International Baccalaureate

Physics Extended Essay

The relationship between force exerted on a piezo material and potential difference.

(3769 Words)

Introduction

Increase of electricity consumption throughout many years, caused humans to find new energy production methods. Apart from non-renewable energy sources like coal, petroleum and nuclear energy, renewable sources are mostly preferred as they are essential to maintain our planet's sustainability.[1] Despite the fact that wind, solar, geothermal, hydroelectric and biomass energy are the most known sustainable resources there are actually many other environment-friendly ones too, such as piezoelectric.[2]

Piezoelectric is basically a type of electricity which is formed when an object which shows piezoelectric property (such as bones, crystals, certain ceramics, enamel, dentin etc.) is exposed to pressure.[3]When a piezoelectric material is being exposed to pressure or stress, its positive and negative charged particles are moved to the opposite sides of the object by the effect, which creates an electric potential in the object. These type of mechanisms which use piezoelectric principals are used in lighters, electronic instruments, microphones, airbag sensors, parking sensors, sonar systems etc.[4] As piezoelectric has a huge potential of a sustainable, environmental and renewable energy source, applications of piezoelectric systems should be increased in life.

In order to benefit from the electrical energy which piezoelectric materials offer, applying these materials to an area which is open to using piezo-energy daily and continuously during day time, is the best way to use energy more efficient and reduce consumption. Therefore, the main objective in this research is to measure the extent of producing potential difference depending on different forces applied in a simple piezo system and using piezo materials in model subway rails accordingly. The electrical potential produced by the system will be applied to the designed underground system, also considering all the other variables which affect the system's efficiency.

Approximately two weeks before I choose my research question, while travelling with subway, I have realized that high amount of electricity is used in the station. Commercial billboards, gateways, lightening of the station all require electricity which is expensive to provide to the whole station. A few days later, I have watched a conference show about sustainable energy sources in class which increased my awareness and therefore, I decided to combine my physics knowledge with sustainable energy production in my research. After some research, I found an alternative way to conserve energy, piezoelectric. Later I learned about working principals of piezoelectric which are open to application in many areas of industry. In the end, I officially decided on my research question. Piezoelectric being compatible to usage in indoor areas like underground stations made it possible for me to apply piezoelectric to underground stations too.

[1] https://www.nationalgeographic.org/encyclopedia/non-renewable-energy/

[2] https://www.nationalgeographic.org/article/renewable-energy/

[3] https://sciencing.com/piezoelectric-materials-8251088.html

[4] https://www.bjultrasonic.com/an-overview-of-piezoelectricity/

Research Question

What is the relationship between exerted force on a PZT-5 type piezoelectric material and potential difference occurred in a piezoelectric system?

The effect will be observed on a piezoelectric system with controlled surface area and material thickness, using a voltmeter and a handmade lego subway model will be made to observe estimated voltage produced when piezoceramics are placed in an underground railway.

Background Information

Electrical Potential Difference (V)

Electrical potential difference is basically work done while moving a unit charge from one specific place to another. Electrical potential difference is expressed with the unit volt (V). It is calculated by the help of the voltmeter.[5]While determining the definition of potential difference, the terms current (I) and resistance (R) must be explained too. Current is the value of electrical charge movement through a section of wire. It is expressed with the unit ampere (I). It is calculated by the help of amperemeter.[6]On the other hand, resistance is the difficulty of electrical charge movement through a consultant material. It is expressed with the unit ohm(Ω), basically (R). According to these definitions, electrical potential difference (V) is calculated with the formula V=I.R.

Piezoelectric Material's Sensitivity to Exerted Pressure (d33)

The d values are basically the value of polarization when the piezo material is being exposed to a pressure, causing it to stress and separate the positive and negative charges. On the other hand, the indices of the d values are to mention the direction of the pressure exerted. It is roughly calculated by the formula,

dxy = (strain)/(applied field)=(short circuit charge)/(electrode area)/(Applied stress)

where, x defines the direction of stress or induced strain and y defines the surface normal direction of electrode. Therefore, d33 coefficient will be used in the experiment according to the direction of exerted masses.

Coupling Factor (kt)[7]

The piezoelectric coupling factor kt is the ratio between converted and supplied energy. It is also described as a measure of the efficiency of the piezo material. The value changes

[5]https://www.elektrikde.com/potansiyel-fark-nedir/

[6]https://www.fluke.com/tr-tr/bilgi-edinin/blog/elektrik/akim-nedir

[7] https://journals.sagepub.com/doi/full/10.1177/1045389X20930104

according to the piezo material which is used in the experiment. PZT-5 type piezo material has the factor value of 0.49, therefore it will be used in the calculations.

