Design Optimization of Wind Belt using Piezoelectric Energy Harvester (PZT) for Low Power Lamp Post

Eliezer R. Gobres[1], Mikko S. Jandumon[2], Clien Luis G. Ong[3], Rio B. Perez[4],
Patrick G. Ramos[5], Engr. Edmon O. Fernandez[6]

Electronics Engineering Department
Technological University of the Philippines[1, 2,3,4,5]
Manila, Philippines
Email:agilampwindbelt@gmail.com[1,2,3,4,5]
eliezer_gobres@gmail.com[1]
namudnajokkim@gmail.com[2]
luisong123@gmail.com[3]
riob.perez@gmail.com[4]
patrickramos960418@gmail.com[5]
edfernandez26@gmail.com[6]

Abstract*— Wind Belt Energy Harvesters are one of the breakthroughs of wind energy harvesting invented by Shawn Frayne in 2004. Wind Belt Energy Harvesters usually generate energy through Electromagnetic Induction wherein coil and magnet moves relatively with each other. There are other ways of generating energy through continuous movements like Static Electricity and Piezoelectricity. With this in mind, the device has a potential to generate more energy when Piezoelectric Energy Harvester is used instead of coil and magnet according to evaluation. The study focused on the optimization of parameters of the Wind Belt Energy Harvesting Device for low power devices wherein each of the parameters of the Wind Belt Energy Harvesting Device was undergo through series of experiments. The device was incorporate in a low power lamp post that will illuminate sufficient area. A small scale of wind slightly about 3 m/s passes through a membrane which is the belt. The vibration is caused by a phenomenon called Aero – elastic Flutter where the belt is pushed into two contradicting forces. Then the piezoelectric transducer at the end of the belt generates through this vibrating motion. The voltage induced from the piezoelectric transducer, which is on AC form, passes through a bridge rectifier and filter and converts into DC form that is desired by low power devices like LEDs.

***Keywords*— Wind Belt Energy Harvester, wind energy, Electromagnetic Induction, Static Electricity, Piezoelectricity, aero elastic flutter, transducer**

I. Introduction

The primary sources of energy such as fossil fuel are currently at risk since most of it is not being utilized the way it must be. It can greatly affect third-world countries since it lacks the ability to produce enough energy to supply its own. These critical issues are being discussed and currently, innovators, engineers, scientists and anyone who's concern is working at hand with so called renewable energy.

The renewable energy is the energy that came from natural sources and it is one of the solutions to the dramatic increase of scarcity of the fossil fuels and nuclear power instability. It has been found out that there were wasted energies or unused power that can be regenerate. These unused powers are often find in forms of environmental sources, industrial machines, structures, etc. With this unused power, the process of energy harvesting is beneficial. It is the gathering of idle power and converting it to useable energy specifically electrical energy. This process has been proposed and applied using electromagnetic, solar, thermoelectric, piezoelectric, and capacitive schemes. In fact, the energy harvesting has the greatest potential as an alternative for the typical or conventional batteries because of its limitation and very short life span compared to the working life of the devices. Therefore, energy harvesting technologies are more beneficial as a self-power source of portable devices or wireless sensor network system.

The windmill, geothermal, watermill, and solar energy are one of the existing energy harvesting technologies nowadays. Definitely, solar energy is one of the most appealing sources for renewable energy and its technology has matured through the years of innovation. However, it faces major challenges such us: (1) implementation of solar technologies that requires "bulky electronics"; (2) efficiency drop due to light intensity (cloudy vs. sunny day) and; (3) considering the significant drop of solar power inside the building. There is another most attractive source next to solar energy namely, kinetic energy. It embodies mechanical vibrations, air flow and human power and it can be converted to electrical energy with the use of piezoelectricity, electromagnetics, or electrostatics mechanism. Among these three, the piezoelectric generates the highest energy density followed by electromagnetic and electrostatic. [2]

The Piezoelectric material has a very simple structure that can convert mechanical vibration into electrical energy. It is a property of certain crystalline materials such as tourmaline, barium titanate, Rochelle salt and quartz that emerge electricity when pressure is applied and it also portrays the pressure electricity. [1] There are various kinds of piezoelectric materials like piezoelectric ceramic (PZT) and piezoelectric polymer (PVDF). Between the two, piezoelectric polymer materials like Polyvinylidene fluoride (PVDF) can generate higher voltage/power than ceramic based piezoelectric materials [3] and it has been proven that it can produce energy from renewable sources such as rain drops and wind. However, the market availability of PZT is much wider than PVDF.

II. Related Works

This section presents the past studies done in the field of Wind Belt.

Gozon, et. al.[4] shows the optimization of the Wind belt Generator in the following parameters: type of magnet, location of magnet, type of belt, belt length, frame length, winding of coil, type of magnetic wire, diameter of coil, number of coil turns. With this parameter, they integrated an IC (LTC 3108) to rectify and boost the power produced by the device and analyze the results through curve fitting in MATLAB. The device produced a voltage of 5V and a current of 4.1 mA.

