistance to the flow of an alternating current (AC) at a particular frequency as a result of resistance and capacitance reactance. Capacitive reactance
is inversely proportional to the signal frequency and the capacitance. The capacitance of the piezoelectric material can be calculated from its permittivity. As a result it is driven by mechanical vibrations of varying amplitude and frequency [26]. Therefore the higher the amplitude of vibrations, the greater the power output of the piezoelectric.

According to Priya et al. [27] there are three main steps in power harvesting using piezoelectricity. The first is trapping the mechanical stress from the available source and applying it to the piezoelectric transducer. With the piezoelectric cantilever geometry the trapping is done through the coupling of the cantilever to its base which transmits the stress from the available vibration source to the piezoelectric material. The second step is converting the mechanical energy into electrical energy using the direct piezoelectric effect. By using the conductive layer the direct piezoelectric effect converts the mechanical stress into electrical energy. The third step is processing and storing the electrical energy.

### 3.9 Governing Equations of Piezoelectricity

The phenomenon of piezoelectricity is described by Eq. 3.2 and 3.4 [28]. The repeated subscripts in the products imply a summation over the different components.

\[
[S_i] = [s_{ij}][T_j] + [d_{ij}][E_k]
\]  

(3.3)
\[ [D_i] = [\varepsilon_{lm}][E_m] + [d_{ln}][T_n], \ i,j = 1 \ldots 6, l,m,n = 1,2,3. \]  

(3.4)

Where \( E \) is applied electric field \([V/m]\), \( D \) is electric displacement \([C/m^2]\), \( T \) is applied mechanical stress \([N/m^2]\), \( d \) is piezo strain tensor \([C/m^2, N/m^2]\), \( \varepsilon \) is permittivity tensor, \( S \) is mechanical strain, and \( s \) is elastic compliance tensor.

Under an applied stress \( T \) and without given electric field \( E \) on a surface of piezoelectric ceramic, the open circuit output electric voltage \( V \) of the ceramic with an area of \( 'A' \) can be generated. The electrical power \( P \) is calculated using Eq. 3.5 with the assumption of a piezoelectric plate as a parallel plate capacitor.

\[ P = \frac{1}{2} CV^2 \quad \text{or} \quad P = \frac{1}{2} \varepsilon d_t F^2 \cdot \frac{t}{A} \]  

(3.5)

Where

\[ V = -gT \cdot t = -\frac{gF \cdot t}{A} \]  

(3.6)

\[ g = \frac{d}{\varepsilon} \]  

(3.7)

\[ C = \frac{\varepsilon A}{t} \]  

(3.8)

Where \( F \) is the external force, \( t \) is the thickness of the ceramic, \( g \) is the piezoelectric voltage constant \([V/m, C/m^2]\), \( \varepsilon \) is permittivity, \( A \) is cross sectional area, \( t \) is thickness, and \( C \) is the capacitance of the material.
CHAPTER 4

MATHEMATICAL MODEL

4.1 PIEZOELECTRIC ENERGY HARVESTING MODEL

An electrical equivalent model was used to explain the working of the piezoelectric generator. This electrical equivalent circuit was applied to represent the mechanical characteristics of the structure. Figure 4.1 [29] shows the schematic diagram of PZT cantilever beam.


The study of the transient dynamic characteristics of a PZT bender utilizing electrical equivalent models has been performed in previous studies and the model has shown fair accuracy in various conditions of mechanical stress. Figure 4.2 [30] shows the circuit representation of a PZT beam.

In the Figure 4.2 a voltage source is connected in series with an inductor, a resistor and a capacitor that build a resonant circuit. The transformer represents the voltage adaptation while the capacitor indicates the inherent capacitance of a device. Equations of the system are determined using Kirchhoff’s voltage law and Kirchhoff’s current law. Summing the currents at node 1 in Figure 4.2 yields the Eqs. 4.1 and 4.2 [31].
Here equivalent inductor $L_m$ represents the mass or inertia of the generator, equivalent resistor $R_b$ represents mechanical damping; equivalent capacitor represents the mechanical stiffness, relating stress to strain is simply the compliance constant or the inverse of elasticity, $E_p$. $\sigma_{in}$ is an equivalent stress generator that represents the stress developed as a result of input vibrations. $n$ represents equivalent turns ratio of the transformer, $C$ capacitance of piezo bender and $V$ voltage across the piezoelectric device.

The equivalent expressions for $\sigma_{in}$, $L_m$, $R_b$, $C$, $n$ and $i$ have to be determined in order to use these expressions in a useful system.

Equivalent inductor $L_m$ represents effect of mass or the inertia of generator.

Since

$$\sigma_m = K_1 K_2$$

(4.3)

Therefore,

$$L_m = K_1 K_2 m$$

(4.4)

Damping force can be expressed as a function of velocity:

$$F_{bm} = b_m \ddot{z}$$

(4.5)
\( \ddot{Z} \) is the second derivative of vertical displacement of beam.

Equivalent resistance \( R \) relates to stress \( \sigma \) and strain rate \( \dot{\varepsilon} \):

\[
\frac{\sigma_{bm}}{K_1} = b_m K_2 \dot{\varepsilon} \quad (4.6)
\]

\[
R = K_1 K_2 b \quad (4.7)
\]

Electric field in the piezoelectric material is related to the voltage across the PZT by:

\[
H = \frac{V}{2t_p} \quad (4.8)
\]

H is the electric field in the piezoelectric material.

And the piezoelectric constitutive relationship between voltage ‘\( V \)’ and stress ‘\( \sigma \)’ is given by

\[
\sigma = -d_{31} E_p H \quad (4.9)
\]

\[
\sigma = n V \quad (4.10)
\]

Here,

\[
n = \frac{-d_{31} c_p}{n_p t_c} \quad (4.11)
\]

\( n \) gives the equivalent turns ratio of the transformer.

