Modelling and Characterization Piezoelectric Transducer for Sound Wave Energy Harvesting

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ABSTRACT

Energy harvesting system is using ambient energy conversion in the environment. The environmental energy will be converted into usable electrical energy that can be used in controlling wireless electronic devices. The available mechanical vibration from the sound energy will then be converted to electrical energy by using a piezoelectric transducer. The size of the piezoelectric represents the surface area of the electrode on the piezoelectric model. A smaller size piezoelectric transducer is unable to produce a good vibration due to the smaller surface area. The bigger dimension of the piezoelectric model would be able to harvest more electrical energy output because the vibration from the bigger piezoelectric model which would able to produce more sound wave energy. The piezoelectric material Lead Zirconate Titanate (PZT-5H) vibration is focused on the resonance frequency at below 1 kHz with sound level decibel is between the range of 35-100 dB. This research is to concentrate on rectangular and trapezium-shaped cantilever. The trapezium shaped cantilever produces higher energy output due to its shape which has better in terms of stress and strain distribution. In addition, researchers have modelled and validated energy harvesters with different proof masses shapes. The improved piezoelectric vibrational energy harvester has a trapezoidal beam and an added triangular proof mass. The arrangement of the piezoelectric tested in parallel, series, combination series and parallel configuration to investigate the performance of the output power generated from the sound wave. The rectangular and trapezium shaped cantilever are resulted in a resonant frequency of 269.4 Hz and 269.88 Hz, respectively. The rectangular and trapezium shaped cantilever produced a maximum output voltage of 3.105 V and 3.635 V respectively. The piezoelectric output during the parallel array configuration, which is 5.636 V, 0.497 mA and 2.803 mW. The output power produced by parallel is 81 % higher than compare in series array configuration and 35.8 % higher than combination of series and parallel. Thus, the produced energy output 5 V would be able to apply at several low power supply applications such as mobile phones, power bank or wireless sensor networks (WSN).

Keywords:
Piezoelectric material; resonance frequency; energy harvester; mathematical modelling; transducer

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1. Introduction

In recent times, researchers concentrated on improving smaller volumes and sustainable power sources by boosting advanced technologies in electronic systems such as wireless sensors. In many fields of application such as agriculture, industry, medicine, and the military, wireless sensor networks (WSN) play a major role. WSN include sensors that monitor various parameters and the information gathered is sent to the control unit through a network. This is capable due to several nodes linked to various sensor kinds in the WSN. These WSN are power by batteries that have always been used for several years because of their greater volume and limited lifespan. The power consumption level for tiny electronic devices is typically mW or μW and the power unit must be tiny to accompany the host device. The piezoelectric energy harvester is a useful mechanism for the collection and conversion of ambient mechanical energy. The energy harvesting using piezoelectric materials offers better energy density and more flexibility to be incorporated into a system in comparison to electrostatic and electromagnetic techniques and therefore has been researched most extensively [1-2].

The general problem that held is the usage of non-renewable energy as the energy source to power devices. One of the major drawbacks of using non-renewable energy as the source for the piezoelectric is when once the sources are fully gone then the energy failed to be replaced [3]. Providing the non-renewable energy supply for the energy harvester is also costly due to its availability. There are several characteristics to be chosen before deciding the best energy source which are availability, energy yield, cost, environment, and renewable or is its sustainability. Taking all this into consideration, the suggested energy source is renewable energy sources such as the wind, water, sound, and sunlight [4-5]. Based on renewable energy sources, sound energy has been chosen. The sound energy is one the most effective solution and much easier to get and it would be 24 hours available in any condition [6-7]. However, as the renewable energy has been chosen as the energy harvester, there are limitation for the shape of the piezoelectric which limits the output performance. A piezoelectric model often comes in a circular shape model which is in size of 28 mm [8-9]. The size of the piezoelectric represents the surface area of the electrode on the piezoelectric model. A smaller size piezoelectric transducer is unable to produce a good vibration due to the smaller surface area [10-11].

Several previous researches that have been conducted to improve this research. One of the researches whereby to study different shape of cantilever effects for the energy output of the piezoelectric energy harvester. He *et al.,* [12], discovered that getting energy from the low frequency vibration environment is a highly efficient way to relieve energy source pressure. The researchers have analysed three types of beam structures which is rectangular, trapezoidal, and truncated triangular. Therefore, Abidin *et al.,* [13], presented the simulation research of the AC-DC converter circuit using a variety of array configurations for the piezoelectric sensor. The full wave bridge rectifier (FWBR), parallel SSHI (P-SSHI), and parallel voltage multiplier (PVM) are the AC-DC converter circuits that have been used in this converter circuit. Hashim *et al.,* [14] researched optimising the geometry and form of piezoelectric transducers to collect more energy. In a COMSOL Multiphysics simulator, many piezoelectric cantilever geometries with different sizes and structures to determine the optimum geometry for maximum achievable power. The parameters of the energy harvester can be varied to any value such as in COMSOL Multiphysics, the study can be run more than one at the same time. Shashank *et al.,* [15] presented that the research includes the electrical output of a test power harvester, the variation of the energy harvester parameters and the analysis of the impact of the factors on energy harvester performance and the comparison of findings. Based on the analysis of the previous researches for the type and method of piezoelectric energy harvester, there are many

different ways and approaches that seem to be very compromising. First, for the shape of the cantilever beams, a variant type of cantilever has been studied, which are the rectangular, triangular, truncated triangular, S-shaped and V-shaped beams [16-17].

Therefore, the output of the piezoelectric energy harvesters has been affected by the type of the material, the addition of the proof mass, the shape and size of the cantilever, and the resonant frequency. Besides, the cause of different parameters such as proof mass, the shape and size of the cantilever, resonant frequency and type of material has provided a major effect towards the output of the piezoelectric cantilever. Next, the review of equivalent circuit of the piezoelectric energy harvester has been studied. Thus, the proposed method is by analysing and comparison between two different shape which is rectangular and trapezium will be conducted in order to identify the shape that in capturing in terms of output voltage, current and power [17-18]. Next, the piezoelectric equivalent circuit analysis experimented with various array configurations such as series, parallel and combination of series and parallel. With piezoelectric connection in array configuration able to produce the highest output, such as 5 pieces of piezoelectric equivalent circuits, will be chosen as the best array configuration in sound energy harvesting system which is targeted to produced output voltage within range 0-5 V for low voltage supply applications.

2. Methodology

The process for modelling the sound wave energy harvester first starts by modelling the two different shapes of piezoelectric harvester using COMSOL Multiphysics software. This will be modelled using the standard parameter of piezoelectric. Thus, it will be simulated based on dimensions of Q220-A 4BR-1305YB piezoelectric transducer as references. The piezoelectric transducer has been modelled with two different shapes which is the rectangular and trapezium shaped in 3D modelling. The simulation has been done alternately and has been compared with other and obtain the piezoelectric transducer which able to produce targeted output 5 V. The simulations have been restricted to the parameters of input sound level within range 50 – 100 dB and also cantilever resonant frequency below 1 kHz. Figure 1 shows the block diagram of the piezoelectric sound wave energy harvester system.
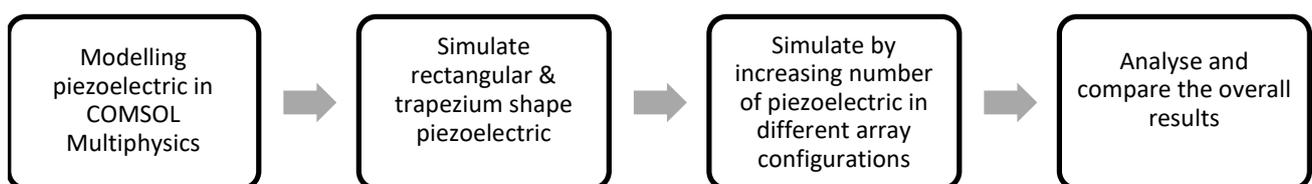
Fig. 1. Block diagram for the modelling the piezoelectric sound waves energy harvester

