Faculty of Mechanical Engineering

ON ENERGY HARVESTING MECHANISM UTILIZING FLEXURAL VIBRATION OF A PIEZOELECTRIC MATERIAL

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DECLARATION

I declare that this thesis entitled ”On Energy Harvesting Mechanism Utilizing Flexural Vibration of a Piezoelectric Material” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not currently submitted in candidate of any other degree.

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATION

”To my beloved parents and family”

ABSTRACT

Awareness of green environment has increased the effort of scientists to seek into alternative methods to provide green energy, in which one of them is by exploiting the free energy from the environment. The way toward procuring the surrounding energy in a system and changing it into a usable electrical electrical energy is is named energy harvesting. One of the most popular methods is the utilization of piezoelectric materials to harvest the ambient vibration. This thesis presents three energy harvester systems: sound energy harvester using polyvinylidene fluoride (PVDF) piezoelectric films, vibration energy harvester using cantilevered lead zirconium titanate (PZT) and vibration energy harvester using single degree of freedom-lead zirconium titanate (SDOF-PZT) system. This study aims to evaluate and to validate experimentally the harvested electrical power for each system. Mathematical models are developed to calculate the energy harvesting performance of the each system. For the sound energy harvester using polyvinylidene fluoride (PVDF) piezoelectric films, single film with load resistance of 400 kΩ at 97 dBA the maximum output power of 48 pW and output voltage of 5.8 mV were obtained. For the vibration energy harvester using cantilevered lead zirconium titanate (PZT) the maximum output voltage 2.04 V and output power $4.16\times10^{-}1$ μW at frequency 100 Hz were recorded. For the vibration energy harvester using single degree of freedom-lead zirconium titanate (SDOF-PZT) system, the maximum output 5.6 mV at frequency 35 Hz was measured. For the three proposed systems, the result reveal that the output power obtained from the ambient vibration source can be used to sufficiently recover the electrical current to power up a small wireless sensor.

ABSTRAK

Kesedaran alam sekitar hijau telah meningkatkan upaya saintis untuk mencari kaedah alternatif untuk memberi tenaga hijau, di antaranya dengan menggunakan tenaga bebas dari alam sekitar. Proses mendapatkan tenaga di persekitaran dalam sistem dan mengubahnya menjadi tenaga elektrik yang boleh digunakan dipanggil tenaga penuaian. Salah satu kaedah yang paling popular ialah penggunaan bahan piezoelektrik untuk menuai getaran di sekelilingnya. Tesis ini membentangkan tiga sistem penuaian tenaga: penuai tenaga bunyi menggunakan filem piezoelektrik polyvinylidene fluoride (PVDF), penangkap tenaga getaran menggunakan Pb-lead zirconium titanate (PZT) dan darjah kebebasan pertama-Pb-lead zirconium titanate (SDOF-PZT). Oleh itu, kajian ini bertujuan untuk menilai dan mengesahkan eksperimen bagi setiap sistem. Model matematik telah dibangunkan untuk mengira prestasi setiap sistem. Apabila penuai tenaga bunyi menggunakan filem polyvinylidene fluoride piezoelectric (PVDF), satu filem dengan voltan keluaran maksimum 5.8 mV dan kuasa keluaran 48 pW diperoleh dengan rintangan beban sebanyak 400 k Ω*. Penggunaan tenaga getaran menggunakan Pb-lead zirkonium titanate (PZT) juluran dengan voltan keluaran maksimum 2.04 V dan 4.16* $\times 10^{-}1$ μ*W kepada frekuensi 100 Hz. Untuk penuai tenaga getaran menggunakan sistem darjah kebebasan pertama-Pb-lead zirconium titanate (SDOF-PZT) maksimum output 5.6 mV pada frekuensi 35 Hz. Bagi ketiga-tiga sistem yang dicadangkan, hasilnya menunjukkan bahawa kuasa output yang diperolehi dari sumber getaran boleh digunakan untuk mendapatkan arus elektrik secukupnya untuk menggerakkan sensor tanpa wayar kecil.*

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LIST OF ABBREVIATIONS

SDOF	**S**ingle **D**egree **O**f **F**reedom
PVDF	**P**olyvinylidene **F**luoride
MEMS	**M**icro **E**lectro **M**echanical **S**ystem
PZT	**Pb-**lead **Z**irconium **T**itanate
$PbTiO_2$	**Pb-**lead **TiO_2**Titanate
$PbZrO_3$	**Pb-**lead **ZrO_3**Zirconte
$BaTiO_3$	**Ba-**Barium **TiO_3**Titanate

LIST OF SYMBOLS

A	Cross-sectional area
b	Width of beam
c	Damping constant
C	Capacitance of piezoelectric material
d	Piezoelectric constant
D	Electric displacement constant
E	Electric field constant
f	Frequency
F	Force
F_s	Shear Force
h	Thickness
H	Electromechanical enthalpy density
I	Electric current
$j = \sqrt{-1}$	Imaginary unit
k	Wavenumber
K	Stiffness
K_s	Stiffness of spring
L	Length
L_p	Sound pressure level
m	Mass
M	Moment inertia
Q	Electric charge
p	Sound pressure
p_0	Reference sound pressure
P	Electric power
R	Electric resistance
R_L	Load Electric Resistance

S	Strain constant
T	Stress tensor
U	Stored energy for piezoelectric
V	Electric voltage
w	Displacement
x	Cartesian coordinate x-direction
y	Cartesian coordinate y-direction
Y	Young's modulus
z	Cartesian coordinate z-direction
ω	Angular frequency
Φ_m	Magnetic flux
ρ	Mass density
θ	Rotation of the beam
ε	Permittivity dielectric constant
ζ	Damping ratio

LIST OF PUBLICATIONS

1. A. Putra, M. Y. Abd, N. A. A Jalil, and S. Susilo, “Modeling of dynamic response of beam-type vibration absorbing system excited by moving mass,” *International Review of Mechanical Engineering (I.R.E.M.E)*, vol. 7, ISSN 1970–8734, July 2013.

2. S. Susilo, A. Putra, K. S. Leong, M. Z. Nuawi, and N. A. A Jalil, “Acoustic energy harvesting using flexible panel and PVDF films: A preliminary study,” *Applied Mechanics and Materials.*, vol. 554, pp. 712–716, 2014.

3. S. Susilo, A. Putra, and K. S. Leong, “Modeling of piezoelectric acoustic energy harvester,” *Applied Mechanics and Materials.*, vol. 695, pp. 757–760, 2015.