Relative Dielectric (ε)

By dielectric constant, the permeability of a specific material is mentioned. It is the value of ability of the material to store electric energy. The value varies in different elements and compounds, therefore the relative dielectric coefficient of PZT-5 will be taken into consideration. Like every material, space also has a specific dielectric constant of 8.85418782 x10^{-12} too. Using the dielectric constant of space, relative dielectric of a material can be calculated and therefore, the value 1900 will be used in the experiment.

Piezoelectricity

Piezoelectricity is the electrical potential difference which occurs when a piezo material is being pressured. Charges inside the piezo material is being moved when the object is squeezed and this situation creates a current inside of the material while electrical charges move positive polar to the negative polar of the object. Therefore, an electrical potential difference (V) is produced according to the V=I.R formula. Producing potential difference by polarization and therefore electricity with these kinds of piezo materials is called piezoelectricity. It is calculated from the formula,

$$V = \frac{d33.kt.t.P}{\varepsilon.\varepsilon 0}$$

Piezoelectric Circuits

An electrical circuit is the system which include circuit elements like power supply, resistor, capacitor, wires etc. in order to use the created energy. Piezoelectric circuits are a type of electrical circuit in which power supply of the system is replaced with a piezoelectric material. In these kinds of systems, energy required is supplied from the pressure exerted on the specific material. Change in electrical potential values will be observed when different kind of forces exerted on the circuit in the experiment.

Hypothesis

Hypothesis:

Magnitude of the exerted force (N) and potential difference (V) are directly proportional in a piezoelectric system. Occurred potential difference increases when the magnitude of the force is increased. Therefore, a significant amount of electrical energy, which is enough to fulfill the lighting requirement of the station, could be produced by underground piezoelectric systems.

It is hypothesized that as the magnitude of the force applied on piezoceramic in an electric circuit increases, the pressure and the electric potential would increase directly proportional to

the force. Therefore, verifying from the pressure formula P=F/S, the little surface area which railways provide (comparing to the subway) would help subway to produce a huge amount of electrical energy by the compression of piezoceramic material which will soon be used in the underground system.[8]

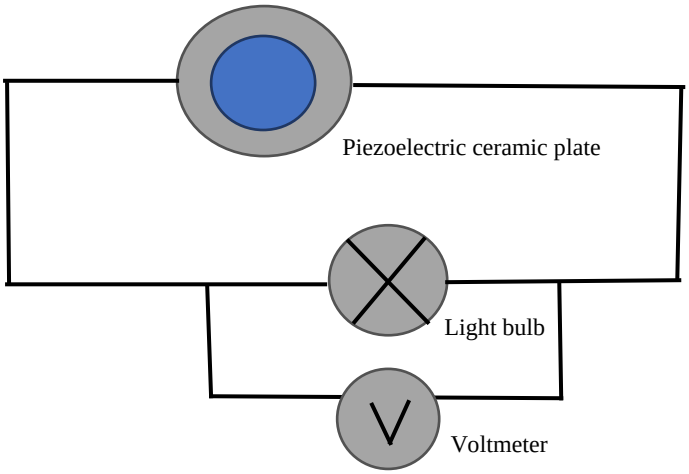


Figure 1: Figure of the piezoelectric circuit which will be used. (Consists of a light bulb, voltmeter and piezoelectric ceramic plate.)

