GENERATION OF ELECTRICITY FROM POPULOUS AREA USING PIEZOELECTRICITY

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ABSTRACT

This study focused on the generation of electricity from populous area using piezoelectric materials such as PZT transducers. A transducer is a device that directly converts mechanical energy from strain to electrical energy. The experimental method of research was used to determine the relationship between the strain on the transducers and the induced electrical energy. Two different prototypes were developed to be able to determine the voltage and energy that piezoelectric materials such as PZT transducers can produce. Using the SPARK Voltage Sensor the varying voltages were automatically recorded. A single 0.08-g PZT transducer can produce a voltage of 0.9 V and nof 196.4 J. On the other hand, a single 0.4-g transducer can produce a voltage of 7.5 V and energy of 1048 J. It was found out the manner of applying the force (tapping) on the transducer, and the mass of the transducer affect the production of voltage and energy.

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INTRODUCTION

Background of the Study

Developing countries like the Philippines undergo energy crisis due to demands brought by its economic growth. As a result, energy soon will be insufficient to supply the necessities and even the provisions of the community. Thus, the country needs to find future alternative sources of energy.

Piezoelectricity was based on the idea of pyroelectricity investigated by Carl Linnaeus and Franz Aepinus in the 18^{th} century. The first exhibition of piezoelectric effect was discovered by Pierre and Jacques Curie, with their knowledge of pyroelectricity and crystal structures they have formulated tests using crystals such as tourmaline, topaz, quartz, cane sugar and Rochelle salt. A certain characteristic of crystalline minerals was discovered by Pierre and Jacques Curie in 1880: when subjected to a mechanical force, the crystal became electrically polarized. In 1881, W. Hankel first proposed the term piezoelectricity, piezo translated as pressure linked with electricity. This behavior was then labeled the piezoelectric effect from the Greek word *"Piezein"* meaning to press or squeeze. Lipmann from thermodynamics principles inferred the converse effect.

The field of piezoelectricity was created by collaborations within the European Scientific Community. By 1910, Voigt's "Lerbuch der Kristallphysic" (Textbook on Crystal Physics) became a basis of reference work dealing with the complicated electromechanical relationships in piezoelectric crystals.

Piezoelectric effect can be found anywhere. From the simplest ignition system (lighter) to complex electronic technologies, one of which is the commonly used speakers and/or buzzers, piezoelectric generators had been used because of its capability to produce highest power output for a given size compared to electromagnetism and static electricity (Table 1, S Roundy and PK Wright). During the World War I, piezoelectric crystals had been practically used in sonar devices. Then, they had used piezoelectricity to read the ridges of a vinyl for phonographs after the war. Moreover, ceramics such as Barium Titanate ($BaTio_3$) and Lead Zirconate Titanate (PZT) were discovered respectively in 1940s and 1950s. These materials display high dielectric and piezoelectric properties. In addition, these new compounds brought the possibility of tailoring these materials into specific applications by the use of dopants (materials used to modify some properties of the compounds).

Piezoelectric materials produce electrical energy when mechanical stress is applied or vice-versa. It will deform physically in the presence of an electric charge. This effect is the result of spontaneous separation of charge within the crystal, thereby, an electric dipole is produced.

Piezo ceramic devices fit into four general categories: generators, sensor, actuators, and transducers. The ceramic element converts the mechanical energy of compression or tension to an electrical energy. This behavior is used in solid state batteries, force-sensing devices, fuel-igniting devices and other products. Although the magnitudes of piezoelectric movements, voltages, or forces are small, and often require amplification, piezoelectric materials have been adapted to an impressive range of application.

A Piezoelectric system can be constructed for virtually any application for which any other type of electromechanical transducers can be used. For any particular applications, however, limiting factors include the weight, the size, and the cost of system. As of today, piezoelectricity is used in different fields. It is used in electric guitars, ultrasounds, printing, doorbells and others.

Statement of the Problem

This study aims to generate electricity using piezoelectric material such as ceramic transducers. In addition, this research aims to investigate the efficiency of the small scale prototype of a piezoelectric mat consisting of PZT circular plates (diaphragm) layered on top of latex rubber mat as piezoelectric generator that will be used to provide electrical charge for the 3W LED light bulb. Furthermore, this study aims to measure (1) the mechanical stress applied (2) the voltage, and energy.

Statement of Purpose and Expected Outcome

The research aims to provide solution to the nation's energy crisis by supplying electricity without using fossil fuel that is considered a limited source of power. It also aims to help solve environmental issues since piezoelectricity does not produce toxic wastes such as carbon monoxide and chlorofluorocarbon. The research also aims to aid the country economically since energy harvesting through piezoelectricity is sustainable because it only requires motion. Motion and vibration--- which is defined as a single cycle of such a motion, occurs naturally and very frequently since vibrations can be classified as seismic, acoustic and forces applied directly to the load on the working surface (Thorlabs, 2013). The types of vibration mentioned above are occurs as natural phenomena and/or produced by human interference. These vibrations can be collected anywhere and anytime thus, proving that piezoelectricity is capable of long-term and productive usage.

It is expected that this study would encourage Filipino scientists and engineers to further develop the use of piezoelectricity as an alternative energy source in the Philippines.

Significance of the study:

Renewable and sustainable power generation by Piezoelectricity is the key allowing technology intended for an entire multitude of potential distributed systems. This study is beneficial to the country not only in solving energy-related problems but also resolves environmental and economic crises. Since the country will be using mechanical energy to produce electricity, the utilization of fossil fuel and depletion of natural fuel would lessen. In addition, centralization of the generators providing power plants in different areas will offer more job opportunities for people and more investments will come about in the country resulting to an economically stable and earth-friendly country attributable to sustainable, flexible and highly accessible energy from piezoelectricity. Lastly, since this study applies the concept of the "Law of Conservation of Energy" wherein energy can only be transformed from one form to another, electrical energy which is considered to be a versatile form of energy will be transformed to be used in other types of energy.