Besinio, et. al.[5] uses piezoelectric crystals through the wheels of mining trolley carts. With the potential of mechanical stress in the wheels, the piezoelectric crystal produces electricity that can be a power source to the lighting of mining trolleys. By implementing this project, the power consumption from power plants will be minimized especially in mining sites.

The study entitled "*Design of a Piezoelectric Stair as an Alternative Source of Energy*" [6] focuses on creating a piezoelectric generator through the stairs since the stairs has a potential of mechanical stress. In testing the prototype, the proponents divided the testing procedure into two parts: Morning before Sunset and Sunset. The result of the project is successful. With the use of an integrated circuit (LT3588-1), it helps manage the energy produced by the stairs. And the prototype produces approximately 19 volts and able to power up LED.

This project study entitled "*Low Power Wireless Monitoring System Dual Powered by Piezoelectric Transducers and Solar Cells*" [7] focuses on weather analysis with the use of alternative power sources. The study aims the weather monitoring systems to be cost – efficient and convenient to monitoring stations. The system is operated with 0.141 mA current produced by the Solar Cells and Piezoelectric Transducers and it is integrated by Zigbee and PIC18LF4620 Microcontroller to make the sources as an energy harvesting system.

Priya, et. al. [2] focused on comparison of piezoelectric materials to electrostatic and electromagnetic materials as mechanisms of energy harvesting. This study found out those piezoelectric materials have three times higher energy density (in mJ/cm3) than electrostatic and electromagnetic materials. This study also mentions different projects on energy harvesting with the use of piezoelectric materials. The piezoelectric transducer is applied in cantilever beams, shoe, and windmill that can provide 25mW or more depending on the force applied and type of the piezoelectric material. This study concludes that it can sustain the power needed by the low powered device only relying on piezoelectricity.

Dewan, et. al. [8] made a journal review entitled *Alternative Power Sources for Remote Sensors.* In this review, several renewable energy sources were discussed (e.g. Solar, Hydroelectric, Microbial Fuel cell, Seawater Battery, Thermoelectric, Piezoelectric, etc.) by individual assessment as substitute to the batteries that are commonly used for remote sensors. Power requirements of remote sensors are also reviewed in this journal that evaluates the potentials and challenges of renewable power sources. With this journal, piezoelectric materials are evaluated to its applications, type of sensor powered, and power that can produce. A piezoelectric transducer (PZT) that has 50mm in length can produce a power of 0.02 – 3.5 mW that can power sensors like accelerometer, radio transceiver, strain gauge, temperature, and humidity measurement that can apply to environmental monitoring. The journal concludes that renewable sources are essential as alternative sources of remote sensors than using batteries that is traditionally used and associated by risks and cost of operation. The main concern of this study is that each renewable source should be reliable on energy harvesting. But because of the environmental conditions, more than one renewable source is used to power remote sensors making it as hybrid energy harvesters.

III. Theoretical Background

This section details the theoretical knowledge used by the researchers in designing the optimized piezoelectric Windbelt. It provides background about piezoelectricity's characteristics and common use in micro-energy harvesting.

A. Piezoelectricity

With all the journals, studies, and published papers, Windbelt has established its own name in the field of energy harvesting. However, its path to be optimized never ends thus, the search for an alternative source of energy.

Figure 1 shows the comparison of the energy density for the three types of mechanical to electrical energy converters. It is 3-5 times higher than the other two. Therefore, many aspirant and innovators want to use piezoelectricity for energy harvesting.

The researchers of this paper proposed that instead of magnets and coil, it will apply theories behind piezoelectricity incorporated with the characteristics of Piezopolymer Polyvinylidene fluoride (PVDF). With this adaptation, it clearly suggests that the study is relatively new and experimental that series of further test and experimentation will be taken in accordance to the optimization of dimensions and designs are required to achieve more efficient output.

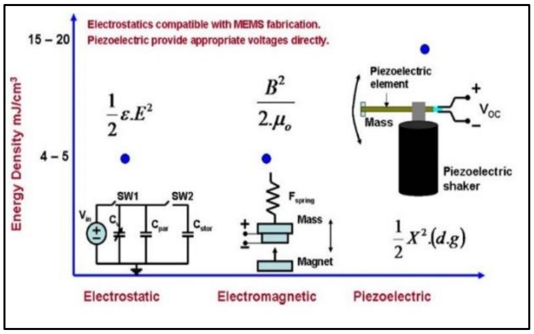


Fig. 1. Comparison of the energy density for the three types of mechanical to electrical energy converters [9]

IV. Methodology

This section describes the whole optimization process of the project. In Figure 2, the optimization process is divided into four parts: Frame, Piezoelectric Transducer, Belt and Load. For frame construction, the proponents created a dynamic frame that can change its own length for initial optimization testing. For piezoelectric transducer optimization, the PZT is tested with its different exposures and determine its induced voltage in each percentage of exposure. For belt optimization, several types of belt materials are tested into different lengths and measure its induced voltage. And for the load, this part depends on the optimized results of the first three parts. After finding the optimized results of the three parts, each part is being evaluated through curve – fitting to find out the critical parameters needed for formulating a mathematical model. The final prototype will be constructed with respect to the optimized parameters. And this prototype will be integrated to a charge control circuit that will boost the output for the Low Power Lamp Post.