Figure 2: Masses which are used in the experiment

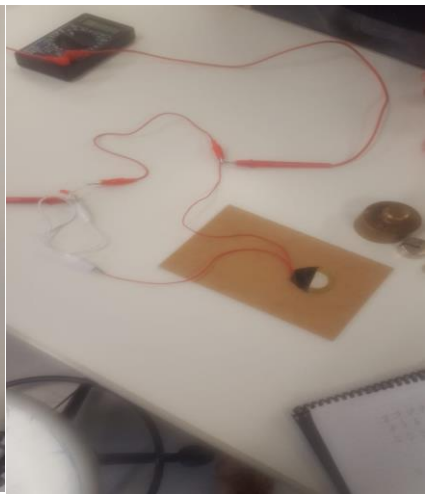
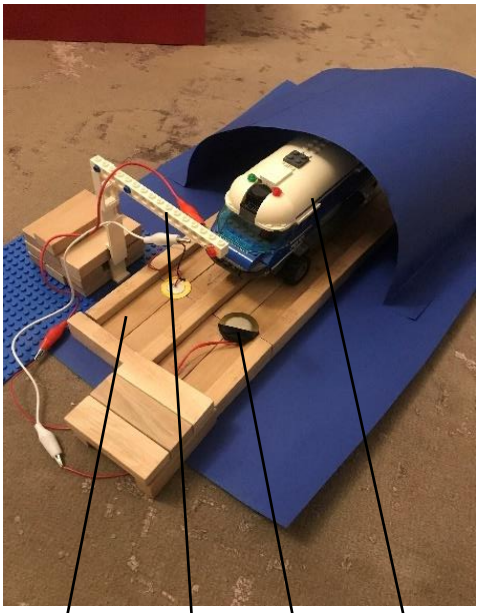


Figure 3: Piezoelectric circuit and voltmeter which are used in the experiment

[8] https://www.khanacademy.org/science/physics/fluids/density-and-pressure/a/pressure-article

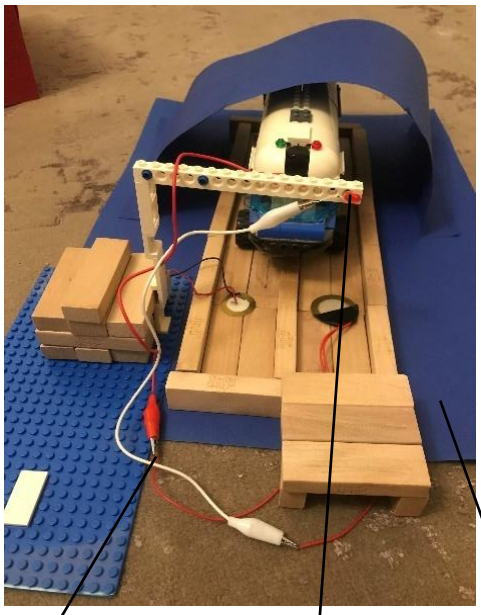


Wooden brick rails

Lego made subway

Lego made lamp

Piezo material PZT-5



Wires

Light bulb

Cardboard

Figure 4 and 5: Handmade subway model which produces voltage to be used in the lightning of the station by piezo plates placed on the rails.

Materials

1. **Piezoceramic** (PZT-5) (2.4cm) (in place of a power supply)[9][10]
2. **Wires** (in order to connect power supply to light bulb.)
3. **Voltmeter** (uncertainty ± 0.001) (2000m DCV)
4. **Light bulb** (in place of a resistor) (0.36 watt)
5. **Different standard masses** (1kg,0.5kg,0.05kg,0.025kg, 0.01kg)
6. **Lego pieces** (in order to build a handmade subway wagon and lamp)
7. **Wooden bricks** (in order to build handmade railway enough to place the piezo material and lego subway on)
8. **Cardboard** (in order to stick the model together, on the same floor)

Procedure

1. Piezoceramic (type PZT-5) with diameter0.024 m, thickness 0.01 m and 1.7Mhz will be connected with the wires and the lightbulb.
2. When the electrical circuit is formed, a voltmeter will be attached to the light bulb with parallel wires to the resistor and a piezo circuit is formed.
3. Masses of 1kg, 0.5kg, 0.05kg, 0.025kg, 0.01kgwill be exerted on the piezoceramic material in order to test the voltage (V) formed accordingly by voltmeter.
4. Obtained data will be ensured by using required data to calculate the voltage created by the piezoelectric formula.[11]

   $$V = \frac{d33.kt.t.P}{\varepsilon.\varepsilon 0}$$

   V: produced electrical potential difference
   P: exerted pressure
   and
   The piezoceramic material (PZT-5)'s properties:
   d33: piezoelectric material's sensitivity to exerted pressure
   t: material thickness
   kt: coupling factor
   ε: relative dielectric
   ε0: permeability constant
5. A handmade model of subway and lamp will be made with lego pieces.
6. A simple railway will be built on a cardboard with placing and sticking wooden bricks to put the piezo ceramic and subway on top. Lego-made lamp will be placed near the railway.