2.1 Development of Rectangular and Trapezium Shaped Piezoelectric Cantilever

Initially, to simulate the rectangular piezoelectric transducer, the configurations to 3D model should be determined. In the geometry section, the size of the piezoelectric is 31.8 mm in width, 12.7 mm in depth and the height of 0.51 mm. The main purpose of this simulation is to identify the types of piezoelectric shape which able to produce the best shape in terms of output voltage, current and power. Thus, Figure 2(a) illustrates the modelled rectangular shaped cantilever in COMSOL Multiphysics. Next for the modelling of the trapezium shape piezoelectric transducer is also based on the rectangular shaped cantilever. The dimensions of the previous rectangular shape in Figure 2(b) have been modified to the trapezium shape. The length and the height of the trapezium have kept

the same as the rectangular shape which is 31.8 mm and 0.51 mm. The trapezium shape first has modelled in the 2D work plane using polygon geometry. Then, the shape has been extruded to the height of 0.51 mm.
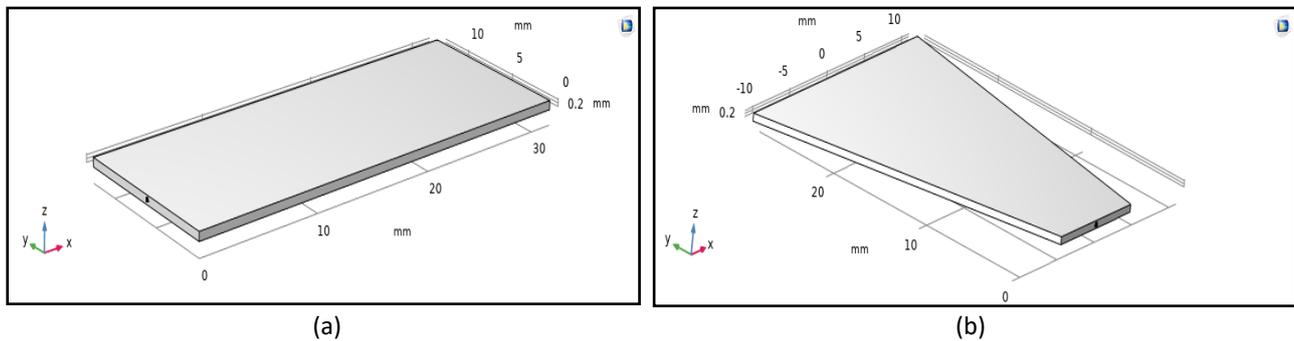
Fig. 2. Modelling shape of piezoelectric transducer

2.2 Expansion of Rectangular and Trapezium Shape to Investigate an Eigenfrequency Characteristics

The simulation for eigenfrequency analysis is once of requires parameters for characterization behaviour of piezoelectric transducer. Therefore, the piezoelectric material Lead Zirconate Titanate (PZT-5H) have been added to each model. This type of material has characteristic of high electric excitations which able to harvest more energy for the piezoelectric. Then, under the solid mechanics, the piezoelectric material, will be considered as modelled shape has been selected. In the design piezoelectric material, the fixed constraint has been preferred at the side as it will be clamped at one side. For the boundary load, the load type pressure has been used and it was chosen to be placed on top of the surface model. The optimum sound level has been used which is below 100 dB to get the maximum output energy harvested. In the free tetrahedral, the element size normal has been used and build all to the cantilever. In Figure 3(a) the meshing for the rectangular shape cantilever has been illustrated. Then, in Figure 3(b) trapezium shape meshing has been shown. The mesh refinement is important to obtain numerical analysis of the piezoelectric cantilever. The eigenfrequency study has been added to find the natural frequencies of the cantilever beam. The first value from the result of the eigenvalue is the resonant value of the cantilever. The solver configuration of the eigenfrequency has been set where the eigenvalue solver has been selected.
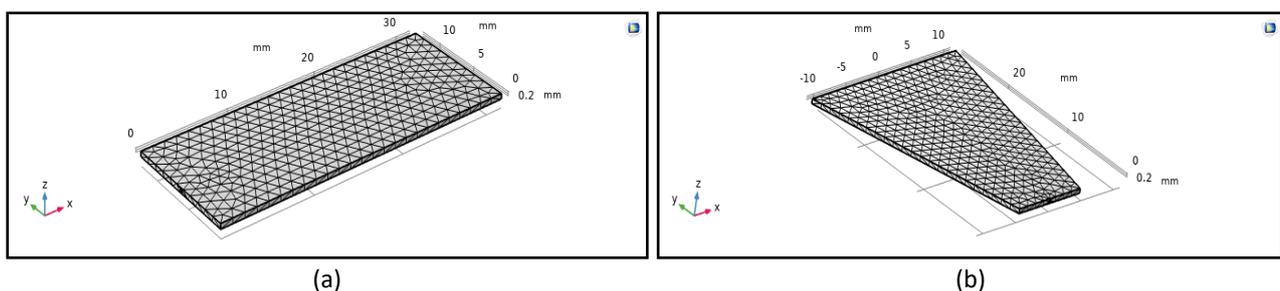
Fig. 3. Meshing for the rectangular and trapezium shaped cantilever

2.3 Development of Rectangular and Trapezium Shape into Examine an Open Circuit Voltage

The open circuit voltage has been modelled by applying the frequency domain study. This range has been used to get the optimum output voltage of the piezoelectric transducer. After computing the studies, to purpose get the derived values, the surface average has been placed on the fixed

constraint where the cantilever will be clamped. The electric potential has been selected to find the output voltage. In Figure 4(a), the surface side that has been chosen for the rectangular shape cantilever that needed to fixed constraint have been shown. In Figure 4(b), the surface side that has been fixed constraint for the trapezium shaped cantilever has been illustrated. This where the point added to the cantilevers will be selected to get the output voltage which has the maximum amount of stress that been converted to electrical potentials.

| (a) | (b) |
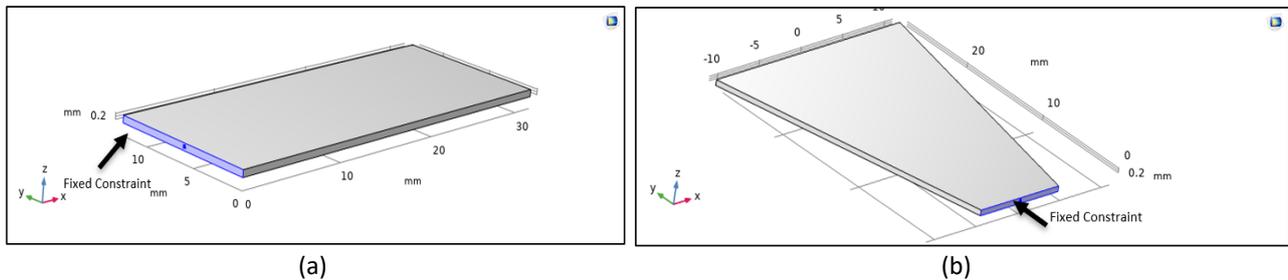
Fig. 4. Fixed constraints side of rectangular shape and trapezium shape

Moreover, the open circuit voltages have been compared with the theoretical values which been derived using the Eq. (1) to Eq. (4). The Eq. (1) is the method to find output voltage for both shape which is using the electrical charge, Q with the capacitance, C [17-18].

$$V = \frac{Q}{C} \tag{1}$$

From the Eq. (1), the electrical charge has been find using the Eq. (2) which is using the multiplication of charge density, D and the areas of the cantilever, A.