The constitutive relations are shown as:

\[
\varepsilon = \frac{\sigma}{\gamma} + dH \quad (4.12)
\]

\[
D = \varepsilon H + d\sigma \quad (4.13)
\]

Where, \( \varepsilon \) is mechanical strain, \( \sigma \) is mechanical stress, \( D \) is the electric density and \( H \) is the electric field.

The current \( i \) as shown in Figure 4.2 represent the current generated as a result of the mechanical stress evaluated at zero electric field. Applying this condition to equation and substituting strain for stress yields,

\[
D = d_{31} E_p \varepsilon \quad (4.14)
\]

Electrical displacement \( D \) is the charge density across a dielectric element which is related to the current for the device,

\[
i = w l e \dot{D} \quad (4.15)
\]

Substituting Eq. 4.14

\[
i = w l e d_{31} E_p \dot{\varepsilon} \quad (4.16)
\]

\( i \) gives the current in the bender.
Capacitance of the PZT bender is given by:

\[ C = \frac{\varepsilon_0 w l_e}{2t_p} \]  \hspace{1cm} (4.17)

C gives the capacitance of the bender.

As a result following Eqs. 4.18 and 4.19 is obtained which includes \( \varepsilon, \dot{\varepsilon}, \) and \( V \) [32].

This equivalent circuit leads to the correlation between strain and voltage, [33].

\[ \dot{\varepsilon} = \frac{-y}{k_1 k_2 m} \varepsilon - \frac{b_m}{k_1 m} \dot{\varepsilon} + \frac{y}{k_1 k_2 m} \frac{d_{31}}{2t_c} V + \frac{y}{k_2} \]  \hspace{1cm} (4.18)

\[ V = \frac{n_p t_c d_{31} Y}{\varepsilon} \dot{\varepsilon} \]  \hspace{1cm} (4.19)

Where, \( \dot{\varepsilon} \) gives the derivative of strain and \( V \) is the voltage across the bender.

### 4.2 Mechanical Energy Harvesting Model

Basic principles of lever and gear mechanism were used to explain the working of the mechanical energy harvesting system. A foot lever was used to convert translational motion into rotational motion. So if we apply a load \( P \) on the lever it will exert some torque on the shaft.

Twisting motion of the shaft can be expressed as:

\[ T = P \times L \]  \hspace{1cm} (4.20)

Where, \( P \) is the force applied at lever, \( L \) is the effective length of the lever.

Resisting torque can be expressed as:

\[ T = \frac{\pi}{16} \times \sigma_s \times d^3 \]  \hspace{1cm} (4.21)

Where, \( \sigma_s \) is the permissible shear stress, \( d \) is the diameter of the shaft.

Tangential load on the tooth of the gear can be expressed as:

\[ W_T = \sigma_b \times b \times \pi m \times y \]  \hspace{1cm} (4.22)

Where, \( \sigma_b \) is the permissible working stress, \( b \) is the face width, \( m \) is the module, \( y \) is the Lewis form factor.

We can assume module for the gear and pinion, and in actual practice the face width is taken as 9.5m to 12.5m.

As the torque from the shaft is known then we can have,

\[ T = W_T \times \frac{D_1}{2} \]  \hspace{1cm} (4.23)

Where, \( W_T \) is the tangential load on the tooth, \( D_1 \) is the diameter of the 1\textsuperscript{st} gear.
Module is the ratio of gear diameter to the number of teeth on the gear.

\[ m = \frac{D_1}{T_1} \]  
(4.24)

Module and diameter of the gear is known. So from this equation we can get the number of teeth on the gear.

Also the tangential tooth load can be given as:

\[ W_T = \frac{P}{v} \times C_s \]  
(4.25)

Where, \( P \) is the load which is the torque transmitted from the shaft, \( C_s \) is the service factor.

And

\[ v = \frac{\pi D_1 N_1}{60} \]  
(4.26)

\( D \) is diameter of the gear, \( N \) speed in rpm.

From this equation we can get speed of the driving gear in revolutions per minute.

If we assume the velocity ratio, \( VR \),

\[ VR = \frac{T_1}{T_2} \]  
(4.27)

We can get the number of teeth on second gear as well the diameter of the second gear.

And hence from the law of gearing:

\[ \frac{D_2}{D_1} = \frac{N_1}{N_2} \]  
(4.28)

Since \( N_2 \) is equal to \( N_3 \),

\[ \frac{D_2}{D_3} = \frac{N_3}{N_4} \]  
(4.29)

This gives the revolutions per minutes of the last gear, and we can select the generator in that particular rpm range to get the desired electrical energy.

Input force on the system:

If a vehicle of mass \( m \) rolls over the speed bump, it will exert the static as well the dynamic load on the bump.

Static load can be given as:

\[ F_G = m \times g \]  
(4.30)

Where, \( F_G \) is input force, \( m \) is mass of the car and \( g \) is the gravitational force.
Total input energy can be given as the product of force applied and the distance travelled.

\[ E_G = F_G \times d \]  \hspace{1cm} (4.31)

Where, \( E_G \) is input energy, \( F_G \) is the input force and \( d \) is the vertical distance covered.

Dynamic load also acts on the system as, if a car moves with a certain velocity this horizontal motion will deliver some energy on the system and can be given as:

\[ E_{KE} = \frac{1}{2}mv^2 \]  \hspace{1cm} (4.32)

Where, \( E_{KE} \) is the kinetic energy, \( m \) is the mass of the car and \( v^2 \) is the velocity of the car.

Total input energy can be given as a sum of static energy and the dynamic energy.