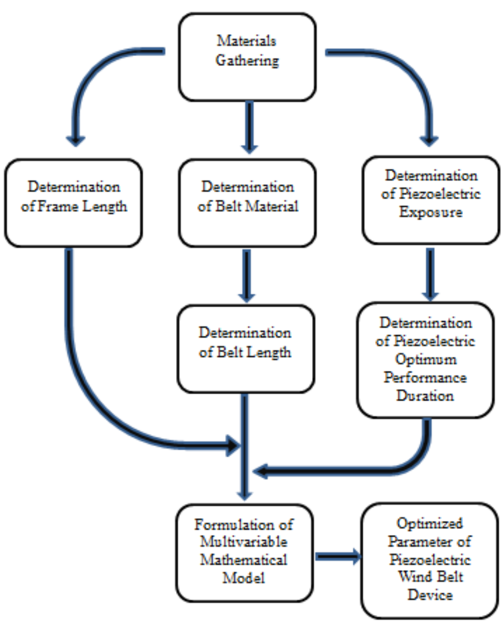


Fig. 2. Research Process Flow of the Study

4.1 Hardware Development

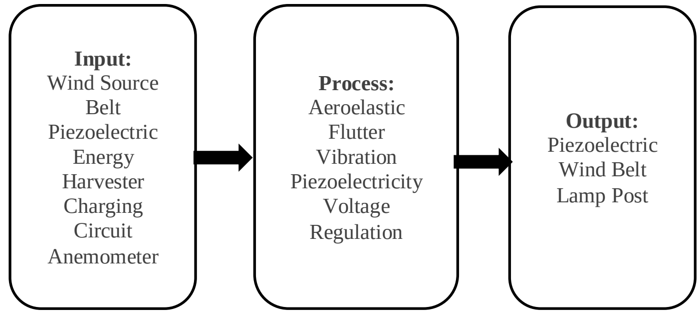


Fig. 3. Conceptual framework of the study

For the input block, these materials are available in the market. The anemometer is used for measuring the parameter in the location such as wind speed. The multimeter is used for measuring output voltage and current. Parameters such as wind speeds, number and position of PZT, number of belts will undergo through number of experiments that will determine the best result for this study. The experiments comprise stretching of belt, PZT connections, PZT quantity and position, different wind speed applications. These blocks are shown in Figure 3.

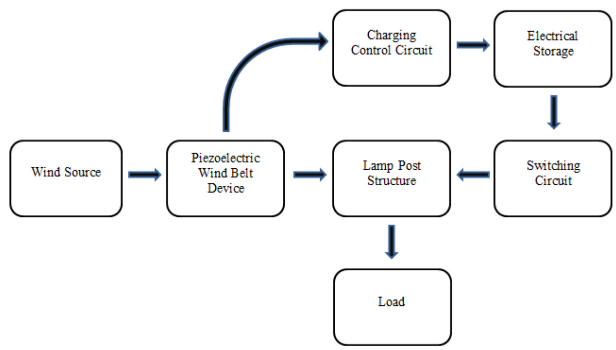


Fig. 4. Block Diagram of the Study

Figure 4 shows the process on how the wind source is converted to Electrical Energy through Mechanical Energy. The prototype embraces the Wind Harvesting Device itself, two circuits such as Power Monitoring and Light Sensing Circuits and an Electrical Storage for the energy produced. The process begins with the wind entering the Wind Energy Harvesting Device that will cause aero elastic flutter and vibration in the belt that makes the PZT undergo mechanical stress and produce electrical energy. The energy produced will proceed to the Power Monitoring Circuit with the implication of LTC 4071. The produced power will be stored in 3.7 V Lithium – Ion Battery. The load LED Strip will be controlled by Light Sensing Circuit to operate only at night.

4.2 Testing

This section describes the whole optimization process of the project. In Figure 4, the optimization process is divided into four parts: Frame, Piezoelectric Transducer, Belt and Load. For frame construction, the proponents created a dynamic frame that can change its own length for initial optimization testing. For piezoelectric transducer optimization, the PZT is tested with its different exposures and determine its induced voltage in each percentage of exposure. For belt optimization, several types of belt materials are tested into different lengths and measure its induced voltage. And for the load, this part depends on the optimized results of the first three parts. After finding the optimized results of the three parts, each part is being evaluated through curve – fitting to find out the critical parameters needed for formulating a mathematical model. The final prototype will be constructed with respect to the optimized parameters. And this prototype will be integrated to a charge control circuit that will boost the output for the Low Power Lamp Post.