$$Q = D * A \tag{2}$$

From the Eq. (2), the charge density has been find using the Eq. (3) [17-18] which is using the piezoelectric constant, d_{33} and the mechanical stress, σ.

$$D = d_{33} * \sigma \tag{3}$$

Then, in Eq. (4) [17-18], capacitance of the cantilever has been find using the permittivity of free space, ε_0, relative permittivity of PZT-5H, ε_r, and the area of the piezoelectric cantilever, A, with the divide of thickness of the cantilever, d.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{4}$$

Stress is an important parameter to be propose because it effects the deformation of the cantilever beam which also effects the deformation of piezoelectric material. In Eq. (5) is the stress and strain derivations [19].

$$\sigma = \frac{M}{W} = \frac{6FL}{bh^2} \tag{5}$$

Besides, for the output current value, Ohm's Law term has been used whereby the output voltage, V is equalling the multiplication current, I and resistance, R [20]. In Eq. (6) is to get the current, the max voltage has been divided with the total resistance.

$$I = \frac{V}{R} \tag{6}$$

The natural frequency of a piezoelectric ceramic may be predicted theoretically based on the mechanical characteristics of the material. The resonance frequency of a simple cantilever beam subjected to an external force is calculated using Eq. (7) [21].

$$f_{(res)} = \frac{\omega}{2\pi} = \frac{0.32\sqrt{k}}{\sqrt{m}} \tag{7}$$

From Eq. (7), E is Young's Modulus and the cantilever spring constant k, have been found in Eq. (8). From Eq. (7), mass, m is $\rho\,h\,L\,w$, where ρ is the resistivity, h is the depth of the cantilever, L is the length of the cantilever, and w is the width of the cantilever [21].

$$k = \frac{3EI}{L^3} \tag{8}$$

The following Eq. (9) is to find I, which is the cantilever's moment of inertia, where b is the width of the bar and h is the depth of the bar [21].

$$I = \frac{bh^3}{12} \tag{9}$$

Furthermore, the second natural frequency, f_2 and third natural frequency, f_3 have been found using the Eq. (10) and Eq. (11) [21].

$$f_2 = 6.268\,f_{(res)} \tag{10}$$

$$f_3 = 17.456\,f_2 \tag{11}$$

Stress is an important parameter to be propose because it effects the deformation of the cantilever beam which also effects the deformation of piezoelectric material. In Eq. (12) is the stress and strain derivations [18].

$$\sigma = \frac{M}{W} = \frac{6FL}{bh^2} \tag{12}$$

For the design piezoelectric equivalent circuit in PSIM simulation, there are required certain values that needed to be considered in order to construct it. First the load resistance, R_L values have been found in Eq. (13) which using the value of resonant frequency, f, and also the capacitance, C of the resonant frequency based on characteristics piezoelectric Q220-A4BR-1305YB.

$$R_L = \frac{1}{2\pi f C} \tag{13}$$

2.4 Equivalent Circuit Modelling of Piezoelectric Energy Harvester

Based on the connection and the parameter values that have been derived, the connection of the circuit has been modelled by using PSIM software. The piezoelectric equivalent circuit has been simulated with the combination of a current source, capacitance, and resistance. The value of the current source has been set according to the desired output. The value of the current source has been tuned accordingly to avoid any sorts of voltages which are too high or low the application. Next, for the capacitance value, it was chosen based on the piezoelectric types characteristics Q220-A4BR-1305YB in piezo.com, each piezoelectric transducer consists of capacitance 52 nF. Besides, for the Rload value, it was derived using Eq. (13) which involves the values of resonant frequency and also the capacitance. Voltage probes has been added parallel in order to identify the voltage across the piezoelectric and also the resistive load. Lastly, an ammeter has been placed in series with the Rload to get the amount of current that passed through the circuit.

2.5 Piezoelectric Series and Parallel Array Configuration in 30 Piece Piezoelectric Transducers

For the series array configuration, the combination of the current source, capacitor and resistor which represent a single piezoelectric added in serial to identify the effect of the output voltage, current and power. In order to compare the maximum amount of the piezoelectric equivalent circuit can able to produce in series array configuration, total number of 30 piezoelectric transducers has been modelled in Figure 5 For the parallel array configuration, the combination of the current source, capacitor and resistor which represent a single piezoelectric has been added in series to identify the effect of the output voltage, current and power. Then, in Figure 6 a total of 30 piece piezoelectric transducers have been modelled to compare the maximum amount of the piezoelectric equivalent circuit can produce in a parallel array configuration.
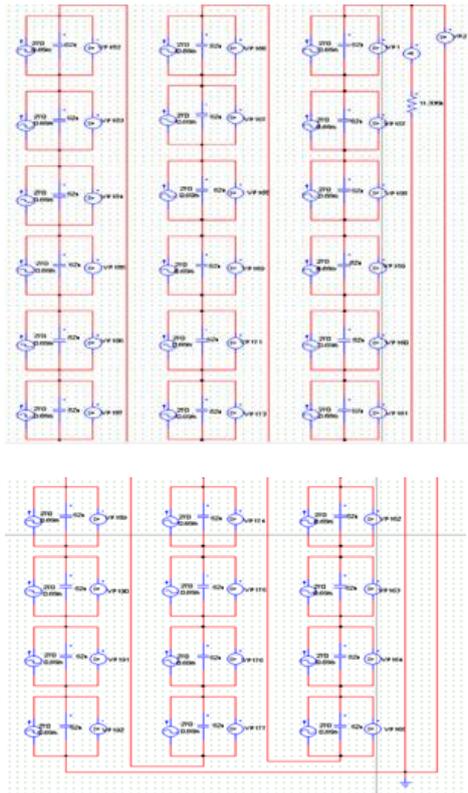
Fig. 5. Series array configuration of 30 piezoelectric circuits using PSIM software
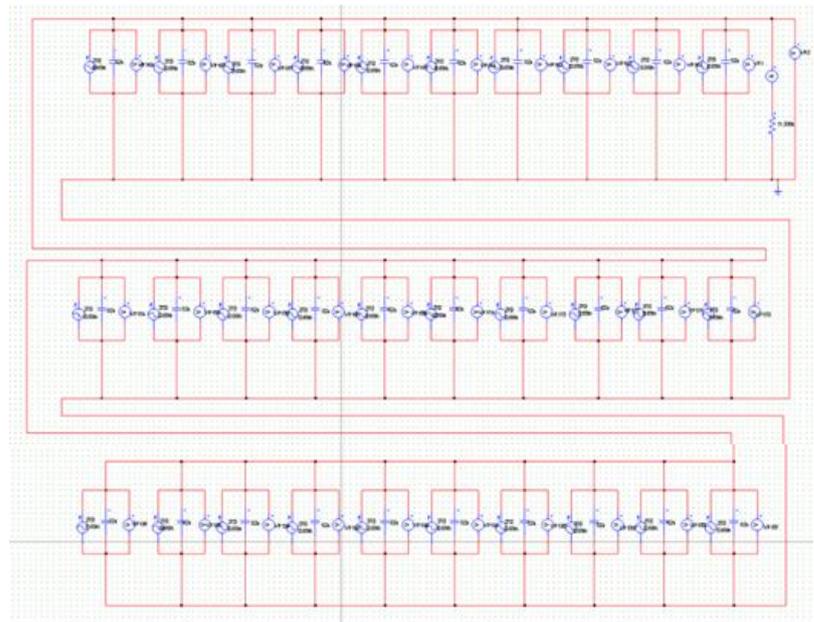
Fig. 6. Series array configuration of 30 piezoelectric circuits using PSIM software

