Experimental Verification of Wide-Band Energy Harvesting using Piezoelectric Multi-cantilever with Resonant Frequency Variation

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***Abstract*—Broadband energy harvesting approach is crucial particularly for extracting electrical energy from ambient vibration which is random. The bandwidth of the harvested energy can be effectively improved by using multi-cantilever with different resonant frequencies, however, as the wider the bandwidth the resonant frequencies are far apart from each others leaving a huge drop of harvested energy between the peak frequencies which would not be practical for harvesting random vibration sources. This issue is being addressed in this paper to investigate the effect of different combinations of electrical connections of the cantilevers. An array of four similar piezoelectric cantilevers were 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 at the tip with an increment of 0.05 g. The bandwidth of the multi-cantilever system is effectively increases to 110 Hz with an open-circuit output voltage peaked at 6 Vrms and the voltage level gap is also improved when connected in series and opposing configuration.**

Keywords*—resonant cantilever; energy scavenger; bandwidth widening; micro-generator

I. Introduction

Piezoelectric cantilever is desirable to harvest energy derived from ambient vibration due to its compactness and high electrical output power density, however, due to its high *Q*-factor [1], a small friction shift of frequency would drastically reduce the electrical voltage output therefore a single piezoelectric cantilever would not be an effective energy harvester for real application particularly in harvesting electrical energy from ambient vibration sources which is random [2].

There have been studies on the strategy to increase the bandwidth of vibration energy harvesting. One of which are tuning methods as described by Dibin Zhu, *et al.* [3]. Whilst tuning methods are effectively increase the bandwith of the harvested energy but the system requires complicated circuitry such as involving microprocessing unit in adjusting the resonant frequency such as being described by Noha A *et al.* [4]. Besides than that there was also research into limiting the movement of the cantilever by using stopper to increase the bandwidth as reported by Ming Song, *et al.* [5]. Electrical impedance matching [6], an approach without involving any mechanical adjustment is another way to improve the performance but at a very limited bandwidth, which is desirable for compact and miniature energy harvesting system at defined vibration sources.

In this paper, an array of cantilevers will be used to harvest wider bandwidth of vibration energy at flexible bandwidth defined by the number of the cantilever at different resonant frequencies. This is regarded as a multi-cantilever system or multi-frequency system, which had earlier been reported by Ferrari M., *et al.* [7]. They used individual bimorph cantilever with different resonant frequencies and combined electrically after voltage rectification to generate electrical energy across a range of frequency up to 400 Hz. Monolithically fabricated multi-cantilever [8] has also being reported in generating an electrical output across a wide band of excitation frequencies.

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-A4-103YB) from Piezo Systems, Inc. The dimension of the device is as shown in Fig. 1.

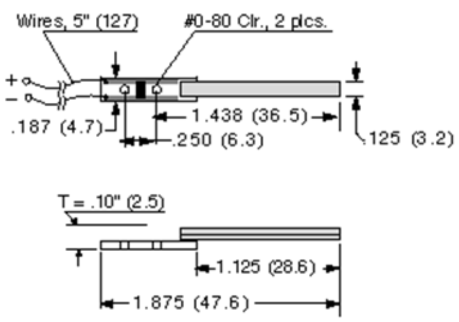


Fig. 1. Dimensions of the piezoelectric generator Q220-A4-103YB used in this experimental

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 C1, Ca, Cb and Cc as shown in Fig. 2. C1 is being used as a reference throughout the experiement.

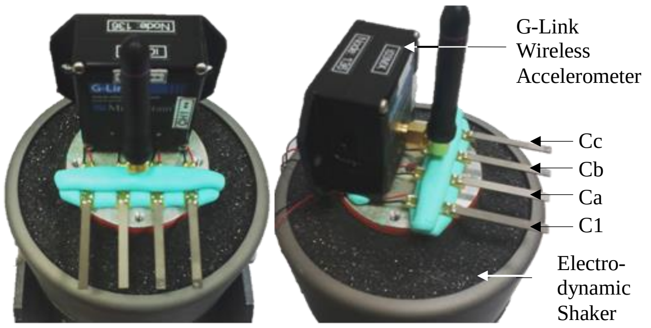


Fig. 2. Experimental Set-up of Multi-cantilever mounted on electrodynamic shaker.