4.3 Multivariable Mathematical Modelling

In this study, there are two parts of formulating this model; the curve fitting part and then the multiple regression method. These two methods are made using Microsoft Excel.

1) Curve Fitting. The first step is to create three columns for the data of belt length, frame length and voltage. After filling it up, highlight two columns at a time then insert a scatter plot. Figure 5 shows what scatter plot looks like. For the curve fitting part, create a Trend line in the layout tab of Excel and set the format in accordance to Figure 6. By doing this, the scatter plot will be updated with an equation as the result of curve fitting.

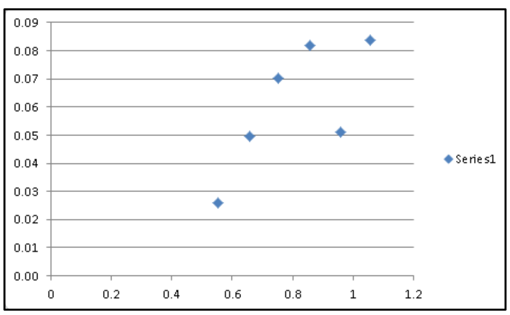


Fig. 5. Scatter plot

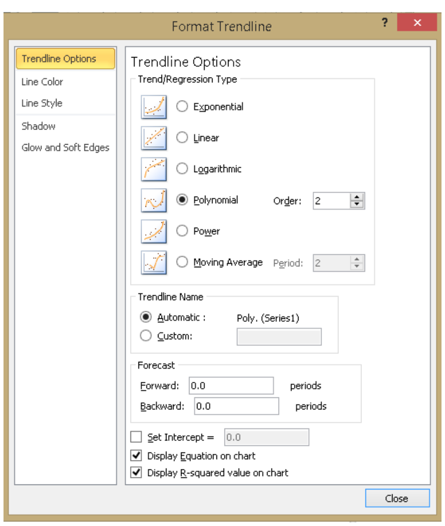


Fig. 6. Trend line set-up for Curve Fitting

2) Multivariate Regression Method. Primarily, the first two steps stated on the curve fitting must be followed. Then, add a second column containing cubes of your x-values. (Note: If you had a second order polynomial, you would cube the values.) Thirdly, click the “Data” tab and then click “Data Analysis.” Next is to select both columns (the x-values and their squares) when choosing x-values on the pop up window. After that, choose the appropriate column for the y-values followed by checking the labels box if you have column headers. Lastly, select the Confidence Level and Residuals boxes and select an output area. Press OK. Figure 7 displays the multivariate regression field after doing what stated above.

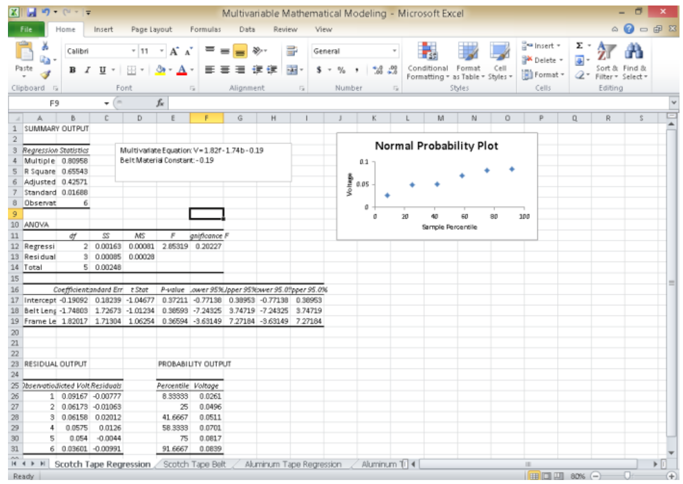


Fig. 7. Multivariate Regression Field

V. Results and Discussion

This section presents the results of the methodologies done in section IV of this paper. It includes the presentation of the result of hardware development and testing.

A. Results of Hardware Development

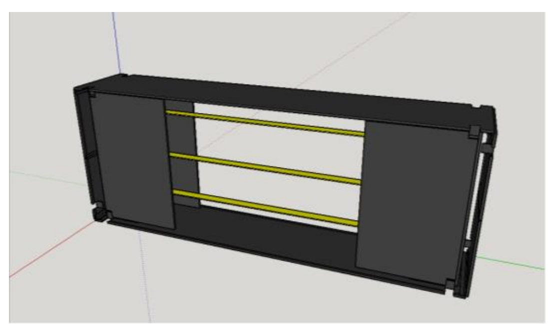


Fig. 8. Sketch-up model of the testing prototype

The proponents of this study constructed an initial testing prototype that will be used during the optimization process (Fig. 7) wherein the device is composed of three belts with two piezoelectric transducers on each belt. The proponents had selected three belts because as the testing is concerned, the belts can flutter efficiently when the device is stacked with maximum of three belts.