2.6 Piezoelectric Series and Parallel Array Configuration in 5 Piece Piezoelectric Transducers

For the series or parallel array configuration, the combination of the current source, capacitor and resistor which represent a single piezoelectric added in serial to identify the effect of the output voltage, current and power. The connection of 5 piezoelectric transducers has been modelled in order to investigate out the effect of the output compared to 30 pieces of piezoelectric. Besides, total 5 number of piezoelectric equivalent circuits has been modelled to compared with different array configurations. Then, in order to compare the maximum amount of the piezoelectric equivalent circuit can able to produce in series array configuration, total number of 5 piezoelectric transducers has been presented in Figure 7 and Figure 8. For the combination series parallel array configuration, the combination of the current source, capacitor and resistor which represent a single piezoelectric, has been added in 2 series and 1 parallel (2S1P) to identify the effect of the output voltage, current and power. Thus, the combination of series-parallel circuit has been simulated using the PSIM software in Figure 9 and Figure 10. After the combination of 2S1P, the simulation of circuit for 3 series 2 parallel (3S2P) has been modelled. The purpose of this combination of series-parallel circuits to distinguish the difference between the efficiency of series and parallel circuits either in separately and combined together.
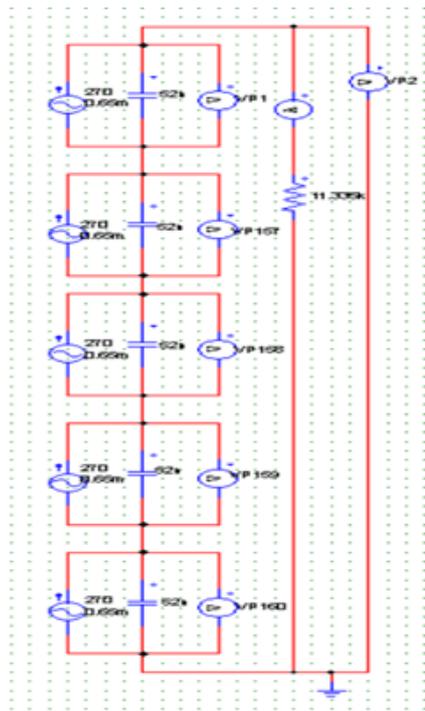
Fig. 7. Series array configuration of 5 piezoelectric equivalent circuit
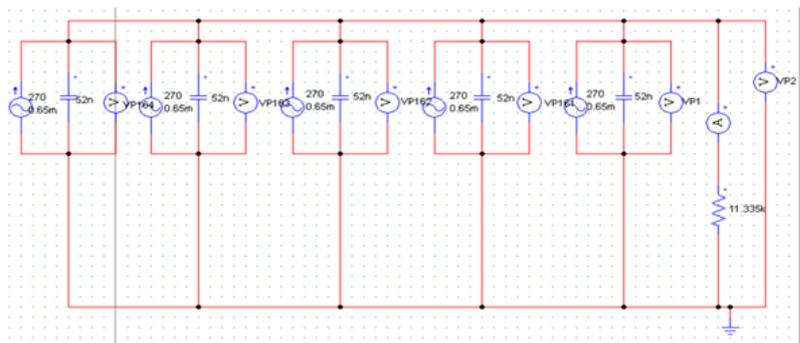
Fig. 8. Parallel array configuration of 5 piezoelectric equivalent circuit
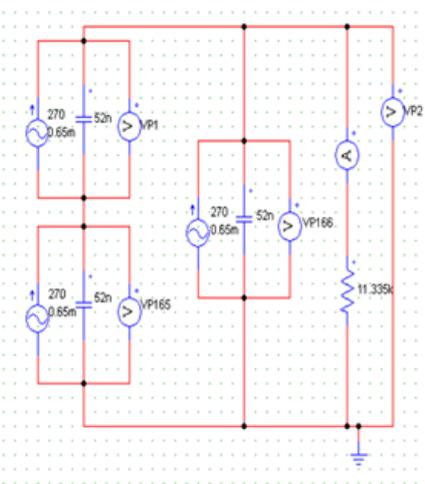
Fig. 9. 2S1P array configuration of piezoelectric equivalent circuit
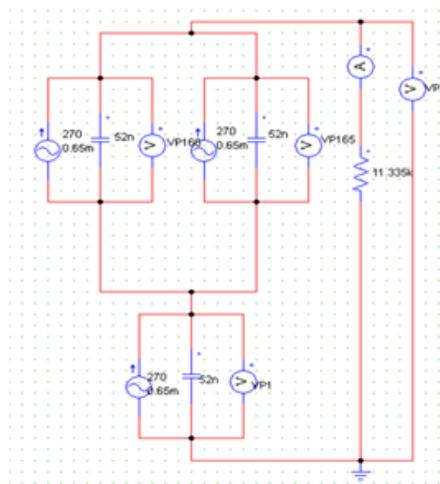
Fig. 10. 2P1S array configuration of piezoelectric equivalent circuit

3. Results

The data was obtained based on the parameters of the eigenfrequency, output voltage, current and power. This eigenfrequency has been used to reveal all the natural frequency and bending resonance frequencies of the piezoelectric. All the simulations have been conducted using the COMSOL Multiphysics software. Both rectangular and trapezium shape cantilever have been simulated. In the end of this study, the discussion of each model output, types of piezoelectric shape which obtains the best output in terms of voltage, current and power will be concluded.

3.1 Simulation Result for Eigenfrequency on Rectangular Shape Piezoelectric

In Figure 11 illustrated all the simulated resonant modes for rectangular shape. The first resonant mode simulated the eigenfrequency value of 269.4 Hz with a displacement of 8.76×10^{-11} mm. The highest eigenfrequency value achieved at 5212.1 Hz during the 6th mode at a displacement of 3.76×10^{-11} mm. Table 1 tabulated the results of natural frequencies and displacement magnitude from the initial position for rectangular shape. Based on all these resonant modes, the first resonant mode which based on the Table 1 that has the eigenfrequency value of 269.4 Hz with a displacement of 8.76×10^{-11} mm been chosen. The main reason for choosing this resonant mode is when during vibration is presented, the first mode is used to avoid charge cancellation in piezoelectric materials. When other mode is used, then there will be some charge cancellations that would have been occurred from the previous modes. Therefore, to prevent any wastages of charge that present, the first resonant mode has been chosen. The resonant frequency has been compared with the calculated value of resonant frequency using Eq. (7). The same agreement of comparison between calculated and simulation error are achieved which have around 14 % is expected due to the added material properties in the COMSOL software which could change the performance of the cantilever.

