Induction of current through Piezoelectricity

How does changing the RPM on a stall torque motor striking piezoelectric cells affect the current produced by the cells?

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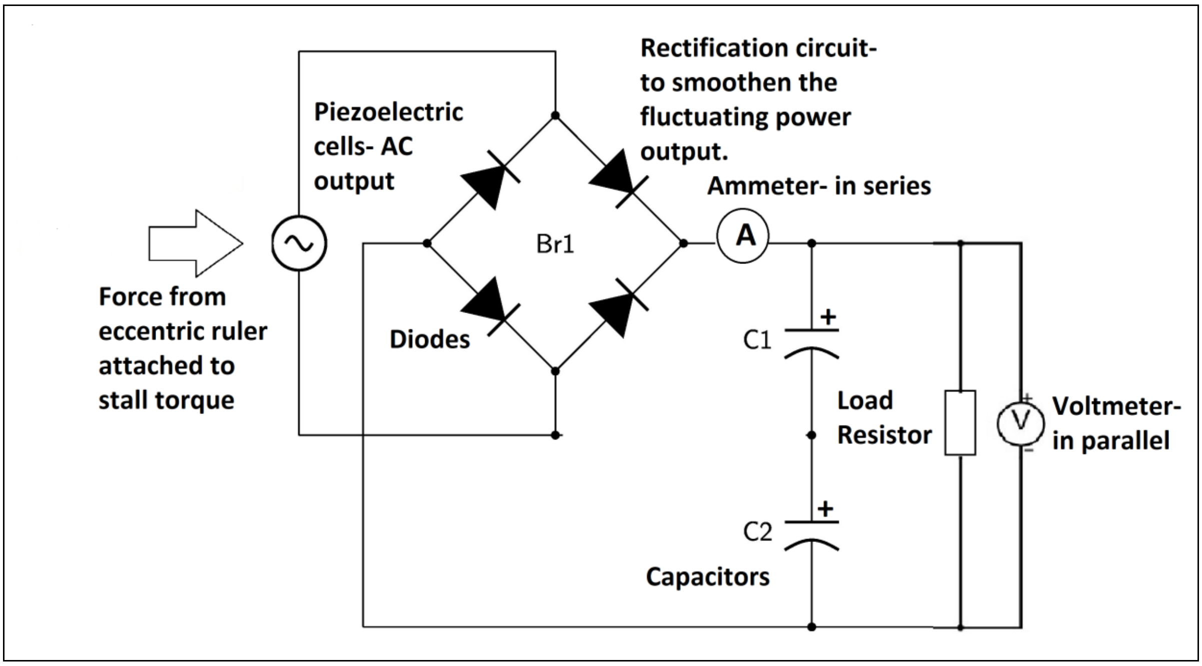
1.0) Introduction
Piezoelectricity involves the conversion of mechanical energy to electrical energy and vice versa. Mechanisms involving piezoelectricity are usually very common, like the household clock. As a part of the physics HL portion, we explored both types of energy, and their connection through such a concept intrigued me.
The concept of piezoelectricity drew links to many aspects of the Physics HL (Electricity) and Chemistry HL (Bonding) portions, allowing me to connect subjects with the concept. Further understanding of the topic would allow me to strengthen these links and develop my understanding of the science of lattices as a whole. Hence I wished to investigate the concept of piezoelectricity and decided to focus on how a mechanical power input (given by the frequency of rotations of a motor) into piezoelectric cells affected the current produced by them.

During the experiment, an eccentric ruler was attached to a stall torque motor, with a constant distance kept from a piezoelectric cell mesh which it hit when the motor was activated.
This allowed me to measure how the current varied with changing RPM.

Design Image- Figure 1.
Figure 1 shows an image of the experimental setup.



Design Diagram- Figure 2.
Figure 2 shows the circuit diagram for the experiment. [1]

[1] Created using MS Paint.

1.1) Research Question
How does changing the RPM on a stall torque motor striking piezoelectric cells affect the current produced by the cells?

1.2) Variables
Independent Variable: The rotations per minute of a stall torque motor with an eccentric shaft which strikes a mesh of piezoelectric cells on rotation of the motor.

Dependent Variable: The current produced by the piezoelectric cells.

Control Variables:
1. Distance travelled by ruler- The distance the ruler was placed above the cells was kept constant, and when coupled with the constant RPM, the time between striking of the mesh was kept constant. This allowed for the assumption that the power input into the cells (Given by the force times the velocity of striking), was constant- as the velocity of striking, given by a constant distance over a constant time was constant. A fluctuating power input could have lead to false peak current and voltage readings.

2. Number of piezoelectric cells being struck- The ruler was placed above the same area of the mesh which was struck. This ensures that the same number of cells were struck, ensuring a constant amount of the piezoelectric ceramic being struck. A non constant amount of cells being activated could lead to fluctuations in the measured voltage and current.

3. Orientation the cells were struck at.- The ruler struck the cells at exactly a 90 degree angle. This ensured that all the force was exerted on the cells (as the sin component (horizontal) would be eliminated by an angle of 0 to the normal of the cell mesh), ensuring constant readings, and hence attributing any changes in readings only to a changing IV.