The actual working efficiency of the system can be obtained as the ratio of power output from the DC generator to the total input energy given to the system.
CHAPTER 5

DESIGN

5.1 PIEZOELECTRIC GENERATOR DESIGN

This section describes the design of piezoelectric and mechanical energy harvester used for analyses and experiment.

The design of piezoelectric energy harvester is a simply supported cantilever beam. Figure 5.1 [33] shows a two layer PZT bender mounted as cantilever.

![Figure 5.1](image)


The simulation was performed using a cantilever design and a conductive material placed on the top of the cantilever. Generator was built on a bimorph cantilever design that has two layers of piezoelectric material and a metal shim layer. This particular generator has a copper center shim sandwiched by two layers of PZT-5H. The thickness of the copper plate and PZT is 0.134 mm and 0.132 mm respectively. The length of the bender is 25 mm and a tungsten proof mass at the tip of the cantilever. Thickness of the proof mass is 2 mm and the length is 2mm.
5.1.1 Cantilever

Cantilever geometry is used to generate a voltage from the piezoelectric material. Mateau et al. studied the optimization of beam structures for energy harvesting. They found that the maximum strain in the beam takes place at its surface. One way to increase the average strain for the piezoelectric film, and therefore the harvested power, is to increase the beam thickness. This can maintain the same amount of piezoelectric material by using heterogeneous bimorphs composed of non piezoelectric films and piezoelectric films [34].

Because of its small displacement and low mass, the natural frequency of the cantilever is high as in thousands of hertz. As shown in Table 5.1 [33], the average frequency is 130 Hz. At this frequency the cantilever would not be excited enough to produce a useable voltage. Therefore the natural frequency of the cantilever will have to change to be optimized for harvesting the energy from common frequencies.

Table 5.1. Summary of Several Vibration Sources

<table>
<thead>
<tr>
<th>Vibration Source</th>
<th>Peak acceleration (m/s²)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>121</td>
</tr>
<tr>
<td>Door frame just as door closes</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Small microwave oven</td>
<td>2.25</td>
<td>121</td>
</tr>
<tr>
<td>Wooden deck with foot traffic</td>
<td>1.3</td>
<td>385</td>
</tr>
<tr>
<td>External windows (2 ft × 3 ft) next to a busy street</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Note book computer while CD is being read</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>Washing machine</td>
<td>0.5</td>
<td>109</td>
</tr>
<tr>
<td>Second story floor of a wood frame office building</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>0.1</td>
<td>240</td>
</tr>
</tbody>
</table>

5.1.2 Metal Shim Layer

This cantilever design has a copper center shim layer sandwiched by two layers of PZT-5H. The safety of the generator has to be considered due to high fragility of the piezoelectric ceramic. However, such structure is very vulnerable for fracture of ceramic PZT materials, under high g conditions, which may limit the applications requiring severe vibration condition such as vehicle. Metal shim layer provides the robustness to the design and increases its application. The thickness of the layer used here is 0.134 mm.

5.1.3 Proof Mass

Cantilever has low mass and therefore a high natural frequency. To decrease natural frequency of cantilever a proof mass is added. This proof mass will also increase the displacement of the cantilever tip. Since, greater displacements results in higher voltages so it is hypothesized that proof mass will increase voltage of the cantilever. The more electrical power drawn from the vibrating beam, the higher the electrical damping. High electrical damping would result in a significant reduction of the beam deflection at the resonance. If the beam has more stored energy, more electrical energy can be drawn from the beam while maintaining the electrical damping low which is a ratio of $E_{\text{generated}}$ to $E_{\text{stored}}$. Therefore the key theory for more power generation is to maximize stored energy. The maximum power harvesting can be achieved by having a proof mass as heavy as possible unless it results in diverse effects such as excessive stress or damping [35].

5.2 Mechanical System Design

The basic component of this mechanical system is a gear reduction design. The gear is essentially a toothed wheel or cylinder that works in tandem with another gear or gears to transmit motion or to change speed or direction. The gear arrangement which is used in this energy harvester is spur gears. Spur gears have wide range of applications including mixers, blenders, copy machines, textile machinery and ice machines.

In a spur gear, the teeth, which are on the outer surface of the cylinder, are straight and parallel to the axis. So when they come together to mesh, they do so in the same plane. As a result of how they meet, spur gears can increase or decrease the speed or torque of whatever they are moving. In any pair of gears the larger gear will move more slowly than the smaller
gear, but it will move with more torque. Thus, the bigger the size differences between two spur gears, the greater the difference in speed and torque.

One of the first steps of addressing an application’s need is to determine what size spur gear is needed for the particular application.

Diametral Pitch: The ratio of number of teeth to the pitch diameter.

Pitch Circle: The imaginary circle that comes in contact with the imaginary circle of another gear when two are in mesh.

Pitch Diameter: The diameter of the pitch circle.

Center Distance: It is the distance between the centers of the shaft on one spur gear to the center of the shaft of other spur gear. In a spur gear drive having two gears, the center distance is equal to one half the pitch diameter of the pinion plus one half the pitch diameter of the gear.

To allow for smooth velocity transmission and gross slip, the fundamental law of gearing must be followed; this law provides that the angular velocity ratio between the gears of a gear set remains constant throughout the mesh [36]. This law works not only for involute gears but for all kinds of gearing. The angular velocity ratio is equal to the ratio of the radius of the input gear to that of the output gear. This can be expressed as

$$m_v = \frac{\omega_{out}}{\omega_{in}} = \frac{r_{in}}{r_{out}} = \frac{N_{in}}{N_{out}}$$

(5.1)

Where, $\omega$ is the angular velocity, $r$ is the radius of the pitch circle and $N$ is the normal to the tooth profile at the point of intersection.