Scope and Limitations

This study focuses on the efficiency of piezoelectricity exhibited in Ceramic Transducers (PZT) an alternative energy source for traditional electric generation and/or fuel used for lighting purposes, which in our case is providing power for a 3W LED bulb. This study initially focuses on one energy conversion which is mechanical to electrical to light energy. Comparison and specifications, not including the voltage, current in amps and wattage to mechanical stress computation of mechanical stress applied to the PZT are outside the scope of this study.

REVIEW OF RELATED LITERATURE

In 2007, a Japanese engineer Kohei Hayamizu developed Jacques and Pierre Curie's discoveries about crystalline minerals into a piezoelectric generator that only needs force and squeeze exertion coming from human and vehicle traffics. His "power-generating floor" device uses flat plates of piezoelectric materials to create electricity from vibrations. This device was imbedded in a square meter of concrete outside of Shibuya Station in Tokyo (Hult, 2011).

In October 2008, NTT innovate an energy harvesting shoes that can generate up to 1.2 watts of electricity just by applying pressure on the soles. Piezoelectricity as an energy source is considered more energy efficient and sustainable yet the disadvantage of the futuristic shoes is its limited range of area where pressure can be applied which is what the research is aiming to develop. The research aims to place piezoelectric materials on populous areas and centralize where to harvest energy so it would be able to provide electricity for a whole community.

As such, Shibuya is one of the busiest railway stations in the world with an estimated two million people passing through on weekdays now serves as a perfect location for taking advantage of the footfalls of people to create electricity.

As mentioned earlier, previous research on piezoelectricity was made and results provided data determining the characteristics of common piezoelectric generators. One property described is the elasticity measured by Young's moduli wherein the "diaphragm"—piezoelectric circular plates were given as example for its relatively considerable capability for strains/force thus able to provide more electrical charge. Another modification is the use of Stack Actuators, a layer of piezoelectric material, which help stipulate even stress distribution due to its direction which is suitable for the kind of mechanical force which is compression---result of compressive stress; pushing force opposite to tension. This study adapts the model of Sunghwan's research but uses substitute materials instead due to lack of availability of the materials caused by very minimal publicity of piezoelectricity as an energy source.

Recent developments in electronics industry have made it feasible to decrease the power requirement of most electronic devices to levels that are comparable to the capabilities to generate piezoelectric harvester devices .Lead Zirconate Titanate (PZT) is the most commonly used piezoelectric material is caused by its large electromechanical coupling characteristics. Goldfarb and Jones previous work (1999) showed a linear model of a PZT stack and studied its capabilities to harvest power.

A research had been made regarding low power energy harvesting with Piezoelectric Generators by Sunghwan Kim, PhD (2002) wherein different forms of piezoelectric generators were reviewed and modified by analyzing the effect of regrouping electrodes of some stressed regions to increase power output. Sunghwan's dissertation emphasized the use of PZT (Lead Zirconate Titanate) which is, by far, the most widely used piezoelectric material among all piezoelectric energy generators. Using PZT, Sunghwan demonstrated mathematical and qualitative properties and characteristics of piezoelectric energy generators and the relations between poling direction, stress, strain, charge, voltage, current, and others using theoretical and constitutive equations. Results showed that generated voltage and charge are relatively small for the extremes of piezoelectric layer thickness therefore applicable only for devices that require less electrical input. Further research is necessary for the modification of piezoelectric energy generators to require less mechanical stress but produce more electrical output. This research aims to investigate the efficiency of piezoelectric energy generator when used in larger scale devices such as light bulb to determine its effectiveness as an alternative energy source for the masses. This will help the community solve its environmental, economic and energy problems in view of the fact that electricity is the most versatile energy source among all.

METHODOLOGY

Research Design

This study used the experimental method of research for a fact that mechanical stress (tapping) on the piezoelectric material was related to the electrical energy induced in the prototype. The greater the number of tapping, and the harder it is, the more energy is induced. It real-life situation, the more mechanical stress the people will exert on the proposed piezomat, the greater the energy can be harnessed.

Paradigm

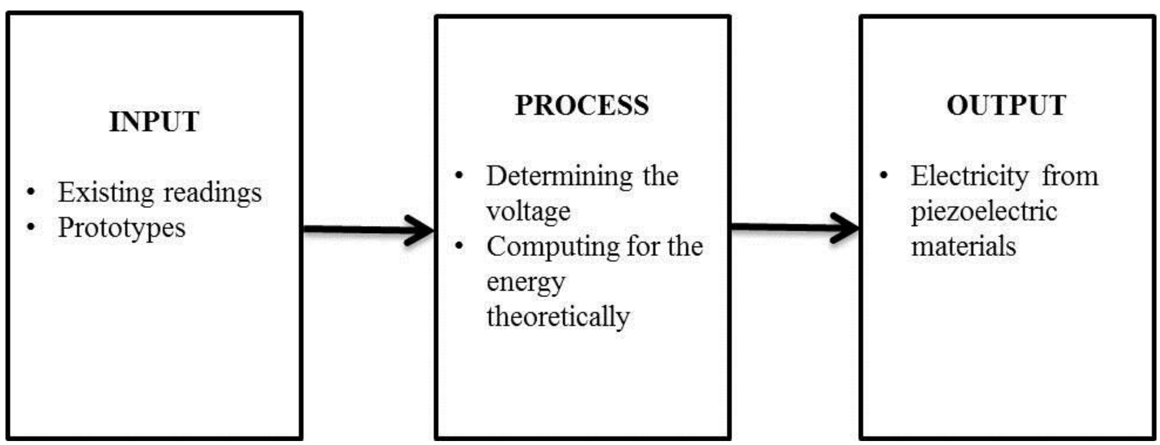

Figure 1: Research Paradigm

The figure above shows the research paradigm of this study. It is the representational pattern or steps undertaken by the researchers. The study is composed of three phases. The input serves as the stepping-stone of the researchers to further develop a prototype that could possibly show how voltage is induced from piezoelectric materials such as PZT transducers. This phase is very important for it directed the researchers on where to start their research. This phase includes the exploration on different review of the related literatures and studies that gave them ideas in developing and testing the prototypes.