4. Which piezoelectric cells were being struck- The ruler was placed above the same cells, which were activated on striking. This accounts for any variation in the cells which may have caused errors.

5. Apparatus used to take measurements- The same apparatus was used for all trials, this included the motor, the voltmeter and the ammeter. This reduced the variation in the readings- if any apparatus showed false readings, the error would be present in all the readings and hence result in a systematic error (which can be addressed in the evaluation section)- but not a random error. This aided the precision of the experiment.

1.3) Outline of the Investigation
In this Investigation, what I propose to do is as follows

The theoretical equation will be derived, to find the relationship between current produced and RPM.

After following the procedure, experimental values of the current will be obtained for different RPM. Using the same values of RPM in the theoretical equation, the theoretical values of current will also be obtained and both experimental and theoretical curves will be plotted on the same graph.

Analysis of the graphs will follow., and I will evaluate both the experimentally obtained and theoretical values before calculating the percentage error and coming to a conclusion.

2.0)Exploration and Research

Variable	Symbol	Unit
V	Voltage across the piezoelectric cells connected in series	Volt (V)
I (DV)	Current in the piezoelectric cells connected in series	Milliampere (mA)
P	Power in the circuit	Watt (W)
F	The force of the eccentric ruler which strikes the piezoelectric cells.	Newton (N)
A	The area of the piezoelectric cells being activated	$Metre^2$
T	The stress in the piezoelectric cells during activation	Newton $Metre^{-2}$
d	The piezoelectric strain coefficient of the ceramic cells which determines the current output per unit stress.	Newton $Volt^{-1}$ $Metre^{-2}$
D	The distance travelled by the ruler which strikes the cells each oscillation (from a maximum to a minimum)	Metre
t	The time taken for the ruler to complete one to and fro motion- an oscillation.	Second
v	The average velocity of the ruler striking the cells	Metres/Second
RPM (IV)	The Rotations per minute set at the stall torque motor which causes the ruler to move and strike the cells.	Rotations/Minute

The theoretical equation helped us determine Voltage from stress by

$$V = d \times T \quad \text{..(1)}$$

Where V was the magnitude of the velocity vector, d was the piezoelectric constant (11.2 in this case obtained from the dealer of the cells) and T was the stress.

We can rewrite the equation to allow us to measure force, where stress is force per unit area.

$$V = d \times \frac{F}{A} \quad \text{..(2)}$$

Force can be expressed as power divided by the velocity of the ruler. The power can be calculated using the Voltage multiplied by the Current for each trial.

$$V = \frac{(d \times P)}{(v \times A)} \quad \text{..(3)}$$

Next, we can express the average velocity as a function of RPM, where the velocity is determined by the distance travelled by the rod in 1 rotation. The rod travels a total of 10cm, 5 down and 5 up, every rotation. This is travelled every time period, given by the Rotations per second, which is simply the RPM/60.
The average velocity is given by the total distance (10cm) divide by the total time (RPM/60). (V=D/t). One can hence multiply the distance travelled by the frequency of oscillation (given by the RPM/60, and hence determine the velocity. (V=D×f)

$$V = \frac{(60 \times d \times P)}{(A \times (RPM) \times D)} \quad \text{...(4)}$$

Lastly, the V cancels from each side, when Power is expressed as Voltage × Current (VI), to give the equation

$$I = \frac{(A \times (RPM) \times D)}{(60 \times d)} \text{...(5)}$$

Where I is the current produced, d is the piezoelectric constant 11.2, A is the area of the top of the rod that strikes the surface given by $45mm^2$, P is the power dissipated per RPM, and D is the distance travelled by the rod in 1 rotation i.e.10cm.

2.1) Apparatus

1. Stall torque motor- with a variable RPM.
2. A ruler that can be attached to the motor- eccentrically. (off centre)- to allow for translational motion as the motor rotates.
3. Ceramic piezoelectric cells wired in series to form a piezoelectric mesh
4. Wires
5. A voltmeter connected in parallel to the mesh
6. An ammeter connected in series to the mesh.

7. A ruler to measure the area of the top of the ruler that strikes the mesh and the distance in travels each time it does so.

2.2)Procedure

The procedure was conducted as follows:
The RPM values of 280, 380, 475, 504, 575, 625, 640, 665 and 700 RPM were considered as readings on a stall torque motor. The RPM values were measured on the motor's panel itself.

Considering each voltage trial for each RPM value. There are 3 trials, the average was calculated using the $(V_1+V_2+V_3)/3$.
Calculating the associated absolute uncertainty was done using the $(max(V_1,V_2,V_3)-min(V_1,V_2,V_3))/2$ formula.