Rotation: The direction in which a gear revolves while in operation is one of the most important concepts in the power transmission. In a spur gear drive having two gears, the pinion and the gear will rotate in opposite directions. In the spur gear train having three gears as in our energy harvester, the pinion and the gear will rotate in the same direction.

In the energy harvester the last gear from the gear train rotates at the maximum speed, and the shaft from which is applied to the DC motor which is used to produce electricity using this rotational motion of the shaft.
CHAPTER 6

ENERGY STORAGE

The average harvested energy from a device is usually low and therefore it is needed to accumulate harvested energy for an intermittent use. The traditional electrolyte capacitors were used earlier but because of their low energy density, the output from the capacitor storage per discharge cycle is very limited. So, different alternatives with higher energy densities were discussed. Rechargeable batteries are considered due to their high energy densities. Also the supercapacitors are considered as their energy density is 10-100 times than that of traditional electrolyte capacitors.

There are various types of energy storage devices including traditional electrolytic capacitors, rechargeable batteries, and supercapacitors. These traditional electrolytic capacitors may not work well because of their low energy densities. Rechargeable batteries mainly include nickel cadmium (NiCad), nickel metal hydride (NiMH) and lithium ion/polymer (lithium). Whereas the NiCad rechargeable batteries have memory effect which is not suitable for shallow charging as energy harvesting is usually shallow charging. So these batteries are not considered as an energy storage device.

6.1 Charge/Discharge Efficiency

Efficiency of supercapacitors or rechargeable batteries is never 100%. Charge/discharge efficiency is also called Coulombic efficiency and is defined as,

\[ \eta = \frac{\text{Discharge energy}}{\text{charge energy}} \]  

(6.1)

Due to low level of source energy in piezoelectric energy harvesting systems, the charge/discharge efficiencies of the energy storage devices are important. An equivalent circuit model for energy storage devices will be valuable to study electrical characteristics. Figure 6.1 [37] shows the equivalent circuit model of the energy storage device.

Charge/ Discharge deficiency comes from the energy loss during the charge/discharge process. This loss of energy exists in two manners: internal series resistance and leakage loss.

### 6.2 Internal Series Resistance

Internal series resistance is usually given in the specifications by the manufacturer. It varies with the electrolyte type of different energy storage devices. For supercapacitors in particular, the internal series resistance is called equivalent series resistance (ESR) and also varies with the cell capacity. The larger the cell capacity smaller the internal series resistance. Internal series resistance of common supercapacitors with capacity from 0.1 F to 3000 F range from 30 Ω to 0.5 m Ω, The internal series resistance of the common rechargeable battery cells of various capacity range from approximately 50 m Ω to 1 Ω [37].

### 6.3 Leakage Resistance

Leakage resistance is an interesting issue but little understood as very little work is done on it. The self discharge resistance has been studied which is a kind of leakage resistance. Self discharge is a natural phenomenon of any rechargeable battery or supercapacitor. After fully charged a rechargeable battery is usually maintained with a trickle charge to compensate for the self discharge. Several researchers used the self discharge resistance as a leakage resistance for the rechargeable batteries. For supercapacitors leakage resistance under other states is not equal but related to the self discharge leakage resistance. Self discharge for some common rechargeable batteries as NiMH approximately 30% per
month, lithium approximately 10% per month and for supercapacitors it is approximately 35% per month [38].

Estimated average self discharge resistance Eq. 6.2 [38].

$$R_{lea, self} \approx \frac{V_{cell} \times \Delta t}{Q_{cell} \times \lambda%}$$  \hspace{1cm} (6.2)

$V_{cell}$ and $Q_{cell}$ are the related voltage and capacity of the cell. $\lambda$% self discharge energy loss percentage in time interval $\Delta t$.

Basically in higher current applications (0.5 to 10 A), the energy loss due to the internal series resistance is much larger than the energy loss due to the leakage resistance. In low current applications (1-200µA) energy loss due to internal series resistance is much smaller than due to the leakage resistance.

As in our energy harvesting systems, the charge discharge current is typically below 200 µA. The leakage resistance is of the most importance in considering the efficiency of energy storage devices in energy harvesting systems.

Charge / Discharge efficiency of the energy storage device can be calculated by

$$\eta = 1 - \frac{\text{Energy loss}}{\text{Charge Energy}}$$  \hspace{1cm} (6.3)

From the experiments carried out by Guan and Liao 2008, it can be concluded that the leakage resistance influences the charge/discharge efficiency most. Therefore storage devices with high leakage resistances are preferred in the piezoelectric energy harvesting systems. As researched, the low capacity supercapacitors from 0.1 F to several Farads have high leakage resistances. Therefore these supercapacitors are good choices in the energy harvesting systems considering the charge/discharge efficiencies.

Life span is also an important factor in considering energy storage device. NiMH has approximately 300-500 cycles; Lithium has 500-1000 cycles [38]. Lithium battery has a time clock that starts ticking as soon as the battery is made in the factory. The electrolyte slowly eats up the positive plate and the electrolyte decays. This chemical change causes the internal series resistance to increase. At a certain point the cell resistance will raise to a point where the battery can no longer deliver the energy although it may still be retained in the battery. The supercapacitors have an average of more than 100,000 cycles. While considering all this features a supercapacitor is the better option for the energy storage device in the energy harvesting system.
CHAPTER 7

RESULTS AND DISCUSSION

This section displays the results from the prototype of a speed bump and from the simulation of a piezoelectric generator used in a speed bump.

7.1 DESCRIPTION OF TEST

The idea is to convert the kinetic energy of a moving vehicle into some useful energy. There are various traffic norms for the design and construction of the speed bumps. So, there are many obstacles while considering any suitable design for the system. Normally, speed bumps are not hollow although some of them have pockets for the ease of installation. Piezoelectric and Mechanical energy harvesting systems are considered to convert kinetic energy into electricity. Mechanical system is applied by making few changes on the conventional bumps. While piezoelectric system is applied with an idea of using the existing pockets in the speed bumps.

