Broadband Energy Harvesting using Multi-Cantilever based Piezoelectric

Bong Yu Jing, Kok Swee Leong
Faculty of Electronic and Computer Engineering
Universiti Teknikal Malaysia Melaka
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
bongyujing@gmail.com"

***Abstract*— Wideband energy harvesting is essential particularly for extracting electrical energy from ambient vibration which is random. Researches show that the frequency bandwidth of the harvested energy can be effectively enhanced by using multiple cantilevers with different resonant frequencies connecting together. This paper investigates the effect of the different electrical configurations towards the output of the piezoelectric array. An array of four similar piezoelectric cantilevers was mounted side-by-side to operate as a system in generating electrical output across frequencies range up to 500 Hz. The resonant frequency of each of the cantilever was varied by introducing a proof mass of 0.15g, 0.50g and 1.00g at the tip of the cantilever. The result shows improvement in the frequency bandwidth of the piezoelectric array, where it is widened to 150 Hz with improved gap when connected in alternating polarities configurations. The piezoelectric array produces higher voltage when connecting in series configuration; but higher power when connecting in parallel configuration..**

***Index Terms*— Bandwidth widening; Energy scavenger; Resonant cantilever; Micro-generator.**

I. INTRODUCTION

Cantilever structured piezoelectric based energy harvester has a simple geometry design and relatively easy to manufacture but it is still able to create large deformation under vibration source. It is commonly used to act as a generator or actuator. This cantilever based piezoelectric would generate electrical charge effectively when it is exposed to continuous harmonic vibration source; vibration with constant frequency and acceleration level. Vibration would cause the cantilever based piezoelectric to bend. This deflation of beam would cause stress and strain force to act on the piezoelectric material and resulting in piezoelectric material to generate electrical charges.

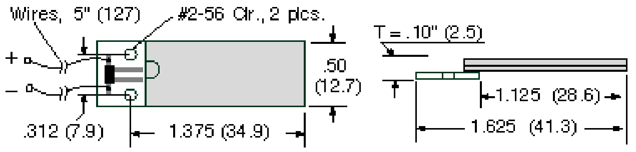
However, cantilever based piezoelectric energy harvester would have the problem of its electrical response to mechanical force decreases largely at frequencies away from the resonant frequency because of the high quality factors of the resonant peak, this is known as "Gain-Bandwidth Dilemma" [1]. This makes the cantilever unreliable in harvesting energy from ambient vibration source. Ambient vibration is mostly frequency random and time-invariant which does not match with the characteristic of piezoelectric cantilevers designed for limited frequency range. There are many researches that have been reported to improve the performance of the piezoelectric cantilever. Many of them are making effort on broadening the bandwidth of the operating frequency range [2-7]. Some of the researches introduce active control mechanisms, such as varying the stiffness of the cantilever by using electrostatic comb drives or varying the location of proof mass on the cantilever in order to change the resonant frequency of the cantilevers so that it would suite the operating frequency of the vibration source [7]. However, these added complex mechanisms are often power hungry and is not preferable for power-stringent wireless sensor applications.

Passive control mechanism on the other hand is more favourable in applications that require low power. One of the approaches is by using non-linear structures. Magnets are being used to alter the natural mechanical response of the cantilevers structure that utilizes the bimorphs with boundary condition to widen the bandwidth of operating frequency [8]. Beside, generator made up from an array of cantilevers with different resonant frequency is also another example of the passive control mechanism [9]. The response of each cantilever is summed up to produce a wider operating frequency bandwidth.

Since the operating frequency bandwidth for piezoelectric cantilever is narrow due to its high quality factor [10]. This generally means that it only can be used to power up electronic device at certain operating frequency. Hence piezoelectric cantilever based power generator is not suitable for powering electronic devices that are operating at ambient vibration source which is random and no distinctive frequency match to the nature frequency of the piezoelectric cantilever. Therefore, in order to design a reliable system operating at ambient vibration source with random low frequencies, the bandwidth of the operating frequency of the device needs to be broadened. This paper improves the output performance of piezoelectric cantilever in term of its bandwidth by analyses the changes in the output of the piezoelectric cantilever arrays when connected in different configurations. The piezoelectric cantilevers are connected in four different configurations which are series with same polarity, series with alternating polarities, parallel with same polarity, and parallel with alternating polarities to observe the maximum voltage and power produced from each configuration. Multiple cantilevers with variation of resonant frequencies are connected together in such a way so that its operating frequency bandwidth is broadened.