Considering each current trial for each RPM value. There are 3 trials, the average was calculated using the $(I_1+I_2+I_3)/3$.
Calculating the associated absolute uncertainty was done using the $(max(I_1,I_2,I_3)-min(I_1,I_2,I_3))/2$ formula.
One can now plot a graph of Average Current v/s RPM

The average power input into the cells using P=VI, from the average values obtained above for each RPM value can be calculated.
The uncertainty for this can be calculated by adding the associated fractional uncertainties of the voltage and current and multiplying the sum by the power value. This gives the absolute uncertainty related to power. (Here, the fractional uncertainty is defined as the absolute uncertainty measured above divided by the value to which the uncertainty is associated.)

The velocity of the ruler was calculated by considering the time period taken to travel one distance. The distance is given by a constant 5 cm, and the time period is given by the RPS.
RPS=RPM/60.
This value was multiplied by 2 (to give 10), to give the voltage (10 because one considers 1 full rotation, where the rod moves 5cm down and 5 cm up in one time period.) This is considered because it is the distance travelled over one time period- in one rotation of the motor.

The associated absolute uncertainty was done by adding the fractional uncertainties in distance and RPS, and multiplying the sum by the value of the velocity.

Then by dividing the Average power for each RPM value with the associated velocity of the rod the value of the force was obtained.
The associated absolute uncertainty was then calculated by adding the fractional uncertainties in average work and velocity, and multiplying the sum by the value of the force.

Since stress (T) is defined as pressure divided by area, dividing the force by 45/1000000 m^2- which is the area of the cells which are activated when struck by the top of the ruler- gives the stress associated with the piezoelectric mesh.
The absolute uncertainty in stress was given by adding the fractional uncertainties in force and area of the top of the ruler and then multiplying the sum by the value of the stress.

This, eventually, when expanded out as done in the previous section on Exploration and Research, gives the relationship between RPM and Current. It is linear. (Equation 5)

To conduct the experiment, the following steps were considered:
Initially, the stall torque motor was set up and the ruler was attached off centre so that its top pushed down as the motor rotates. This made the ruler repeatedly move up and down and strike the piezoelectric cells which were placed below the motor mechanism. This allowed for a force to strike the cells with the ruler at a certain velocity. The distance between the ruler and the mesh was kept constant at 5 cm so that the velocity was constant for a single RPM and hence, the force was constant for a constant power output from said RPM. This allowed for the elimination of confounding variables and made the stress for a single RPM constant.

The piezoelectric cells were lined in series and an ammeter was attached in series to the cells, with a voltmeter attached in parallel.

The motor was set at a different RPM, with chosen values at 280, 380, 475, 504, 575, 625, 640, 665 and 700 RPM. The voltage output and current produced was noted for each RPM value.

Each RPM value had 3 trials conducted.

3.0)Data and Analysis

3.1)Theoretical Data

The theoretical equation is used with fixed RPM values to obtain the following results.

THEORETICAL DATA		
Trial no.	**RPM**	**Current$_{Th}$**
		I_{th} /mA
1	280	1.88
2	380	2.54
3	475	3.18
4	504	3.38
5	575	3.85
6	625	4.19
7	640	4.29
8	665	4.45
9	700	4.69

Table 1.- Theoretical Data

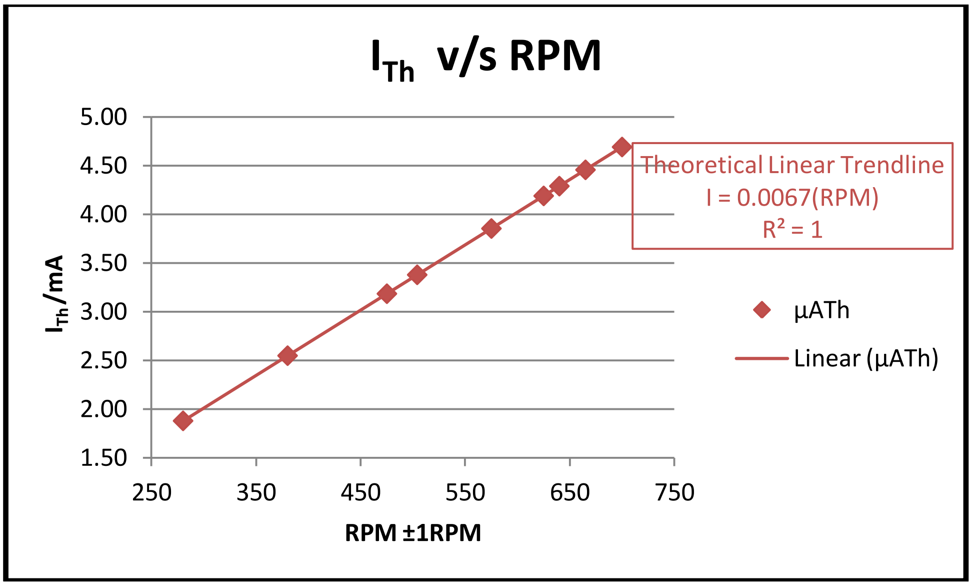


Figure 3. - Theoretical Graph

In figure 3, a theoretical graph is plotted. Here, we use the theoretical equation I v/s RPM, where I is the magnitude of the current, and the RPM values are selected as IVs. The graph is plotted from the equation above. (Equation 5)