The piezoelectric generator used in this study is a bimorph cantilever design. It consists of two layers of a piezoelectric material and a metal shim layer. Copper is considered for a metal shim layer which is sandwiched by two layers of PZT-5H. The mechanical system generator used here is based on a gear reduction mechanism. The idea is to convert the linear motion into rotational. The rotational speed is increased by the gear reduction mechanism and this rotational energy is further converted to electricity using a DC motor. In order to get the best suitable energy harvesting system for the speed bump, the outputs from Piezoelectric and Mechanical energy harvesting systems is compared.

7.2 MODEL FOR ENERGY HARVESTING SYSTEM

This section shows the working of piezoelectric as well as the mechanical energy harvesting system.
7.2.1 Piezoelectric Energy Harvesting System

Piezoelectric energy harvester is considered because of its small size and high efficiency. These harvesters can fit well into the small hollow pockets provided for the ease of installation of speed bumps.

These actuators are classified into two different types based on the energy conversion direction. The first one is the actuator type in which piezoelectric element undergoes a dimensional change when an electric field is applied. The electric energy is converted into mechanical energy based on the indirect piezoelectric effect. The second type is called sensor type, in which an electric charge is produced when a mechanical stress is applied. The PZT generator is based on the mechanical to electrical energy conversion based on the indirect piezoelectric effect. An analytical model of the generator was studied that facilitates the estimation of the amount of power possibly being harvested at a given vibration level.

Vibrations are the cause of mechanical acceleration that in turn cause the mass component to oscillate and move. This dislocation causes damping and opposing frictional forces against the mass component. This reduces and eventually diminishes the oscillations. And this energy from damping forces is converted into electricity using a piezoelectric material. A cantilever structure is used as it produces higher strain for a given force. From the previous studies of optimization of beam structure, it is known that the maximum strain in the beam is at its surface. So a heterogeneous bimorph cantilever was used as it increases the beam thickness with the same piezoelectric material and therefore the harvested power.

7.2.2 Mechanical Energy Harvesting System

This design is considered because the speed bumps, which are normally built are not hollow though they have hollow pockets for installation. But these hollow pockets are not big enough to house a mechanical system. While considering the factor of safety we can not have a linear distance of more than one inch. So the design should be one that does not cause any damage to the vehicle and the passenger as well.

The goal of this system is to harness the mechanical energy lost in speed bumps and convert it into some useful electrical energy. As the energy produced is not large, it is essential to store this energy so it can be used whenever needed to light the parking structure, traffic lights etc. As the sources of energy are starting to diminish, alternate ways of
harvesting energy is becoming more and more important. Although the speed bumps will not be able to solve the energy crisis but it is definitely a right approach to the cause. This is done as vehicle traffic drives over the bump. In this process of slowing down the traffic some of the kinetic energy of the vehicle is converted into electrical power output which can be further used.

A 3D CAD design was built to have a better understanding of the desired system. Prototype was built considering the economic aspect. Readily available parts were used and few are machined to the desired specification.

Figure 7.1 shows the inclined speed bump, which makes contact with the tire as it passes over. This inclined bump is rested on a push plate which is fixed with a pair of spring so that, it is always in contact with the bump. Further this push plate is fixed on the shaft, same as the first gear of the speed increase gear set.
From the side view of the gear box (see Figure 7.2) we can easily locate the gear reduction. This is done in order to increase the RPM of the generator. A DC generator is used to convert this rotational motion into some useful energy. In the nutshell this mechanism is all about converting linear motion into rotational motion and at a higher spin rate. To have a unidirectional motion of the gear box one way bearing is used, which resists the motion in the opposite direction. This is actual working prototype of the system. This design can be installed on the surface of the road while the gear box can go beneath the surface.

![Figure 7.2. Side view of speed bump.](image)

### 7.2.2.1 Speed Increase Gear Set

The speed increase gear set system was designed and built using plastic gears. The role of speed gear set was crucial to increase the speed of rotation and to provide sufficient input speed to the generator. This increase in speed was essential because without the speed increase, rotation speed from the speed bump is not sufficient for the electric generator to provide enough voltage for the energy harvesting system. Figure 7.3 depicts the gear train block diagram which represents increasing gear ratio steps on the shafts until the generator input is reached.
7.2.2.2 Generator Unit

The first phase is to design an appropriate gear box to increase the rotational speed, so that it should provide sufficient rotation speed to the generator. Here generator used is permanent magnet direct current electric motor. This generator is connected to the output shaft of the gear box to generate electricity.

The faster the generator turns, the higher the output voltage that is generated as seen in equation,

\[ V = k \cdot n \cdot \phi \]  

(7.1)

Where, \( V \) is induced voltage, \( k \) is machine coefficient, \( n \) is the revolutions per minute and \( \phi \) is magnetic flux.

7.3 Comparison of Mechanical and Piezoelectric System

In the recent years several new devices and applications have been introduced to improve life in general. Many of these applications utilize new technologies. However these applications are still fully dependent on the conventional powering methods such as battery power. This research will address the problem of unused waste energy from the speed bumps that could be harvested. The purpose of this study is to analyze, design and build energy harvesting device capable of mechanical to electrical energy conversions. Analytical simulation and design software packages were used to develop proper and efficient energy harvesting systems. Two different energy scavenging techniques were examined. Vehicle
kinetic energy can be transferred in a number of different ways, so the main source was energized by vehicle power to operate two ambient energy sources. These two forms of ambient energy sources are waste mechanical energy from an inclined speed bump and the vibrational energy when the vehicle rolls over the bump.

