INVESTIGATION AND EXPERIMENTAL WORK ON POWER GENERATION BY PIEZOELECTRIC DEVICES

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ABSTRACT

This project was carried out to study the characteristics of different types of piezoelectric device and experimental work on how to obtain power generation by piezoelectric device. The objectives of this research are to investigate the different characteristic from different types of piezoelectric device and to find the method how to obtain power generation by piezoelectric devices. A test rig consists of the releaser, steel ball, specimen holder, and ruler to run this experiment. The types of piezoelectric used are single layer piezoelectric disc and two layer piezoelectric discs. The voltage produces from the piezoelectric devices are from the different impact forces applied on the device. The impact forces are from the steel ball which is release from different heights. The voltage signal produced from piezoelectric was captured by electrical device called oscilloscope. The voltage output for the single layer piezoelectric and two layers piezoelectric at the different impact force were recorded and analyzed. All the value recorded was compared to the different impact force applied. The result shows that the voltage output from the single layer piezoelectric are higher than the voltage output from the two layers piezoelectric at any impact force applied. The deflection of the piezoelectric is directly proportional to the voltage output. The conclusion has shown that the voltage produces by two layers piezoelectric are lower than single layer piezoelectric because the placement of the specimen is not optimum which mean there is limitation for the specimen to gain maximum deflection.

ABSTRAK

Projek ini dijalankan sebagai kajian terhadap penyiasatan berdasarkan cirri-ciri yang terdapat dalam jenis-jenis *piezoelectric* yang berlainan dan juga eksperimen yang dijalankan bagi menghasilkan kuasa daripada *piezoelectric*. Objektif bagi kajian ini adalah untuk menyiasat ciri-ciri daripada *piezoelectric* yang berlainan jenis dan untuk mencari kaedah bagi menghasilkan kuasa daripada *piezoelectric*. Satu alat ujikaji yang terdiri dari pelepas, bebola besi, pemegang spesimen dan pembaris dibina untuk jalankan eksperimen. Jenis piezoelectric yang digunakan adalah cakera *piezoelectric* satu lapis dan cakera *piezoelectric* dua lapis. Voltan yang dihasilkan daripada *piezoelectric* adalah hasil dari kesan daya yang berlainan yang dikenakan ke atas *piezoelectric*. Kesan daya yang dikenakan ke atas *piezoelectric* adalah dari bebola besi yang dilepaskan dari ketinggian yang berbeza. Isyarat voltan yang dihasilkan dari *piezoelectric* direkod oleh *oscilloscope*. Nilai voltan yang dihasilkan oleh *piezoelectric* satu lapis dan *piezoelectric* dua lapis pada kesan daya yang berbeza direkod dan dianalisis. Semua nilai voltan yang direkod kemudiannya dibandingkan dengan nilai voltan pada kesan daya yang berlainan. Hasil menunjukan bahawa nilai voltan dari *piezoelectric* satu lapis adalah lebih tinggi daripada nilai voltan dari *piezoelectric* dua lapis pada sebarang kesan daya yang dikenakan ke atas spesimen. Kelenturan *piezoelectric* adalah berkadar langsung dengan hasil voltan. Kesimpulannya, hasil voltan dari *piezoelectric* dua lapis adalah kurang daripada nilai voltage dari *piezoelectric* satu lapis disebabkan oleh kedudukan spesimen tidak optimum, bermaksud terdapat had untuk spesimen melentur pada maksimum.