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CHAPTER 1

INTRODUCTION

In recent years, harvesting energy from ambient has been a growing interest area and becomes important focus of researches (Anton and Sodano, 2007; Harne and Wang, 2013). Ambient energy, especially as a substitution for batteries, comes into attention to solve issues on demanding maintenance activities and the cost of operation. Energy harvesting from ambient in the future is expected to enable to power-up wireless and electronic equipments to become totally self-powered devices, independent on the need of a chemical battery (Yildiz, 2007).

1.1 Background of Study

Portable electronic and autonomous wireless devices are still dependent on electrical power from batteries. Batteries in wireless sensor networks for a large scale of network system which consists of many of hundreds or even thousands of portable electronic devices require high cost in maintenance (Gotmare and Rotake, 2014). The idea to drastically reduce the maintenance cost is to have a ’free’ continuous energy from the ambient which can avoid the energy dependency on conventional batteries and at the same time, can reduce the chemical waste products.

The spirit is in conjunction with the current modern wireless and electronic circuit devices where these become less in power consumption, has been decreasing to a few hundred micro watts and more. Therefore it becomes possible to power-up these instruments by utilizing energy harvested from the ambient Roundy et al. (2003); Zhu et al. (2010). When connected with storage devices, such as batteries, capacitors and the others, the ambient energy represents a relatively infinite available source of energy (Beeby et al., 2007).

Ambient energy can be defined as the energy which is not stored explicitly, but is available in the surroundings. Several sources can be used to harvest energy from ambient sources, including wind, solar, ocean waves, physical motion, thermoelectric, light and thermal as seen in Table 1.1 (Alippi and Galperti, 2008; Donovan, 2012). These sources have the advantages that they are essentially free, their conversion mechanism are clean (there is no pollution associated with the conversion process), and the sources have potential infinite lifespan (Seah et al., 2009).

Table 1.1 Power available from energy harvesting sources.

Ambient Source	Source	Source Power	Harvested Power
Light	Indoor	0.1 mW/cm^2	10 μW/cm^2
	outdoor	100 mW/cm^2	10 mW/cm^2
Vibration	Human	1 m/s^2 at 50 Hz	4 μW/cm^2
	Machine	10 m/s^2 at 1 kHz	100 μW/cm^2
Thermal	Human	20 mW/cm^2	30 μW/cm^2
	Machine	100 mW/cm^2	1-10 mW/cm^2
Radio Frequency (RF)	GSM BSS	0.3 μW/cm^2	0.1 μW/cm^2

Figure 1.1 shows an example of energy harvested from pressure obtained from walking activities. The tiles were constructed to include embedded piezoelectric materials which can convert the pressure applied on the tiles into electricity.

Numerous works on harvesting ambient energy using piezoelectric materials have been proposed by researchers. Although it has lower energy density compared to other sources, it has been shown that it can recover and can be used as electrical current sufficient to power a small electric devices and/or small wireless sensor. The potential for making possible small electric devices and/or wireless sensor applications such as structural health monitoring,

Figure 1.1 Tiles in floor to harvest energy from pressure from walking activities (Rosenfeld, 2014)

wildlife tracking monitoring and also can be applied in medical field (Dagdeviren et al., 2014).

This study concerns on harvesting ambient energy by using piezoelectric materials where the ambient sources are sound and mechanical vibration. This report discusses the mathematical model and predicted values of energy harvested from ambient to be electrical power and to conduct experiments to test the validity of the proposed theoretical model. A parametric study is also presented to observe the optimisation for the power harvesting process.

1.2 Problem Statement

Although studies on energy harvesting utilising piezoelectric materials are well established, a few issues can be extended or can be improved in order to provide new knowledge in the area of energy harvesting, particularly those with piezoelectric materials.

Three studies are addressed:

1. Sound energy harvesting using Polyvinylidene Flouride (PVDF) piezoelectric materials. Almost all existing works related with energy harvesting from sound here dealed with Helmholtz resonator (Liu et al., 2008; Yang et al., 2013). The piezoelectric material is located in a closed compartment and the natural frequency of the system is then tuned with the dominant frequency of the ambient sound to optimize the deflection of the piezoelectric material (Li et al., 2013). The device is thus limited to a specific case with a known 'single' dominant frequency of sound. Here, an 'open system' is introduced where a flexible panel is used utilizing its mode of vibration due to random incident sound and therefore can be used within band of frequency range instead of only a single frequency. The polyvinylidene flouride (PVDF) are attached around the edges of the panel to harvest the flexural vibration of the host panel.

2. Vibration energy harvester using cantilevered lead Zirconium Titanate (PZT). Most of published works present the piezoelectric materials attached on beam structure as the host structure with added proof mass (Kim et al., 2010; Diyana et al., 2012) . In this study, PZT piezoelectric material itself is directly utilized as the beam structure. This system is proposed to harvest energy from based excitation vibration.

3. Vibration energy harvester using SDOF-PZT system. Similar to the proposed cantilevered PZT, the study is also extended where the piezoelectric material is attached with a single-degree-of-freedom (SDOF) system consisting of proof mass and spring elements subjected to based excitation. Discussion of the latter is still found to be lack in the literatures.

For each of the proposed system, mathematical model to solve the displacement of the piezoelectric material are developed. Particularly for the system No. 2 and No. 3, models of vibration wave propagation in a structure are employed.

1.3 Objective of Study

Numerous works on harvesting ambient energy using piezoelectric materials have been proposed by researchers. Although it has lower energy density compared to other sources, it has been shown that it can recover and used as electrical current sufficient to power a small electric devices and/or small wireless sensor. The objective of this thesis is to study and to develop existing mathematical models for the energy harvesting system from vibrating structure using piezoelectric material. Based on two methods and mechanism vibration ambient energy harvesting based on piezoelectric material will employed, the performance of the energy harvesting each method and mechanism will be discussed as well.

Aiming at an energy harvesting system from vibrating structure based piezoelectric material energy harvester, the scope of this study can be divided into:

1. To develop mechanism model of energy harvesting from flexural vibration of piezoelectric beam.
2. To validate the mechanism model.