Eigenfrequency (Hz): 269.4	Eigenfrequency (Hz): 1261.7	Eigenfrequency (Hz): 1665.7
(a) 1st Bending mode	(b) 1st Torsional mode	(c) 2nd Bending mode
Eigenfrequency (Hz): 4077.8	Eigenfrequency (Hz): 4693.1	Eigenfrequency (Hz): 5212.1
(d) 2nd Torsional mode	(e) 3rd Bending mode	(f) 1st Lateral mode
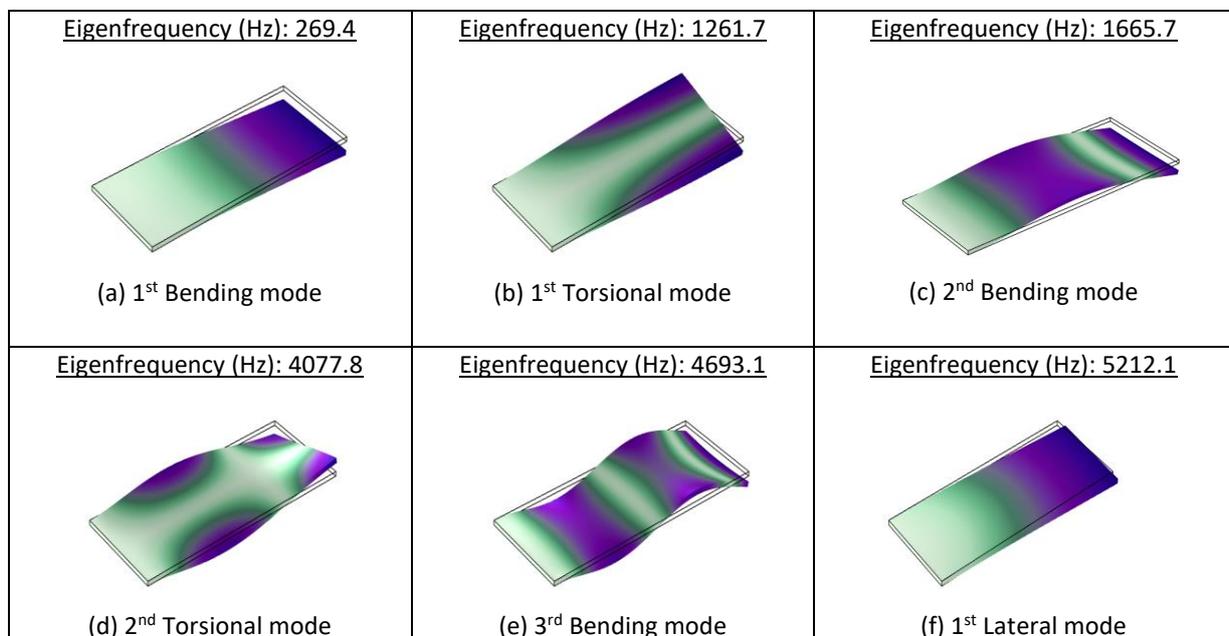
Fig. 11. Resonant modes with its eigenfrequencies for rectangular shape piezoelectric

Table 1
Natural frequencies of the rectangular shape piezoelectric

Eigenfrequency (Hz)	Displacement magnitude (mm)
269.4	8.76×10^{-11}
1261.7	2.25×10^{-11}
1665.7	1.81×10^{-11}
4077.8	6.79×10^{-12}
4693.1	6.86×10^{-12}
5212.1	3.76×10^{-11}

3.2 Simulation Result for Eigenfrequency on Rectangular Shape Piezoelectric

The eigenfrequency study resulted to 6 resonant modes for the trapezium shaped cantilever. The highest eigenfrequency value achieved at 4665.5 Hz during the 6th mode at a displacement of 8.43 x 10^{-12} mm. Based on Figure 12, the colour contour represents the surface displacement for the difference resonant modes. The darker blue contour indicates the displacement that occurred during resonant mode of the trapezium shape cantilever. In Figure 12, the first mode has been chosen for this trapezium shape cantilever. The main reason is during the first bending of the piezoelectric the resonant frequency has obtained the lowest compared all-natural frequencies. Thus, this first natural frequency provides the highest deflection which leads to producing the most electric energy.

Eigenfrequency (Hz): 269.88	Eigenfrequency (Hz): 808.87	Eigenfrequency (Hz): 1966.6
(a) 1st Bending mode	(b) 1st Torsional mode	(c) 2nd Bending mode
Eigenfrequency (Hz): 3565.1	Eigenfrequency (Hz): 4268.3	Eigenfrequency (Hz): 4665.5
(d) 2nd Torsional mode	(e) 1st Lateral mode	(f) 3rd Bending mode
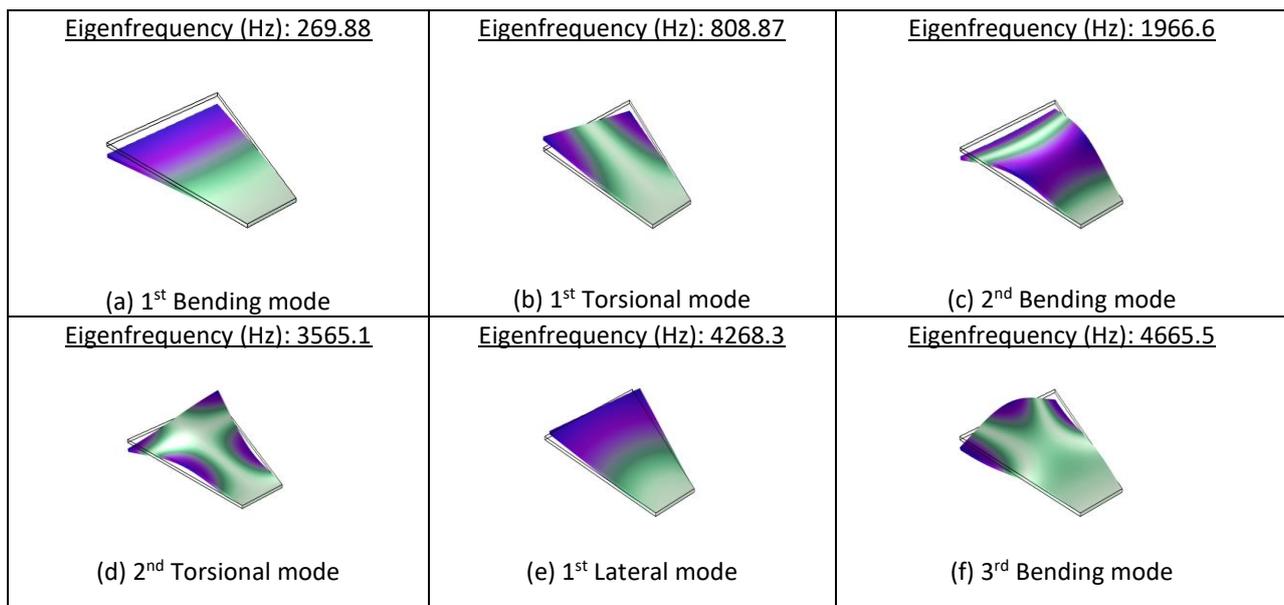
Fig. 12. Resonant modes with its eigenfrequencies for trapezium shape piezoelectric

Based on Table 2, as the eigenfrequency value for trapezium shape keep on increases as the resonant mode growths. The resonant frequency is 269.88 Hz with a displacement of 7.78 x10^{-11} mm. All the frequencies of the other modes were kept on rising as the resonant mode increases. If a different mode is chosen, certain charges that would have occurred in prior modes would be cancelled. Thus, when the piezoelectric cantilever beam is operated at its resonance frequency, the mechanical energy will be maximally converted to electrical energy.

Table 2
Natural frequencies of the trapezium shape piezoelectric

Eigenfrequency (Hz)	Displacement Magnitude (mm)
269.88	7.78 x 10^{-11}
808.87	2.85 x 10^{-11}
1966.6	1.39 x 10^{-11}
3565.1	1.39 x 10^{-11}
4268.3	5.87 x 10^{-11}
4665.5	8.43 x 10^{-12}