An inclined speed bump was constructed as a first ambient energy source. An energy harvesting system was built and tested to capture and convert waste mechanical rotation from an inclined speed bump.

The aim of gear set is to increase the speed of rotation generated from the inclined speed bump to provide sufficient speed to a DC motor, which then serves as a generator unit. This step up in speed is required because without the increase in speed, the rotation rate from the speed bump will not be sufficient for the generator. So the gear set was designed to increase speed to provide enough rotation to turn on electricity generation. Electric motor is based on the fact that any conducting wire which cuts a magnetic field and has a relative motion will generate an electric potential. Electric motors include rotating coils of wire that are driven by the magnetic force exerted by a magnetic field on an electric current. They transform electrical energy into mechanical energy. So, any permanent magnet direct current motor back driven will make a generator and the faster the generator turns, the higher the output voltage generated.

The second source of harvesting ambient energy was waste kinetic energy from the vehicles and was studied using piezoelectric ceramics as PZT-5H, which are capable of generating electricity from vibrations. The reason for choosing these ceramics to capture the tensions and vibrations from the motion is the nature of piezoelectric material which is capable of converting vibrations into electric current.

Piezoelectric material belongs to a class of materials called ferroelectrics. These exhibits a local charge separation called an electric dipole. The dipoles are oriented randomly throughout the material composition but when an electric field is applied, these dipoles reorient themselves relative to an electric field, this process is called poling. After poling is completed the material will exhibit the piezoelectric effect. When material is deformed or stressed an electric voltage can be recovered along any surface of the material via electrodes. It can be generalized for two cases the first is a bender that operates in 13 modes and second is stack configuration which operates in 33 modes. This sign convention assumes that poling
direction is always in the “3” direction. These modes are important when defining the
electromechanical coupling coefficient. In a nutshell, the conversion starts with a mechanical
energy source when the vibrations are converted into electricity via piezoelectric element.
The electricity produced is thereafter formatted by a static converter before supplying a
storage system or an electrical device.

7.4 SUMMARY OF PIEZOELECTRIC GENERATOR

The piezoelectric materials have a crystalline structure that provides the ability to
transform mechanical strain energy into electrical energy and vice versa, to convert an
applied electric potential into mechanical strain. This property provides these materials with
the ability to mechanical energy or mechanical vibrations in the speed bumps when the
vehicles roll over and transform it into electrical energy. As discussed earlier, mechanical
vibrations are the most efficient way to apply strain energy to the piezoelectric material. One
of the earlier work using vibrations for power generation is proposed by William and Yates
in 1996, which generated electricity when embedded in a vibrating environment [39]. To
evaluate the viability of the device and to optimize the design, harmonic analysis of the
generator was performed. It is determined that the amount of power generated was
proportional to the cube of the vibration frequency also low damping factor was required to
maximize the power generation [40].

As discussed earlier piezoelectric actuators have two modes of vibration that is 31
direction and 33 direction which is usually called stacked piezoelectric device. Concerning
the fundamentals of a generator, this transformed mechanical energy into electrical energy,
Umeda et. al. carried out an investigation using a piezoelectric vibrator and a steel ball. It
was determined that maximum efficiency decreases as the potential energy of the ball
increased. A large part of the applied energy was returned to the steel ball in the form of
kinetic energy causing it to bounce off the plate. It was concluded that energy generated
would be large if the steel ball did not bounce off rather vibrated with the piezoelectric plate
[41]. In 1999 Goldfarb and Jones analyzed the efficiency of piezoelectric stacked actuator
and suggested that the maximum efficiency of power generation can be achieved by
minimizing the amount of energy stored inside the piezoelectric material. The efficiency of
the model was determined across the spectrum of frequencies and resistive loads. It was
found that for frequencies above 100 Hz, the efficiency of the stack actuator was negligible and highest efficiency was obtained at 5 Hz [42]. Because of these reasons, stacked actuator is not considered for the power generation from the speed bump.

In 2004 Roundy and Wright, build a two layer (bimorph) bender mounted as a cantilever beam with a mass placed on a free end. There are two reasons for choosing a cantilever, first for a given force input, it results in a highest average strain, secondly the cantilever mounting results in a lowest resonance frequency for a given size, it is important because, input vibrations are of low frequency. This particular design is of 1 cm$^3$ in size and generated a power output of 375 µW from a vibration source of 2.5 m/s$^2$ at 120 Hz [43].

A two layer bender cantilever beam with a proof mass. It consists of a three layers, top and bottom as piezoelectric layer and middle layer as metal. This design was chosen because of lower frequencies between 60 to 200 Hz and higher strain attainable. The system is designed to utilize the z-axis vibration as the only vibration source for the device. When the beam is excited with an input sinusoidal acceleration with amplitude of 1 g and frequency of 95 Hz, voltage at the output is measured. The peak value of the output has been reached to 11.49 Volts at a amplitude of acceleration with 9.8 m/s$^2$. The experimental results were 1149 V whereas the results from three analytical models are 10.47 V, 11.69 V and 10.25 V [43].

This research investigates energy harvesting using a piezoelectric cantilever design. The piezoelectric material used is Lead Magnesium Niobate-Lead titanate (PMN-PT) and a Polydimethylsiloxane (PDMS) coating is applied to the cantilever to decrease stress concentration of the thin PMN-PT and therefore increases the strength of the cantilever. It is also added to decrease the natural frequency of the cantilever to common vibration frequencies and to increase displacement and voltage output. The experimental results found that the peak voltage of 16.8 V can be obtained at a frequency of 1322 Hz, stage displacement of 1405 µm and a stage acceleration of 55 m/s$^2$ [44].