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LIST OF SYMBOLS

g_{ij}	Piezoelectric constant, Voltage constants
d_{ij}	Piezoelectric constant, Charge constant, or Strain constant
β_{ij}	Impermeability constant
s_{ijkl}	Elastic compliance constant
c_{ijkl}	Elastic stiffness constant
T_{ij}	Mechanical stress
S_{ij}	Mechanical strain
E_i	Electric field strength
D_i	Electric charge density
E, superscript	Constant electric field
D, superscript	Constant charge density
S, superscript	Constant strain
T, superscript	Constant stress
ϵ_{ij}	Permittivity constant, dielectric constant
ε	Mechanical strain
σ	Mechanical stress
U	Energy
C	Capacitance
h_p	Piezoelectric layer thickness
Q	Charge
F	Force
A	Area

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND STUDY

Piezoelectric is a type of electronic device that uses piezoelectric effect to measure pressure, acceleration, strain, or force by converting them to an electrical charge. Piezoelectric sensors have proven to be versatile tools for the measurement of various processes. They are used for quality assurance, process control and for research and development in many different industries. Piezoelectric effect was discovered by Pierre Curie in 1880, but it was applied only in the 1950s for industrial sensing applications. It has been successfully used in various applications, such as in medical, aerospace, nuclear, instrumentation, and as a pressure sensor in the touch pads of mobile phones (Arnau, 2008).

In recent years, the self- powered generation electronics devices demand are increasing due to today modern era and has caused a lot of research into power harvesting devices. From the advances wireless technology criteria, sensor are being developed that can be placed almost everywhere. However, because these sensors are wireless, they required their own power supply which is in most cases is the convectional electrochemical battery. The goal of a power harvesting device is to capture the normally lost energy surrounding a system and convert it into usable energy for the electrical device to consume. The idea of vibration-to-electricity conversion is from the literature that is first appeared in a journal article by William and Yates in

1996. They described the basic transduction mechanisms that can be used for this purpose and provided a lumped-parameter base excitation model to simulate the electrical power output for electromagnetic energy harvesting. As stated in William and Yate, the tree basic vibration-to-electric energy conversion mechanisms are the electromagnetic, electrostatic, and piezoelectric transductions. Over the last decade, several articles have appeared on the use of these transduction mechanisms for low power generation from ambient vibrations. Two of the review articles covering mostly the experimental research on all transduction mechanisms are given by Beeby et al. and Cook-Chenault et al.. Comparing the number of publications appeared using each of these three transduction alternatives, it can be seen that the piezoelectric transduction has received the greatest attention especially in the last five years. Four review articles have appeared in four years (2004-2008) with an emphasis on piezoelectric transduction to generate electricity from vibrations (Henry, Sodano and Daniel, 2005)

1.2 PROBLEM STATEMENT

Many researchers have been done by the researcher all around the world on this piezoelectric device especially for industrial uses. Existing piezoelectric devices may have the different parameters because of the different types of piezoelectric. Some theory was related to the different parameters such as material used and type of the piezoelectric. Hence, this project is focus on the characteristics of the piezoelectric and power generation by the piezoelectric devices by conduct the experiment to obtain power from the piezoelectric. The equipment required to catch the signal produces by the piezoelectric are oscilloscope and ammeter. The signal was interpret to compare the parameters of the piezoelectric devices.

1.3 OBJECTIVES

The objectives of this project that need to be achieved are:

i. To investigate the characteristic of different type of piezoelectric.
ii. Experimentation on how to obtain power generated by piezoelectric.

1.4 PROJECT SCOPE

The focus area will be done based on the following aspect:

i. Review of existing piezoelectric power generators for the specific characteristic for examples voltage current, power, frequency etc.
ii. Investigate method to initiate/extract power generated by piezoelectric devices
iii. Acquired piezoelectric devices
iv. Develop a procedure and test bench for piezoelectric device testing.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