Developing mathematical model is important to know the effectiveness of the harvesting system. Euler-Bernoulli beam theory is employed as to model the dynamics of the energy harvester beam. Model of the harvester is basically the fundamental principle of conservation of energy (the first law of thermodynamics) for a linear piezoelectric continuum (Tiersten, 1969). In mathematical modelling, we using MATLAB® software to predict the coupled system dynamics of piezoelectric energy harvesters. The piezoelectric materials are used in this study are PVDF and PZT. The PVDF piezoelectric material film is proposed to harvest acoustic energy with sound pressure as an input the excitation. The PZT piezoelectric material beam is proposed to harvest energy from base vibration excitation in frequency range. All the harvesters are connected to the load resistance for knowing the output current, output voltage and output power as the parameters performance of the harvesters.

1.4 General Methodology

The study starts with literature review on the previous study starts with literature review on the previous works concerning the energy harvester system from sound and vibration energy particularly those using piezoelectric materials. The mechanism and performance of existing models are discussed.

The next step is to develop mathematical models representing the mechanism of the proposed systems as in Sections 1.2 and 1.3. Developing mathematical model is important to know the effectiveness of the harvesting system. Euler-Bernoulli beam theory is employed to model the dynamics of the energy harvester beam. The harvester basically uses the fundamental principle of conservation of energy (the first law of thermodynamics) for a linear piezoelectric continuum (Tiersten, 1969). For the mathematical modelling, MATLAB® software is used to calculate the output power as the result of the coupled electro-mechanical relationship of the piezoelectric energy harvesters. The piezoelectric materials used in this study are PVDF and PZT.

The PVDF piezoelectric material are used to harvest the acoustic energy impinging on a flexible panel where these piezoelectric materials are attached. Meanwhile the PZT piezoelectric materials beam are used to harvest energy from base vibration excitation. The harvesters are connected to the load resistance to obtain the output current, output voltage and output power as the parameters representing performance of the harvesters.

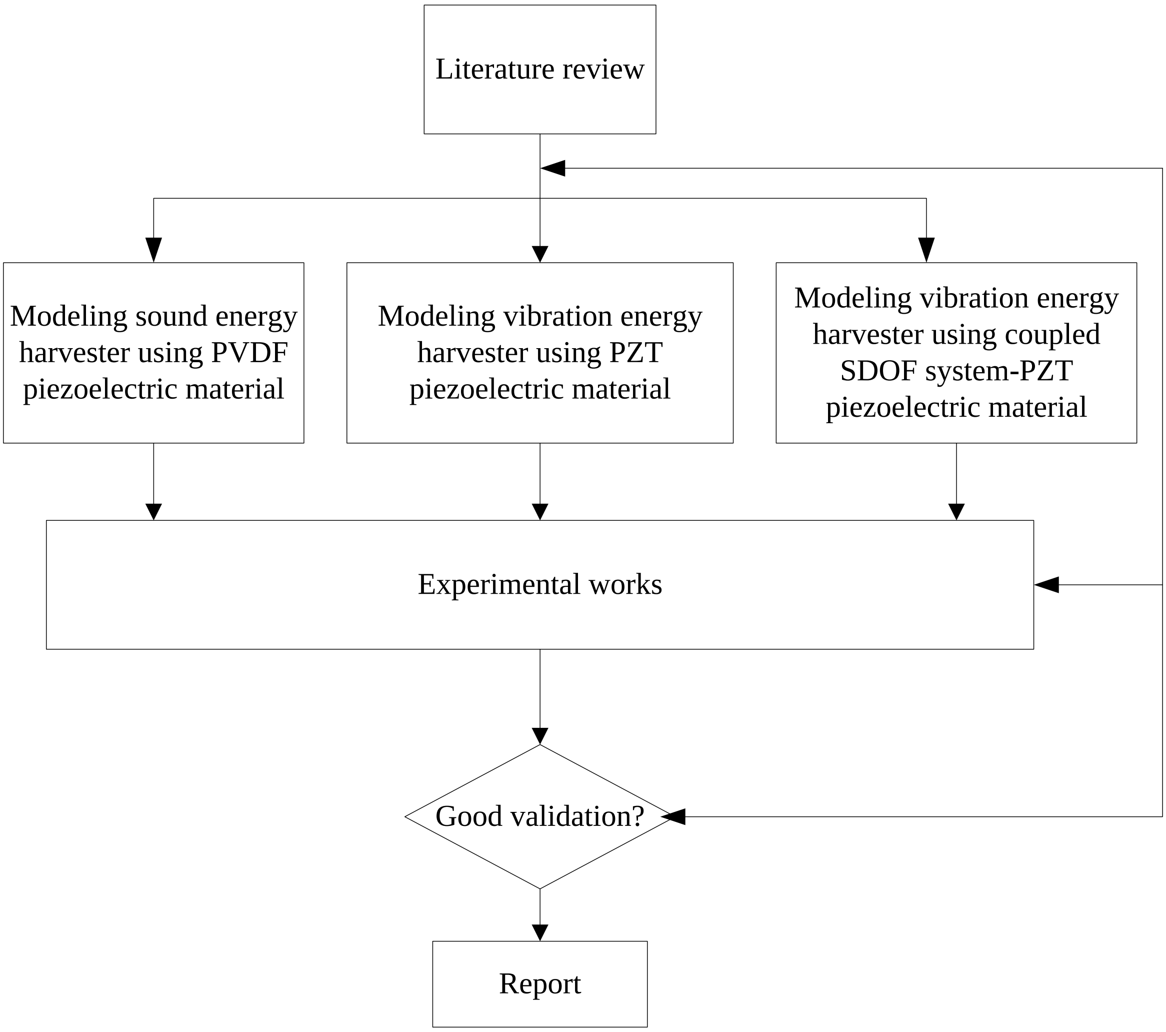


Figure 1.2 Flow chart of the methodology

Experiment was then conducted to validate the results obtained from the models. The flow of the methodology is shown in Figure 1.2.

1.5 Thesis Outline

The structure of the thesis is as follows:

Background information for this study, provided in Chapter 2, includes an explanation of piezoelectric material and a literature review on related research. This chapter also includes several existing methods and models as the theoretical background for energy harvesting from ambient based on a piezoelectric material.

In chapter 3 focuses on the methodology to develop mathematical modelling and experimental test set up. A model is developed for an acoustic, cantilevered PZT and a single-degree-of-freedom (SDOF)-PZT energy harvester are described and for experimental works vice versa. Modelling methods from Du Toit (No el Eduard, 2005) and Euler-Bernoulli beams theory (Inman, 2008) are implemented to calculate the output power from energy harvester.