II. EXPERIMENTAL SET-UP

The piezoelectric cantilevers which were being used in this research are a standard quick-mount bending generators with pre-mounted and wired at one end (Q220-A4-303YB) from Piezo Systems, Inc [11]. The dimension of the device is as shown in Figure 1.



(a) Top View *(b) Side View*

Figure 1: Dimension of Piezoelectric Cantilever (Q220-A4-303YB) adapted from Piezo Systems Inc [11].

The piezoelectric generators operate in bending mode in the form of a cantilever, whereby electrical charges develop when one side of the piezoelectric layer is stretched and the other side is compressed. These charges are collected for power generation when external electrical load is connected. Four identical piezoelectric cantilevers are mounted on an electrodynamics shaker are being studied with an annotation of CL, CL1p, CL2p, and CL3p as shown in Figure 2. CL is being used as a reference throughout the experiment.

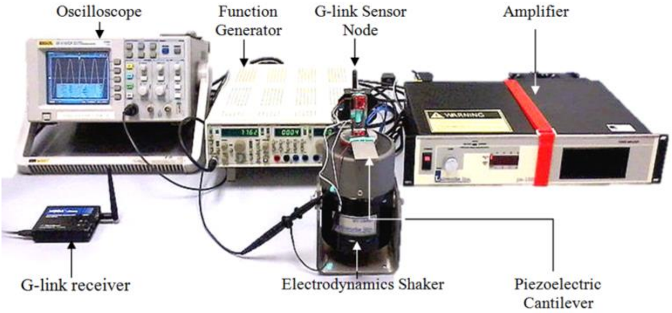


Figure 2: Experimental Set-up

In order to vary the natural frequency of the cantilever, proof masses of 0.15g, 0.50g and 1.00g is attached on the tip of the cantilever with an annotation of CL1p, CL2p, and CL3p representing cantilever CL with proof mass as shown in Figure 3. By adding proof masses to the cantilever, the resonant frequency of the cantilever will shift to lower frequency region [12].

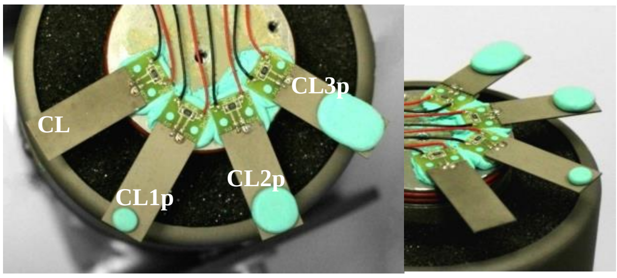


Figure 3: Natural frequency variation with a proof mass attached at the tip of the each of the cantilever denoted as CL1p, CL2p and CL3p, with CL as the reference without proof mass attached

The cantilevers would then be excited from very low frequency to 500 Hz at a constant acceleration level of 1-g (9.81 m/s2) and the open-circuit output voltage will be measured with oscilloscope with the arrangement as shown in Figure 4. Four combinations of terminal connections between each of the piezoelectric cantilever will be studied as shown in Figure 5. The polarity of the piezoelectric cantilever is constant for the entire cantilever being used and the performance of each of the cantilever is depended on conditional of fabrication by the manufacturer. The mechanical resonance frequency of the cantilever is 275 Hz, as stated in the datasheet [11]. Figure 5(a) shows a series connection at the electrical terminals of the piezoelectric cantilevers. Figure 5(b) is also connected in series but with opposing polarities. Figure 5 (c) and (d) are connected in parallel. One is with similar polarity another is with alternating polarities respectively.

