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Investigation on Phase Shifting Effect on The Voltage Output of Piezoelectric Cantilever Array

B Y Jing and K S Leong*

Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

Email: *sweeleong@utem.edu.my

Abstract. This paper analyses the phase shifting of the output waveform produced by piezoelectric cantilevers under a range of vibration frequencies. The phase shift of four piezoelectric cantilevers with different resonant frequency are inspected while it is excited with the vibration from the electrodynamics shaker at a range of frequencies from 100 Hz to 500 Hz with the acceleration level (g-force) fixed at constant magnitude of 1g-level (9.81 m/s2). Time different and Lissajous pattern methods were used in this research to measure the phase shift of the output waveform. Both methods show similar result where the major phase shift happened at the resonant frequency of respective cantilevers. The phase difference remains low around 0 degrees or in other term in phase before the resonant frequency of the cantilever. When the frequency of the vibration source approaches the resonant frequency of respective cantilever, the phase different start to increase rapidly and reach 180 degree which is out of phase after the resonant frequency. This major phase shifting contributes to the significant rise of the gap in between the peaks formed when multiple piezoelectric cantilevers are connected together. As a result, it indirectly improves the output performance of the piezoelectric cantilevers array.

1. Introduction

Piezoelectric based energy harvesting had gained interest over the time due to the advancement in integrated circuit [1]. Improved integrated circuits had its power consumption reduced greatly, making it possible to be powered up by using micro-power energy harvester. Since piezoelectric had shown promising result and potential in harvesting energy to power-up micro-power electronic devices [2-5], it sparked research interest in lot aspects, mainly on maximizing the performance of the piezoelectric material, including technique to optimize the output from the piezoelectric material and widening the operating bandwidth of the piezoelectric energy harvester [1].

Piezoelectric energy harvester especially cantilever based piezoelectric will only produce optimum output within certain excitation frequency range. If the frequency of the vibration shifts, the output of the piezoelectric material will decrease radically. Therefore, many techniques were introduced to broaden the operating frequency bandwidth of the piezoelectric material before its practical deployment. The techniques included resonant frequency tuning [6] which adjust the resonant frequency of the piezoelectric material using mechanical, magnetic, or piezoelectric method; nonlinear energy harvesting configuration that use magnets to adjust the nonlinear stiffness and nonlinear piezoelectric coupling of the material; and multimodal energy harvesting which utilise multiple degree-of-freedom system of the piezoelectric cantilever by using multiple bending modes of a piezoelectric cantilever or by connecting multiple cantilevers into an array.

Researches shown when multiple cantilevers are connected together into an array, the operating frequency bandwidth of the model broadened [7-13]. Ideally, when connecting two or more alternating current (AC) outputs in series connection with same polarity the total output should be the sum of all the connected output, while series connection with alternating polarities will cause the generated output to cancel out each other. However, researches shown different outcome when piezoelectric cantilevers with different resonance frequencies are connected in an array [14]. This implied that the output produced by the piezoelectric cantilevers with different resonance frequencies might not in phase.

Hence, this paper investigate the phase difference of the output waveform from the piezoelectric cantilevers with difference resonance frequencies and also its effect on the output of the piezoelectric cantilever array when connected in series with same polarity and alternating polarities.

2. Experimental Set-up

This research uses piezoelectric standard quick-mount bending generator with pre-mounted and wired at one end (Q220-A4-303YB) from Piezo Systems, Inc [15] as the test subject. The dimension of the piezoelectric generator is shown in Figure 1.

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

Figure 1. Dimension of Piezoelectric Cantilever (Q220-A4-303YB) [11].

The experiment set-up of this research is as shown in Figure 2, which consists of a G-link wireless sensor and receiver, an electrodynamics shaker, a gain amplifier, a function generator, an oscilloscope, and piezoelectric cantilevers. In order to generate a controllable artificial vibration for test purpose, function generator, gain amplifier, electrodynamics shaker, and G-link wireless accelerometer were used. The function generator was used to supply AC input power to the electrodynamics shaker. Since the power supplied by the function generator alone is not sufficient to generate vibration with high acceleration level (g-force), the gain amplifier was used to amplifier the power before supplying it to the electrodynamics shaker.