Fig. 9. Actual tri-face model of the device

Fig. 10. Actual Tri-face model of the device integrated in a post

In figure 6, the proponents construct a tri – face model of the device for deployment purposes to conserve the space and materials consumed during production. This model will be installed in a post as seen on figure 7.

B. *Results of Testing*

Refer to Table 1; these results were obtained during the optimization process with constant parameters of: 3.8 m /s wind speed and one (1) piece of piezoelectric transducer. As the electrical parameters are concerned, the output is measured after it passes a bridge rectifier circuit. So, these electrical parameters are clearly a DC output.

TABLE I. SUMMARY OF ELECTRICAL PARAMETERS DURING OPTIMIZATION PROCESS

Parameters	***Optimum Result***
Piezoelectric Position	75% Exposure
Piezoelectric Optimum Application Time	After 210 minutes of usage
Belt Material	Latex Rubber
Belt Length	0.61 m
Frame Length	0.73 m
Voltage	5.1 V
Current	0.132 mA
Power	0.673 mW

In figure 8, constant parameters (3.8 m / s wind speed, 75% piezoelectric exposure, latex rubber belt material and 0.73 m frame length) and independent parameter of belt length are considered in this experiment. At 0.61 m belt length, the device produced an approximate of 14 V AC voltage and a 0.653 mA current. These electrical parameters are measured directly from the piezoelectric transducer.

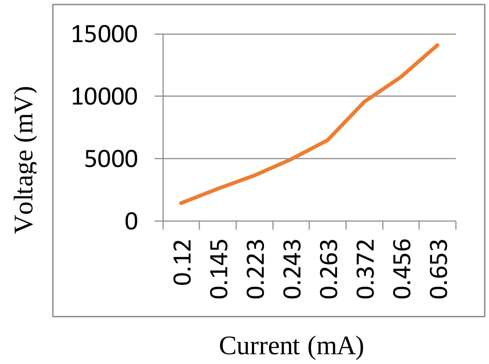


Fig. 11. Voltage vs. Current graph of the initial testing prototype

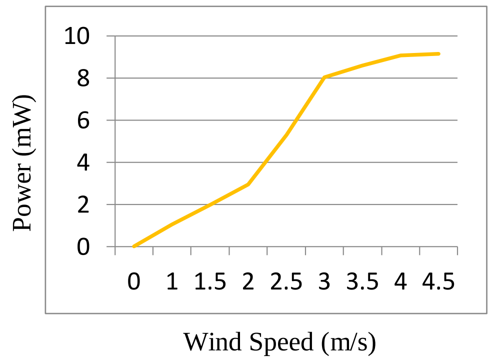


Fig. 12. Power curve of the device

In figure 9, constant parameters (75% piezoelectric exposure, latex rubber belt material, 0.73 m frame length and 0.61 m belt length) and independent parameter of wind speed are considered in the experiment. The power generated by the device reaches up to 9 mW when exposed to a 4.5 m / s wind speed.

C. *Multivariable Mathematical Modelling*

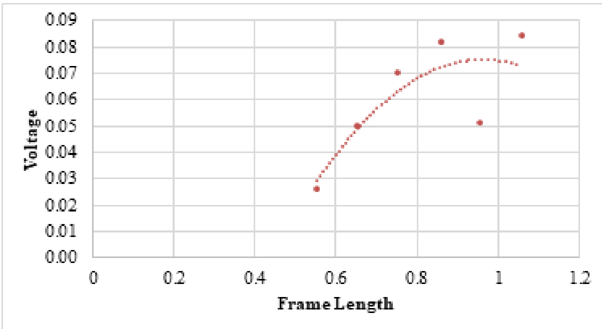
To successfully achieve the multivariable mathematical model, relationship of parameters to the voltage must be established. Table 2 shows the following results gathered from the tabulated data.

TABLE II. RELATIONSHIP OF PARAMETERS TO THE VOLTAGE

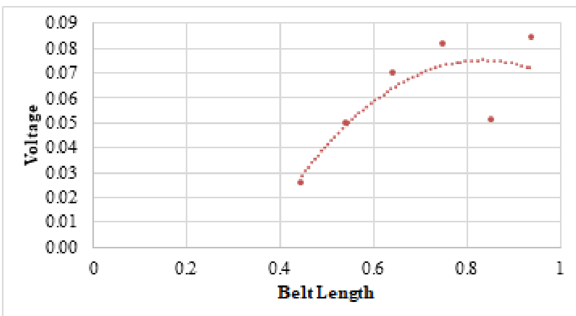
Parameters	***Relationship to the Voltage***
Wind Speed	Directly Proportional
Piezoelectric Exposure	Directly Proportional
Frame Length	Geometric Regression
Belt Length	Geometric Regression

After identifying the relationship of the parameters to the voltage, curve fitting has been conducted. Figures 13 – 18 are the Curve Fitting results of the critical parameters of each belt material which are the belt and frame length. As the graphs are concerned, the results behave in a geometric regression trend.