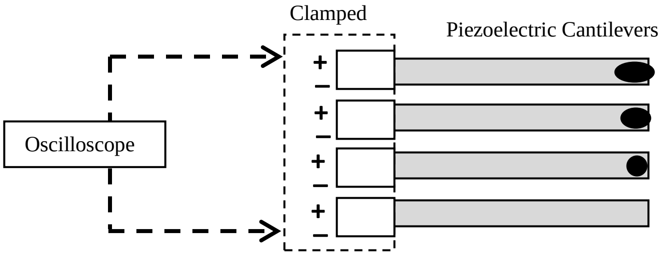


Figure 4: Illustration of an Open-circuit Measurement Configuration

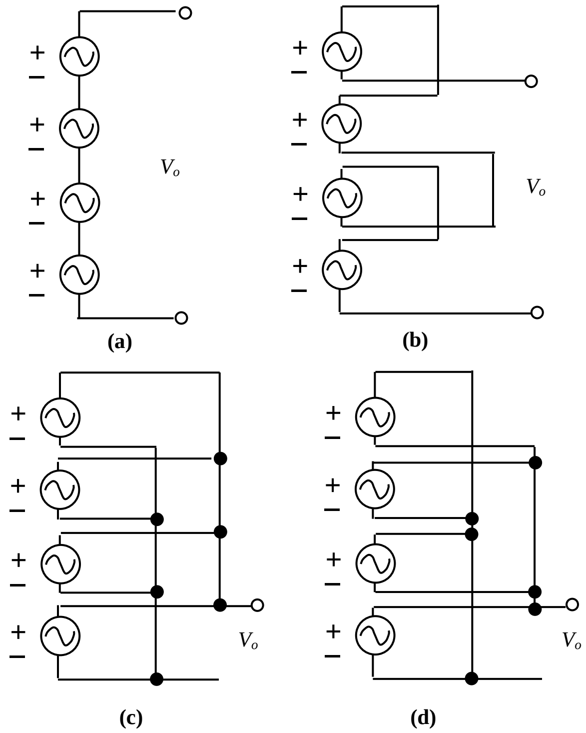


Figure 5: Illustration of different combinations of electrical connections: (a) series, (b) series-alternating, (c) parallel and (d) parallel-alternating

III. EXPERIMENTAL RESULTS

Before the electrical terminals of the piezoelectric cantilevers are connected for further experiment to be taken place, the mechanical resonance frequency of the piezoelectric cantilevers are measured by exciting it with the electrodynamic shaker at a range of frequency from 10 Hz to 500 Hz with acceleration level (g-level) set at a constant magnitude at 1-g (9.81 m/s2). The obtained results are plotted and shown in Figure 6 in term of voltage output and Figure 7 in term of power output. The resonant frequency of the cantilever changed from 300 Hz for C1 without proof mass to 270 Hz, 220 Hz and 180 Hz with additional proof mass of 0.15 g, 0.50 g and 1.00 g respectively.

After the resonance frequency of the piezoelectric cantilevers are tuned to different values, the cantilevers are then connected in a few different connections in order to identify the most optimum connection to harvest energy from a wide frequency band. The piezoelectric cantilevers are first connected in series for two different configurations. One is with consecutive polarity as shown in Figure 5(a) and the other is alternating polarity as shown in Figure 5(b). Then follow by connecting in parallel and again for two different configurations. One is with similar polarity as shown in Fig 5(c) and the other is alternating polarity as shown in Figure 5(d).

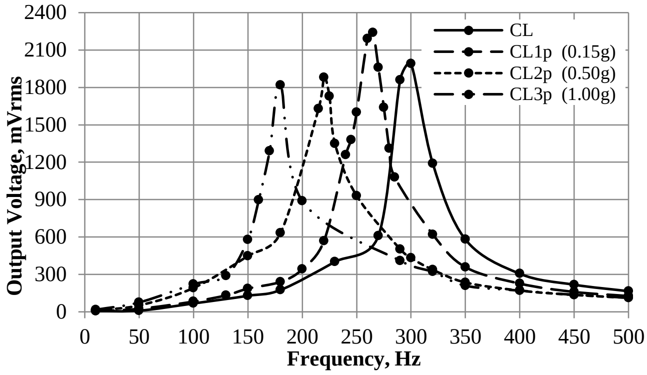


Figure 6: Frequency Response in term of Output Voltage for Multiple Cantilevers with Proof Mass.