3.2)Experimental Data

RAW DATA					
Trial no.	Current produced by piezoelectric cells			Average Current produced	Uncertainty
	I_1 /mA ±0.1 /mA	I_2 /mA ±0.1 /mA	I_3 /mA ±0.1 /mA	I_{AVG} /mA ±0.1 /mA	in current
1	2.0	2.0	1.9	2.0	0.1
2	2.9	2.8	2.8	2.8	0.1
3	3.4	3.5	3.5	3.5	0.1
4	3.6	3.7	3.7	3.7	0.1
5	4.2	4.1	4.2	4.2	0.1
6	4.4	4.5	4.4	4.4	0.0
7	4.6	4.7	4.6	4.6	0.1
8	4.8	4.8	4.9	4.8	0.1
9	5.0	5.1	4.9	5.0	0.1

Table 2- Raw data for Current measured

In table 3, raw data for each RPM is noted, where each of the 3 trials has been noted, and had an average taken, and this average has a range based uncertainty calculated. Here, we can use this data to plot the graph in figure 5- for current v/s RPM. It should be noted that some uncertainties were so small, that they were rounded to 0, to fit the decimal places on the experimental values.

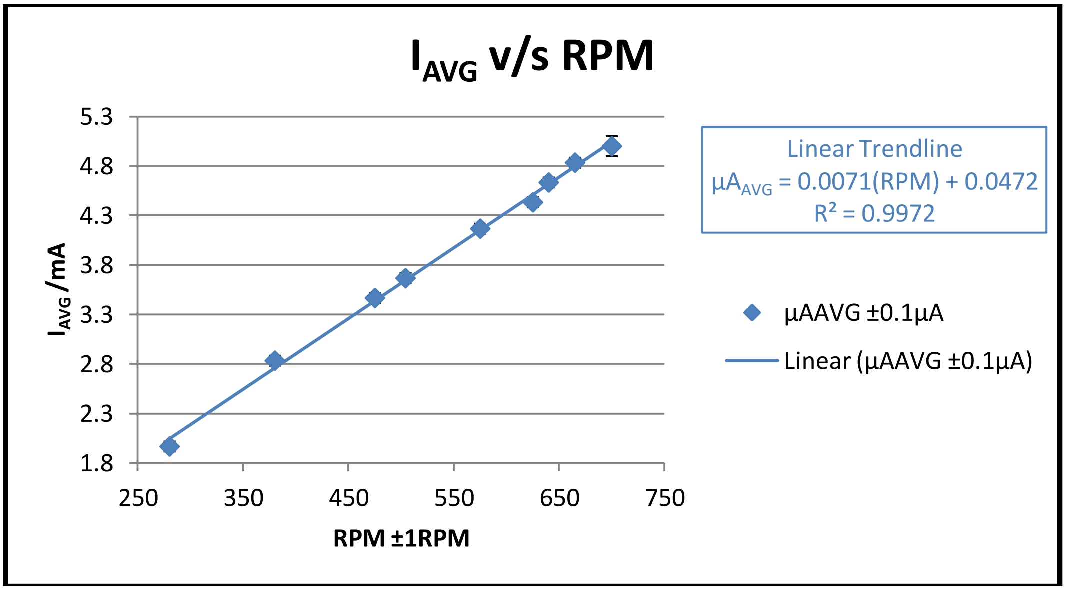


Figure 4.
Raw Data graph of RPM v/s Current

In figure 5, we see a plot of average current.
The high R^2 value suggests a linear relationship as seen in the graph, but this relationship should include no y intercept. This follows from the theory discussed. The theory suggests a clear relationship between the current and the RPM, which is observed here. The linear graph provides a viable and analyzable line of best fit from which conclusions can be drawn.
The RPM uncertainty is fairly small, but the uncertainty in the current is more noticeable- due to the small ranges of values noted. Both uncertainties are fairly small, allowing for a precise relation to be drawn, but due to the propagation of errors, the large least count on the voltmeter has significantly increased the errors.
The slope of the graph corresponds to the increase in the current output of the cells with an increase in the RPM of the stall torque motor. The linear relationship shows a constant increase of the current with RPM of about 0.0071 milliamperes per RPM.

One can consider 2 reasons for this y intercept- the first being that the current has been overestimated by 0.4 milliamperes each time, highly unlikely considering the scale of measurement, and the other being more likely- the RPM values are noted at slightly lower values than they should be, which is very probable, considering the fact that RPM is considered in the hundreds, in a larger scale here.
A larger source of error could be considered in theory, when equating the VI, power to Fv, it is assumed that 100% of the power has been converted, but obviously , this is not the case. Although piezoelectric cells do not dissipate much heat, there is always some power loss which can and will be a source of error in comparison. This would shift the graph down, but has been counteracted by the error in the RPM reading which has effectively shifted the graph up.
It should be noted though, that though cells are known for efficiencies of about 30%, this will not create an error of 70%, as the approximate conversion efficiency of the material is a factor in calculation of the piezoelectric strain coefficient (11.2).
The small error bars on the graph leave little room for lines of maximum and minimum slope and so obtain a range for the slope and a range of viable answers.
All data points are fairly close to the line of best fit, adding to the credibility of the experiment.