[9] http://www.yuhaipiezo.com/intro/11.html?gclid=CjwKCAiAtdGNBhAmEiwAWxGcUvIhkfze_3NDIkOoiFTDSisj-KAghoNeixVTmfhB7je_8NZS20ajexoCsvAQAvD_BwE

[10] https://en.bdbier.com/product/251.html

[11] https://sites.pitt.edu/~qiw4/Academic/MEMS1082/Lecture%208-1.pdf

7. Previous piezo material will be placed on the wooden rails of the train and the bulb will be connected to the lego-made lamp. (Bulb and piezo material is connected with wires)
8. Handmade lego subway will be put on the wooden bricks and model subway mechanism will be completed. The subway will be moved on the piezo material and the bulb will be lit by the pressure.

Identification of Variables

Correlation Between Force and Potential Difference in Circuit (5 different force magnitudes with 10 trials each):

VARIABLES:	**Name of Variable**	**Method of Management and/or Measurement**
Independent Variable	Magnitude of applied force	Masses of 1kg, 0.5kg, 0.05kg, 0.025kg, 0.01kgwill be exerted on the ceramic
Dependent Variable	Magnitude of potential difference produced	The electrical potential difference value (voltage V) formed on the voltmeter and obtained from the formula
Controlled Variables	Type of Piezoceramic Used (PZT-5 type piezoceramic)	Same type of piezoceramic will be used while obtaining data. (type PZT-5 0.024 m diameter)
	Voltmeter used in measuring	Same voltmeter will be used to calculate voltage(v) occurs.
	Surface area and material thickness force is being applied on	Surface area and thickness of the piezoceramic will remain constant through the experiment (0.012 m radius) (0.01 m)
	Wires used in circuit	Wires will be kept constant as well as the other elements of the electrical circuit.
	Light bulb used in circuit	Same lightbulb will be used through the experiment also to observe the brightness according to exerted force.

Table 1: Table indicating the variables and how they are kept constant.

Justification

1. While experimentation, the size of the piezoelectric material (PZT-5) will be kept constant. Measurement of 0.012 m radius and 0.01 m thickness is chosen specifically in order to make the circuit to fit the model subway rails and it is easy to find. Calculations of obtaining potential energy will be maintained accordingly.
2. Piezoceramic type PZT-5 which will be used as a power source in the circuit is chosen because of its easy manageable properties. It can be found in small sizes and it has the potential to create required energy for the model with its height and width. It is one of the cheapest and the most reachable piezoceramics, as most of the piezo materials are used in military purposes and very expensive to purchase.
3. Magnitudes of applied forces are chosen 1kg, 0.5kg, 0.05kg, 0.025kg, 0.01kg because of piezo material's durability to pressure exerted. These magnitudes of masses are easy to find and it is enough to see the correlation between force and voltage created. Greater magnitudes might damage the piezo system, so it is prevented by choosing appropriate masses.
4. Created electrical potential difference (V) will be measured with a voltmeter because it is the most reliable measurement device in terms of calculating voltage. Then the value will be verified by calculating the pressure formed and voltage by the piezoelectric formula. Furthermore, the voltmeter will be connected parallel to the circuit in order to make the voltmeter work properly. Connected series would cause the circuit to collapse because of the voltmeter's high resistance.
5. Putting the masses slow and softly plays an important role in avoiding possible errors in the experiment. Putting them as slow as possible reduces the effect of gravitational force exerting on the piezoceramic in the moment of placing masses. This process is required to get the most accurate results.

Risk Assessment

Despite there is not much to be considered as possible risk at the research, all the materials which are dealt with are handled carefully. While the masses are exerted on the circuit, they are handled carefully in order not to make any mistake while measuring values and damage the system or myself. Also, while measuring the voltage created when force is applied on the piezo material, any contact with electricity is avoided even though the electricity produced is not enough to damage too.

Raw Data

Voltage Occurred Depending On Initial Effect Of Exerted Masses (2000m DCV) (volt, V) (uncertainty ± 0.001)

	Trials *Potential Difference (Volts)* ± 0.001									
Standard Masses (kg)	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
0.010	*0.006*	*0.008*	*0.005*	*0.004*	*0.006*	*0.008*	*0.007*	*0.009*	*0.002*	*0.004*
0.025	*0.022*	*0.034*	*0.014*	*0.009*	*0.013*	*0.009*	*0.021*	*0.032*	*0.031*	*0.019*
0.050	*0.119*	*0.127*	*0.092*	*0.082*	*0.069*	*0.074*	*0.098*	*0.078*	*0.061*	*0.091*
0.500	*0.708*	*0.823*	*0.453*	*0.756*	*0.693*	*0.749*	*0.744*	*0.962*	*0.632*	*0.573*
1.000	*1.459*	*1.154*	*1.294*	*1.003*	*1.088*	*1.274*	*1.004*	*1.326*	*1.013*	*1.055*

Table 2: Raw data table of voltage depending on exerted masses of 0.010, 0.025, 0.050, 0.500, 1.000 kg.