The result from mathematical modelling for the acoustic, cantilevered PZT and SDOF-PZT under vibration base excitation energy harvester and results from the experimental works are presented in Chapter 4. A mathematical modelling is presented and validated with experimental measurements. Then brief discussion regarding the experiment are performed and the test results are presented. A summary of the results is used to compare and evaluate the performance of the energy harvester system.

Finally, Chapter 5 summarizes the result and the conclusion of the study and provides recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

Energy harvesting is a process of utilizing ambient energy into usable energy form, which is converting ambient energy into electrical energy in order to power-up electronic devices. One of kind from ambient energy can be harvested as sources is vibration. There is three kind mechanisms in vibration energy harvesting the electrostatic, electromagnetic, or piezoelectric effects can be employed as converter vibration to electrical energy. These three mechanisms will be discussed briefly in this chapter, before focusing on piezoelectric energy harvesting.

2.1 Previous Study

Energy harvesting (also known as energy scavenging or power harvesting or ambient power) is a process of utilizing ambient energy into usable electrical energy form, which is converting ambient energy into electrical energy in order to power-up electronic devices. Energy can be harvested from environment are light source, temperature gradient, wind, vibration, etc.

Photovoltaic is harvested energy from the light source. Photovoltaic can generate electrical power by changing over light radiation either in inside or outside into direct electrical power utilizing semiconductors that demonstrated the photovoltaic effect. Photovoltaic generation utilizes solar panels based on various cells containing a photovoltaic material.

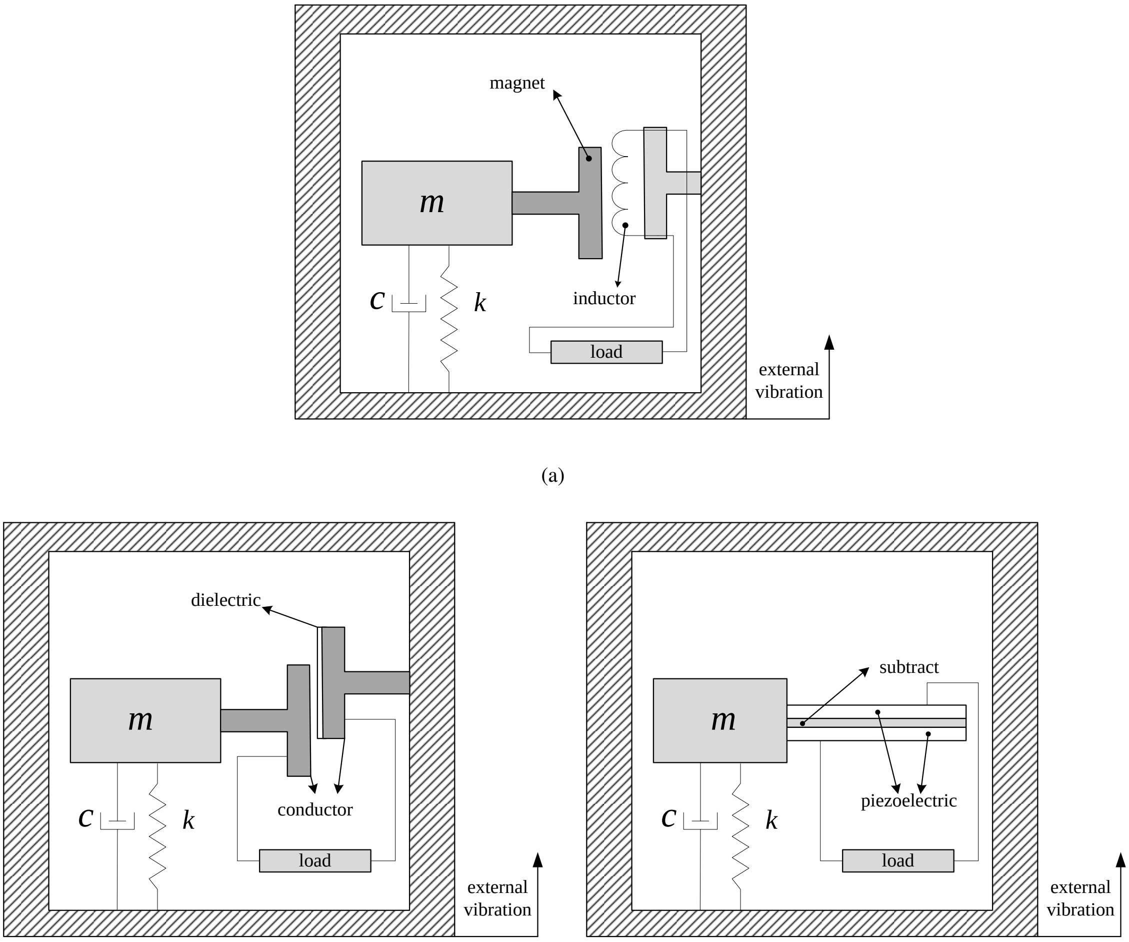
Thermoelectric consists of junction of two dissimilar materials. Electrical energy can be generated with the existence of temperature gradient. These can be utilised to capture energy from industrial structures, machine equipment, and even the human body. The systems are typically coupled with heat sinks to improve temperature gradient.

Wind turbines are used to harvest wind energy readily available in the environment in the form of kinetic energy to electricity. Currently, researches are progressing towards micro wind turbines used to power up the low power electronic devices such as wireless sensor nodes.

2.1.1 Types of Vibration Energy Harvesting

Vibration energy harvesting has attracted much attention of research. Many vibration sources can be founded from the environment, such as buildings, bridges, engines or even body movement. Some watches are already powered by vibration energy where the movement of the arm is used as ambient kinetic energy sources. The arm movement causes the mainspring inside the watch to wind. This then provides a rate of change of flux, which results in electrical induced on the coils. The concept is simply related to Faraday's Law and this concept is usually called the electromagnetic energy harvesting.

Vibration energy harvesting can be categorised into three main methods in terms of the mechanical to electrical converting processes, namely electrostatic, electromagnetic, and piezoelectric materials. The diagram is illustrated in Figure 2.1. These three mechanisms are discussed briefly in this chapter.



(a)

(b)

(c)

Figure 2.1 (a) Electromagnetic vibration energy harvesting, (b) Electrostatic vibration energy harvesting and (c) Piezoelectric vibration energy harvesting.