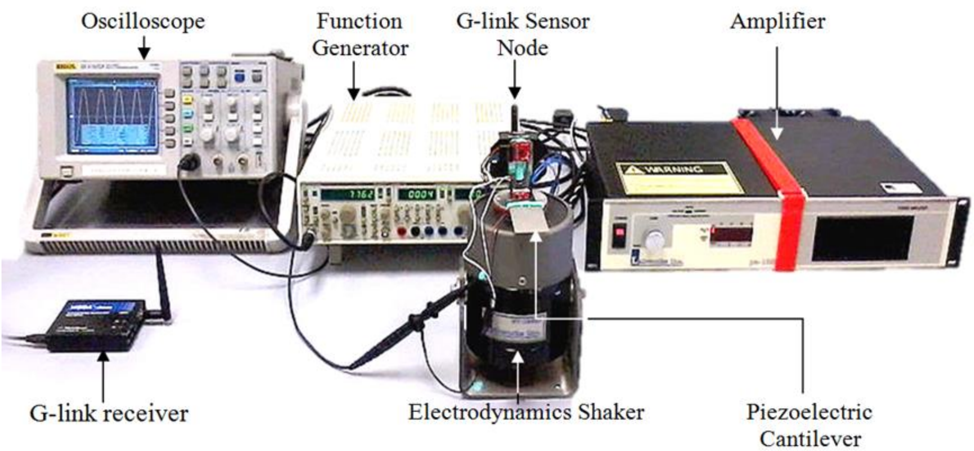

Figure 2. Experimental Set-up

Five units of piezoelectric cantilevers were used in this research. The cantilever is named C1, C2, C3, C4 and CC for reference convenience. In this case, the constant cantilever, CC is a cantilever with its resonant frequency far away from the other cantilevers to acts as a test subject to compare the phase shifting of the other cantilevers. Its resonant frequency is tuned to higher frequency by clamping the cantilever over than its clamping base, towards its flexible beam [16]. While the resonant frequencies of the piezoelectric cantilever C2, C2, and C4 is altered to lower frequency by attaching proof mass to the tip of the cantilevers. After the resonant frequency of each cantilever is tuned to different value of 180 Hz (C4), 220Hz (C3), 270Hz (C2), and 300Hz (C1), the phase difference between cantilever C1, C2, C3, C4 and a constant cantilever CC is recorded and examined. In this research, the phase shift of the cantilevers is measured by using time different method and Lissajous pattern method. The results obtained from both methods are then compared for verification purpose.

After the phase difference of the cantilevers are measured and examined, the research continued with observing the output produced by the cantilevers when connected in series connections. The output is observed when cantilevers are connected in series with same polarity and series with alternating polarities connections to examine the effect of phase shifting of the piezoelectric cantilevers towards it output performance.

2.1. Time Different Method

For time different method, the cantilever CC and C1 are connected individually to the oscilloscope, and the output is viewed in time base setting as shown in Figure 3. The cantilevers were excited with vibration from the electrodynamics shaker at a range of frequency from 10 Hz to 500 Hz with the acceleration level (g-force) fixed at constant magnitude 1-g (9.81 m/s2) and the phase different between the cantilevers was calculated using Equation 1.

$$\theta = \left(\frac{w}{x}\right) \times 360° \qquad (1)$$

where, θ is the phase shift of cantilever, w represents the phase shift in term of centimeter (cm) and x represents one period in term of cm. The test was then repeated by replacing the cantilever C1 with C2, C3 and C4.

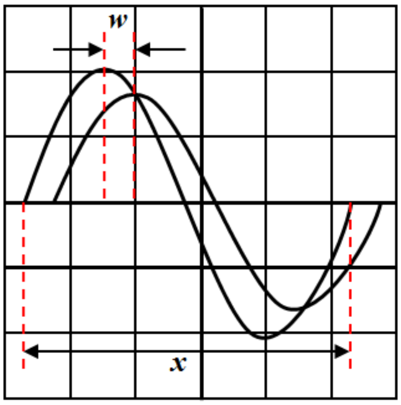

Figure 3. Illustration of phase shift measurement by using Time Different Method

2.2. Lissajous Pattern Method

While for Lissajous pattern method, the cantilever CC and C1 are connected individually to the oscilloscope, and the output is viewed in X-Y mode of the oscilloscope as shown in Figure 4, where the phase different between cantilevers CC and CL can be observed and measured. The cantilevers were again excited with vibration from the electrodynamics shaker at a range of frequency from 10 Hz to 500 Hz with the acceleration level (g-force) fixed at constant magnitude 1-g (9.81 m/s2) and the phase different between the cantilevers was calculated using Equation 2.

$$\theta = 180° - (sin^{-1}\left(\frac{y}{z}\right)) \quad (2)$$

where, y represent the intersection at y-axis in cm and z represent the maximum height of the ellipse in cm. The test was then repeated by replacing the cantilever C1 with C2, C3, and C4.