3.3 Stress Analysis for Rectangular and Trapezium Shaped Cantilever

For the stress analysis of the rectangular shape piezoelectric, the study for the frequency domain has been set at the range of 200 to 250 Hz. Figure 13 displayed the stress generation of the rectangular beam that occurred at the resonant frequency of 270 Hz. Based on Figure 13, the maximum stress achieved at 5.19×10^6 N/m^2 and the minimum stress occurred at 10.1×10^3 N/m^2. The maximum stress occurred at the fixed constraint of the beam; this is due to the cantilever that only can vibrate towards the fixed constraint side. For the trapezium shaped beam, the maximum stress achieved at 5.74×10^6 N/m^2 and the minimum stress occurred at 2.95×10^3 N/m^2. In Figure 14, expressed clearly visible with the help of the colour contour of von Mises stress, the place that has the maximum amount of stress have been presented.
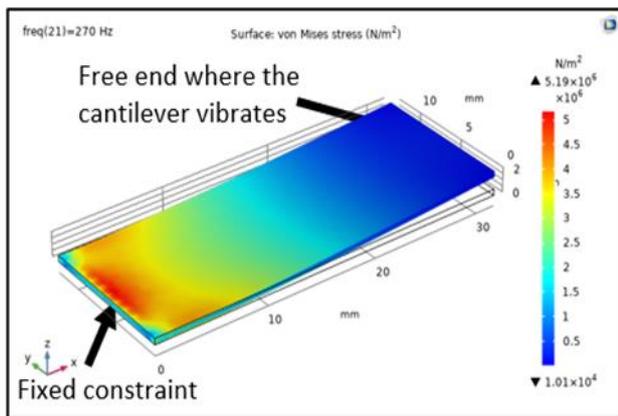
Fig. 13. von Mises stress for rectangular shape piezoelectric
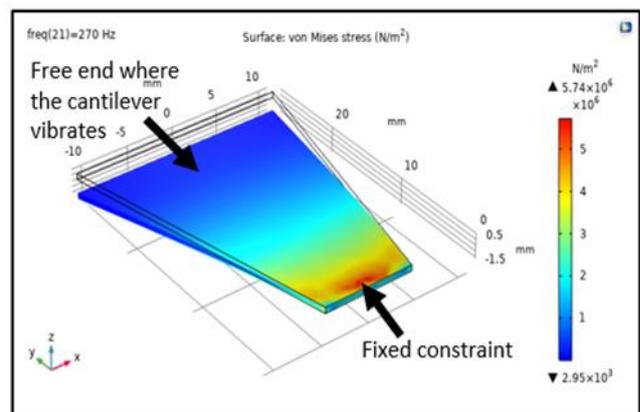
Fig. 14. von Mises stress for trapezium shape piezoelectric

In Figure 15(a), observed that all the stress values for the applied pressure from 0.1 Pa to 1 Pa has been tabulated. The minimal pressure results the lowest amount of stress and during the maximum amount of pressure of 1 Pa, total amount of 29563 N/m^2 stress been formed. The simulated values of the stress have been compared with the calculated values of stress whereby the total simulated and calculated values have the average error amount of 20%. The calculated values have been found using the Eq. (12). The present error could be due to the piezoelectric material that has been applied on the rectangular cantilever which would act as a load which compared to the direct calculation with the total force with the dimension of the cantilever. Next, the input pressure from 0.1 Pa to 1 Pa has been tabulated Figure 15(b), in order to get the overall stress output for the varied pressure loads. During the maximum pressure load, the highest stress has been recorded which are 18085.4 N/m^2. The simulated values have been compared with the calculated values in order to prove the simulation is correct. The error between the simulation and calculated values are averaging around 20%. As the previous rectangular cantilever, due to the piezoelectric materials that has been added on the cantilever, it would have been an extra load on the cantilever that would be a cause for the changes of the stress value. When compared to the rectangular shaped cantilever, the starting stress has been lowering during the minimum and also the maximum input load. However, during the surface von Mises stress, which is the maximum stress, the trapezium shape cantilever, able to produce the highest stress.

(a)   (b)
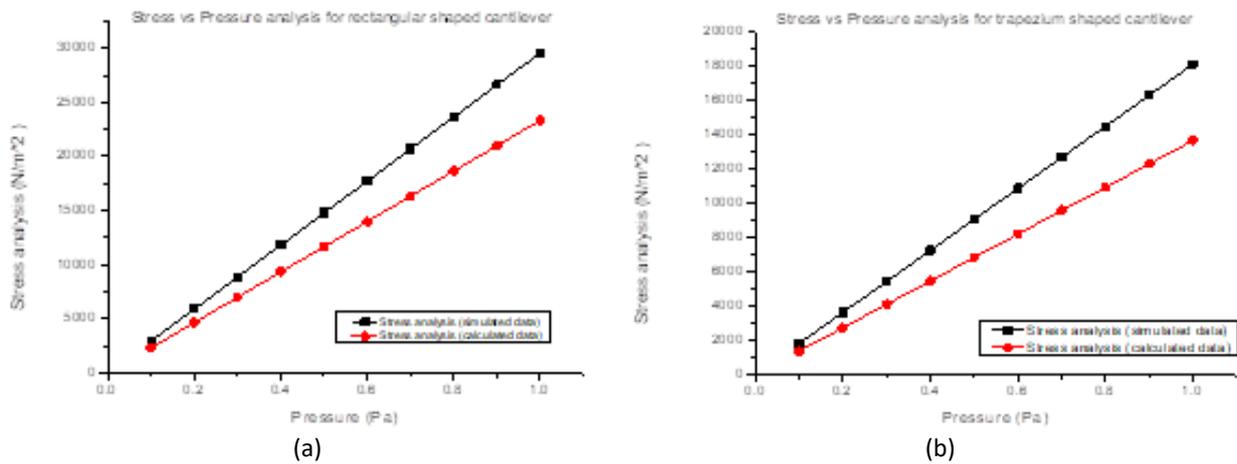
Fig. 15. Stress analysis with the applied pressure for rectangular and trapezium shaped cantilever

3.4 Open Circuit Voltage Result for Rectangular Shaped Cantilever

The open circuit voltage has been calculated for both shapes of the beam. Both shapes have been tested with the same resonance frequency. In Figure 16, the output voltage and input pressure has been illustrated. The output voltage becomes higher as the amount of input pressure increases. The maximum output voltage recorded at 3.1049 V. The optimum voltage has been chosen to be compared to the trapezium shaped output voltage. The simulated values have been compared with the theoretical values which has been computed from Eq. (11). The error for both simulated and also calculated values are average of around 4% whereby this proves that the simulation is correct and would be accepted. Figure 17 presents the output voltage at various frequencies from 200 Hz to 300 Hz that have been tested. During the resonance frequency, the output voltage peaked at 3.105 V. That is the optimum output voltage that can be achieved during the bending of the beam. At the resonant frequency, the voltage increased to the peak response, then when surpasses the resonance, the output voltage dropped and returned to the initial condition. As shown in the eigenfrequency analysis at the resonance frequency, the bending of the cantilever occurs and causes the output voltage to rise during the resonance frequency. From Figure 17, after passing the resonance frequency, the voltage started to return to the initial position.
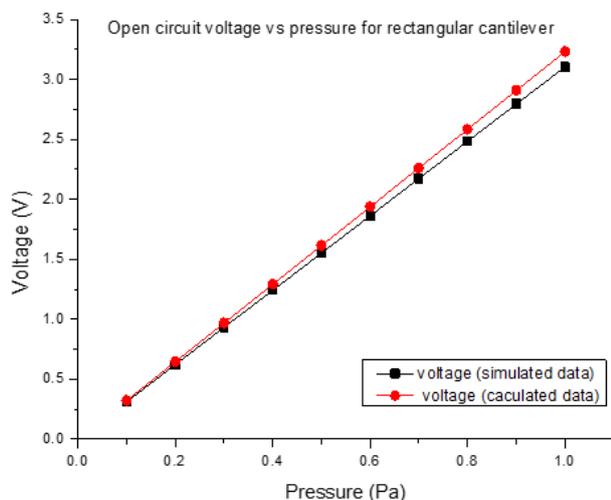
Fig. 16. Open circuit analysis on voltage and pressure for rectangular shaped cantilever
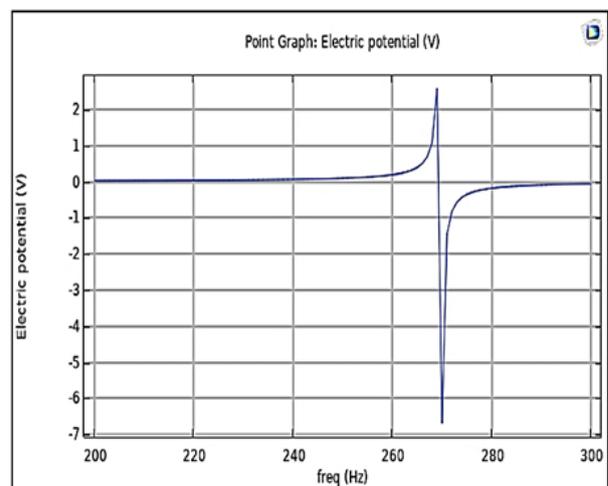
Fig. 17. Open circuit voltage output for rectangular cantilever