3.3)Comparative Data

COMPARITIVE DATA				
Trial no.	**RPM of Motor**	**Theoretical Current**	**Experimental Current**	**Uncertainty in**
	RPM ±1RPM	**I_{Th} /mA**	**I_{AVG} /mA**	**I_{AVG} /mA**
1	280	1.875	2.0	0.1
2	380	2.545	2.8	0.1
3	475	3.181	3.5	0.1
4	504	3.375	3.7	0.1
5	575	3.850	4.2	0.1
6	625	4.185	4.4	0.0
7	640	4.286	4.6	0.1
8	665	4.453	4.8	0.1
9	700	4.688	5.0	0.1

Table 3

Table 3 shows data from table 1 and table 2, allowing for a comparison of both experimental and theoretical data. It should be noted that some uncertainties were so small, that they were rounded to 0, to fit the decimal places on the experimental values.

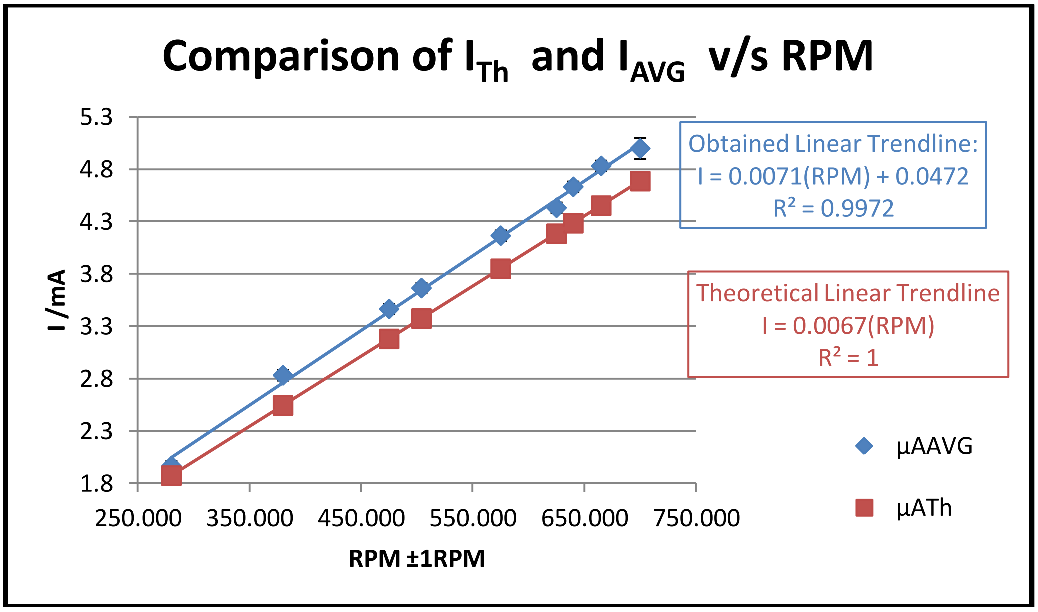


Figure 5

Figure 5 shows a comparative graph plotting both the theoretical and experimental current values on one graph for comparison.

The comparative data confirms the linear relationship observed. The high R^2 values and the similarity to the theoretical graph provide the experiment with a fair amount of reliability and precision- which helps in drawing accurate conclusions.
As discussed below Figure 5, the noticed errors are fairly small, leading to a precise experiment, which, while not error free, can be said to control for various variables so as to attribute any changes in the Y variable (Current) only the change in the X variable (RPM).
We can see a similar graph in both cases, showing produced currents of similar orders. It should be noted, that the cells were aligned in series, and hence have a small current value and a larger voltage value. A systematic error is apparent, in that the experimental values are all shifted higher than they should be. This error, as discussed in Fig 5, is probably due to the underestimation of RPM values. This error would shift the graph left and hence increase the y intercept. The y intercept on the theoretical equation is present because values were rounded off to fit the decimal places of the experimental graph.

3.4)Error Calculation
We can compare our value of the slope to the one obtained theoretically.
$((0.0071-0.0067/0.0071)\times100= 5.6\%$
Here, we have calculated the percentage deviation of our result for the value of the slope and its percentage deviation- 5.6% which is fairly small.

3.5)Hypothesis
In a piezoelectric substance, each individual crystal's elements show a higher than usual electro negativity difference.
This means that one atom of the piezoelectric molecule tends to pull electrons towards itself more than the other ones do, causing a resultant dipole formed by the charge imbalance in the molecule. (Fig 6.) This charge imbalance is caused due to the uneven distribution of elections in the molecules.
Hence, each atom pair which shares electrons creates a dipole moment, which, due to the asymmetric nature of the piezoelectric molecule, does not get cancelled out in the molecule. Therefore, each molecule has a dipole vector in a particular direction, equal to the sum of all the dipole vectors between the atoms in it, caused by charge imbalances due to electro negativity differences in the atoms. [2]

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[2] Brown, Catrin, and Mike Ford. "Bonding- Chapter 4." *Higher Level Chemistry*. Harlow, Essex: Pearson Education, 2014. N. pag. Print.