The process phase includes the testing and doing trial experimentations of the developed prototypes. The prototype A was tested in De La Salle University with the expertise of Dr. Gil Nonato Santos, Mr. Roy Soriano, and Mr. Alcantara. The experimentation was aided by SPARK Voltage Sensor.

Finally, the output phase is the generating of electricity from piezoelectric materials such as PZT transducers resembling the real-life generation of electricity from populous area using the concept of piezoelectricity.

Prototypes

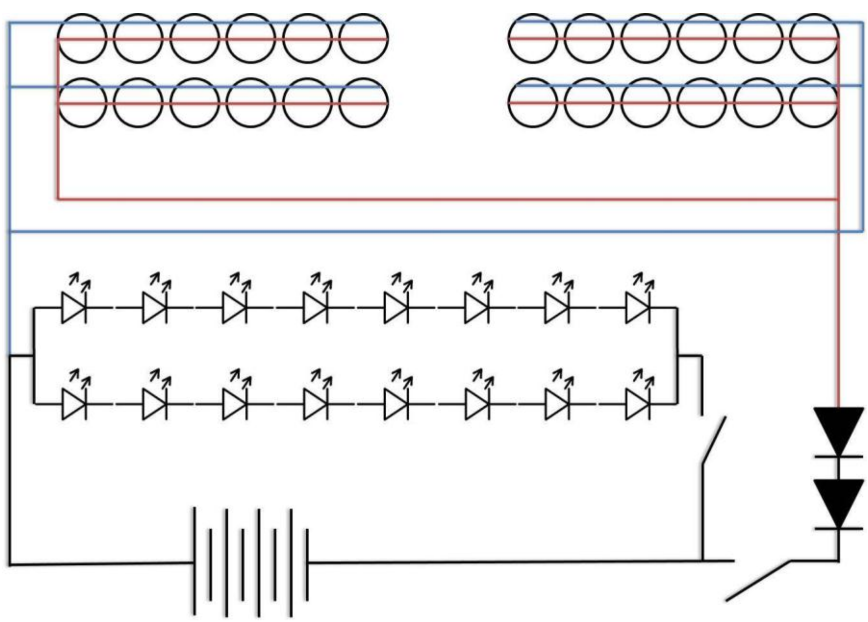

Figure 1: The prototype A consisted of 24 pieces PZT transducers

The figure 1 above presents the prototype A. The prototype A depicts a residential area that utilizes mechanical energy and converts it to electrical energy using piezoelectric material such as PZT transducers. This prototype is composed of 24 PZT transducers and 16 light-emitting diodes. Out of 24 piezoelectric disks, 19 are 0.4-g PZT transducers with a diameter of 35 mm, thickness of 0.48 mm, and area of 0.0038 m^2. The other 5 are 0.08-g PZT transducers with a diameter of 27 mm, thickness of 0.24 mm, and area of 0.0023 m^2. The mass, thickness, and diameter were obtained using a digital weighing scale, micrometer, and vernier caliper respectively. All of these transducers are connected series to a storage system. The storage system is consisted of 4 pieces 3-V button batteries. These batteries are connected parallel to the 16 light-emitting diodes. Two blocking diodes and 2 switches control storing of electrical energy and flow of electric charges into the circuit.

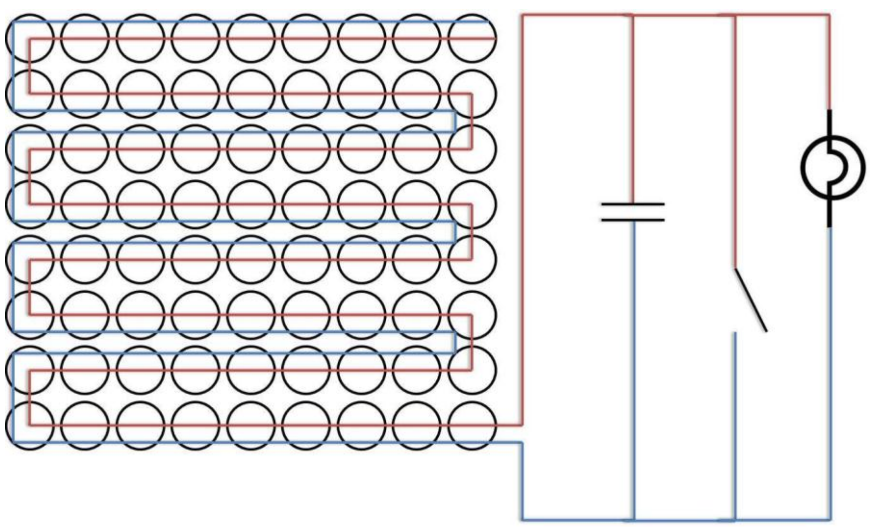

Figure 2: The human size prototype B consisted of 72 transducers

The prototype shown in Figure 2 depicts a life-size piezoelectric mat that utilizes mechanical energy, and converts it to electrical energy using piezoelectric material such as PZT transducers. It is combined of 0.4-g, 0.08-g, 0.05-g, and 0.04-g 72 pieces PZT transducers connected in series as the piezoelectric material component and latex rubber mat as non-piezoelectric material. The piezoelectric material component was piled between 2 rubber mats and is connected parallel to a storage system (capacitor), a switch, and a 3-Watt LED bulb.

General Procedures

A. Inducing and storing voltage

In prototype A, the mechanical stress was applied through finger-tapping and passing a 1.47-N miniature car on the PZT transducers back-and-forth. The vibrations caused by the tapping and the passing of the car produced voltage that were directly stored in the batteries connected series. It was ensured that the induced voltage would really be stored using blocking diodes. On the other hand in prototype B, the voltage was produced by foot-tapping on mat. The voltage was then delivered and stored to a capacitor.

B. Measuring the voltage

The voltage was measured through the use of a device called SPARK Voltage Sensor that is designed to measure the voltage and other quantities such as current, power, and frequency. It was connected parallel to individual ceramic PZT transducer through alligator clips to measure the voltage. The device automatically lists the data in a table and plots it in a graph. Similarly, each transducer was tested with a multi-tester to check the voltage measured by the device. The figures showed by the multi-tester were the same as the results of the voltage sensor. Below are the pictures showing how voltage was measured.