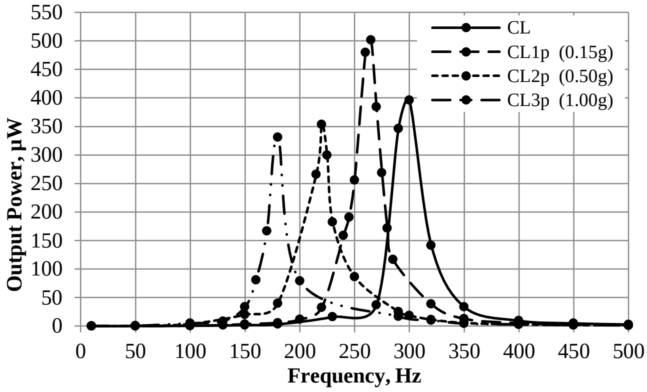
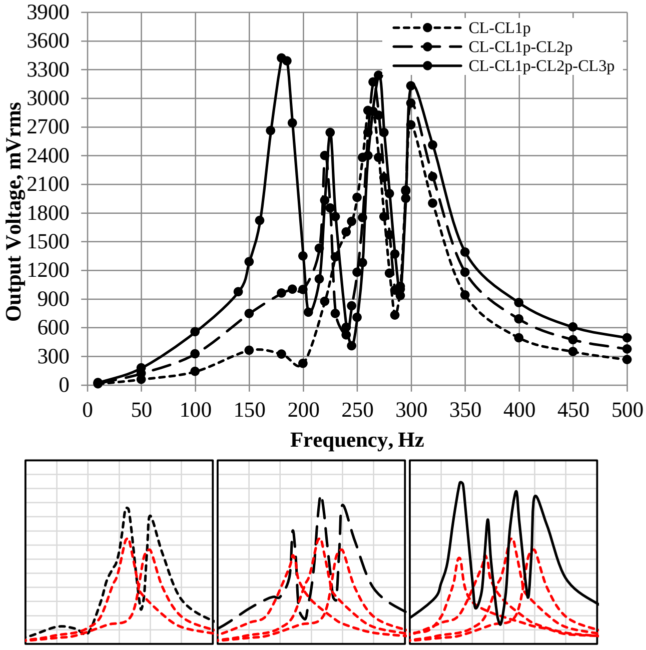


Figure 7: Frequency Response in term of Output Power for Multiple Cantilevers with Proof Mass

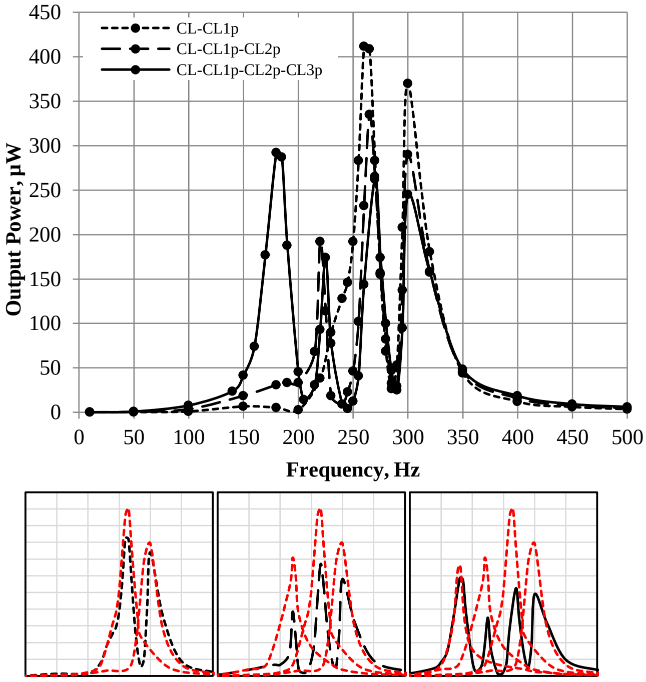
A. Series with Same Polarity Connection

The overall experimental results for regular series connection are shown in Figure 8. The individual results for 2 connected cantilevers, 3 connected cantilevers and 4 connected cantilevers compared with the individual resonance frequency of the cantilever with proof mass are shown in Figure 8(a), b), and (c) respectively. When two piezoelectric cantilevers with different resonant frequencies are connected together in series-consecutive configuration, two distinctive frequencies are being observed. The magnitude of the output voltage at the overlapping frequencies is at its minimum which is lesser than the overlapping output voltage when they are not connected. When more cantilevers with different resonant frequencies are added, the number of output voltage peak is in accordance to the number of cantilever being added to the system as shown in Figure 8(b) and (c).



(a) (b) (c)

Figure 8: Frequency Responses (Voltage) for Cantilevers Connected in Series with Same Polarity Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected



(a) (b) (c)

Figure 9: Frequency Responses (Power) for Cantilevers Connected in Series with Same Polarity Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected

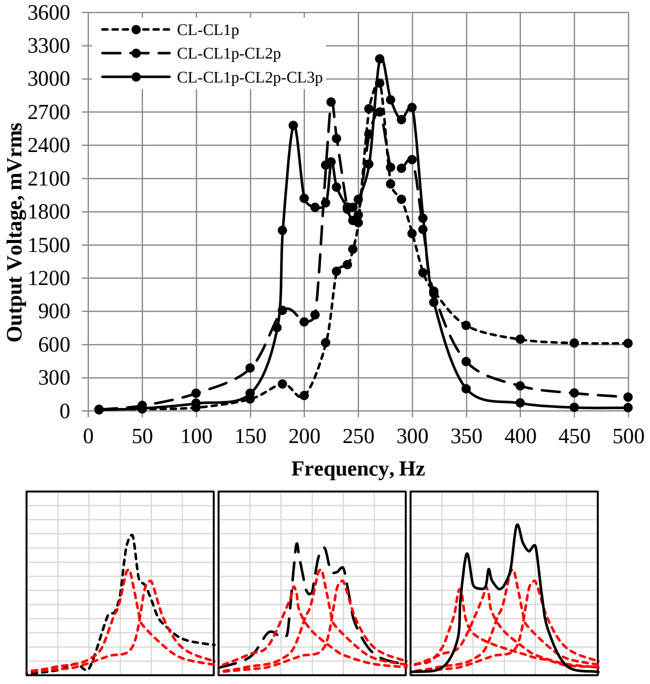
Notice that the operating bandwidth increases in respect of increasing number of the connected cantilevers. The maximum voltage produced by each peak is also higher than their original voltage output produced. However, there is huge drop of voltage in between the peaks and it is undesirable. For example, note that when connecting four cantilevers all together in series with same polarity, the operating frequency bandwidth widen to between 160Hz to 335Hz for application that need 1.80V voltage input. However, the application will not work in between 145Hz to 220Hz, between 230Hz to 260Hz, and between 280Hz to

295Hz because the voltage drop lowers than 1.80V in between that frequency.

On the other hand, result in term of power output is shown in Figure 9. Same as the result shown in Figure 8, the operating bandwidth of the multiple connected cantilevers in term of power output increase when more cantilevers is added, but there is still a huge gap in between that makes the connection not able to function accordingly. Notice that the power value also decreased compared to their original power output produced because series connection reduced the current value. Hence, it is not desirable to apply this particular connection for the generator.

B. Series with Alternating Polarities Connection

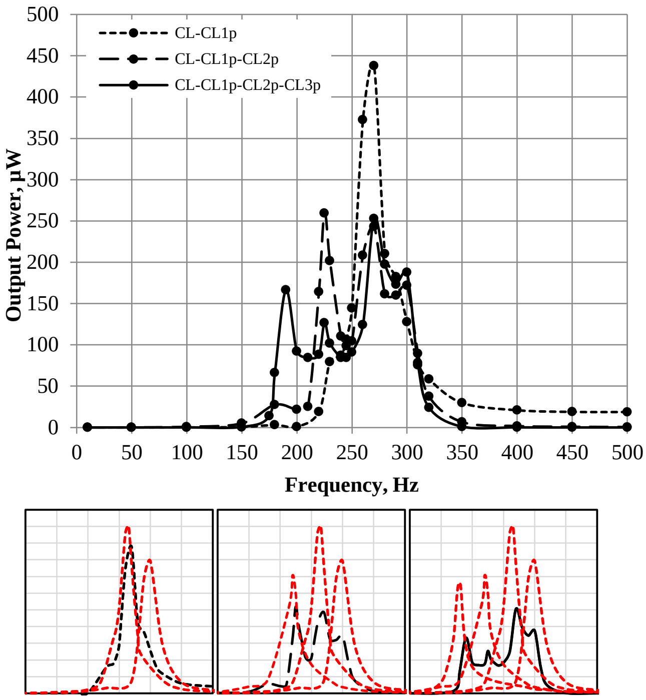
The result of the frequency response of series with alternating polarities connected cantilevers is shows in Figure 10 while result after converted to power value in shows in Figure 11. Same as in series with same polarity connection, peaks were formed whenever cantilevers are added. These peaks were also formed around the resonant frequency of each respective cantilevers added with maximum output voltage higher than the original voltage output produced from non-connected cantilevers. However, notice that the waveform formed has clear difference from the waveform formed in by same polarity connection, where the gap or valley between peaks are not as low as in waveform produced by the same polarity connection.



(a) (b) (c)

Figure 10: Frequency Responses (Voltage) for Cantilevers Connected in Series with Alternating Polarities Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected

Overall this connection produces voltage not less than 1.94V and power not less than 94µW at frequencies between 180Hz to 310Hz. Even though the maximum power output decreases as compared to the result obtained for same polarity connection, but the gap in between peaks increased.