In order to vary the natural frequency of the cantilever, a variation of proof masses with an increament of 0.05 g is attached on the tip of the cantilever from zero additional mass to 0.15 g with an annotation of C2, C3 and C4 representing cantilever Ca with proof mass of 0.05 g attached, cantilever Cb and Cc with attachment of 0.1 g and 0.15 g proof masses respectively as shown in Fig. 3.

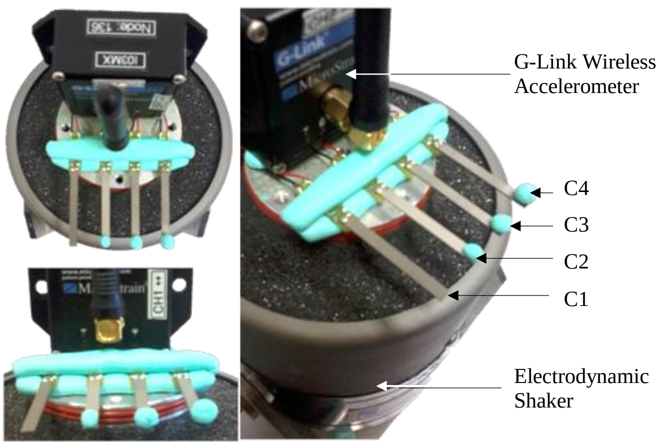


Fig. 3. Natural frequency variation with a proof mass attached at the tip of the each of the cantilever denoted as C2, C3 and C4, with C1 as the reference without proof mass attached.

The cantilevers would then be excited from very low frequency to 500 Hz at a constant acceleration level of 1-g (9.81 m/s^2) and the open-circuit output voltage will be measured with oscilloscope with the arrangement as shown in Fig. 4(a). Four combinations of terminal connections between each of the piezoelectric cantilever will be studied as shown in Fig. 4(b)-(e). The polarity of the piezoelectric cantilever is constant for all the 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 sated in the datasheet [9]. Fig. 4(b) shows a series connection at the electrical terminals of the piezoelectric cantilevers. Fig. 4(c) is also connected in series but with opposing polarity. Fig. 4 (d) and (e) are connected in parallel. One is with similar polarity another is with alternating polarity respectively.

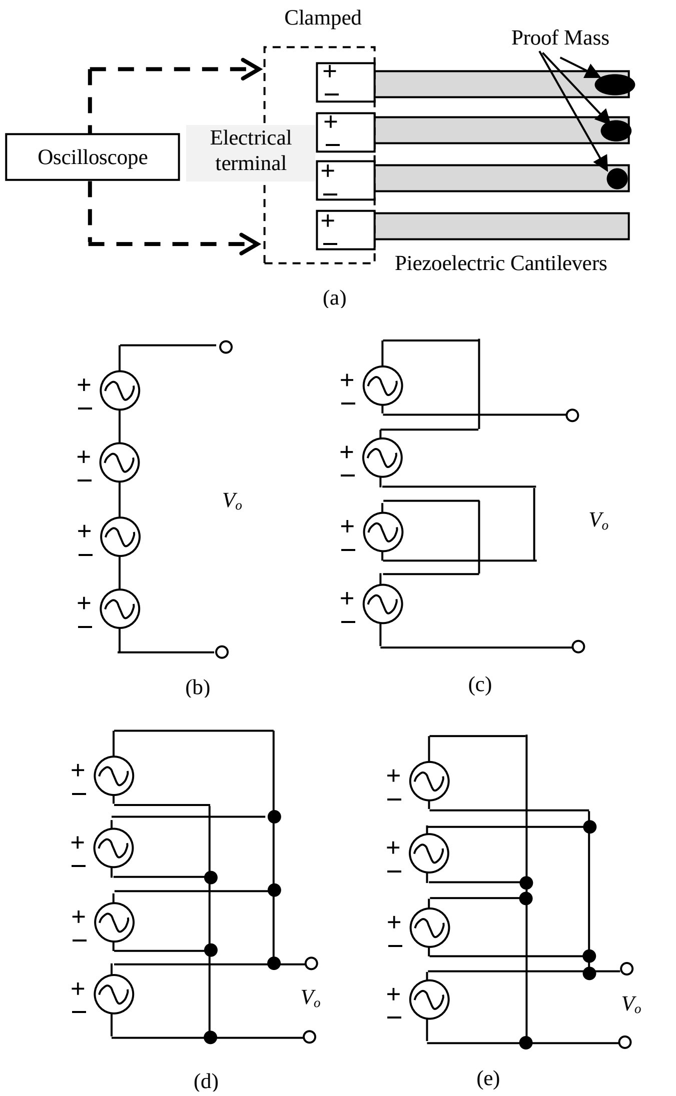


Fig. 4 (a) Open-circuit measurement with different combinations of electrical connections: (b) series, (c) series-alternating, (d) parallel and (e) parallel-alternating.