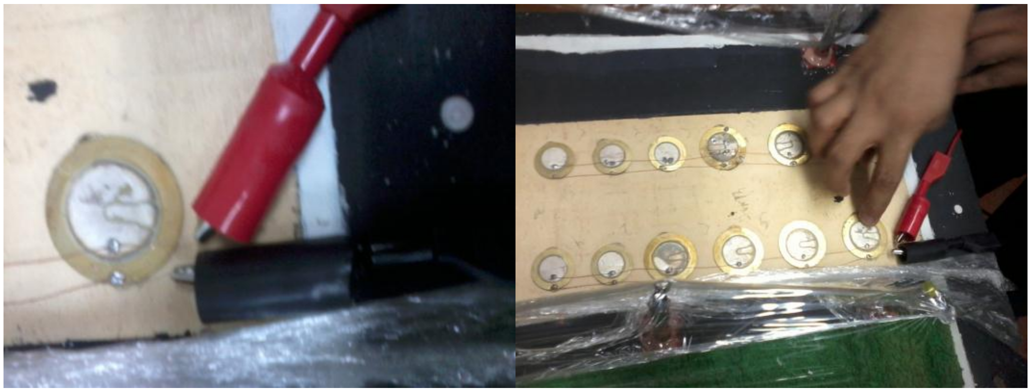

Figure 3: Hand-tapping a 0.4-g PZT transducer

Figure 4: SPARK Voltage Sensor showing the varying voltage produced

Figure 5: Measuring the voltage using a multi-tester

C. Computing for the electrical energy

The total energy that can be harnessed using the proposed prototypes was theoretically computed using piezoelectric equations Physikinstrumente – that is a company fabricating and researching on piezoelectric materials. The energy can be computed using equation 1 that is derived from other equations:

$$\mathbf{U = 2\,F_o\,\Delta L_o\,[(3M / m) + 1]} \quad \text{(Equation 1)}$$

where: U is the energy

F_o is the force applied on the transducer

ΔL_o is the maximum nominal displacement without external force

M is the additional mass on the transducer

m is the mass of the transducer

$$\mathbf{F_o = k_T\,\Delta L_o} \quad \text{(Equation 2)}$$

where: F_o is the force applied on the transducer

k_T is the piezomaterial's stiffness constant

ΔL_o is the maximum nominal displacement without external force

RESULTS AND DISCUSSIONS

Voltage

Two different PZT transducers were continuously tapped in 20 seconds. The tapping (vibration) was measured to be 10 Hz. Using the SPARK Voltage Sensor the varying voltages were automatically recorded. The figures below present the produced voltages of two different transducers. Both transducers produced varying amount of voltage ranging from 0 V to 0.9 V for the 0.08-g PZT transducer and 0 V to 7.5 V for the PZT 0.4-g transducer. The results that can also be attributed to the manner of tapping, suggest that the 0.4-g PZT transducer produces more voltage than that of 0.08-g PZT transducer. In addition, a single 0.4-g PZT transducer operates a voltage like that of two 3-V button batteries.