Meaning, these two different graphs per belt material have a potential to combine through multivariate regression method.

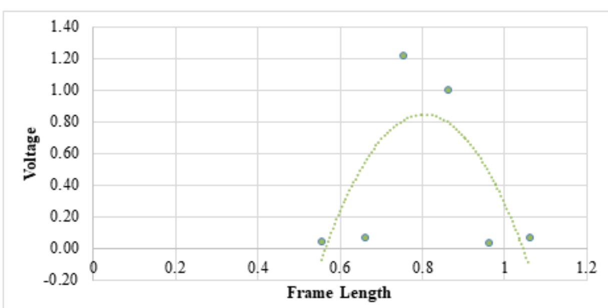


(a)



(b)

Fig. 13. Curve fitting of scotch tape: (a) frame length, and (b) belt length



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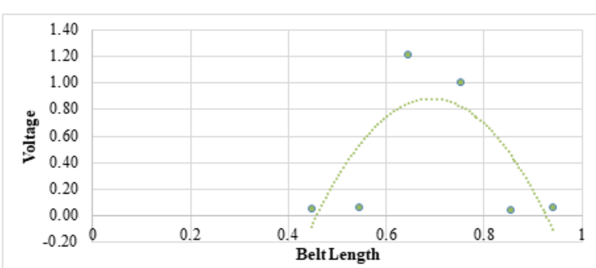
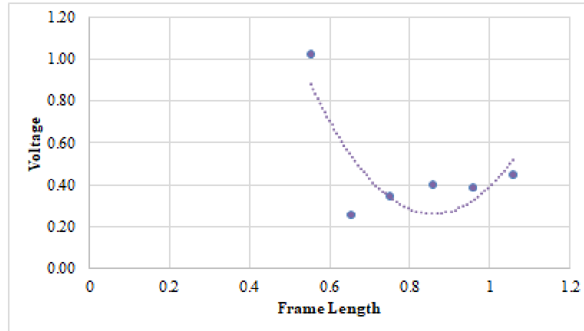


(b)

Fig. 14. Curve fitting of aluminum tape: (a) frame length, and (b) belt length



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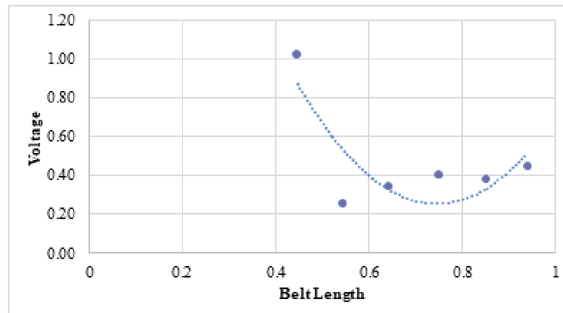
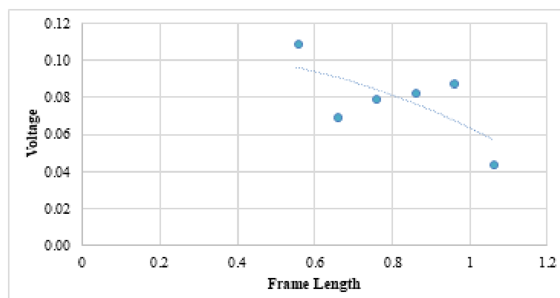
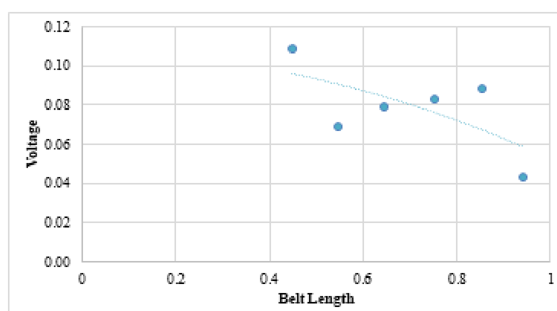


(b)

Fig. 15. Curve fitting of electrical tape: (a) frame length, and (b) belt length

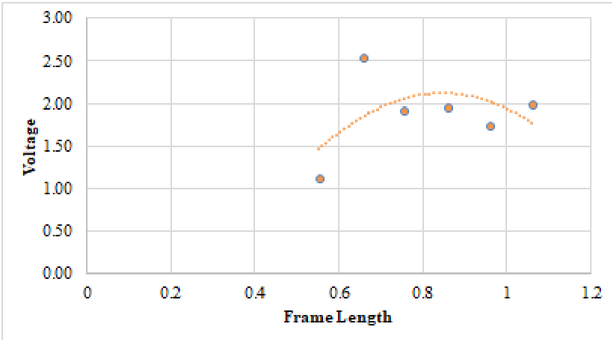


(a)