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 electricdynamic 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 ploted and shown in Fig. 5. There is an variation of open-circuit output voltage from 2.3 V to 4 V with a constant resonant frequency at 275 Hz which is in agreement with the datasheet [9]. The resonant frequency of the cantilever changed from 275 Hz for C1 without proof mass to 230 Hz, 190 Hz and 170 Hz with additional proof mass of 0.05 g, 0.1 g and 0.05 g respectively. As expected, the peak output voltage is significantly increased to as much as 35% compared with no proof mass. The main thing to notice is that, ideally the overlapping bandwidth can be increased to more than a factor of 4 when compared to single cantilever as shown in Fig. 6.

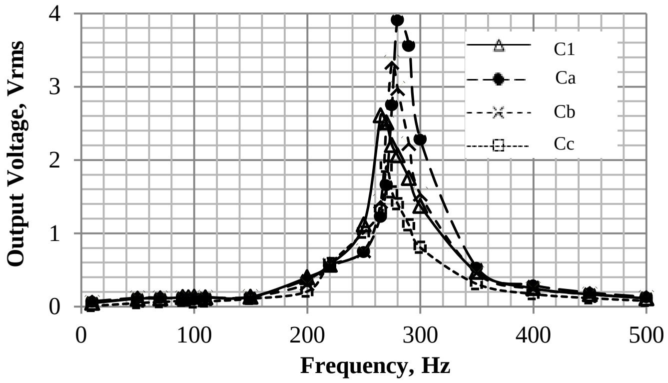


Fig. 5. Frequency response of the cantilevers (C1, C2, C3, and C4) at a constant acceleration level of 1-g (9.81 m/s2).

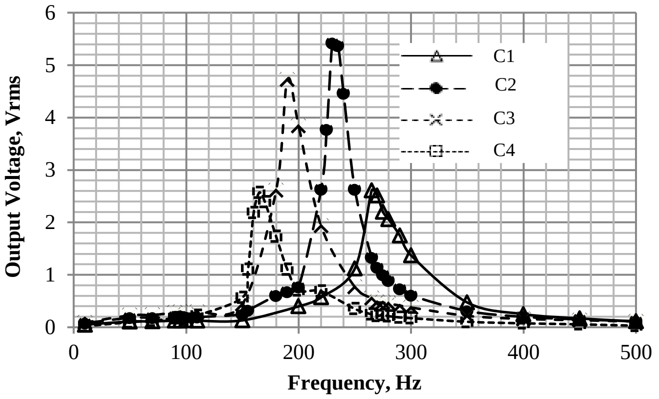


Fig. 6. Frequency response of the cantilevers with proof masses (0.05g, 0.10g, and 0.15g) and the reference cantilever C1 at a constant acceleration level of 1-g (9.81 m/s2).

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 Fig 4(b) and the other is alternating polarity as shown in Fig 4(c). Then follow by connecting in parallel and again for two different configurations. One is with similar polarity as shown in Fig 4(d) and the other is alternating polarity as shown in Fig. 4(e).

A. *Series Connections*

a) Common series connection: The overall experimental results for common series connection are shown in Fig. 7(a) and 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 Fig. 7(b), (c), and (d) respectively. When two piezoelectric cantilevers with different resonant frequencies are connected together in series-consecutive configuration, two distintive frequencies is 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. It is also noticed that the resonant frequency of the reference cantilever C1 is shifting to the right from 275 Hz to 280 Hz as shown in Fig. 7(b). 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 Fig. 7(c) and (d). This resulting in widening the energy harvesting bandwidth to 110 Hz compared to individual bandwidth of about 20 Hz. However, the gaps in between two adjacent resonant frequencies are obviously dropped to their minimum and lesser compared to the overlapping output voltage produced by individual cantilever. Besides that, it is also noticed that the overall output voltage decreased when 4 cantilevers are connected together.