2.1.1.1 Electromagnetic Vibration Energy Harvesting

The first mechanism of vibration energy harvesting is electromagnetic vibration energy harvesting which is based on Faraday's law. The principle work employs the magnetic induction transducer to create magnetic flux. A coil moving in a magnetic field causes a variation in the magnetic flux through the electrical circuit and thus generates current flows. This mechanism can be realised by a moving magnet with fixed coil or fixed magnet with moving coil to create magnetic flux variation. As illustrated in Figure 2.1(a) this mechanism is utilised to convert motion (vibration) into electrical energy.

(Williams and Yates, 1996) first developed micro-electromagnetic generator with dimensions of around 5 mm×5 mm×1 mm. (Amirtharajah and Chandrakasan, 1998) utilised 500 mg mass with conventional spring to drive a signal processing circuit. (Ching et al., 2000) developed an electromagnetic micro generator that PCB-integrated capable to producing 245 mV peak to peak voltage with 104 Hz input frequency. (Williams et al., 2001) then improved the system by fabricating a linear micro-generator which was capable of generating 0.3 μW at an excitation frequency of 4 MHz. A set of smaller electromagnetic generators, with component volume of 0.1 cm^3 have also been reported for application in low ambient vibration (Beeby et al., 2007).

Some researchers introduced a mechanical frequency up-conversion mechanism to increase the efficiency of a low frequency vibration of an electromagnetic energy harvester by using extra magnetic materials (Zorlu et al., 2009). Some studies have reported to arrange a cantilever with a wound coil and four magnets as a generator located in the moving magnetic field to increase the performance of the harvester (Zhang et al., 2008). However, it is difficult to fabricate an electromagnetic generator at a micro scale, because of the poor properties of the magnets itself and the limited number of rounds that can be created when producing coils for the energy harvester devices.

2.1.1.2 Electrostatic Vibration Energy Harvesting

Electrostatic vibration energy harvesting is based on the concept mechanism of variable capacitor. In simple capacitor there is two charged plate conductors and isolated by dielectric material. A variable capacitor consists of two conductors separated by a dielectric material, the two plates are electrically isolated from one another by air, a vacuum, or an insulator (Erturk et al., 2009). Electrostatic vibration energy harvesting use the movements between the charge plate conductors to generate the electricity. In the simplest case, an external mechanical vibration causes the gap between the plate conductors varies the changes in the capacitance of the plates changes as illustrated in Figure 2.1(b). When the plate conductor is placed in an electric field and the other side plate conductor move relative to each other, then the electricity is generated (Yen and Lang, 2006). In order to produce electricity in electrostatic vibration energy harvesting and extract the useful energy, the plate conductors should be charged first as well is a capacitor and the force from mechanical vibration work against to the electrostatic generator (Susanto, 2009). An overview of simulations show the properties for the different micro electro mechanical system (MEMS) electrostatic harvesting result show that the output power density of the generator is 116 μW/cm^3 and it is possible can be obtained from vibrations input source of 2.25 m/s^2 at 120 Hz Roundy et al. (2002). Some generator consists of an in-plane variable capacitor polarised means of a SiO_2/Si_3N_4 electret. In order to improve the transformation characteristics of the generator the capacitor (Sterken et al., 2004). On other hand, an experimental based prototype based on a variable parallel plate capacitor was developed for low frequency operation (Mitcheson et al., 2004). Some method to fabricating a MEMS electrostatic vibration energy harvesting has been proposed with thick device layer was used for large capacitance is an oxide layer 2 μm and 500 μm for the handle wafer device (Chu et al., 2005). In electrostatic energy harvesting an external voltage should be applied to the materials as a trigger. However, the charge drop overtime caused limited the lifetime of the dielectric.

2.1.1.3 Piezoelectric Vibration Energy Harvesting

Interest in the application of piezoelectric material energy harvesting has been studied over the latest few decades. A conventional piezoelectric energy harvester is a system consisting of a cantilever beam structure. Numerous studies have been published regarding the mathematical modelling of the electrical energy which can be harvested from this system (Meninger et al., 2001; Lu et al., 2003). A number of experimental works in energy harvesting based on piezoelectric material have also been reported in recent years (Kim et al., 2010; Shan et al., 2017). From the previous works, they find out that the performance of the harvester can be vary greatly, depending on the properties of the devices, excitation of the vibration input parameters and mechanism of energy conversion (Erturk and Inman, 2009). The piezoelectric devices also have the potential to extract energy at low velocity (Mineto et al., 2010; Ardito et al., 2015). The simple structure of the piezoelectric material makes it compatible with MEMS technology (Zhu, 2011; Kulah and Najafi, 2008).

Simple concept of piezoelectric energy harvesting is based base excitation because the device can be easily attached at vibration source as can be see in the Figure 2.1(c). It has also shown that many vibration sources can be used as an excitation for the harvester devices (Mateu and Moll, 2005). Similar to the example in Figure 1.1, Shenck and Paradiso (2001) created a piezoelectric energy harvester placed in shoes to harvest energy from the pressure obtained when walking or running. Meanwhile, Guigon et al. (2008) utilised the impact of the rain drop, converting it into electrical energy. The harvester can be potentially used in the area where the rain frequency is high. Solid state wind vibration devices can harvest energy from the ambient wind flows by utilising the fluttering PVDF film piezoelectric material (Li et al., 2011). 'Eel' structure has been developed which uses the PVDF piezoelectric material for converting mechanical energy in the sea or water flows of the rivers into electricity for powering remote located sensors (Techet et al., 2002; Taylor et al., 2001).

Another mechanism of vibration energy harvesting is the use of acoustic energy as the excitation source for the piezoelectric material (Phipps et al., 2009; Pillai and Deenadayalan, 2014). A few works have been done to harvest the acoustic energy utilizing piezoelectric materials. A novel methods using electromechanical Helmholtz resonators have been reported by Horowitz et al. (2006) and Zhou et al. (2017). The acoustic energy harvester employs the conventional Helmholtz resonator with a tuned natural frequency matching with that of the incoming sound. The air pressure in the cavity causes the deflection of the piezoelectric materials (Khan and Izhar, 2013).

A generator acoustic energy harvester consolidating sonic crystal tube and curved beam shape piezoelectric material has likewise been reported (Wang et al., 2010). The pressure difference between the two side of the curved beam act as an external force to vibrate the piezoelectric material.

Environmental noise has also been demonstrated to be possible as the ambient sources (Kralov et al., 2011) created MEMS for acoustic energy harvester as noise reduction in the railway system. A quarter-wavelength straight-tube acoustic resonator with polyvinylidene fluoride (PVDF) piezoelectric material has also been proposed to harvest acoustic energy at a low frequencies. The length of the tube is 58 cm and the corresponding first acoustic natural frequency is 146 Hz of the harvesters (Li and You, 2012; Lien and Shu, 2012).