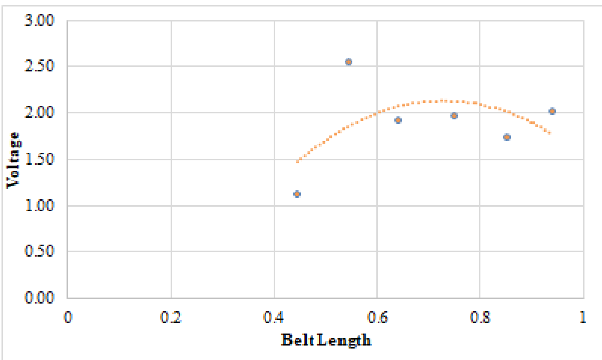


(b)

Fig. 16. Curve fitting of silk cloth: (a) frame length, and (b) belt length

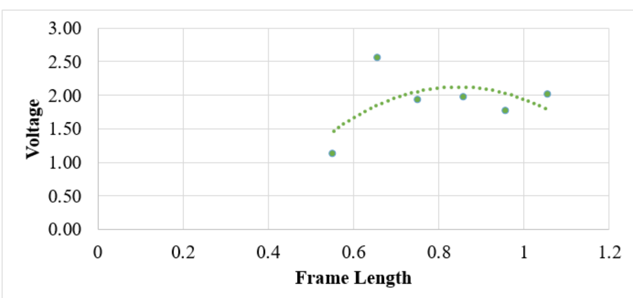


(a)



(b)

Fig. 17. Curve fitting of garter: (a) frame length, and (b) belt length



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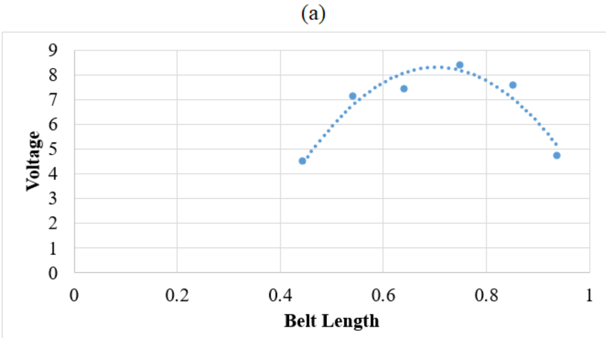

(b)

Fig. 18. Curve fitting of latex rubber: (a) frame length, and (b) belt length

Based on figures 19 – 24, the two graphs earlier in curve fitting part are simplified to one simple graph through multivariate regression.