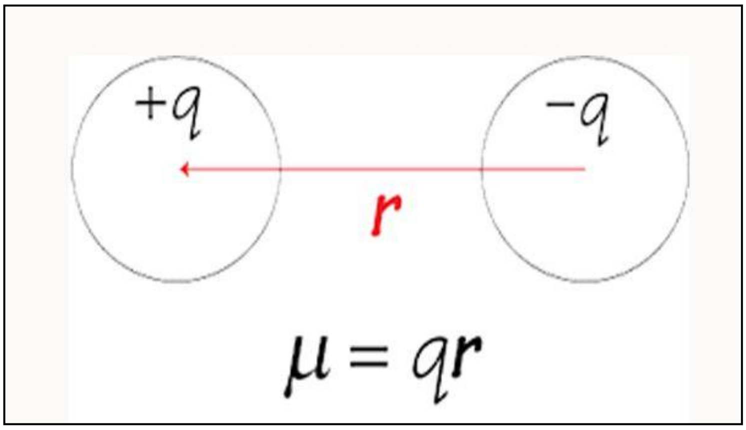

Figure 6.
Figure 6 shows a dipole vector between 2 charges, which represent atoms in a piezoelectric molecule.[3]

Molecules of Piezoelectric substances also are aligned in lattices, where all the molecules in the lattice align with a certain dipole moment for a certain area of the lattice- called a domain.
Each crystals lattice dipoles align in domains with similar dipole directions, this results in a resultant dipole for each domain. Usually, the whole crystal is formed of multiple domains, whose resultant dipoles cancel each other out, making the crystal electrically neutral.

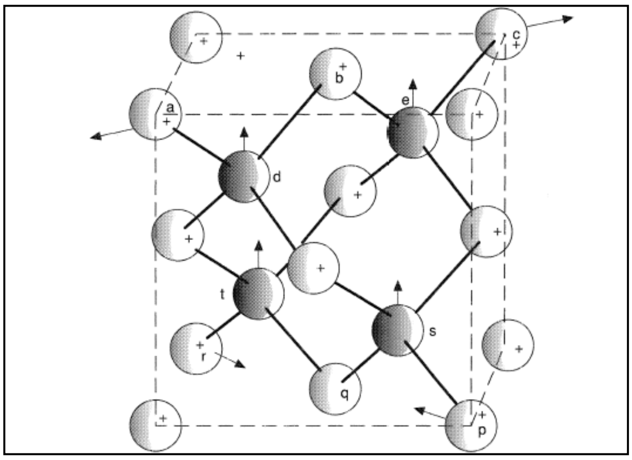

Figure 7.
Figure 7 shows a lattice with dipole moments from each positive ion to the negative ions. The net dipole moment of the lattice is 0, while certain domains hold different dipole moments.[4]

In piezoelectric substances, applying a force shifts these domains around, disturbing the balance of the dipole vectors of each domain, causing a resultant dipole to the crystal. This separation of charge in the dipole is what causes a potential difference, or voltage, which establishes an electric field- causing the flow of electrons- which is the created current.

If one increases the force, the domains are shifted further out of place and the voltage produced and consequently the current achieved increase. By increasing the RPM on a motor, we increase the velocity with which the motor's axle ruler hits the cells, hence increasing the acceleration of the ruler and so increasing the force.

This is why, increasing the RPM should increase voltage and the current produced by the cells.
This can be explained by an increasing RPM increasing the power output, with a linear relationship to both voltage and current, show a power of 2 relationship to power. The power, when divided by velocity of the rod, which is directly proportional to the RPM, should give the force, which should turn out to be directly proportional to the RPM, and hence, the stress, which is directly proportional to the force (where the

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[3] Thomas. "Dipole Moment : Definition, Unit, Formula and Examples in Chemistry." *Guidance Corner*. N.p., 24 Mar. 2019. Web. 01 Oct. 2019. <https://guidancecorner.com/dipole-moment/>.
[4] "PIEZOELECTRICITY." *THERMOPEDIA*. N.p., n.d. Web. 01 Oct. 2019. <http://www.thermopedia.com/content/1030/>.

constant of proportionality is 1/the area of the plate being activated) , should increase directly with an increase in RPM. This linear relationship between current and stress and a linear relationship between stress and RPM, should result in a linear relationship between RPM and current.

*It should be noted that the dipoles for each piezoelectric crystal are different (based on molecular structure) and so, the lattice that represents them would be spaced differently.

4.0)Conclusion

The RPM of the stall torque motor varies linearly with the current produced by the piezoelectric cells which it strikes.