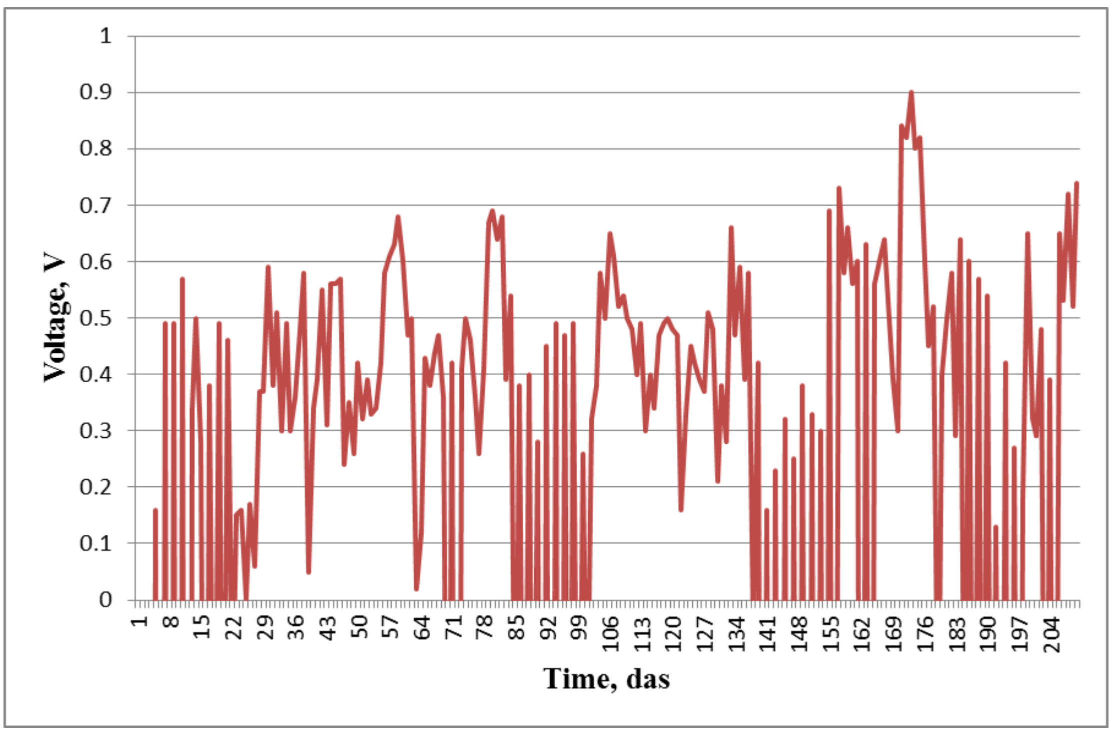

Figure 1: Voltage produced by tapping a 0.08-g PZT, the time is in deka-second

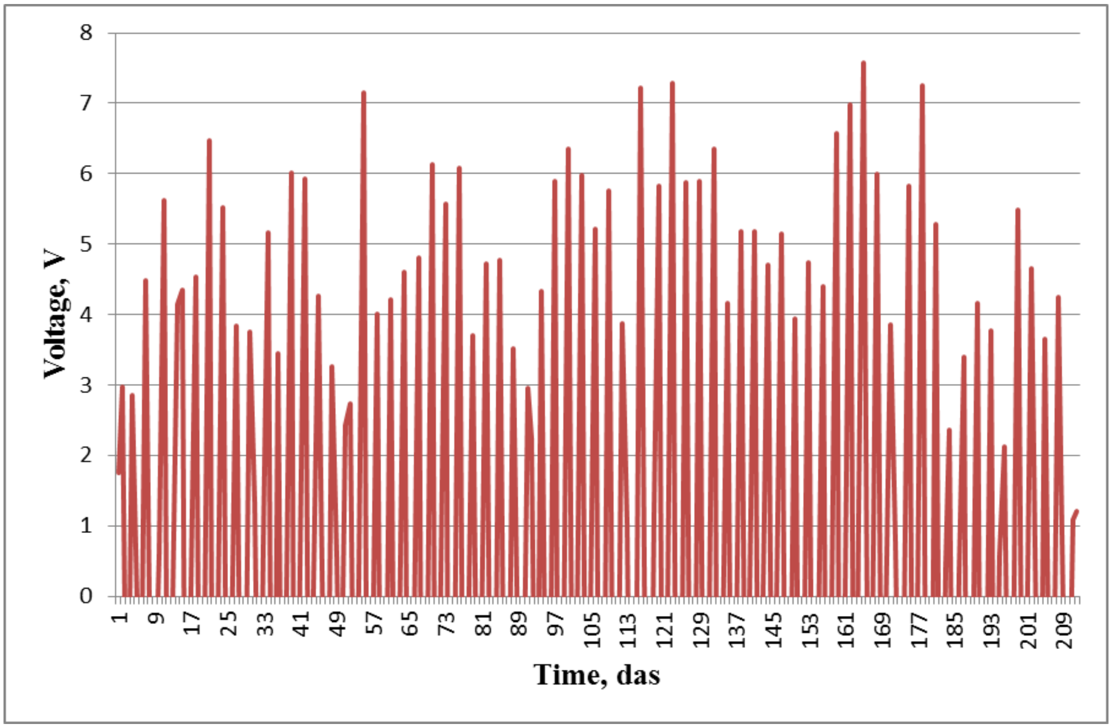

Figure 2: Voltage produced by tapping a 0.4-g PZT, the time is in deka-second

Table 1: Possible Voltage that can be harnessed by two prototypes

PROTOTYPE A		**PROTOTYPE B**	
Transducer	**Maximum Voltage**	**Transducer**	**Maximum Voltage**
19 pcs 0.4-g PZT	19 x 7.5 V = 142.5 V	20 pcs 0.4-g PZT	20 x 7.5 V = 150 V
5 pcs 0.08 PZT	5 x 0.9 V = 4.5 V	52 pcs 0.08 PZT	52 x 0.9 V = 46.8 V
TOTAL	**147 V**	**TOTAL**	**196.8 V**

Table 1 shows the possible voltage that can be harnessed from the two prototypes. Notice that a single 0.4-g PZT transducer can produce 7.5 V, and a single 0.08-g PZT transducer can produce 0.9 V. As such, for prototype A that is composed of 19 pieces 0.4 PZT transducers and 5 pieces 0.08-g PZT transducers can provide an output voltage of 147 V. Similarly, prototype B that is composed of 20 pieces 0.4 PZT transducers and 52 pieces 0.08-g PZT transducers can provide an output voltage of 196.8 V. The data implies that both prototypes are capable of supporting appliance requiring 120-V to operate.

Electrical Energy

Using equations 1, and 2 from the previous chapter, the energy that can be harnessed from a single transducer was theoretically computed. The results were summarized in Table 2 below.

$$\mathbf{U = 2\, F_o\, \Delta L_o\, [(3M / m) + 1]} \qquad \text{(Equation 1)}$$

where: U is the energy

F_o is the force applied on the transducer

ΔL_o is the maximum nominal displacement without external force

M is the additional mass on the transducer

m is the mass of the transducer

$$\mathbf{F_o = k_T\, \Delta L_o} \qquad \text{(Equation 2)}$$

where: F_o is the force applied on the transducer

k_T is the piezomaterial's stiffness constant

ΔL_o is the maximum nominal displacement without external force

Table 2: Theoretically computed amounts of electrical energy by each PZT transducer.

Quantity	**0.4-g PZT Transducer**	**0.08-g PZT Transducer**
$\mathbf{k_T}$	0.5 N/m	0.5 N/m
$\mathbf{\Delta L_o}$	5×10^{-3} m	4×10^{-3} m
$\mathbf{F_o}$	2.5×10^{-3} N	2.0×10^{-3} N
U	5.6 J	18 J

The electrical energy that can be produced by a single 0.4-g PZT transducer and a single 0.08-g PZT transducer are 5.6 J and 18 J respectively as shown in Table 2. Given the same stiffness constants equal to 0.5 N/m, and different $\mathbf{\Delta L_o}$ and $\mathbf{F_o}$, it was found out that the two different PZT transducers produced different amount of electrical energy. The lesser the mass the transducers has, the greater the energy it can provide. On the other hand, the greater the mass the transducer has, the lesser the energy can be obtained from it. The possible electrical energy that can be harnessed from the two proposed prototypes is summarized in Table 3. It suggests that prototype B that is the human-size piezomat can produce greater electrical energy equal to 1048 J than that of prototype A which can only produce 196.4 J.