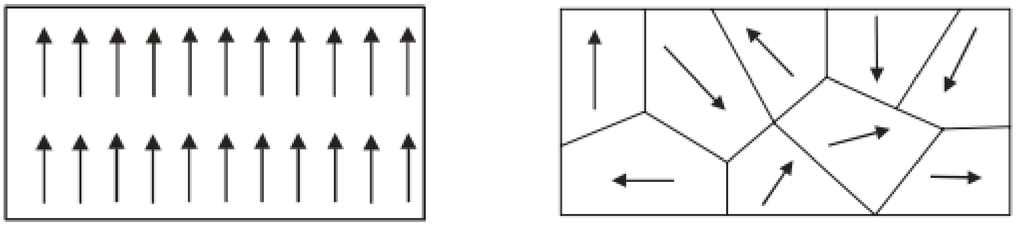
The piezoelectric phenomenon is a complex one and covers concepts of electronics as well as most of the areas of classical physics such as: mechanics, elasticity and strength and materials, thermodynamics, acoustics, wave's propagation, optics, electrostatics, fluid dynamics, circuit theory crystallography and more. Probably, only a few disciplines of engineering and science need to be so familiar to so many fields of physics. The new generation of smart materials technology, featuring a network of sensors and actuators, control capability, and computational capability, will have a tremendous impact on the design and manufacture of the next generation of products in diverse industries such as aerospace, manufacturing automotive, sporting goods, medicine, and civil engineering (Choi and Han, 2010)

Some classes of smart materials will be able to execute specific functions autonomously in response to changing environmental stimuli. Self-repair, self-diagnosis, self-multiplication, and self-degradation are some of the anticipated principal characteristics of the supreme classes of smart materials. These inherent properties of smart materials will only eventually be realized in practice by incorporating appropriate control techniques. Currently, there are several smart materials that exhibit one or more functional capabilities. Among them, electrorheological fluid, magnetorheological fluid, piezoelectric materials, and shape memory alloys are effectively employed in various engineering applications (Henry, Sodano and Daniel, 2005)

2.2 PIEZOELECTRIC EFFECT

The word *Piezoelectricity* comes from Greek and means “electricity by pressure” (Piezo means pressure in Greek). This name was proposed by Hankel in 1881 to name the phenomenon discovered a year before by the Pierre and Jacques Curie brothers. Piezoelectricity is an electromechanical phenomenon that involves interaction between the mechanical (elastic) and the electrical behavior of a material. A typical piezoelectric material produces an electric charge or voltage in response to a mechanical stress, and vice versa. The former is known as the direct piezoelectric phenomenon, while the latter is known as the converse piezoelectric phenomenon (Arnau, 2008)

Conversely, a mechanical deformation (the substance shrinks or expands) 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 u 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 molecules are shaped. The polar axis is an imaginary line that runs though the center of both charges on the molecule. In a monocrystal the polar axes of all of the dipoles lies in one direction. The crystal is said to be symmetrical because the polar axes will be same direction as the original if we cut the crystal at any point. In a polycrystal, there are different region within the material that have a different polar axis. T is symmetrical 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 (Arnau, 2008).

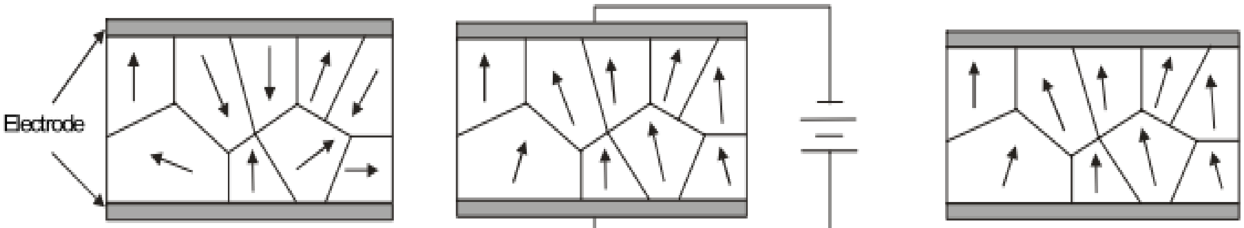


Monocrystal with single polar axis

Polycrystal with random polar axis

Figure 2.1: Mono vs. poly Crystals

To produce the piezoelectric effect, the polycrystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction as shown in figure below.