This is given by the experimental equation-

$$I = 0.0071(RPM) + 0.0472 \qquad (6)$$

The theory predicts a directly proportional relationship given by-

$$I = 0.0067(RPM) \qquad (7)$$

However, the y intercept in the experimental graph is very small, and hence within the limits of experimental error, the relationship can be considered to be directly proportional.

5.0)Evaluation

5.1)Strengths of the investigation (and how they impacted results)

1. Control Variables were easy to control- The variables controlled were easy to control. As discussed in the Control variables section, the control procedure was a matter of setting the experiment up in such a way as to control it. For example, controlling the orientation of the rod striking the surface was a matter of setting it into the motor at a 90 degree angle to the floor. The controls reduced the chance that the change in the DV was external and hence attributed these changes only to the changing IV.

2. Large range of IV's- The large range of independent variables allowed for a better analysis and a better graph from which conclusions can be drawn. These accurate conclusions can help draw implications and extensions to the experiment.

3. 3 Trials per IV to reduce human error- The chance of random errors and outliers were reduced by conducting multiple trials and so, reducing the chance of any particular variable unfairly affecting all readings.

4. Small uncertainty in data- high precision- The small observed uncertainty aids the precision of the experiment, and hence allows for better conclusions to be drawn. This is due to the small ranges of values obtained.

5. Similarity to theoretical data- high reliability and accuracy- The conclusions drawn agreed with the theory and the graphs of the data held a high R^2 value, similar to the theoretical graphs. This provides reliability to the experiment, aiding reliability and establishing the accuracy of the conclusions.

5.2)Weaknesses and Errors of the investigation (with suggested improvements)

1. It is apparent from the graphs, that the RPM of the motor has not been judged very accurately. This would have impacted the readings. The RPM of the motor resulted in a systematic error which was apparent on viewing the graphs. The theory predicts a directly proportional relationship (with 0 y intercept) however, due to this error, a y intercept is introduced, and hence, the experimental relationship is deemed linear rather than directly proportional. This could have significantly impacted readings. The reading given by the motor did not accurately represent the RPM. This impacted the power input into the cells and so the current output. Checking the RPM with another measurement device to confirm its value would allow for better readings by eliminating this error.

2. The theory behind the experiment assumes a 100% power conversion rate from mechanical to electrical energy (Motor to piezoelectric cells) (When Fv is equated to VI) - This assumption is false, but the same amount of power was converted in each reading, and the power conversion is accounted for in the

piezoelectric strain coefficient in the theory, which is why this assumption is safe and affects readings but not conclusions.

3. Another assumption made in the theory, was that the power was delivered from the motor to the cells instantly, which was not the case. In reality, the power was only delivered as long as the cells were in contact with the motor. This is another reason, that the not all 100% of the power would be given to the cells at any point in time, as it would be distributed over a time interval during which the ruler and the cells were in contact. This possibly caused a drop in induced currents which lowered the y intercept, however its effect was probably counteracted by the miscalculation of the RPM discussed under point 1, in this section.

4. The RPM of the motor showed considerable fluctuations.- The RPM of the motor showed fluctuations, and this was hard to control, so the noted value was the initial RPM. This random error could significantly impact the voltage and current output, and hence induce errors. This was partially combated by the multiple readings, but if it was possible to check the voltage, and in a recording of the setup, check the exact RPM at the time, this error could have been reduced and hence its impact on the precision of the experiment reduced.

5. The orientation of the striking was not constant, although there was an attempt to control this.- This random error could impact the readings by not diverting all the force to the cells, instead causing a component of it to act in a horizontal direction as an angle would be induced between the ruler and the normal to the cells. This random error was combated with multiple readings, but placing the ruler in a fixed shaft, and only then allowing it to move up and down (as done in a traditional linear actuator), would reduce it.

6. The ammeter may not have recorded the peak current. The ammeter recorded current in small time intervals, keeping track of the maximum, which was used. However, if the peak occurred between readings taken by the ammeter, the ammeter could not have recorded it, and so, would give a reading lower than the actual reading. This random error could have impacted results and the precision of the experiment, and to control this, one can obtain an ammeter which takes readings for the maximum current more frequently and then extrapolates a current versus time graph and so obtains the maximum current. This would allow one to make sure the maximum current has been obtained and that the experimental current does not have an error as the maximum occurred between the times the ammeter took readings.

7. The measurement devices had large least counts relative to the units being measured, and so, larger uncertainties. The least counts on the voltmeter and the ammeter were only 0.1 volts and milliamperes. This caused error propagation to have larger uncertainties and error bars than there could have been, significantly reducing the precision of the experiment. This could have been improved by using better measurement devices with smaller least counts, and hence reducing uncertainty- providing precision to the experiment and accuracy to the drawn conclusions.

6.0)Applications

1. As an extension, one could consider using these plates on the bottom of a shoe, to produce voltage and charge a battery. This can be used to charge anything in a shoe, like a GPS sensor, for children who may get lost, or a simple battery pack for a phone. This extension has been followed through, and it works well. A small capacitor is needed to smoothen the current produced and feed it into a battery, and charge a cell. As shown in Figure 7.