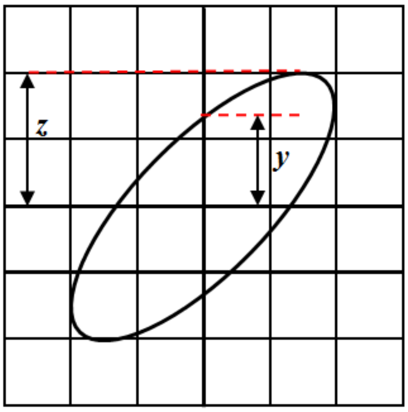

Figure 4. Illustration of phase shift measurement by using Lissajous Pattern Method

3. Experimental Result

The output waveform of C1, C2, C3, and C4 is being observed by comparing to CC. The result of the phase different for the cantilevers is shown in Figure 5 for Time Difference Method and Figure 6 for Lissajous Pattern Method.

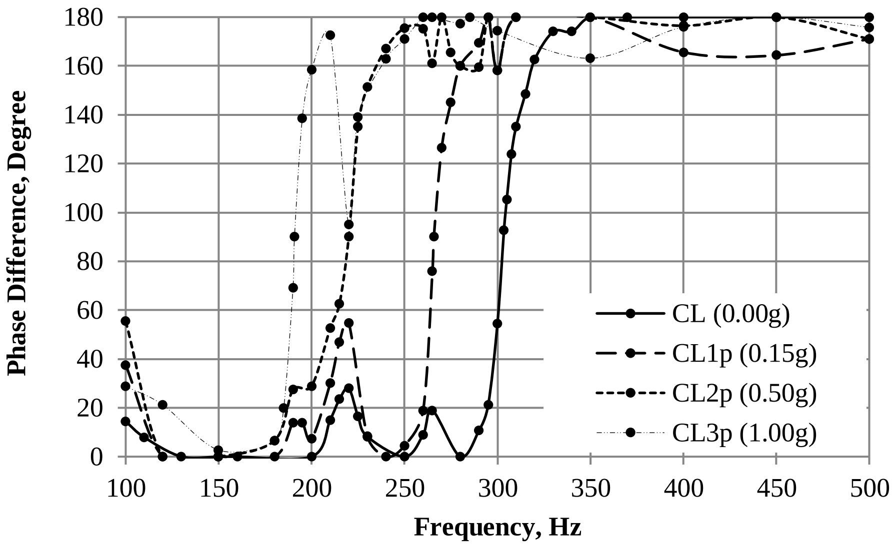

Figure 5. Phase shift of Cantilevers with Proof Mass Attached Obtained using Time Different Method

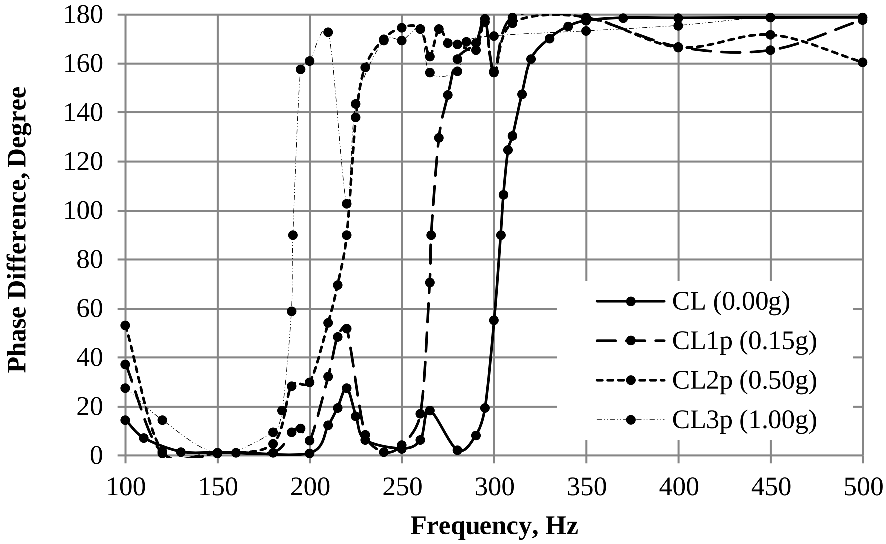

Figure 6. Phase shift of Cantilevers with Proof Mass Attached Obtained using Lissajous Pattern Method