**7.5 Power Output**

This section displays the power output from the piezoelectric as well as the mechanical energy harvesting system.
7.5.1 Mechanical System

The Figure 7.4 shows the prototype of the speed bump. As discussed earlier this system was built to convert the kinetic energy of the vehicle traffic into some useful energy. The energy conversion of this prototype is based on gear reduction mechanism and considering the economic factor, it is built on plastic gears and rest of the parts are obtained from scrap. The DC generator is used to convert mechanical energy into electrical energy. The voltage obtained is 5.015 V and current is 2.75 mA, it is measured using the Fluke 175 True RMS Multimeter. This system is able to light an LED, as the energy output is not too high it is better to accumulate the energy for the useful usage.

![Figure 7.4. Prototype of the speed bump.](image)

The power output from the prototype can be expressed as an instantaneous electrical power.

\[ P(t) = I(t).V(t) \]  \hspace{1cm} (7.2)

Where, \( P \) is the power, \( I \) is the current, \( V \) is the voltage and \( t \) is the time.

We know that,
\[ V = I \cdot R \] (7.3)

Therefore, Power \((P)\) can be given as

\[ P = \frac{v^2}{R} \] (7.4)

Power can be obtained as a product of Voltage and Current.

\[ P = V \times I \] (7.5)

\[ P = 5.015 \times 2.75 \]

\[ P = 13.79 \text{ mW} \]

The power obtained is 13.79 mW.

The efficiency of the system is obtained by power output by power input and is calculated around 3.05%.

Power output assumption from a real speed bump:

When a car of mass 3000 kg rolls over the speed bump it will exert static as well dynamic load on the system. Force applied on the system by the static load is given as:

\[ F_G = 3000 \times 9.81 \] (7.6)

\[ F_G = 29430 \text{ N} \]

If the system has a vertical displacement of 2 inches it will produce a energy of 1495.044 J, when a work is done for 1 second.

For dynamic load, if a car moves at a velocity of 15 miles/hr it will produce a kinetic energy and can be given as:

\[ E_{KE} = \frac{1}{2} \times 3000 \times (6.7)^2 \] (7.7)

\[ E_{KE} = 67335 \text{ J} \]

Total energy applied to the system is given as:

\[ T_{Total} = E_{KE} + E_G \] (7.8)

\[ T_{Total} = 69 \text{ J} \]

If the input power supplied to the system is 69 J and the efficiency of the DC generator is assumed to be 85% then the power output from the system can be calculated as:

\[ P_{Output} = 69 \times 0.85 \] (7.9)

\[ P_{Output} = 58.65 \text{ W} \]

The power output from the system is approximately 59 W, when a vehicle of 3000 kg moving at a velocity of 15 miles/hr rolls over the speed bump.
7.5.2 Piezoelectric System

FEM analysis was performed using COMSOL multiphysics FEMlab software. The model of the cantilever was built using COMSOL’s solid modeling software. The physics that is used to solve the problem is piezo plane stress and the boundary conditions are the vertical surfaces on the left side of the cantilever which are constrained with zero movement, while all the other surfaces are free. Simulation results show that, when the bender is vibrated at an Eigen frequency of 148.904 Hz it will produce the output of 8.062 V. The following images give the information about the electric potential and electric field with respect to the Eigen frequency.

From the simulation results, voltage of the system is obtained as 8.062 V. The voltage obtained is an open circuit voltage and from the basic energy harvesting scheme, open circuit voltage can be written as:

\[ \frac{V_{oc}}{2} = \frac{I_p}{2\omega C_p} \]  

(7.10)

Where, \( V_{oc} \) is open circuit voltage, \( I_p \) is peak amplitude of current source, \( \omega \) is the frequency and \( C_p \) is the internal capacitance of the piezoelectric material.

Therefore,

\[ I_p = 8.062 \times 148.9 \times 9 \times 10^{-9} \]  

(7.11)

\[ I_p = 10.8 \mu A. \]

As shown in the mechanical system the theoretical power output from the piezoelectric system can be obtained using Eq.7.12.

\[ P = V \times I \]  

(7.12)

Where \( P \) is the power (W), \( V \) is the voltage (V) and \( R \) is the resistance (Ω)

Therefore,

\[ P = 8.062 \times 10.8 \]  

(7.13)

\[ P = 87.06 \mu W. \]

The power obtained is 87.06 \( \mu W \).

Equation 7.14 is used to get the theoretical efficiency of the piezoelectric bender.

The simulation result gives the maximum voltage output at a given eigen frequency, as shown in Figure 7.5. The simulation result provides the relation between Electric field, norm per tip displacement, as shown in Figure 7.6.
Figure 7.5. Shows the eigenfrequency as well the electric potential (V) from the bender.
Figure 7.6. Shows the electric field (V/m).
The theoretical efficiency of the piezoelectric bender is calculated around 79.47%.

And the actual working efficiency can be obtained by using the equation 7.15:

$$\eta = \frac{\sum_{n=2}^{m} \frac{(V_n-V_{n-1})^2/R}{((F_n-F_{n-1})(d_n-d_{n-1})/(t_n-t_{n-1}))}}{m} \times 100\%$$  \hspace{1cm} (7.15)

Where, V is voltage drop, R is load resistance, F is the force applied to the base plate, d is displacement of the plate, t is the time increment between data points, n is the data point index and m is the total number of data point measured.

From the previous work done the actual working efficiency of the piezoelectric bender is around 3.5 to 4.2%.

### 7.6 Cost Analysis

A cost analysis is performed on the desired components which are to be used to build the piezoelectric generator and the mechanical generator. This study gives a comparison of estimated cost for a piezoelectric generator and mechanical generator. Piezo Systems Inc is used to get the cost of various components for the piezoelectric generator and for the mechanical system it is obtained from the various vendors that deal with mechanical components.