Random Dipole

Polarization

Surviving Polarity

Figure 2.2: Polarization of ceramic materials to generate piezoelectric effect

Before the poling process, the piezoelectric materials exhibit no piezoelectric properties, and it is isotropic because of the random orientation of the dipoles, as shown in Figure 2.3(a). However, during developing a poling voltage in the direction of the poling axis, the dipoles rearrange to form a certain class of anisotropic structures as shown in Figure 2.3(b). Then, a driving voltage with a certain direction of polarity causes that the cylinder deforms (Arnau, 2008)

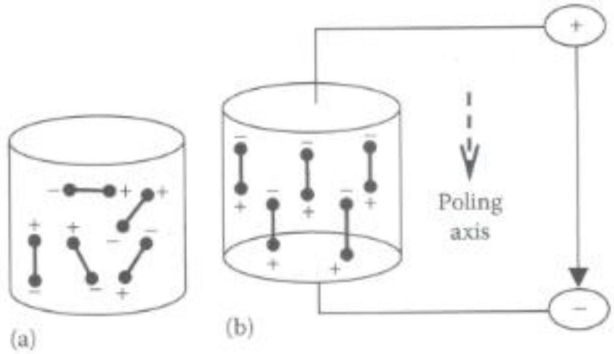


Figure 2.3: The micromechanism of the piezoelectric effect. (a) No voltage (b) poling voltage

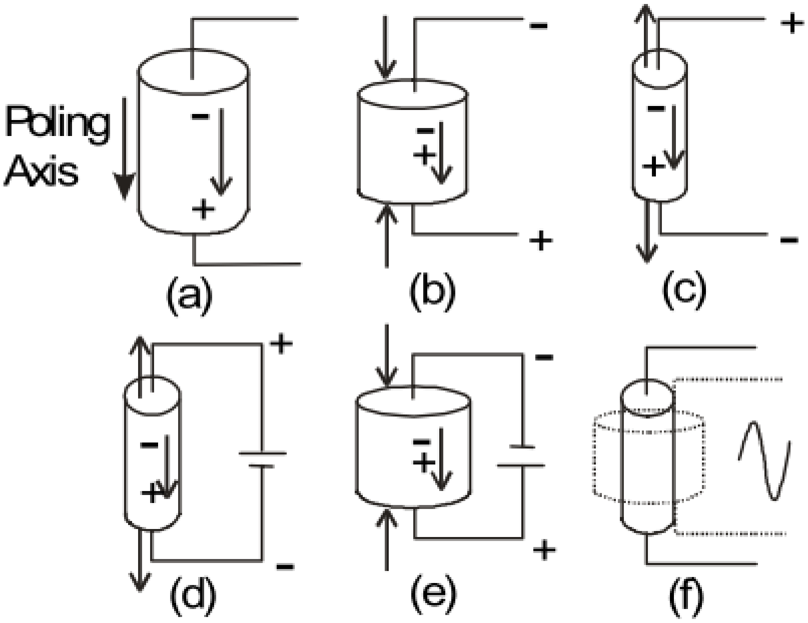


Figure 2.4: Example of Piezoelectric Effect

Figure 2.4(a) shows the piezoelectric material without a stress or charge. Figure 2.4(b) shows the voltage of the same polarity as the poling voltage will appear between the electrodes if the material is compressed. Figure2.4(c) shows if stretched, a voltage of opposite polarity will appear. Figure 2.4(d) shows a voltage with opposite polarity as the poling voltage will cause the material to expand. Figure 2.4(e) shows a voltage with the same polarity will cause the material to compress. Figure 2.4(f) shows if AC signal applied then the material will vibrate at the same frequency as the signal. Figure 2.5 shows the field-strain relation of a typical piezoelectric material (Uchino, 1997).