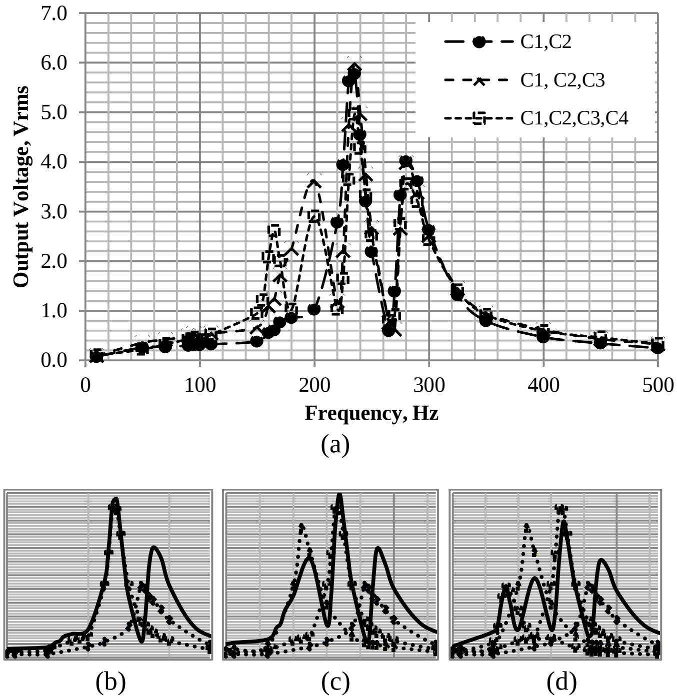
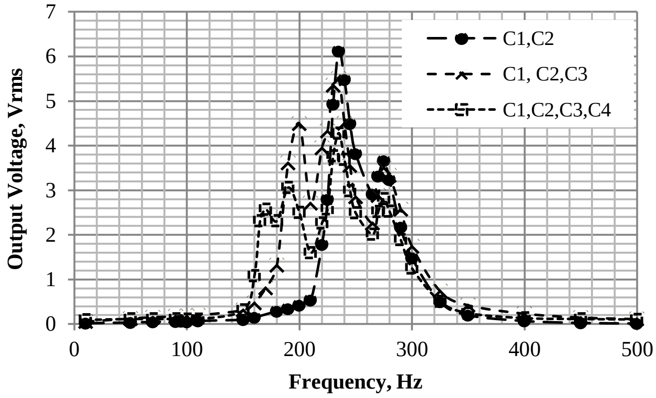


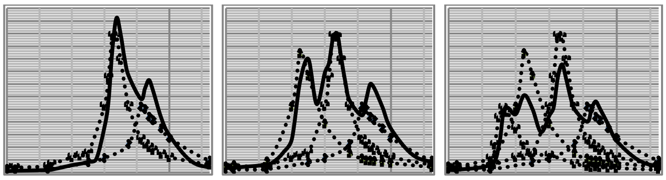
Fig. 7. (a) Overall frequency response of the series-consecutive connected cantilevers with proof masses (0.05g, 0.10g, and 0.15g) and C1 at a constant

acceleration level of 1-g (9.81 m/s^2). The frequency response for (b) two, (c) three and (d) four connected cantilevers.

b) Series with alternating polarity connection: The overall experimental results for series with alternating connections are shown in Fig. 8(a) and the open-circuit output voltage measurement for two, three and four connected cantilevers compared with the individual cantilever frequency response are shown in Fig. 8(b), (c), and (d) respectively. It is noticed that there is an improvement in the overlapping output voltage between two adjacent resonant frequencies compared to series-consecutive configuration as shown in Fig. 7. The minimum output voltage between the two adjacent frequencies has increase to near to half of that of the peak output voltage at resonant frequency of 230 Hz. This shows that series with alternating polarity connection is more effective in harvesting a wider frequency band compared to common series connection although the overall output voltage decreses.



(a)

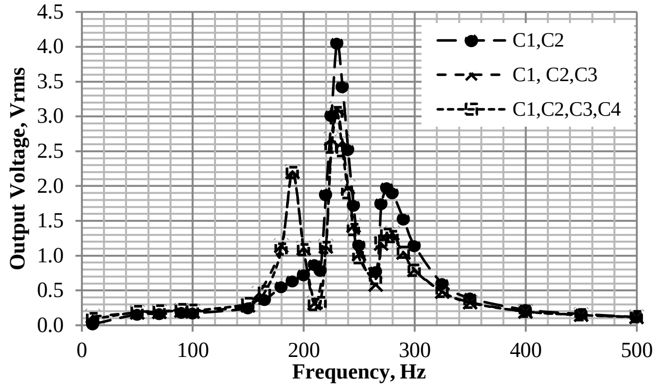


(b) (c) (d)