Processed Data

Mean Voltage Occurred Depending on Initial Effect of Exerted Masses
(2000m DCV) (volt, V) (uncertainty ± 0.01)

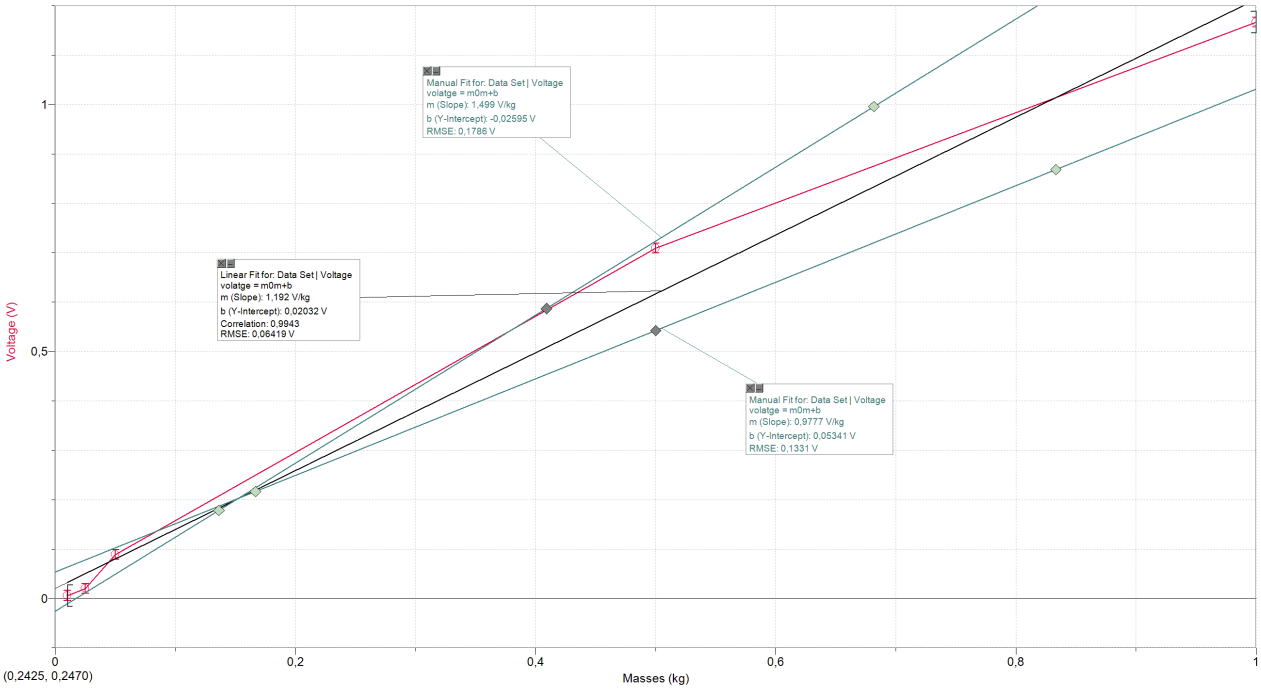
Masses (kg)	***0.010***	***0.025***	***0.050***	***0.500***	***1.000***
Mean Voltage (Volt)	*0.0059± 0.01*	*0.0204± 0.01*	*0.0891± 0.01*	*0.7093± 0.01*	*1.167± 0.01*

Table 3: Table which shows mean voltage (V) formed depending on the masses of 1kg, 0.5kg, 0.05kg, 0.025kg, 0.01kg.

Standard Deviation of Voltage Occurred Depending on Initial Effect of Exerted Masses (To three significant figures)

Masses (kg)	***0.010***	***0.025***	***0.050***	***0.500***	***1.000***
Standard Deviation	*0.00207*	*0.00890*	*0.0200*	*0.131*	*0.153*

Table 4: Table which shows the standard deviation of voltage (V) formed depending on the masses of 1kg, 0.5kg, 0.05kg, 0.025kg, 0.01kg.