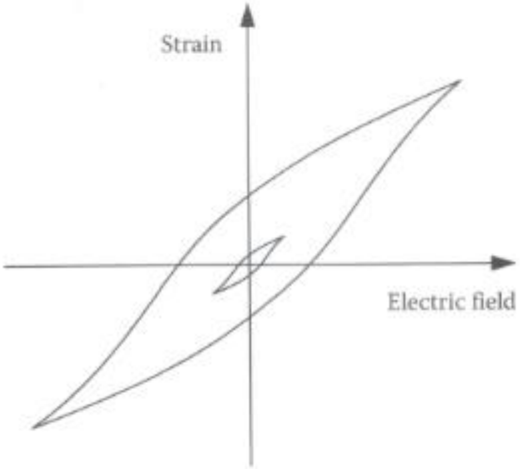


Figure 2.5: Field-strain relation of a typical piezoelectic material

2.2.1 MATHEMATICAL FORMULATION OF THE PIEZOELECTRIC EFFECT.

A first approach

The Curie brothers was performed the experiments to demonstrated that the surface density of the generated linked charge was proportional to the pressure exerted, and would disappear with it. This relationship is a follows:

$$P_P = d\,T$$

Where:

P_p = Piezoelectric polarization vector
d = Piezoelectric strain coefficient
T = Stress to which the piezoelectric material is subjected

The Curie brothers also verified the reverse piezoelectric effect and demonstrated that the ratio between the strain produced and the magnitude of the applied electric field in the reverse effect, was equal to the ratio between the produced polarization and the magnitude of the applied stress in the direct effect. The relationship is as follows:

$$S_P = d\,E$$

Where:

S_P = Strain produced by the piezoelectric effect
d = Piezoelectric strain coefficient
E = Magnitude of the applied electric field

The direct and reverse piezoelectric effects can be alternatively formulated, considering the elastic properties of the material, as shown below:

$$P_P = d\,T = d\,c\,S = e\,S$$
$$T_P = c\,S_P = c\,d\,E = e\,E$$

Where:

c = Elastic constant relates the stress generated by the application of a strain (T = c S)
s = Compliance coefficient relates the deformation produced by the application of a stress (S = s T)
e = Piezoelectric stress constant

2.2.2 PIEZOELECTRIC CONTRIBUTION TO ELASTIC CONSTANTS

The piezoelectric phenomenon causes an increase of the material's stiffness. To explain this, let the piezoelectric material is subjected to a strain S. The strain will have two effects. First, it will generate an elastic stress T_e which will be proportional to the mechanical strain $T_e = c\,S$; and the second effect s, it will generate a piezoelectric polarization P_p = e S. This polarization will create an internal electric field in the material E_p given by:

$$Ep = \frac{Pp}{\varepsilon} = \frac{e\,S}{\varepsilon}$$

Where:

ε = Dielectric constant of the material

This electric field of piezoelectric origin produces forces against the deformation of the material's electric structure, creating a stress $T_p = e\,E_p$. this stress, as well as that of elastic origin, is against the material's deformation. Consistently, the stress generated as a consequence of the strain S will be:

$$T = Te + Tp = c\,S + \frac{e^2}{\varepsilon}\,S = \left(c + \frac{e^2}{\varepsilon}\right)S = \bar{c}\,S$$

Where:

$\bar{c}$ = Piezoelectrically stiffened constant which includes the increase in the value of the elastic constant due to piezoelectric effect.

2.2.3 PIEZOELECTRIC CONTRIBUTION TO DIELECTRIC CONSTANT

When an external electric field E is applied between two electrodes where a material of dielectric constant ε exists, an electric displacement is created towards those electrodes, generating a surface charge density $\sigma = \sigma_o + \sigma_p$ which magnitude is $D = \varepsilon\,E$. if that material is piezoelectric, the electric field E produces a strain given by $S_P = d\,E$. This strain of piezoelectric origin increases the surface charge density due to the material's polarization in an amount given by: $P_p = e\,S_p = e\,dE$. Because the electric filed is maintained constant, the piezoelectric polarization increases the electric displacement of free charges toward the electrodes in the same magnitude ($\sigma_p = P_P$). Therefore, the total electrical displacement is:

$$D = \varepsilon E + P_p = \varepsilon E + e\, dE = \bar{\varepsilon} E$$

Where:

$\bar{\varepsilon}$ = effective dielectric constant which includes the piezoelectric contribution.