Table 3: Possible electrical energy that can be harnessed by two prototypes

PROTOTYPE A		**PROTOTYPE B**	
Transducer	**Energy**	**Transducer**	**Energy**
19 pcs 0.4-g PZT	19 x 5.6 J = 106.4 J	20 pcs 0.4-g PZT	20 x 5.6 J = 112 J
5 pcs 0.08 PZT	5 x 18 J = 90 J	52 pcs 0.08 PZT	52 x 18 J = 936 J
TOTAL	**196.4 J**	**TOTAL**	**1048 J**

SUMMARY AND CONCLUSION

This study focused on the generation of electricity from populous area using piezoelectricity. Two different prototypes were developed to be able to determine the voltage that piezoelectric materials such as PZT transducers can produce. In addition, the electrical energy was theoretically computed using equations provided by some previous researches.

Using the SPARK Voltage Sensor the varying voltages were automatically recorded - that is for the 0.08-g PZT transducer, 0 V to 0.9 V and for the PZT 0.4-g transducer, 0 V to 7.5 V. The 0.4-g PZT transducer produces more voltage than that of 0.08-g PZT transducer. The harder the tap on the transducer, the greater is the voltage produced.

It was also found out that prototype A that is composed of 19 pieces 0.4 PZT transducers and 5 pieces 0.08-g PZT transducers can provide an output voltage of 147 V. Similarly, prototype B that is composed of 20 pieces 0.4 PZT transducers and 52 pieces 0.08-g PZT transducers can provide an output voltage of 196.8 V.

The electrical energy that can be produced by a single 0.4-g PZT transducer and a single 0.08-g PZT transducer are 5.6 J and 18 J respectively. The energy seem to be dependent on the mass of the transducers, meaning that the lesser the mass the transducers has, the greater the energy it can provide. On the other hand, the greater the mass the transducer has, the lesser the energy can be obtained from it. The possible electrical energy that can be harnessed from the two proposed is equal to 1048 J that can be obtained from the human-size prototype.

RECOMMENDATIONS

The researchers encourage the future researchers to use other piezoelectric materials other than PZT transducers. Moreover, to improve the existing prototypes A and B initially proposed by the researchers. Lastly, it is also a suggestion to identify other contributing factors in the production of voltage and electrical energy of these piezoelectric materials.

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APPENDICES

Appendix A: Voltage produced by 0.4-g PZT transducer recorded by SPARK Voltage Sensor

Time s	Current A	Voltage V
0	-5.31E-04	1.75
0.1	-5.31E-04	2.98
0.2	0	-3.41
0.3	-5.31E-04	2.86
0.4	-5.31E-04	-0.06
0.5	0	-2.3
0.6	-5.31E-04	4.48
0.7	-5.31E-04	-1.63
0.8	-5.31E-04	-2.05
0.9	-5.31E-04	0.59
1	0	5.63
1.1	-5.31E-04	-6.33
1.2	-5.31E-04	-0.16
1.3	-5.31E-04	4.14
1.4	-5.31E-04	4.35
1.5	0	-5.81
1.6	-5.31E-04	0.13
1.7	-5.31E-04	4.53
1.8	0	-5.43
1.9	0	-0.74
2	-5.31E-04	6.48
2.1	0	-7.9
2.2	0	-0.36
2.3	0	5.52
2.4	-5.31E-04	-5.28
2.5	0	-0.9
2.6	-5.31E-04	3.84
2.7	-5.31E-04	-3.27
2.8	-5.31E-04	-1.03
2.9	-5.31E-04	3.75
3	0	1.34
3.1	-5.31E-04	-3.81
3.2	-5.31E-04	0.73

3.3	-5.31E-04	5.16
3.4	-5.31E-04	-7.06
3.5	-5.31E-04	3.45
3.6	-5.31E-04	-2.75
3.7	0	0.09
3.8	-5.31E-04	6.02
3.9	-5.31E-04	-6.07
4	-5.31E-04	0.42
4.1	0	5.93
4.2	0	-5.06
4.3	-5.31E-04	0.11
4.4	-5.31E-04	4.27
4.5	0	-0.93
4.6	-5.31E-04	-4.02
4.7	-5.31E-04	3.27
4.8	-5.31E-04	0.56
4.9	0	-2.49
5	-5.31E-04	2.43
5.1	-5.31E-04	2.74
5.2	-5.31E-04	-4.26
5.3	-5.31E-04	0.24
5.4	-5.31E-04	7.16
5.5	-5.31E-04	-7.65
5.6	0	-1.3
5.7	-5.31E-04	4.01
5.8	-5.31E-04	-5.47
5.9	0	-0.7
6	-5.31E-04	4.22
6.1	0	-4.95
6.2	-5.31E-04	0.57
6.3	-5.31E-04	4.61
6.4	0	-5.61
6.5	-5.31E-04	-0.73
6.6	-5.31E-04	4.8
6.7	0	-5.56
6.8	-5.31E-04	-0.78
6.9	-5.31E-04	6.14
7	0	-5.69
7.1	0	0.34
7.2	0	5.57
7.3	-5.31E-04	-6.66
7.4	-5.31E-04	-1.45

7.5	-5.31E-04	6.08
7.6	0	-5.45
7.7	-5.31E-04	-1.06
7.8	-5.31E-04	3.71
7.9	-5.31E-04	-3.19
8	-5.31E-04	-0.83
8.1	-5.31E-04	4.73
8.2	-5.31E-04	-3.63
8.3	-5.31E-04	-0.81
8.4	-5.31E-04	4.77
8.5	0	-2.98
8.6	-5.31E-04	-1.15
8.7	-5.31E-04	3.52
8.8	-5.31E-04	-0.98
8.9	0	-2.43
9	-5.31E-04	2.96
9.1	-5.31E-04	2.25
9.2	-5.31E-04	-4.34
9.3	-5.31E-04	4.34
9.4	-5.31E-04	-1
9.5	-5.31E-04	-2.16
9.6	-5.31E-04	5.89
9.7	-5.31E-04	-3.71
9.8	-5.31E-04	-1.16
9.9	-5.31E-04	6.36
10	0	-4.04
10.1	-5.31E-04	-0.74
10.2	0	5.98
10.3	0	-5.69
10.4	0	-0.34
10.5	-5.31E-04	5.21
10.6	0	-5.16
10.7	-5.31E-04	-0.58
10.8	-5.31E-04	5.76
10.9	-5.31E-04	-3.36
11	0	-1.47
11.1	-5.31E-04	3.87
11.2	-5.31E-04	1.03
11.3	-5.31E-04	-5.33
11.4	-5.31E-04	-0.09
11.5	-5.31E-04	7.22
11.6	0	-1.85