Graph 1: Graph which shows mean voltage occurred depending on initial effect of exerted masses including best fit and worst fit lines. (most and least steep lines)

Best Fit Line Slope: 1.192

Steepest Line Slope (Worst Fit 1): 1.489

The Least Steep Line Slope (Worst Fit 2): 0.9785

Slope of the best fit line basically gives the relationship between two variables. It shows how does y-variable change when x-variable is changed to a different value, according to the differential definitions. Therefore, it means that, when the slope of the line gets sharper, the correlation between two variables gets stronger.[12] Furthermore, error propagations could be calculated with the help of the slope too.

[12] https://sciencing.com/how-8175502-calculate-slope-line-fit.html

Calculations

1) Mean of the Voltage (V) Occurred Depending on Initial Effect of Exerted Masses

$$\overline{\mathbf{X}} = \frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{xi}}{\mathbf{n}}$$

where

n: the number of trials while a single mass is used

x: all values obtained from the trials of a single mass

This was repeated for every mass which is evaluated.

Example (0.05kilograms):

$$\frac{0.119 + 0.127 + 0.092 + 0.082 + 0.069 + 0.074 + 0.098 + 0.078 + 0.061 + 0.091}{10}$$

$= 0.0891 \pm 0.01$

2) Standard Deviation of Voltage (V) Occurred Depending on Initial Effect of Exerted Masses

$$\boldsymbol{\sigma} = \sqrt{\frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{xi} - \overline{\mathbf{X}})^2}{\mathbf{n}}}$$

where

n: the number of trials while a specific mass is used

x: all values obtained from the trials of a single masses

$\overline{x}$: the mean of all values obtained from the trials of a single masses

This was repeated for every mass which is evaluated.

Example Standard Deviation (0.05kilograms):

$$\sqrt{\frac{(0.119 - 0.0891)^2(0.127 - 0.0891)^2(0.082 - 0.0891)^2(0.069 - 0.0891)^2(0.074 - 0.0891)^2(0.098 - 0.0891)^2(0.078 - 0.0891)^2(0.061 - 0.0891)^2(0.091 - 0.0891)^2(0.092 - 0.0891)^2}{10}}$$
$\cong 0.0200$

3) Slope Line Uncertainty of* Mean *Voltage (V) Occurred Depending on Initial Effect of Exerted Masses in Graph

$$\boldsymbol{Best\ Fit\ Slope\ Uncertainty}(\pm) = \frac{\boldsymbol{gradient1 - gradient2}}{\mathbf{2}}$$

where,

gradient 1: the slope of the worst fit line 1 (the steepest line)

gradient 2: the slope of the worst fit line 2 (the least steep line)

According to the best and worst fit line graph, gradient 1 is equal to 1.4890 and the gradient 2 is equal to 0.9785. Therefore,

$$\frac{1.4890 - 0.9785}{2} = \pm 0.25525$$

The best fit line slope turns out to be 1.192 ±0.25525.

Calculations of Theoretical Value

Properties	**PZT-5A**
d33	390 x 10^{-12}
ε	1900
ε0	8.85418782 x10^{-12}
kt	0.49

Table 5: Properties of PZT-5A type piezo material

1) **Theoretical Value of Voltage (V) Occurred Depending on Initial Effect of Exerted Masses**

$$\boldsymbol{V = \frac{d33.kt.t.P}{\varepsilon.\varepsilon 0}}$$

where

V: produced electrical potential difference

P: exerted pressure

d33: piezoelectric material's sensitivity to exerted pressure

t: material thickness

kt: linking coefficient

ε: relative dielectric

ε0: permeability constant

$$\boldsymbol{F = m\ x\ a}$$

where

f: force

m: mass

a: gravitational acceleration (taken as 9.80665m/s^2)

$$\boldsymbol{P = \frac{F}{A}}$$

where

P: exerted pressure

F: force

A: surface area of the piezoceramic

$$\boldsymbol{A = 2\pi r^2}$$

A: surface area of the piezoceramic

R: radius of the piezoceramic

Example (0.05 kilograms)[13]:

$\boldsymbol{F = m\ x\ a}$

0.05 x 9.80665 = 0.4903325 Newton

$\boldsymbol{A = 2\pi r^2}$

2 x π x $(0.012)^2$= 0.00090477868 m^2

$\boldsymbol{P = \frac{F}{A}}$

$\frac{0.4903325}{0.00090477868}$ =541.9363993 P

$\boldsymbol{V = \frac{d33.kt.t.P}{\varepsilon.\varepsilon 0}}$

$V = \frac{390\ x\ 10^{-12}\ x\ 0.49\ x\ 0.01\ x\ 541.9363993}{1900\ x\ 8.85418782\ x10^{-12}} = \frac{1035{,}640459}{16.822.957} \cong$ 0.0616 Volt (three significant figures)

Masses	**0.01 kg**	**0.025 kg**	**0.05 kg**	**0.5 kg**	**1 kg**
Theoretical Value (Volt)	*0.0123*	*0.0308*	*0.0616*	*0.616*	*1.232*

Table 6: Table which shows the theoretical values of voltage occurred depending on the exerted masses. (V) (three significant figures)

[13] https://piezo.com/pages/intro-to-piezoelectricity

Percentage Error:

Percentage error in results obtained from the experiment is calculated by the formula:

$$Percentage\ Error = \frac{|Theoretical\ Value - Experimental\ Value|}{|Theoretical\ Value|}\ x\ 100$$

Therefore,

Error Example (0.05 kilograms):

$$\frac{|0.0616 - 0.0891|}{|0.0616|}\ x\ 100 = \frac{0.0275}{0.0616}\ x\ 100 \cong 44.64$$

= 44.64 %

Masses	**0.01 kg**	**0.025 kg**	**0.05 kg**	**0.5 kg**	**1 kg**
Percentage Error	*52.03 %*	*33.76 %*	*44.64 %*	*15.14 %*	*5.27 %*

Table 7: Table which shows the percentage error of experimental values of voltage occurred depending on the exerted masses.

Calculation of Estimated Voltage Produced

In order to reach an estimated value of voltage occurred when a piezo system is built on the rails of a subway, a real-life example must be taken as an example. Therefore, mass of the subway and properties of the currently used rails are taken from the website of a nearby subway station.[14]

Subway used in the nearby station

Mass: 32.439 kilograms

Length: 22.78 meters

Rails used in the nearby station

Type: S-49

Height: 0.149 meters

[14] https://www.ego.gov.tr/tr/sayfa/2109/m2-ankara-metrosu2-kizilay-cayyolu-teknik-ozellikler

Width: 0.0654 meters

On the other hand, if the production of energy were to be tested and applied to a real subway system, the piezoceramic type PZT-5A would not be enough to handle the heat and pressure formed when the subway passes through the rails. Type PSI-5A4E would be more appropriate in that condition as it has more heat resistance. Therefore, properties of PSI-5A4E will be used in the calculations to provide a realistic estimation.

Properties	**PSI-5A4E**
d33	390 x 10^{-12}
ε	1800
ε0	8.85418782 x10^{-12}
kt	0.73

Table 8: Properties of PSI-5A4E type piezo material.

$$\boldsymbol{F = m\ x\ a}$$

$32439\ x\ 9.80665 = 318117.91935$ Newton

Surface Area of Rails = 22,78 **(length of the subway)** × 0,0654 **(width of the rails)** × 2 **(number of rails)** = $2.979624 m^2$

$$\boldsymbol{P = \frac{F}{A}}$$

$\frac{318117.91935}{2.979624}$ = 106764.450598 Pascal

$$\boldsymbol{V = \frac{d33.kt.t.P}{\varepsilon.\varepsilon 0}}$$

$V = \frac{390\ x\ 0.73\ x\ 0.149\ x\ 106764.450598}{1800\ x\ 8.85418782} \cong$ 284.171 Volt (six significant figures) (instant voltage)

Conclusion and Evaluation

In the end of the research, my hypothesis of force exerted and potential difference occurred in a piezoelectric circuit is directly proportional, proved to be right. According to the obtained data from the experiment, voltage occurred in the light bulb measured by the voltmeter increased when the weights become more heavier as the experiment goes on.

Although my hypothesis is proved to be right in the experiment, percentage error increased as the exerted weights become lighter. Presumably, the percentage error increased because of the difficulties I dealt with when I was working with 0.01 and 0.025 kilograms of mass. While working with light weighted objects, the voltmeter's and piezo ceramic's sensitivity became a problem. Most probably, the masses of 0.01 and 0.025 kilograms could not exert enough pressure on the ceramic plate to compress it and make the positive and negative charges gather in the opposite sides of the object. This situation made it harder to produce voltage with the potential difference created in the object for the voltmeter to measure.