Common method for piezoelectric vibration energy harvesting uses the fundamental vibration mode, which is known as free-standing structure in the form of cantilevers (Roundy and Wright, 2004). These methods were designed to operate as an ambient vibration energy harvester from a host structure. An analytical model in beam structure with PZT elements attached in cantilever boundary conditions provide an effective configuration for capturing transverse vibrations and convert it into useful electrical power (Sodano et al., 2004). Similar methods were proposed by Chen et al. (2006) and Fang et al. (2006) where the electrical response is expressed in terms of the beam vibration. Ajitsaria et al. (2007) developed an analytical approach based on the equations of Euler-Bernoulli and Timoshenko beam theory to model PZT bender for voltage and power generation. Recently, free-standing thick piezoelectric film cantilevers made from a combination of conventional thick film technology and sacrificial layer techniques to harvest ambient vibration in low frequency has been reported (Kok et al., 2008). The combination of energy harvester with a rechargeable batteries or with another energy storage components like a thin film rechargeable battery or a super capacitor is the best approach to enable energy generation of the electronic devices (Vullers et al., 2009). The dynamic vibration absorber (or dynamic magnifier), which works through the interaction of coupled elastic structures, has been considered by some investigators (Wang et al., 2012; Dicken et al., 2012). Many dynamic models have been presented which come from various disciplines such as mechanical, electrical, civil and materials engineering to simulate piezoelectric material harvester and several works related to experimentation (Galchev et al., 2011; Telba and Ali, 2012).

2.2 Theoretical Background

This section will look into the theory of piezoelectric energy harvesting. The theory is concentrating on develop mathematical model from flexural vibration in beam into electromechanical coupling equation of piezoelectric material as energy harvester.

2.2.1 Flexural Vibration in Beam

Structure such as including buildings, aircraft, ships, bridges, pipelines and others of are subjected vibration coming from the structure-borne sources. The vibration may result in perceptible vibration and annoying radiated noise from the structure.

The beam is used in design and analysis of a variety of structures, from buildings to bridges to the load-bearing of human bones. The term 'beam' has a very specific meaning in mechanical engineering field, it is a component designed to support the transverse load. Vibration of the beam in the direction perpendicular to its length is transverse vibration or flexural vibration, because they move across the length of the beam. The vibration of a beam can be decomposed as the sum of three different kinds of waves: compressive, rotational and bending waves. Consider a uniform and thin beam for wavelength which are greater than ten times the cross-sectional dimensions of the element beam (Petyt, 2010). For this reason, the Euler-Bernoulli beam theory can be applied. Bending waves are assumed to propagated through the length of the beam. The equation of motion of the flexural vibration is given by:

$$YI\frac{\partial^4 w(x,t)}{\partial x^4} + \rho A\frac{\partial^2 w(x,t)}{\partial t^2} = 0 \tag{2.1}$$

where $w(x,t)$ is flexural displacement through the beam with constant cross-sectional area

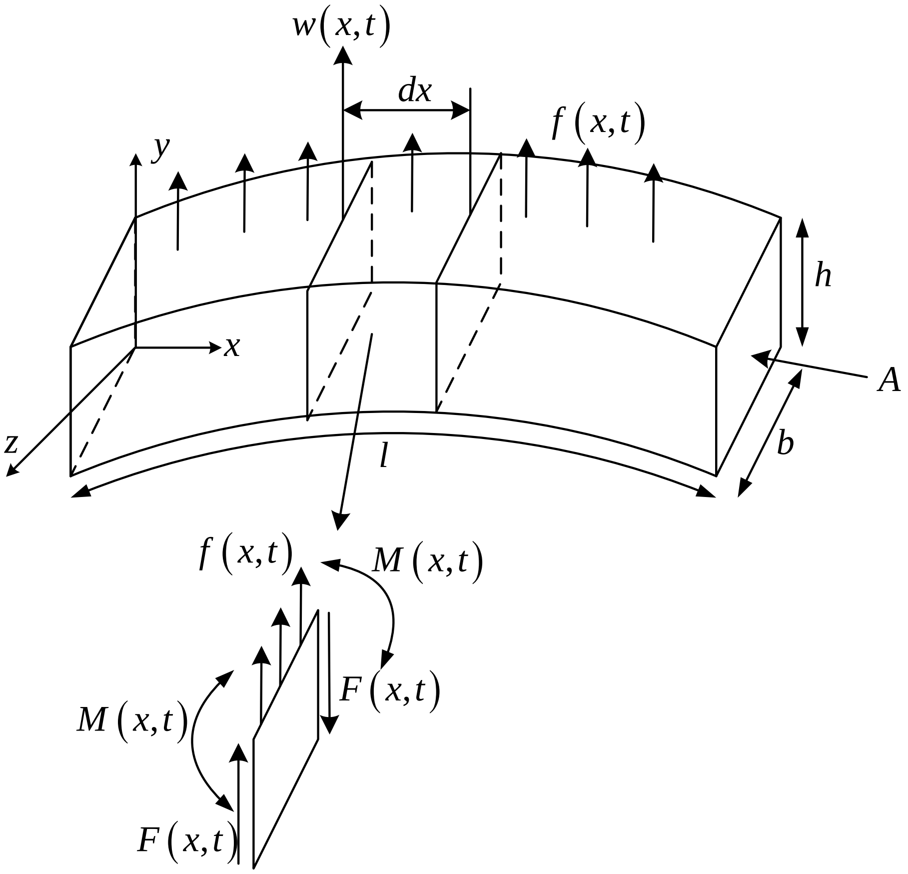


Figure 2.2 Beam indicating the variable used in the vibration model

A, Young's elastic modulus Y, second moment of area I and density ρ. The general solution to the Eq.(2.1) is assumed for a time harmonic solution of the form (Carrera et al., 2011).

$$w(x,t) = W(x)e^{jwt} \tag{2.2}$$

where the solution can be written as

$$W(x) = a_1 e^{-jkx} + a_2 e^{jkx} + a_3 e^{-kx} + a_4 e^{kx} \tag{2.3}$$

and the wavenumber is k defined as

$$k = \sqrt{\omega}\left(\frac{\rho A}{YI}\right)^{\frac{1}{4}} \tag{2.4}$$

where a_n is the amplitude of the waves and $a_n e^{j(\omega t - kx)}$ is a harmonic wave which varies in space and time and propagate in the negative x-direction and $a_n e^{j(\omega t + kx)}$ in the positive x-direction. If the forward and backward travelling waves have the same amplitudes they interfere and result in a standing wave, also known as a stationary wave.