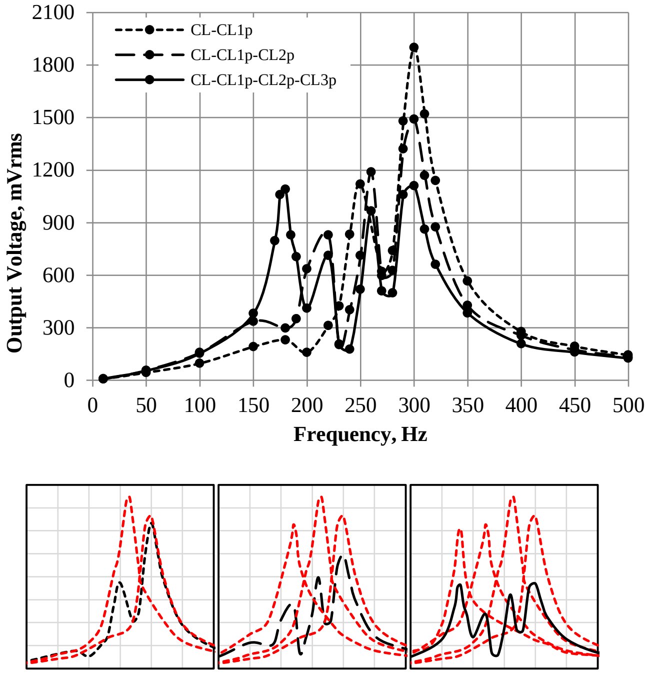
(a) (b) (c)

Figure 11: Frequency Responses (Power) for Cantilevers Connected in Series with Alternating Polarities Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected

C. Parallel with Same Polarity Connection

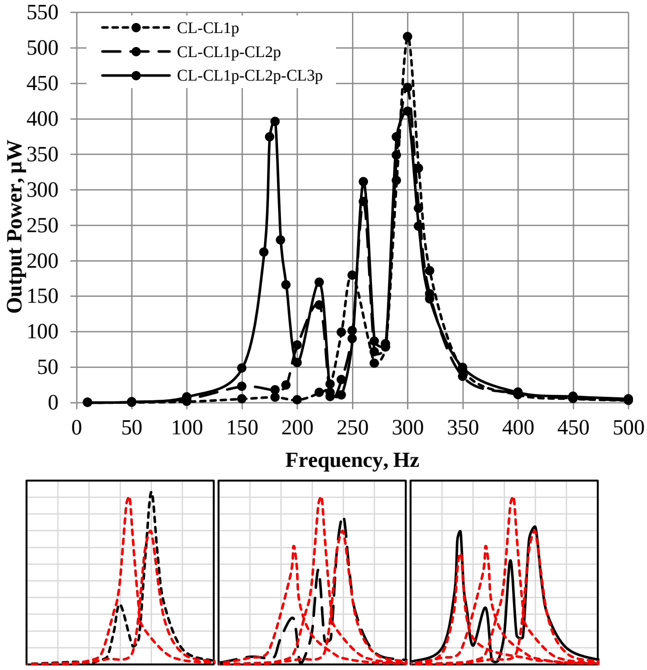
The frequency response of parallel with same polarity connected cantilevers is observed in this particular section. The result in term of voltage output is shows in Figure 12 while result after converted to power value in shows in Figure 13. Peaks are again formed on resonant frequency of each respective cantilever. Same as the result obtained in series with same polarity connection, where the gap or valley in between peaks are quite low. Besides that, the voltage outputs generated by this series with same polarity connected cantilevers are low. The maximum voltage produced by four connected cantilevers is just 1.11V for parallel connection compared to 3.42V for series connection.

However, in terms of power output, these parallel connected cantilevers produced higher output power. But still, the gap in between peaks for power output as shown in Figure 13 is quite low. Although the operating frequency bandwidth of the output has widen but the deep gap in between the peaks would definitely affect the function of the generator. Hence, this parallel with same polarity connection is not favored as the orientation of cantilevers to produce optimum output.



(a) (b) (c)

Figure 12: Frequency Responses (Voltage) for Cantilevers Connected in Parallel with Same Polarity Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected.