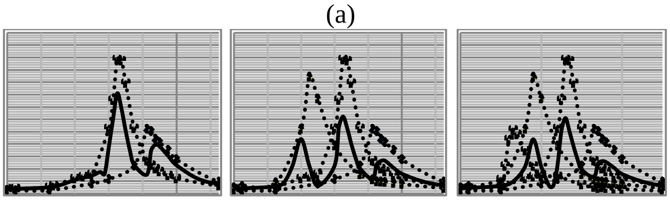
Fig. 8. (a) Overall frequency response of the series-alternating polarity connected cantilevers and connection between (b) two (c) three and (d) four cantilevers with proof mass (0.05g, 0.10g, and 0.15g) and the reference cantilever C1 when excited at a constant acceleration level of 1-g (9.81 m/s2).

B. Parallel Connections

a) Common parallel connection: It is noticed from the experiment results that the minimum output voltages at the overlapping of two adjacent resonant frequencies are lower than that of the individual cantilever when they are not connected which is similar to common series connection but at a reduced overall output voltage as shown in Fig. 9(a)-(d) . It is also noticed that the 4th peak that can be seen in Fig. 8 when cantilever C4 was connected, has totally disappeared. It is as expected that when connected in parallel the open-circuit output voltage will be consistant to the lowest output voltage when they are connected.



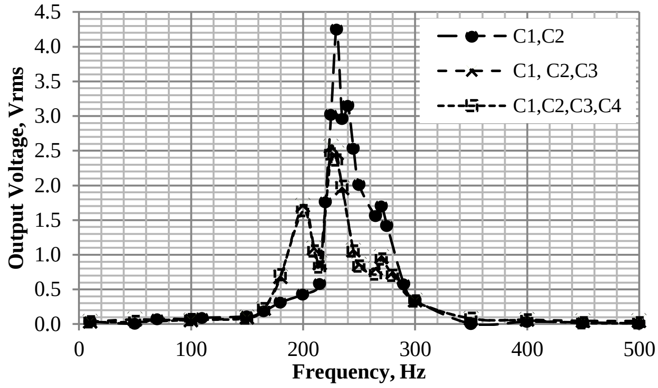
(a)



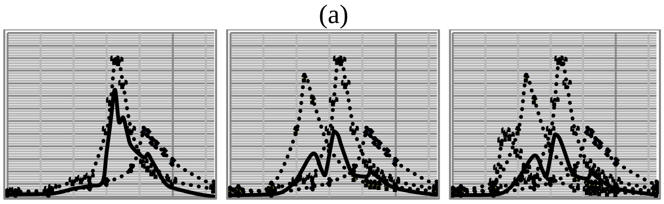
(b) (c) (d)

Fig. 9. (a) Overall frequency response and connections of (a) two (c) three and (d) four cantilevers when excited at a constant acceleration level of 1-g (9.81 m/s2).

b) Parallel with alternating polarities connection: The experimental results for parallel with alternating connecting has increased the overlapping outupt voltage but the total average output voltage has been reduced to half of its maximum when they are not connected. The overall experiment results are shown in Fig. 10(a) and the output voltage of two connected, 3 connected and 4 connected cantilevers are shown in Fig. 10(b), (c), and (d) respectively.



(a)



(b) (c) (d)

Fig. 10. (a) Overall frequency response at a constant acceleration level of 1-g (9.81 m/s2) for the parallel with alternating polarities connected cantilevers with proof masses (0.05g, 0.10g, and 0.15g) and the reference cantilever C1; Connections of (b) two (c) three and (d) four cantilevers.

IV. CONCLUSION

The experimental results show the possibility of widening the energy harvesting operational frequency band by integrating an array of cantilevers with different natural frequencies to form a multi-cantilever system. The natural frequency can be simply varied by adding proof mass at the tip of the cantilever and which effectively increase the bandwidth between two cantilevers. However, the wider the bandwidth, the gap of the output voltage widen between the peaks widen and minimize the overlapping output voltage which is not practicle in harvesting random vibration sources. The connection between all the elements of the multi-cantilever system is important in maintaining the level of the overlapping output voltage. From the experiment results, series with alternating polarities connection of the multi-cantilever is the configuration that is most effective in harvesting a wide-band vibration sources compared to common series and parallel connections. The operating frequency bandwidth of the configuration is shown to be in between 170 Hz to 280Hz before the output voltage fall to a factor of √2 compared to it lowest peak of the bandwidth.

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