From Eq.(2.3) the first two terms represent waves propagating in the x-direction that is positive and negative, and the last two terms are near-field waves. This latter type of waves only have significant amplitude close to discontinuities in the beam and in this case, is at the ends of the beam. In addition, the amplitude of the near-field wave decays exponentially with the distance. Figure 2.3 illustrates the direction of the displacement, force and the waves.

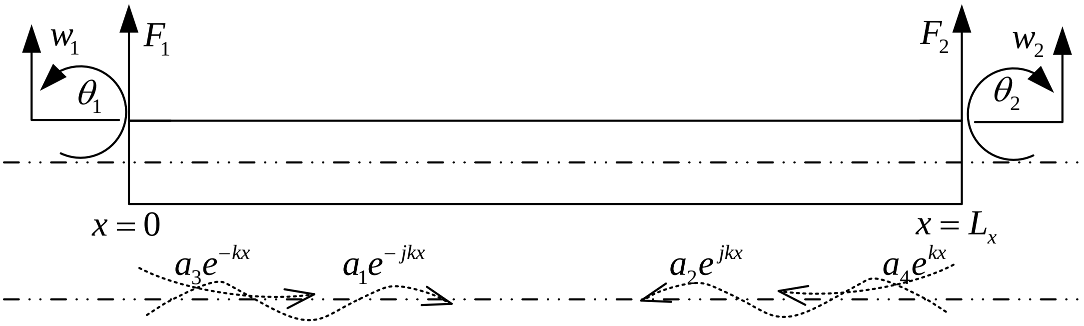


Figure 2.3 Wave propagating in beam

The beam present two degrees of freedom, i.e the displacement $w(x,t)$ and the rotation $\theta(x,t)$, where the rotation is defined as:

$$\theta(x,t) = \frac{\partial w(x,t)}{\partial x} \tag{2.5}$$

Then, from Eqs.(2.2),(2.3) and (2.5), the vector of the degrees of freedom is given by

$$\begin{bmatrix} w_1 \\ \theta_1 \\ w_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -jk & jk & -k & k \\ e^{-jkL_x} & e^{jkL_x} & e^{-kL_x} & e^{kL_x} \\ -jke^{-jkL_x} & jke^{jkL_x} & -ke^{-kL_x} & ke^{kL_x} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{2.6}$$

where subscript 1 represent $x = 0$, and 2 for $x = L$. The displacement of the beam is the result of two effects, namely the shear force F and bending moment M (Inman, 2006). These forces are expressed as

$$M\left(x\right) = YI\frac{\partial^2 w}{\partial x^2} \tag{2.7}$$

$$F\left(x\right) = YI\frac{\partial^3 w}{\partial x^3} \tag{2.8}$$

Substituting Eq.(2.6) gives the general matrix of force written as

$$\begin{bmatrix} F_1 \\ M_1 \\ F_2 \\ M_2 \end{bmatrix} = YI \begin{bmatrix} -jk^3e^{-jkx} & jk^3e^{-jkx} & k^3e^{-kx} & -k^3e^{kx} \\ -k^2e^{-jkx} & -k^2e^{jkx} & k^2e^{-kx} & k^2e^{kx} \\ -jk^3e^{-jkL_x} & jk^3e^{-jkL_x} & k^3e^{-kL_x} & -k^3e^{kL_x} \\ -k^{2-jkL_x} & -k^2e^{jkL_x} & k^2e^{-kL_x} & k^2e^{kL_x} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \tag{2.9}$$

These forces can be written in terms of matrix from

$$\tilde{F} = K\tilde{w} \tag{2.10}$$

where $\tilde{w}$ is the vector of the degree of freedom in Eq.(2.6) and K is the dynamic stiffness matrix.The dynamic stiffness matrix can then solved by

$$K = \tilde{F}\tilde{w}^{-1} \tag{2.11}$$

After the definition of the dynamics element of the beam, it is then possible to develop a simple order to estimate the displacement of any point using the dynamic stiffness matrix an to finally find the response of the beam.

2.2.2 Piezoelectric Effect

In 1880, Jacques and Pierre Currie found the piezoelectric phenomenom in certain crystalline materials: when the materials are subjected to a mechanical power, crystal become to be polarized electrically. The polarities for tractable and compressive forces are inverse and the polarity is corresponding to the applied force. The reverse phenomenon is also agreed: when the crystalline material subjected to an electrical field (Smits et al., 1991). The latter is known as the inverse piezoelectric effect . Piezoe comes from the Greek Word ”piezo,” which means ”press”. Piezoelctric materials have been commonly used for both sensors and actuators in the macro-scale applications and in the last few years. Common piezoelectric materials are lead zirconate titanate (PZT), lead titanate ($PbTiO_2$), lead zirconate ($PbZrO_3$), barium titanate ($BaTiO_3$), quartz, zinx oxide, and PVDF. These several ceramic materials have been described as showing piezoelectric effect (Sharapov, 2011).

An electromechanical system is a system in which mechanical and electrical systems interact such that energy is transferred from one system to another (Kelly, 2007). There are two piezoelectric effects: direct effect and inverse effect. The direct effect (designated as a

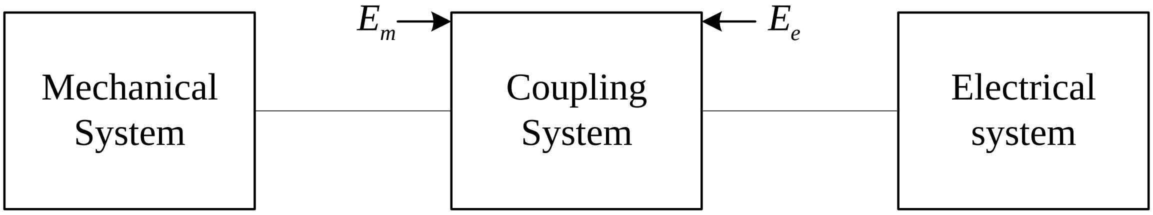


Figure 2.4 Schematic of an electromechanical system: Energy is transferred from the electrical and mechanical systems and stored in the coupling field

generator) is identified with the phenomenon in which the electrical charge generated from a mechanical stress, whereas the inverse effect is associated with mechanical movement generated by the application of an electrical field. Therefore, piezoelectric energy harvesting is to use the direct effect. The energy transfer occurs in coupling field, also called a transducer, as illustrated schematically in Figure 2.4.