Furthermore, the least percentage error in different trials of masses is 5.27%, most probably caused by human based error. Even if I tried to put the objects softly and smoothly as possible, in order to make the least instant effect on the plate, which is only provided by the weight of the object, it always has a small interval which causes the object to exert more pressure to the ceramic plate. Also, partial surface area exceptions caused by the wires, being attached on the top of the piezo ceramic plate could have played a little part in the percentage errors too. Eventually, minimizing these effects only makes the results more accurate but not perfect.

Data I found in the research supported my idea of placing a piezo electric circuit on the rails of a subway, thinking it would create huge amount of energy caused by the weight of the subway. Therefore, I calculated the estimated value of instantly produced voltage when a subway wagon passes through the rails, considering the properties of a subway which is currently used in a nearby station. In the end of my calculations, approximately 284.171 V of potential difference is created in the piezo ceramics on the railways. Based on the information I found in this research, the voltage produced could be even higher when the weight of the passengers are considered too.

Evaluating a standard street light operating voltage is between 120 and 240 Volts, an instant production of 284.171 V is pretty enough to operate some of the lights of the station, depending on the operating voltages of these lights.[15] Although this outline might be considered as a reliable source of energy, it has some weaknesses too. The piezo ceramic PSI-5A4E which is perfect for this condition with its high production of energy and heat resistivity, is a relatively expensive material to cover all of the rails with. Furthermore, the system would not work and produce energy when the subway is not working, so the voltage production would not be continuous all the time.

[15] https://www.lrc.rpi.edu/programs/transportation/pdf/Columbus-Survey.pdf

Considering these disadvantages, this idea must be evaluated with all of its benefits and loses eventually.

Strengths	Possible Errors	Possible Error Modifications
Process of making a lego subway model at home by myself helped me to understand the way piezoelectric circuits work even better.	The voltmeter's and piezo ceramic's sensitivity while working with light weighted objects.	Choice of heavier objects or high sensitivity voltmeter could be better to work with, on the other hand it would create another problem which is the suitability of the surface area of the exerted mass and the piezo ceramic plate. It would also be harder to find heavier objects too.
Making the subway model with materials found at home provided the mechanism to work for free.	Human error while placing objects on the piezo material	Placing the masses on the piezo material as smooth and careful as possible is the main key to prevent this kind of error. Tenderness is very important in the process.
Working with standard masses and high sensitivity of the voltmeter provided lower uncertainties to the experiment.	Partial surface area exceptions occurred because of the wires on top of the plates.	There is no possible modification.
No particular environment polluting/threatening materials are used in the process. Experiment was totally nature-friendly and did not involve any risks.	Expensive piezoelectric material in the making of piezo circuits under the rails.	There is no possible modification.
	Discontinuous energy production because of the underground station time schedule.	There is no possible modification.

Table 9: Table which shows strengths and errors of the research.

In conclusion, my hypothesis turned out to be true as voltage caused by the potential difference formed in the piezo material increased when the exerted force to the material is increased too, with the results:

0.01 kg	0.025 kg	0.05 kg	0.5 kg	1 kg
0.0059± 0.01	0.0204± 0.01	0.0891± 0.01	0.7093± 0.01	1.167± 0.01

As pressure is a coefficient in the piezo electrical potential difference formula and force is a coefficient in the pressure formula; it affected the results directly with the same proportions of the exerted masses. Furthermore, the best fit slope turns out to be 1.192 ±0.25525 which supports the thesis of two variables change in the same ratio, as the slope is really close to 1.

Afterwards, knowing more force exerted on the plate, more voltage occurs; I started to calculate the estimated voltage produced in my subway piezoelectric circuit outline. In the end of my calculations and building my model, I realized that the project has some disadvantages besides its advantages too. Although the voltage produced by the help of the piezoceramic plates on the rails has a huge potential of providing the required energy to the subway station to lighten the place for passengers, it would be really hard and expensive to built the circuit and place the appropriate material, PSI-5A4E on the rails. Furthermore, the system would not work continuously all the time, the energy production would depend on the station's working hours. Therefore, I reached to the conclusion, the project should be evaluated and investigated properly to decide whether it is worth it, in order to reach out to a verdict. Benefiting from the possible high voltage production with excessive weight of an every-day vehicle does not turned out to be the best option to produce renewable energy with its different inabilities in the end of the research.

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