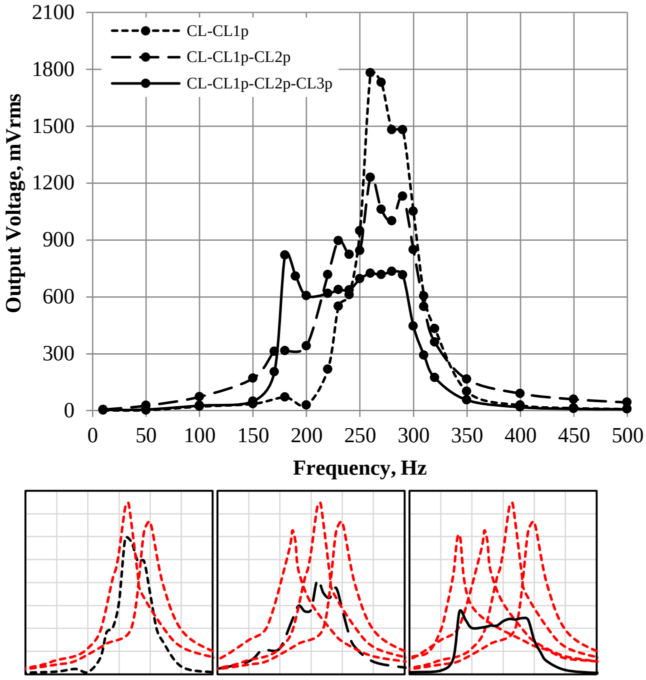


(a) (b) (c)

Figure 13: Frequency Responses (Power) for Cantilevers Connected in Parallel with Same Polarity Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected

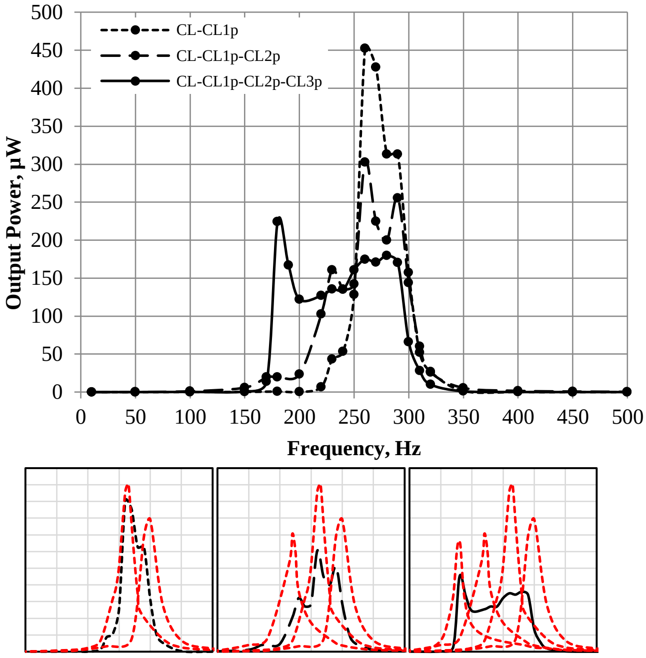
D. Parallel with Alternating Polarities Connection

The frequency response of parallel with alternating polarities connected cantilevers is observed in this particular section. The result in terms of voltage output is shown in Figure 14 while result after converted to power value in shown in Figure 15. Peaks are again formed on resonant frequency of each respective cantilever when the cantilever is added. However, when CL3p is added, the peaks become not quite visible. This is due to the alternating polarities connection that causes the valley in between peaks to be shallow and it flattened out the peaks.



(a) (b) (c)

Figure 14: Frequency Responses (Voltage) for Cantilevers Connected in Parallel with Alternating Polarities Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected



(a) (b) (c)

Figure 15. Frequency Responses (Power) for Cantilevers Connected in Parallel with Alternating Polarities Connection. (a) Two cantilevers are connected. (b) Three cantilevers are connected. (c) Four cantilevers are connected.

Notice that another peak is formed whenever another cantilever is added. Also notice that the operating bandwidth increases in respect of increasing number of the connected cantilevers. The maximum voltage produced by each peak is also higher than their original voltage output produced. However, there is huge drop of voltage in between the peaks and it is undesirable. This narrow gap will not form if the output waveforms for each cantilever are in phase. Based on finding in [13], it is proven that the phase of the output waveform shifts at the resonant frequency of each cantilever, it explains the reason why when two waveforms are connected in series with same polarity the total output is not the sum of maximum output of both waveforms, but lesser because the waveforms are not in phase.

Same as in series with same polarity connection, when the piezoelectric cantilever is connected in series but with alternating polarities, peaks were formed whenever cantilevers are added. These peaks were also formed around the resonant frequency of each respective cantilevers added with maximum output voltage higher than the original voltage output produced from non-connected cantilevers. However, notice that the waveform formed has clear difference from the waveform formed in by same polarity connection, where the narrow gap between peaks are not as low as in waveform produced by the same polarity connection. Phase shifting is the reason for the significant rise at the gap in between the peaks formed in when the cantilever are connected in alternating polarities. As the waveform is shifted, when the cantilevers are connected in alternating polarities, the value of the positive peak will not totally cancel out by the value from negative peak of the other cantilever. Hence, the gap in between the peak is not narrow as in same polarity connection. In fact, the output performance of the piezoelectric cantilever array can be improves when the relation of the phase shifting and resonant frequency is carefully calculated and takes into account.