2.2.4 THE ELECTRIC DISPLACEMENT AND THE INTERNAL STRESS

The electric displacement produced when an electric field E is applied to piezoelectric and dielectric materials is:

$$D = \varepsilon E + P_p = \varepsilon E + e S_p$$

Under the same circumstances we want to obtain the internal stress in the material. The reasoning is the following: the application of an electric filed on a piezoelectric material causes a deformation in the material’s structure given by: $S_P = d E$. This strain produces an elastic stress whose magnitude is $T_e = c S_p$. On the other hand, the electric filed E exerts a force on the material’s internal structure generating a stress given by: $T_p = e E$. This stress is, definitely, the one that produces the strain and is of opposite sign to the elastic stress which tends to recover the original structure. Therefore, the internal stress that the material experiences will be the resultant of both. That is:

$$T = c S_p - e E$$

Eventually, both stresses will be equal leaving the material strained and static. If a variable filed is applied, as it is the common practice, the strain will vary as well, producing a dynamic displacement of the materials particles. This electromechanical phenomenon generates a perturbation in the medium in contact with the piezoelectric material. This effect is used in transducers, sensors, and actuator (Uchino, 1997)

2.3 CONSTITUTIVE EQUATION

The relation between stress and strain for the common material is described using the material's elastic properties. But in the piezoelectric material, there is an additional effect of strong electro-mechanical coupling that must be considered. The fully-coupled constitutive relation between stress, strain, electric field and charge are accepted as the standard way of describing piezoelectric materials, and can be written as:

$$S_{ij} = s^{E}_{ijkl} T_{kl} + d_{kij} E_k$$

$$D_i = d_{ikl} T_{kl} + \epsilon^{T}_{ik} E_k$$

$$S_{ij} = s^{D}_{ijkl} T_{kl} + g_{kij} D_k$$

$$E_i = -g_{ikl} T_{kl} + \beta^{T}_{ik} D_k$$

$$T_{ij} = c^{D}_{ijkl} S_{kl} - h_{kij} D_k$$

$$E_i = -h_{ikl} S_{kl} + \beta^{S}_{ik} D_k$$

Where the notation used is defined in the nomenclature. The subscripts *i, j, k and l* are indices which span 1 through 3 and show the direction within material. These subscripts follow common tensor notations in elasticity and can be converted to common subscripts. Table 2.1 shows the rules to convert the subscript.

Table 2.1: Subscripts conversion table

Pair i,j or k,l	Single subscript
11	1
12 or 21	6
13 or 31	5
22	2
23 or 32	4
33	3

With those conversion rules, four tensor subscripts become two common subscripts, and two tensor subscripts become one common subscript. Some of the parameters of piezoelectric materials in previous equations have three subscripts, and will be converted to two subscripts. Among the three, the first subscript is the surface indicator, and the other two indicate direction of the field. As shown in Figure 2.6, the first subscript shows the surface and the second subscript shows vector direction (Arnau, 2008).

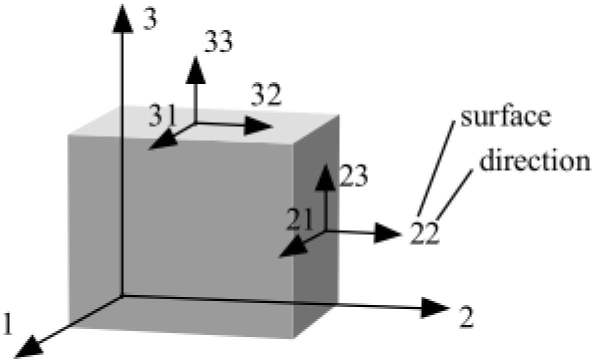


Figure 2.6: Subcript notation for piezoelectric constant

The energy equation for piezoelectric material consist of two parts. The one is elastic energy, and the other is electric energy. The general energy equation for piezoelectric material is described as

$$\text{Energy} = \tfrac{1}{2} \times \text{Strain} \times \text{Stress} + \tfrac{1}{2} \times \text{Charge} \times \text{Electric field}$$