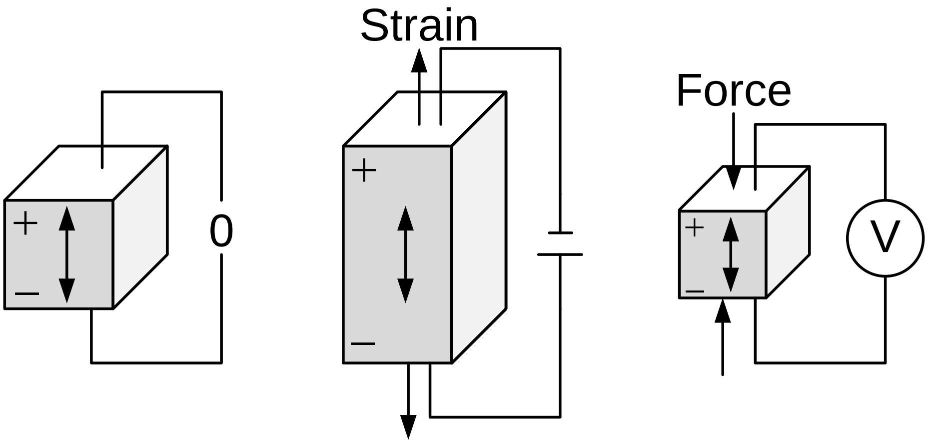
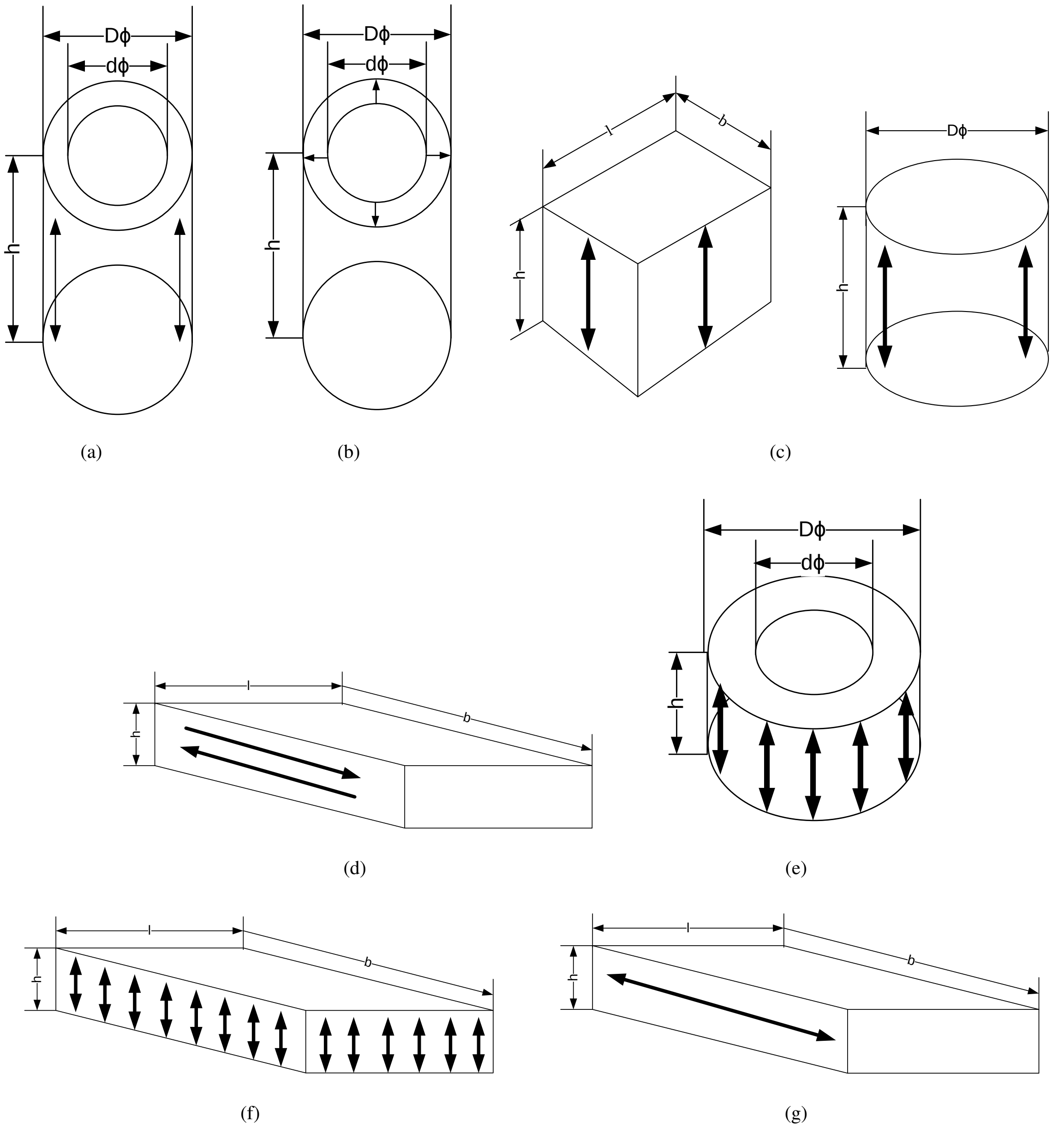


Figure 2.5 Schematic showing the response of piezoelectric effect

Piezoelectric materials can produces electrical charges when they are subjected to an external load or force. Figure 2.5 shows the principle working of piezoelectric material, they has various modes that can be used to construct a piezoelectric energy harvesting device. The common modes of vibration are summarized in Figure 2.6 (Cook-Chennault et al., 2008).

Among the various concepts for piezoelectric energy harvesters, the cantilevered beams are the simplest ones. As discussed in chapter before, the harvester beam is positioned onto



(a) (b) (c) (d) (e) (f) (g)

Figure 2.6 (a) Length mode (thin wall tube), (b) Circumferential (thin wall tube), (c) Longitudinal mode (d) Shear mode plate, (e) Thickness mode (thin disk), (f) Thickness mode (plate), (g) Length mode (thin bar)

a vibrating host, where the dynamic strain is induced in the piezoelectric material layer generate an alternating voltage output across their electrodes. Figure 2.3 shows a schematic of a cantilever tested under base excitation and a harmonic base motion is applied to the structure than electricity is produced.