Both methods showed similar result where the major phase shift happened at the resonant frequency of respective cantilevers. The phase difference remains low around 0 degrees before their resonant frequency. When the frequency of the vibration source approaches the resonant frequency of respective cantilever, the phase different between the test cantilever and the constant cantilever start to increase rapidly and reach 180 degree after the resonant frequency. Major phase shifting happen at 300Hz for C1, 270Hz for C2, 220Hz for C3, and 180Hz for C4. Notice that there are also ripples shows in the graph. Cantilevers with heavier proof mass, have larger ripples. Proof mass was attached to the tips of the cantilevers in order to alter its resonant frequency. Frequency responses for individual cantilevers with added proof mass of 0.15g, 0.50g, and 1.00g to C2, C3, and C4 respectively are shown in Figure 7. Notice that the resonant frequency of C1, C2 and C3 is reduced. Resonant frequency for C1, C2, C3, and C4 are 300 Hz, 270 Hz, 220 Hz, and 180 Hz with maximum voltage of 1.99V, 2.24V, 1.88V, and 1.82V respectively.

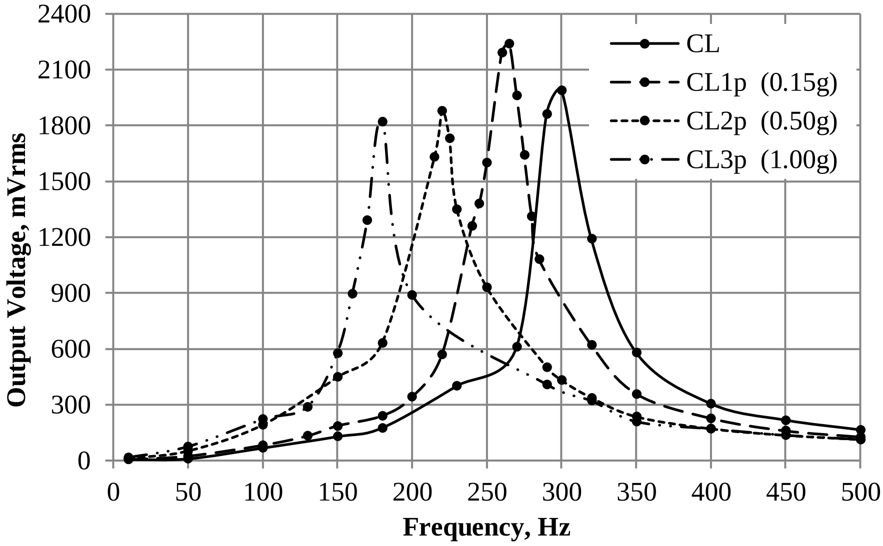

Figure 7. Frequency Response in term of Output Voltage for Multiple Cantilevers with Proof Mass

These altered cantilevers were then connected together electrically in series connections in order to observe the effect of phase shifting of the piezoelectric cantilever toward its output performance. The frequency responses for cantilevers connected in series with same polarity connection is shown in Figure 8, while result for series with alternating polarities connection is shown in Figure 9.

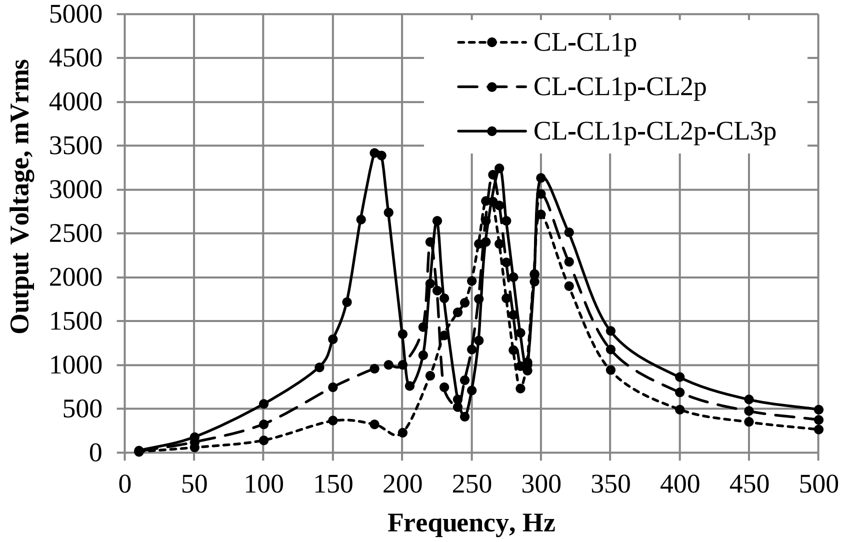

Figure 8. Frequency Responses (Voltage) for Cantilevers Connected in Series with Same Polarity Connection.