**Piezoelectric System:** A piezoelectric bender is used as a cantilever for the energy generation. A two layer bender actually has 9 layers consisting of 4 layers of electrodes, 2 piezoceramic layers, 2 adhesive layers and a center shim. It costs around $75, with a specification of rated voltage ± 80, resonant frequency 270 Hz and a free deflection of ± 300 µm.

A piezoelectric harvesting circuit, as the source is alternating, so the diode bridge rectifier is used as an AC-DC rectifier. As discussed earlier an optimal rectifier voltage $V_{\text{rect_opt}}$ is used to harvest the energy for maximum power. It is one half the peak open circuit voltage $V_{\text{oc}}$. It costs around $349, with the specification as max instantaneous input voltage ± 500 V, max instantaneous input current 400 A, max instantaneous input power 500 mW and max output current as 1 A.
Solder kit used to connect the cantilever with the harvesting circuit. It costs around $49, it consists of a lead free solder for nickel electrodes, liquid flux for soldering to electrodes and brass, stainless steel center shim and red and black wires.

The estimated cost of the piezoelectric generator could be $473.

**Mechanical System:** The cost analysis is performed based on the costing of the different materials that have been utilized in building a prototype of the mechanical system. Apart from piezoelectric generator the mechanical system generator has a lot of small components, which completes the structure. The cost of the components used is:

- Bump shell - $11.80
- Roller bearing - $5.62
- Shaft - $29.55
- Spring - $12.60
- DC generator - $182
- Gears - $28.60
- Wire connectors - $7.25

The estimated cost of the mechanical system generator could be $277.42.

**7.7 Suggestion for Future Research**

As the energy output from the mechanical and piezoelectric systems is not too high. So it is suggested to accumulate the energy before any usage. There are few suggestions for the future research that can be implemented to achieve the higher energy output. One of them is by using a multimodal energy harvesting system that combines piezoelectric and electromagnetic energy harvesting mechanism. The device consists of piezoelectric crystals bonded to a cantilever beam. The tip of the cantilever beam has an attached permanent magnet which oscillates within a stationary coil fixed to the top of the system. The permanent magnet serves two purposes, first, it acts as a tip mass or proof mass for the cantilever beam and lowers the resonance frequency, and second, it acts as a core which oscillates between the inductive coils resulting in electric current generation through Faraday’s effect. Thus, this design combines the energy harvesting from two different mechanisms, thereby improves the energy output of the system. Another suggestion would be using the array of piezoelectric
cantilever generator across the length of the speed bump. As, small size of the generator favors the use of array to increase the power output of the system.

### 7.8 Comparison of Cost Analysis and Results

Comparison of cost analysis and power output is performed in order to obtain the sustainability of the harvesting system in the real working condition. Estimated cost of the desired components is obtained to get the approximate cost of the harvesting system. As discussed in the previous section, the mechanical energy harvester costs approximately 278 $ and the piezoelectric generator costs approximately 473 $. If we compare the power output of the mechanical and piezoelectric energy harvesting system, the mechanical working prototype provides 13.79 mW of energy, the voltage and current is measured using the Fluke 175 True RMS multimeter. Whereas, the piezoelectric generator is an analytical model and COMSOL multiphysics FEMlab software is used for the FEM analysis. The potential difference is measured as 8.062 V and the current is obtained using the basic energy harvesting scheme. The theoretical power output is obtained as 87.06 µW. The power output can be increased by using an array of piezoelectric harvesters across the length of the speed bump. The power output from the mechanical system can be increased by using the cast iron gears with bearing to increase the rotational speed of the generator shaft. The speed bumps are mostly placed in the harsh environment, so it is desired to have a sturdy energy harvesting system to withhold all the surrounding stresses. Due to brittle nature of the piezoelectric element, mechanical energy harvesting system is more desirable for the speed bumps. The power output from the mechanical system is more when compared to the piezoelectric energy harvesting system. Also the sturdiness of the mechanical energy harvester improves the overall lifecycle of the system.
CHAPTER 8

CONCLUSION

Energy harvesting is an emerging technology combining both electrical and mechanical fields. Out of the current popular methods of energy harvesting, vibration energy and kinetic energy from the moving vehicle is the most promising for energy harvesting from a speed bump. In this thesis piezoelectric cantilever built from PZT were analyzed for energy harvesting through vibrations and a mechanical system built on a gear reduction mechanism were used to harvest kinetic energy from the vehicle.

The piezoelectric cantilever used in this study is of higher energy quality, but the piezoelectric element is extremely fragile. To counteract the delicate nature an inactive layer of copper is used as a center metal shim layer which gives strength to the cantilever. As the natural frequency of the cantilever is high, a proof mass is added to the tip of the cantilever, which decreases the natural frequencies of the cantilever and one of the other benefits of proof mass is, it increases the power output of the cantilever. The gear reduction mechanism used in this study is one of the best ways of converting translational motion into rotational motion at the maximum. DC generator was used to convert rotational motion energy into electrical energy. The gear reduction mechanism increases the rotational motion at the end, out of the initial translational push. The higher the rotational motion of the shaft, the higher the energy output from the DC generator.

This study compares the cost analysis and power output of the piezoelectric energy harvester and mechanical system energy harvester. The purpose of this study is to get the better understanding of the feasibility of the energy harvester in the real working conditions. As discussed in the previous section, the energy harvester is desired to be sturdy because of the harsh working conditions. There are few techniques to improve the power output of the energy harvesters, but still the energy output would not be big enough to serve a working load. Therefore, it is desired to accumulate the energy to be used in a fruitful way. On comparing the mechanical and piezoelectric energy harvester, mechanical energy harvester produce more energy and looks sturdier than the piezoelectric energy harvester, which
improves the overall life span of the system. In the nutshell the mechanical energy harvesting system looks more favorable for the energy harvesting from the speed bump.
REFERENCES