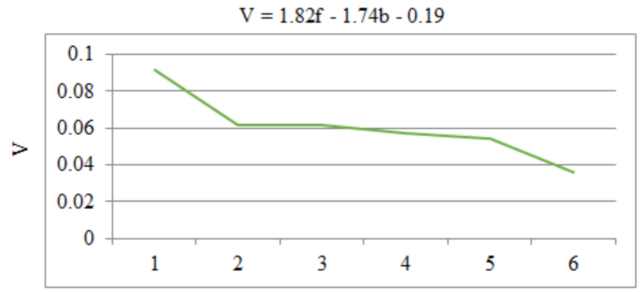

Fig. 19. Multiregression of Scotch Tape Belt Material

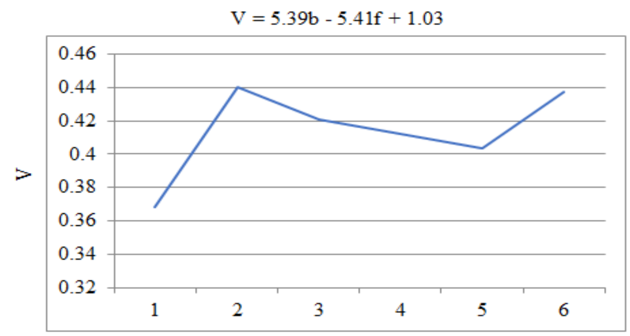

Fig. 20. Multiregression of Aluminum Tape Belt Material

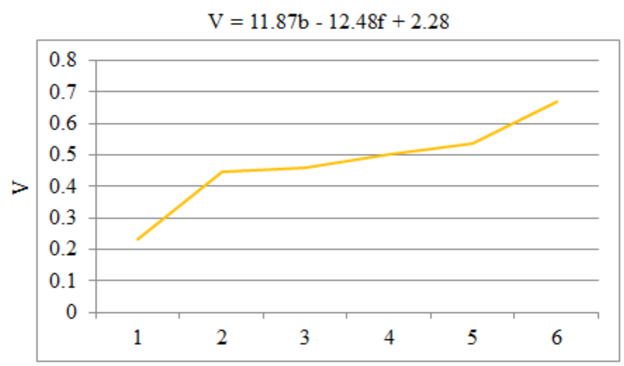

Fig. 21. Multiregression of Electrical Tape Belt Material

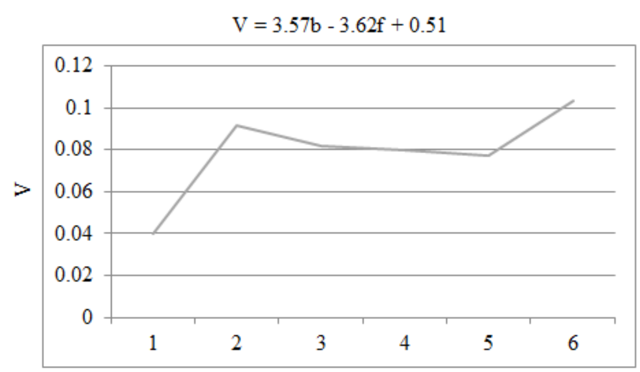

Fig. 22. Multiregression of Silk Cloth Belt Material

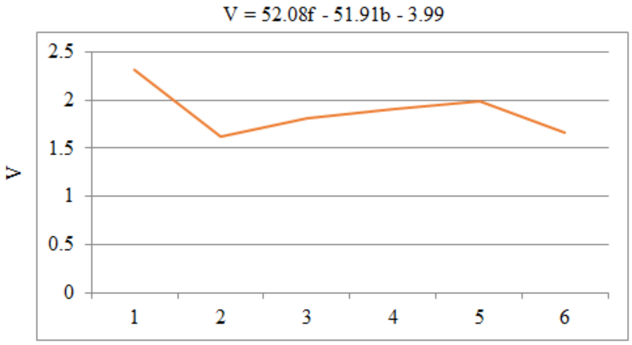

Fig. 23. Multiregression of Garter Belt Material

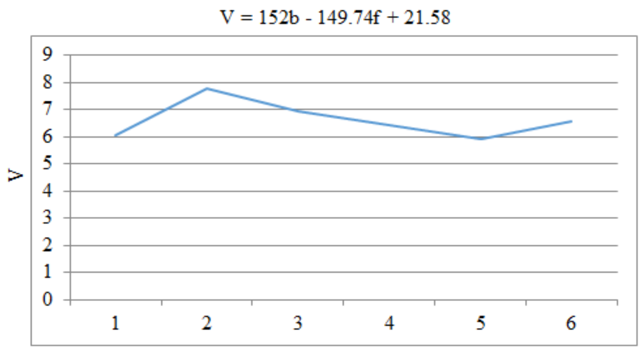

Fig. 24. Multiregression of Latex Rubber Belt Material

As the results are concerned, the mathematical model is simplified into a first degree equation with two variables. Taking the latex rubber as an example the equation is shown below:

Scotch Tape**:**	V = 1.82f - 1.74b - 0.19	(1)
Aluminum Tape:	V = 5.39b - 5.41f + 1.03	(2)
Electrical Tape:	V = 11.87b - 12.48f + 2.28	(3)
Silk Cloth:	V = 3.57b - 3.62f + 0.51	(4)
Garter:	V = 52.08f - 51.91b - 3.99	(5)
Latex Rubber:	V = 152b - 149.74f + 21.58	(6)

Where V is the induced voltage, b is the belt length, and f is the frame length. Other equations are mentioned in the next section.

Looking at Table 3, constants per belt material are formulated in the equation.

TABLE III. MATHEMATICAL MODEL CONSTANTS PER BELT MATERIAL

Belt Material	***Constants***
Scotch Tape	-0.19
Aluminum Tape	1.03
Electrical Tape	2.28
Silk Cloth	0.51
Garter	-3.99
Latex Rubber	21.58

As the value of the constant increases, its potential to produce voltage with a piezoelectric transducer increases. Therefore, the Latex Rubber became the optimized belt material with a 21.58 as its constant.

VI. Conclusions

The conclusions were observed based on the data results of the experiments of the whole study:

The piezoelectric wind belt energy harvesting device was developed by design optimization using available materials. The following are the optimum parameters of the piezoelectric wind belt:

- PZT Dimension: 70 x 53 x 0.03 mm
- PZT Exposure: 75% Exposure
- Frame Length: 730 mm
- Belt Material: Latex Rubber
- Belt Length: 610 mm
- Belt Width: 200 mm

Mathematical models are developed by determining the critical parameters of the device which are: frame and belt length with a geometric regression relationship with the induced voltage. A multivariate mathematical model formed form the two quadratic mathematical models formed during curve – fitting and merged through multivariate regression. The following are the results of the process:

- Scotch Tape**:** V = 1.82f - 1.74b - 0.19
- Aluminum Tape: V = 5.39b - 5.41f + 1.03
- Electrical Tape: V = 11.87b - 12.48f + 2.28
- Silk Cloth: V = 3.57b - 3.62f + 0.51
- Garter: V = 52.08f - 51.91b - 3.99
- Latex Rubber: V = 152b - 149.74f + 21.58

Where V is the induced voltage, f is the frame length, and b is for the belt length.

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