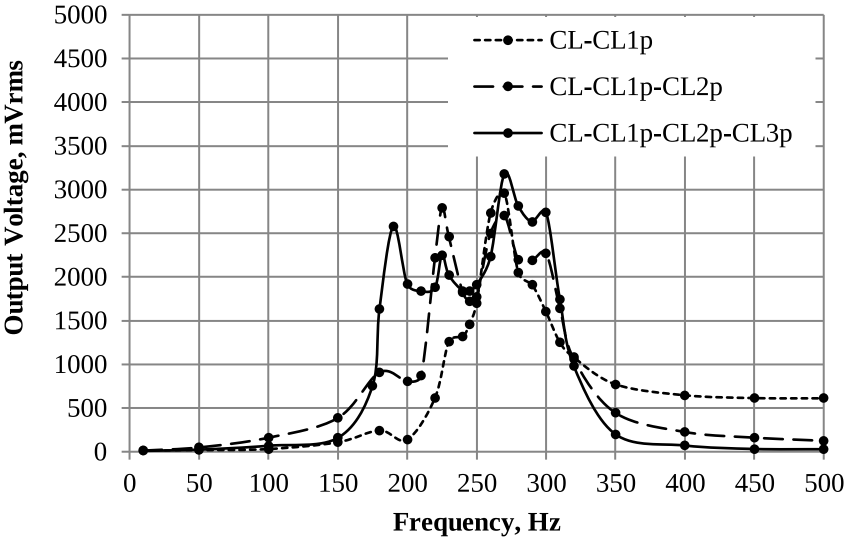

Figure 9. Frequency Responses (Voltage) for Cantilevers Connected in Series with Alternating Polarities Connection.

Notice that another peak is formed whenever another cantilever is added. For example, when two cantilevers are connected, two peaks were formed; while when three cantilevers are connected, three peaks were formed. These peaks are formed around the resonant frequency of each respective cantilevers added, where when C1 and C2 are connected, peaks formed at 300Hz and 270Hz; when C1, C2 and C3 are connected, peaks formed at 300Hz, 270Hz and 220Hz; and when C1, C2, C3 and C4 are connected, peaks formed at 300Hz, 270Hz, 220Hz, and 180Hz. 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. 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.

This narrow gap will not form if the output waveforms for each cantilever are in phase. Both result in Figure 5 and 6 proved that the phase of the output waveform shift at the resonant frequency of each cantilever, it explain 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.

This report is further proven by the result shown in Figure 9, where the piezoelectric cantilever is connected in series but with alternating polarities. 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 narrow gap between peaks are not as low as in waveform produced by the same polarity connection. For example, for applications that operate with 1.8V voltage input, the operating frequency of four connected cantilevers increased to the range of 180Hz to 310Hz compared to same polarity connecting, this alternating polarities connecting does not have gaps in between the operating frequency.

This major phase shifting is the reason for the significant rise at the gap in between the peaks formed in Figure 9. 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 shown in Figure 8. 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.

4. Conclusion

The result showed the output waveform of piezoelectric cantilevers do shift at its respective resonant frequencies. Both time different and Lissajous pattern method showed that the major phase shift happened at 300Hz for C1, 270Hz for C2, 220Hz for C3, and 180Hz for C4. The phase difference remains low around 0 degrees before their resonant frequency. When the frequency of the vibration source approaches the resonant frequency of respective cantilever, the phase different between the test cantilever and the constant cantilever start to increase rapidly and reach 180 degree which is out of phase after the resonant frequency. Since the output waveform is not in phase, it contributed to the significant rise at the gap in between the peaks formed when piezoelectric cantilevers are connected in series with alternating polarities.

In nutshell, it proves that the output waveform of piezoelectric cantilever do experience major phase shifting at its respective resonant frequencies. This finding could take into account in order to maximize the performance of the output from piezoelectric cantilever array in other applications.

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