IV. CONCLUSION

The focus of this research is to investigate the changes in the output of the piezoelectric cantilever arrays when connected in different configuration. Multiple cantilevers with different resonant frequencies is connected together in order to broaden the operating frequency range of the generator. The resonant frequencies of the cantilevers were decreased by introducing additional proof mass to the tips of each cantilever. The increasing of the weight of the proof mass resulted in decreasing of the resonant frequency of the cantilevers. By connecting the cantilevers with different resonant frequencies together, the operating frequency bandwidth of the piezoelectric cantilevers widens. When connected in series, the voltage output is higher as compared to parallel configuration. While in parallel configuration, the power output is higher. Alternating polarities connections increase the output gaps between the peaks because of its phase shifting at frequency near to its resonant frequency. This eliminates or minimizes the gaps, making it possible for the applications that are powered by micro-power to able to function in wider frequency range.

ACKNOWLEDGEMENT

The authors would like to thank the UTeM Zamalah Scheme for the scholarship award, as well as the facility support by the Advanced Sensors and Embedded Control System (ASECs) Research Group, Centre for Telecommunication Research and Innovation (CeTRI), Faculty of Electronic and Computer Engineering, UTeM.

REFERENCES

[1] Y Hajati, A.a.K., and Sang, G., (2011). Ultra-wide Bandwidth Piezoelectric Energy Harvesting. Applied Physics Letters, 99(8).

[2] H. Xue, Y. Hu and Q. m. Wang, (2008). Broadband piezoelectric energy harvesting devices using multiple bimorphs with different operating frequencies. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 55(9), pp. 2104-2108.

[3] Jing-Quan Liu, Hua-Bin Fang, Zheng-Yi Xu, Xin-Hui Mao, Xiu-Cheng Shen, Di Chen, Hang Liao, Bing-Chu Cai, (2008) A MEMS-based piezoelectric power generator array for vibration energy harvesting. Microelectronics Journal, 39(5), pp. 802-806.

[4] S.M. Shahruz, (2006). Design of mechanical band-pass filters for energy scavenging. Journal of Sound and Vibration, 292(3–5), pp. 987-998.

[5] M. S. M. Soliman, E. M. Abdel-Rahman, E. F. El-Saadany, and R. R. Mansour, (2008). A wideband vibration-based energy harvester. Journal of Micromechanics and Microengineering, 18(11), 115021.

[6] M. Marzencki, M. Defosseux and S. Basrour, (2009). MEMS Vibration Energy Harvesting Devices With Passive Resonance Frequency Adaptation Capability. Journal of Microelectromechanical Systems, 18(6), pp. 1444-1453.

[7] Tang Lihua, Yaowen Yang, and Chee Kiong Soh, (2013). Broadband Vibration Energy Harvesting Techniques. Advances in Energy Harvesting Methods. pp. 17-61.

[8] Stanton, SC, McGehee, CC, and Mann, BP., (2009). Reversible hysteresis for broadband magnetopiezoelastic energy harvesting. Applied Physics Letters, 95, 174103.

[9] Yu, H., Zhou, J., Deng, L., and Wen, Z., (2014). A Vibration-Based MEMS Piezoelectric Energy Harvester and Power Conditioning Circuit. Sensors 2014, 14, pp.3323-3341.

[10] Kok S.L., Mohamad N., Yap D.F.W., Chen S.K. and Dee C.F., (2011). Multi-frequency energy harvesting using thick-film piezoelectric cantilever. In: Proceedings of International Conference of Electrical, Control and Computer Engineering, Pahang, pp. 420-423.

[11] Datasheet of Q220-A4, Piezo Systems, Inc. http://www.piezo.com/catalog8.pdf%20files/Cat8.42.pdf (accessed on 2nd April 2017)

[12] Bong. Y.J., and Kok. S.L., (2016). Parametric Studies on Resonance Frequency Variation for Piezoelectric Energy Harvesting With Varying Proof Mass and Cantilever Length. Journal of Engineering & Technology, 8(5), pp. 119-123.

[13] Bong. Y.J., and Kok. S.L., (2017). Investigation On Phase Shifting Effect On The Voltage Output Of Piezoelectric Cantilever Array. IOP Conference Series: Materials Science and Engineering 210: 012038.