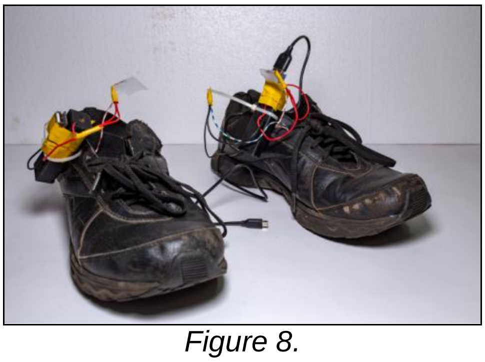
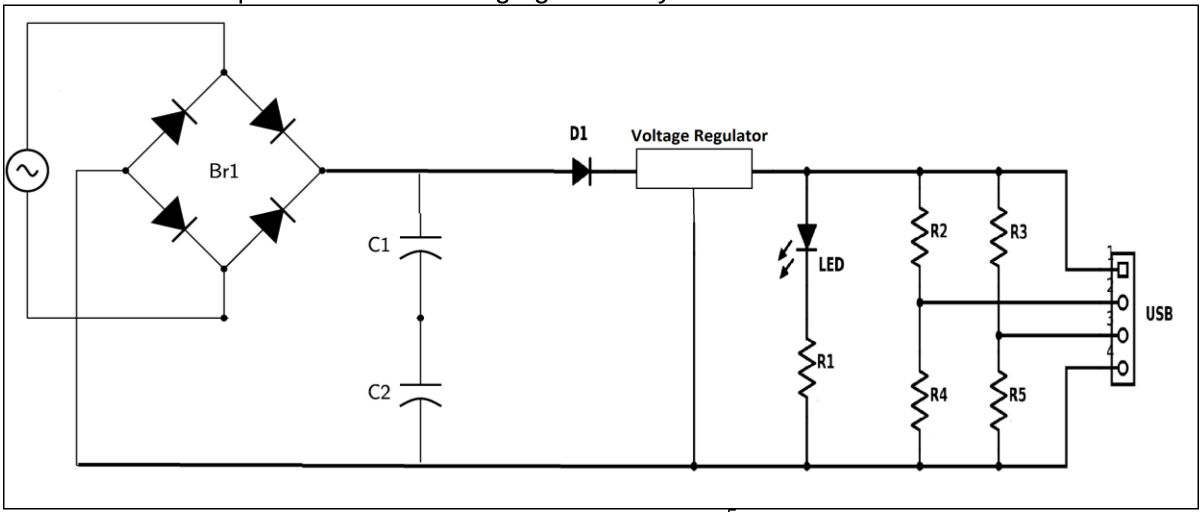


Figure 8.

Figure 8 shows a piezoelectric shoe, converting the users weight of their footstep to charge a power bank implanted in the shoe as they walk.

Figure 9.
Figure 9 shows a clearer picture of the cells on the sole of the shoe.

For a USB output, the circuit diagram must be slightly altered. This consisted of incorporating a voltage regulator to smoothen outputs and make charging a battery more viable.



Design Diagram 10.[5]

2. It is also possible to use these cells in car tyres, to produce some voltage and maybe even help charge the car battery by storing energy.

7.0)Extensions
1. A possible extension to the investigation would involve considering the same variables for cells connected in parallel instead of series. The voltage analysis could be beneficial in determining which setup should be used in real world applications.
2. One could also consider the angle at which the cells are struck. Since piezoelectric substances are anisotropic (they show different properties in different directions), they would show different current outputs at different striking angles. Considering the current produced at a certain angle which best mimics the human foot walking for different materials (where their piezoelectric strain coefficients are the IV) could help find the best material for usage in human shoes to produce electricity.

[5] "Electronics Explained In Simple Ways." *Build Electronic Circuits*. N.p., n.d. Web. 01 Oct. 2019. <http://www.build-electronic-circuits.com/>.

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9.0)Appendix

Voltage Data collected during the experiment

Trial no.	RPM of Motor	Voltage produced by piezoelectric cells			Average Voltage	Uncertainty
	RPM ±1RPM	/V_1 ±0.1V	/V_2 ±0.1V	/V_3 ±0.1V	V_{AVG} ±0.1V	In voltage
1	280	3.5	3.4	3.5	3.5	0.1
2	380	3.8	3.8	3.7	3.8	0.0
3	475	3.8	3.9	3.9	3.9	0.1
4	504	3.9	3.9	3.9	3.9	0.0
5	575	4.1	4.0	3.9	4.0	0.1
6	625	4.1	4.2	4.1	4.1	0.1
7	640	4.1	4.2	4.1	4.1	0.1
8	665	4.2	4.3	4.2	4.2	0.0
9	700	4.4	4.4	4.2	4.3	0.1

Table 4: Shows the Voltage data collected during the experiment. This was not included in the experiment as it was not relevant to the investigation.

**NOTE: It should be noted that some uncertainties were so small, that they were rounded to 0, to fit the decimal places on the experimental values.*