11.7	0	-3.9
11.8	0	1.19
11.9	0	5.83
12	0	-6.57
12.1	-5.31E-04	-0.32
12.2	-5.31E-04	7.29
12.3	0	-6.34
12.4	-5.31E-04	-0.49
12.5	-5.31E-04	5.88
12.6	0	-4.17
12.7	-5.31E-04	-0.96
12.8	0	5.9
12.9	-5.31E-04	-5
13	-5.31E-04	-0.42
13.1	0	6.36
13.2	0	-4.53
13.3	-5.31E-04	-0.82
13.4	-5.31E-04	4.17
13.5	0	-2.65
13.6	0	-0.97
13.7	0	5.18
13.8	-5.31E-04	-3.56
13.9	-5.31E-04	-0.06
14	-5.31E-04	5.19
14.1	-5.31E-04	-4.77
14.2	-5.31E-04	0.02
14.3	-5.31E-04	4.71
14.4	-5.31E-04	-4.01
14.5	-5.31E-04	-0.13
14.6	-5.31E-04	5.15
14.7	0	-4.54
14.8	-5.31E-04	-0.87
14.9	-5.31E-04	3.95
15	-5.31E-04	-3.98
15.1	-5.31E-04	-0.17
15.2	-5.31E-04	4.74
15.3	-5.31E-04	-4.86
15.4	-5.31E-04	-0.8
15.5	-5.31E-04	4.4
15.6	0	-4.4
15.7	-5.31E-04	-0.18
15.8	0	6.58

15.9	0	-5.63
16	-5.31E-04	0.04
16.1	-5.31E-04	6.98
16.2	-5.31E-04	-5.42
16.3	-5.31E-04	1.17
16.4	0	7.57
16.5	0	-3.13
16.6	0	-1.03
16.7	-5.31E-04	5.99
16.8	0	-3.07
16.9	-5.31E-04	-0.52
17	-5.31E-04	3.85
17.1	0	0.79
17.2	-5.31E-04	-3.41
17.3	-5.31E-04	-0.66
17.4	-5.31E-04	5.82
17.5	-5.31E-04	-5.44
17.6	0	-0.28
17.7	0	7.25
17.8	0	-6.09
17.9	-5.31E-04	-1.86
18	0	5.28
18.1	-5.31E-04	-5.29
18.2	-5.31E-04	0.41
18.3	-5.31E-04	2.36
18.4	0	-4.82
18.5	-5.31E-04	0.32
18.6	-5.31E-04	3.4
18.7	-5.31E-04	-5.49
18.8	0	-1.4
18.9	0	4.17
19	-5.31E-04	-4.66
19.1	-5.31E-04	-2.03
19.2	-5.31E-04	3.77
19.3	0	-4.04
19.4	-5.31E-04	0.58
19.5	-5.31E-04	2.12
19.6	0	-3.75
19.7	-5.31E-04	-1.45
19.8	-5.31E-04	5.49
19.9	-5.31E-04	-3.49
20	0	-1.27

20.1	-5.31E-04	4.65
20.2	-5.31E-04	-0.63
20.3	-5.31E-04	-2.13
20.4	-5.31E-04	3.66
20.5	-5.31E-04	-2.23
20.6	-5.31E-04	-0.49
20.7	0	4.25
20.8	0	-0.25
20.9	0	-2.76
21	-5.31E-04	1.09
21.1	-5.31E-04	1.21

Appendix B: Voltage produced by 0.08-g PZT transducer recorded by SPARK Voltage Sensor

Time s	Current A	Voltage V
0.0	-5.31E-04	-0.51
0.1	-5.31E-04	-0.3
0.2	-5.31E-04	-0.53
0.3	-5.31E-04	-2.95
0.4	-5.31E-04	0.16
0.5	-5.31E-04	-2.61
0.6	-5.31E-04	0.49
0.7	-5.31E-04	-2.65
0.8	-5.31E-04	0.49
0.9	-5.31E-04	-2.82
1.0	-5.31E-04	0.57
1.1	-5.31E-04	-3.4
1.2	-5.31E-04	0.34
1.3	-5.31E-04	0.5
1.4	-5.31E-04	0.28
1.5	0	-1.05
1.6	-5.31E-04	0.38
1.7	-5.31E-04	-0.56
1.8	-5.31E-04	0.49
1.9	-5.31E-04	-0.64
2.0	-5.31E-04	0.46
2.1	-5.31E-04	-0.2
2.2	-5.31E-04	0.15
2.3	-5.31E-04	0.16
2.4	-5.31E-04	0
2.5	0	0.17
2.6	-5.31E-04	0.06
2.7	-5.31E-04	0.37
2.8	-5.31E-04	0.37
2.9	-5.31E-04	0.59
3.0	-5.31E-04	0.38
3.1	-5.31E-04	0.51
3.2	-5.31E-04	0.3
3.3	-5.31E-04	0.49
3.4	-5.31E-04	0.3
3.5	-5.31E-04	0.36
3.6	-5.31E-04	0.48