3.5 Open Circuit Voltage Result for Trapezium Shaped Cantilever

For the trapezium piezoelectric beam, it has been also tested with various pressure from 0.1 to 1 Pa. In Figure 18, the output voltage and input pressure has been illustrated with the output voltage peaked at 3.635 V. Thus, similar to the rectangular beam, as the input pressure increases, the generated output voltage increases. When compared to the rectangular shaped cantilever, the trapezium shaped cantilever able to produce 14.34 % higher output voltage during the minimum input pressure of 0.1 Pa. Besides, when compared with the maximum input pressure of 1 Pa, the trapezium shaped cantilever produces 14.50 % higher output voltage. The trapezium shaped cantilever simulation has been compared with the theoretical calculation of output voltage. The reason for comparing the difference between the simulation and theoretical result is due to the created dimension of the trapezium and since the trapezium shape able to produce highest peak stress so, this results higher simulated values. In a nutshell, when compared with the input pressure, the trapezium shaped cantilever able to produce higher output voltage compared to the rectangular shaped cantilever.

From Figure 19, at the frequency of 200 Hz to 240 Hz, there's no output voltage detected. After 240 Hz, the output voltage started to increase slowly and during the resonance frequency of 270 Hz, the output voltage peaked at 3.635 V. This is when the bending of the cantilever has reached the maximum and has the maximum amount of stress is achieved. After reaching the resonance frequency, the cantilever started to move back down and return to its original position. Based on the analysis from both shapes of piezoelectric, the amount of pressure exerted have directly affected the generation of the output voltage. This led to the direct piezoelectric effect where the mechanical stress that has been applied, produces electrical charge and voltage. When compared to both shapes, the trapezium shape generates higher both minimum and maximum values in terms of stress and voltage respectively. The reason is mainly due to the shape of the trapezium which has better stress and strain distributions that affordable the shape to produce higher output. Thus, the trapezium shape cantilever is better compared to the rectangular shaped cantilever.
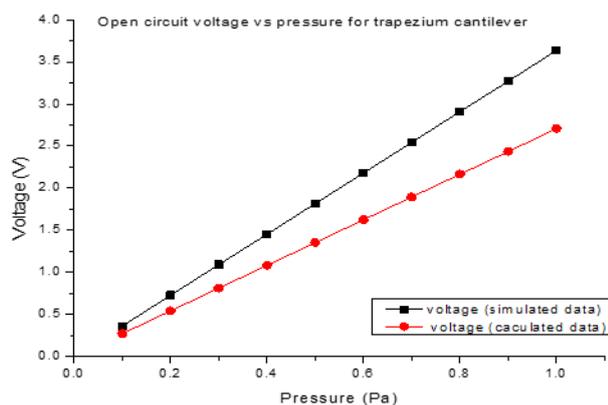
Fig. 18. Open circuit analysis on voltage and pressure for trapezium shaped cantilever
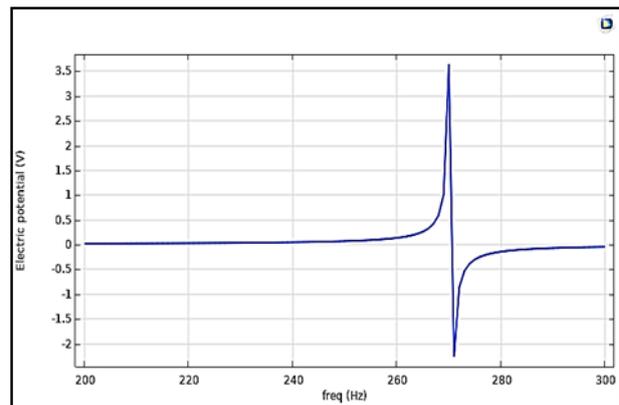
Fig. 19. Open circuit voltage output for trapezium cantilever

3.6 Analysis for the Rectangular Shaped Piezoelectric Cantilever in Closed Circuit Condition

In closed circuit situation, both rectangular and trapezium shaped cantilevers have been tested with a R_load of 12 kΩ. From Figure 20, the maximum voltage, current and power during the closed loop application for rectangular cantilever has reached up to 0.0304 V, 0.9627 nA and 1.4653 nW at the resonance frequency of 270 Hz. Besides, in Figure 21, the maximum voltage, current and power

during the closed loop application for the trapezium cantilever has reached up to 0. 0466 V, 0.2602 uA and 6.0187 nW. As the output voltage has kept been increasing until reaches its maximum of 0. 0466 V The output voltage becomes constant and the increase of the R_load does not give any effect to the output. This is due to when any operating point enters the saturation region of the system thus, the slope becomes horizontal and the voltage becomes zero.
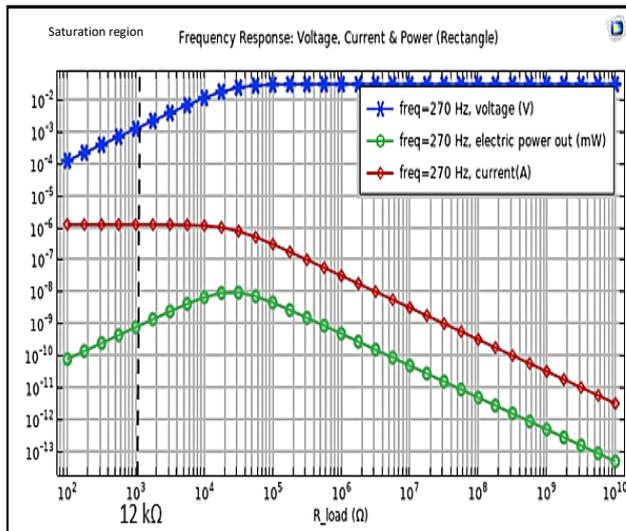
Fig. 20. Output voltage, current and power for rectangular cantilever
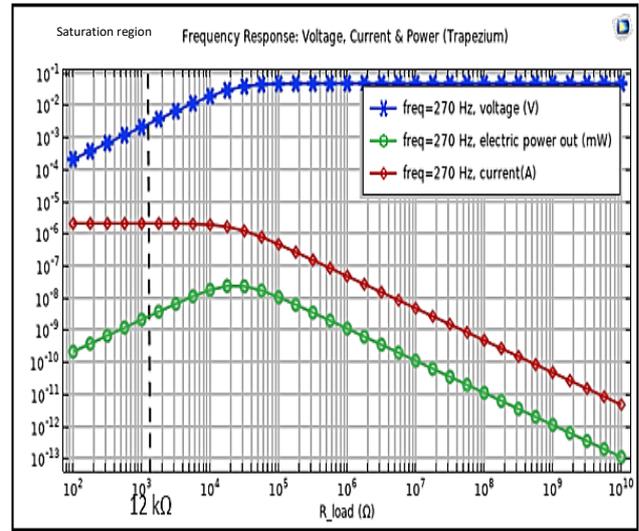
Fig. 21. Output voltage, current and power for trapezium cantilever