3.7	-5.31E-04	0.58
3.8	-5.31E-04	0.05
3.9	-5.31E-04	0.34
4.0	-5.31E-04	0.39
4.1	-5.31E-04	0.55
4.2	-5.31E-04	0.31
4.3	-5.31E-04	0.56
4.4	-5.31E-04	0.56
4.5	-5.31E-04	0.57
4.6	0	0.24
4.7	-5.31E-04	0.35
4.8	-5.31E-04	0.26
4.9	-5.31E-04	0.42
5.0	-5.31E-04	0.32
5.1	-5.31E-04	0.39
5.2	-5.31E-04	0.33
5.3	-5.31E-04	0.34
5.4	-5.31E-04	0.42
5.5	-5.31E-04	0.58
5.6	-5.31E-04	0.61
5.7	-5.31E-04	0.63
5.8	-5.31E-04	0.68
5.9	-5.31E-04	0.6
6.0	-5.31E-04	0.47
6.1	-5.31E-04	0.5
6.2	0	0.02
6.3	0	0.12
6.4	-5.31E-04	0.43
6.5	-5.31E-04	0.38
6.6	-5.31E-04	0.44
6.7	-5.31E-04	0.47
6.8	0	0.36
6.9	-5.31E-04	-0.83
7.0	0	0.42
7.1	0	-1.92
7.2	-5.31E-04	0.41
7.3	-5.31E-04	0.5
7.4	-5.31E-04	0.46
7.5	-5.31E-04	0.36
7.6	0	0.26
7.7	-5.31E-04	0.41
7.8	0	0.67

7.9	-5.31E-04	0.69
8.0	-5.31E-04	0.64
8.1	-5.31E-04	0.68
8.2	-5.31E-04	0.39
8.3	-5.31E-04	0.54
8.4	-5.31E-04	-0.45
8.5	-5.31E-04	0.38
8.6	-5.31E-04	-0.65
8.7	-5.31E-04	0.4
8.8	-5.31E-04	-0.61
8.9	-5.31E-04	0.28
9.0	-5.31E-04	-2.07
9.1	-5.31E-04	0.45
9.2	-5.31E-04	-1.41
9.3	-5.31E-04	0.49
9.4	-5.31E-04	-2.1
9.5	-5.31E-04	0.47
9.6	0	-0.92
9.7	-5.31E-04	0.49
9.8	-5.31E-04	-0.64
9.9	-5.31E-04	0.26
10.0	-5.31E-04	-0.33
10.1	-5.31E-04	0.32
10.2	-5.31E-04	0.38
10.3	0	0.58
10.4	0	0.5
10.5	-5.31E-04	0.65
10.6	-5.31E-04	0.61
10.7	0	0.52
10.8	-5.31E-04	0.54
10.9	-5.31E-04	0.5
11.0	-5.31E-04	0.48
11.1	0	0.4
11.2	-5.31E-04	0.49
11.3	-5.31E-04	0.3
11.4	-5.31E-04	0.4
11.5	-5.31E-04	0.34
11.6	-5.31E-04	0.47
11.7	-5.31E-04	0.49
11.8	-5.31E-04	0.5
11.9	-5.31E-04	0.48
12.0	-5.31E-04	0.47

12.1	-5.31E-04	0.16
12.2	-5.31E-04	0.33
12.3	-5.31E-04	0.45
12.4	-5.31E-04	0.42
12.5	-5.31E-04	0.39
12.6	-5.31E-04	0.37
12.7	-5.31E-04	0.51
12.8	-5.31E-04	0.48
12.9	-5.31E-04	0.21
13.0	-5.31E-04	0.38
13.1	-5.31E-04	0.28
13.2	-5.31E-04	0.66
13.3	-5.31E-04	0.47
13.4	-5.31E-04	0.59
13.5	-5.31E-04	0.39
13.6	-5.31E-04	0.58
13.7	-5.31E-04	-0.06
13.8	-5.31E-04	0.42
13.9	-5.31E-04	-1.36
14.0	-5.31E-04	0.16
14.1	-5.31E-04	-1.68
14.2	-5.31E-04	0.23
14.3	-5.31E-04	-1.63
14.4	0	0.32
14.5	-5.31E-04	-2.35
14.6	-5.31E-04	0.25
14.7	-5.31E-04	-1.69
14.8	-5.31E-04	0.38
14.9	-5.31E-04	-1.51
15.0	-5.31E-04	0.33
15.1	-5.31E-04	-1.96
15.2	-5.31E-04	0.3
15.3	-5.31E-04	-1.71
15.4	-5.31E-04	0.69
15.5	-5.31E-04	-1.42
15.6	-5.31E-04	0.73
15.7	-5.31E-04	0.58
15.8	-5.31E-04	0.66
15.9	-5.31E-04	0.56
16.0	0	0.6
16.1	-5.31E-04	-1.75
16.2	-5.31E-04	0.63

16.3	0	-1.79
16.4	-5.31E-04	0.56
16.5	-5.31E-04	0.6
16.6	-5.31E-04	0.64
16.7	-5.31E-04	0.53
16.8	-5.31E-04	0.39
16.9	-5.31E-04	0.3
17.0	-5.31E-04	0.84
17.1	-5.31E-04	0.82
17.2	-5.31E-04	0.9
17.3	-5.31E-04	0.8
17.4	-5.31E-04	0.82
17.5	-5.31E-04	0.6
17.6	-5.31E-04	0.45
17.7	-5.31E-04	0.52
17.8	-5.31E-04	-0.32
17.9	-5.31E-04	0.4
18.0	-5.31E-04	0.5
18.1	-5.31E-04	0.58
18.2	-5.31E-04	0.29
18.3	-5.31E-04	0.64
18.4	-5.31E-04	-0.54
18.5	-5.31E-04	0.6
18.6	-5.31E-04	-0.75
18.7	-5.31E-04	0.57
18.8	-5.31E-04	-0.82
18.9	-5.31E-04	0.54
19.0	-5.31E-04	-0.84
19.1	-5.31E-04	0.13
19.2	-5.31E-04	-0.98
19.3	-5.31E-04	0.42
19.4	0	-1.94
19.5	-5.31E-04	0.27
19.6	-5.31E-04	-1.37
19.7	0	0.18
19.8	-5.31E-04	0.65
19.9	-5.31E-04	0.32
20.0	-5.31E-04	0.29
20.1	0	0.48
20.2	-5.31E-04	-0.89
20.3	-5.31E-04	0.39
20.4	-5.31E-04	-1.07

20.5	-5.31E-04	0.65
20.6	-5.31E-04	0.53
20.7	-5.31E-04	0.72
20.8	-5.31E-04	0.52
20.9	-5.31E-04	0.74