3.7 Series and Parallel Array Configuration of Piezoelectric Equivalent Circuit with Total 30 Number of Piezoelectric

The maximum number of piezoelectric required for array configurations are total 30 equivalent piezoelectric circuits. In Figure 22(a), the comparison data of the outputs from the piezoelectric equivalent circuits has been presented. The maximum output voltage, current and power has reached the maximum of 7.3637 V, 0.6497 mA and 4.7842 mW. However, when the piezoelectric equivalent circuit started to enter 5 total equivalent circuits, the output from the piezoelectric equivalent circuit started to reduce the amount of increase. This is where the piezoelectric equivalent circuit started to enter the saturation stage whereby any more increase of number of piezoelectric will not affect the output. Next, for the parallel array configuration, the output voltages are being able to observe a drastic increase compared to the series configuration. From the output in Figure 22(b), the maximum output voltage, current and power has reached 14.0031 V, 1.2354 mA and 17.2994 mW. As the number of piezoelectric equivalent circuit increases, the output voltages kept on become higher. However, when 20 piezoelectric equivalent circuits were added, the increment of output voltages began to decrease and at 30 piezoelectric equivalent circuits, output voltage became constant. Moreover, the output current increase utterly as the number of piezoelectric equivalent circuit increases.

(a)   (b)
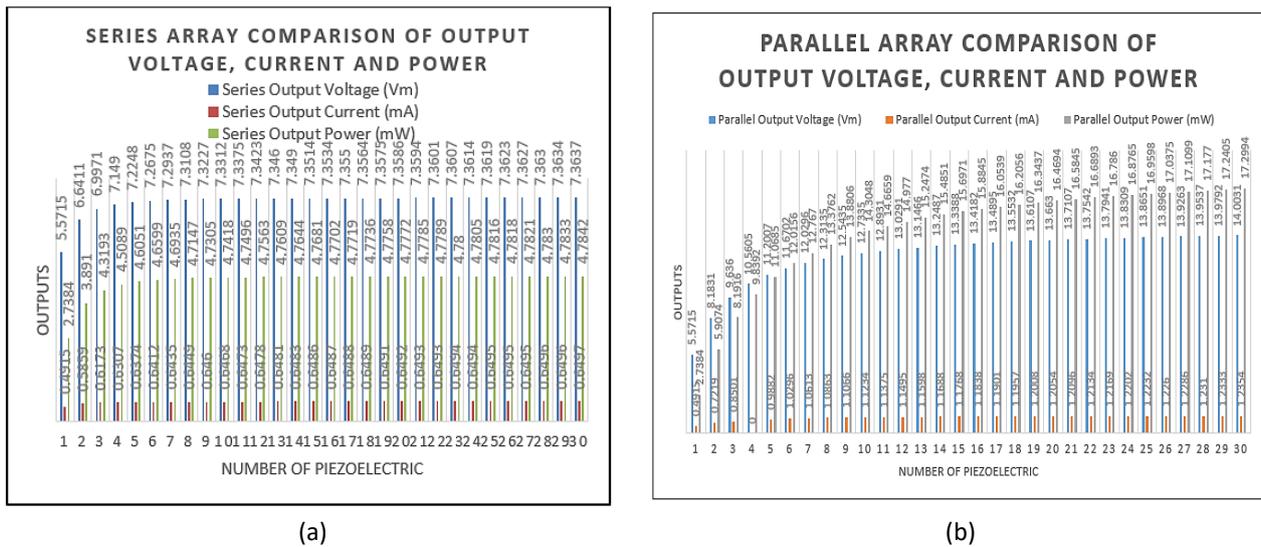
Fig. 22. Comparison of series and parallel array configuration with output voltages, current and power

3.8 Comparison of Output Voltage, Current and Power in Array Configuration with Total 5 Number of Piezoelectric

In Table 3 presented the overall comparison of output voltages, current and power. It is clear that based on the values, the output voltages, current and power are produced higher in parallel (P) array configurations compared to the series (S), series-parallel (S-P) and parallel-series (P-S) array configurations. The main reason for the parallel arranged piezoelectric equivalent circuits able to produce higher output voltages are because that the electrons, that pass through the circuit only get energy from one circuit at a time. The peak output voltage for the parallel array configuration is recorded at 11.2007 V during 5 number of piezoelectric. The peak output voltage for the series array configuration, is recorded at 7.2248 V. For the combination of series-parallel and parallel-series, the output voltages are higher compared to the series array configuration, however it is still lower compared to the parallel array configurations. The highest peak voltage recorded during the during the combination 2S1P which is 9.4584 V.

Table 3
Overall output voltage, current and power in difference array configurations

Number of piezoelectric/ Array configurations		Voltage (Vm)	Current (mA)	Current calculated (mA)	Power (mW)
Series	1	5.572	0.492	0.492	2.738
	2	6.641	0.586	0.586	3.891
	3	6.997	0.617	0.613	4.319
	4	7.149	0.631	0.607	4.509
	5	7.225	0.637	0.637	4.605
Parallel	2	8.183	0.722	0.722	5.907
	3	9.636	0.850	0.850	8.192
	4	10.56	0.932	0.932	9.838
	5	11.20	0.988	0.988	11.07
2S1P		9.458	0.834	0.834	7.892
3S2P		8.099	0.715	0.715	5.788
2P1S		8.356	0.737	0.737	6.160
3P2S		8.741	0.771	0.771	6.741

Next, for the output current, the series output current is much low compared to other array configurations. The highest output current also recorded at 0.637 mA which has the lower compared to the 2 parallel connected piezoelectric equivalent circuits. The maximum parallel output is recorded at 0.988 mA during 5 number of piezoelectric. The output current for the combination of series-parallel and parallel-series the maximum output is recorded at 0.834 mA. The calculated current is obtained from Eq. (6) which represented as theoretical estimated analysis value.

The parallel array configuration able to produce the highest output power compared with all the other array configuration because the maximum power is recorded at 11.07 mW. The combination of series-parallel and parallel-array able to produce the highest output power of 7.892 mW which is more than the series array configuration but still lower than the parallel array configuration.

4. Conclusions

In conclusion, the shapes of these cantilevers have been compared with each other using the same resonance frequency that the model has which is at 270 Hz. The trapezium shaped cantilever has a higher amount of von Mises stress which is 5.74×10^6 N/m^2. This is higher compared to the rectangular maximum stress which is at 5.19×10^6 N/m^2. Next, for the open circuit voltage analysis, both have been run through the various amount of pressure which is from 0.1 to 1 Pa. The trapezium shape generates a higher voltage which is 3.635 V compared to the rectangular shape which is 3.105 V. The reason is mainly due to the shape of the trapezium which has better stress and strain distributions that capable the shape to generate higher output. Besides, for the open circuit analysis, maximum output of to 0.0304 V, 0.9627 nA and 1.4653 nW have reached for rectangular cantilever. When compared to the rectangular cantilever, the output voltage, current and power for the trapezium have achieved higher, which is 0.0466 V, 0.2602 uA and 6.0187 nW. Therefore, the trapezium shape cantilever is considering as the most effective and recommended piezoelectric shape that can be used for the application of sound wave energy harvester. Then in parallel array configuration able to produce the highest output voltage current and power which is 5.636 V, 0.497 mA and 2.803 mW. The 5 V output voltage can be accomplished efficiently in parallel array configuration with lesser amount of piezoelectric equivalent circuit compared to other array configurations. As for the future work, a proof mass magnet can be added to extend the output bandwidth and enhance the output performances. If the system is needed to be applied in a low resonance frequency, then the added proof mass is necessary for the system. For some specific application, would require a less resonant frequency, thus this proof mass can be added.

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