Characterization on Resonant Shifting of Cantilever Based Piezoelectric for Battery-Less Low-Frequency Acceleration Measurement

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Abstract*— Piezoelectric cantilever is a structure that can translate maximum mechanical vibration energy into an electrical signal used as both sensor and generator or vice versa. At a frequency near to the resonant of the piezoelectric cantilever, larger deviation angle can be achieved which lead to potentially higher electrical power can be generated; therefore piezoelectric cantilever is mostly functioned as a micro-power generator at resonance region. While at a non-resonant frequency, the voltage output generated is rather linear and proportional to the acceleration level of the vibration; therefore in this non-resonance region, piezoelectric cantilever often functions as an accelerometer. This paper shows the potential of the ready-made piezoelectric cantilever to be altered in order to perform as a self-powered accelerometer which is independent to the influence of the frequency. The output response of the piezoelectric cantilever is characterized by modifying the length of the cantilever. The cantilever length is reduced in order to shift the resonant frequency region of the piezoelectric cantilevers to higher frequency region to make sure that the output is independent toward the vibrating frequency. The resonant frequency of cantilever at its original condition is 290H. After length reduction of 0.7cm, the resonant frequency increased to 320Hz. The resonant frequency of the cantilever continues shifted to 400Hz after length reduction of 1.0cm, 500Hz for length reduction of 1.2cm, and lastly 780Hz for length reduction of 1.5cm. After the resonant frequency of the cantilever is shifted to 780Hz, the linearity of the piezoelectric cantilever improved from 90% deviation at a frequency range of 100Hz to 250Hz, to 15% deviation at a frequency range of 100Hz to 300 Hz. These results show a major improvement in the linearity of the output of the piezoelectric cantilever when the resonant frequency is a shift away from the operating frequency.

***Index Terms*— Accelerometer; Energy Harvester; Linearity; Self-Powered.**

I. Introduction

The piezoelectric crystal is known for its capability to convert mechanical energy to electrical charges when force is applied on the material, or vice versa where external electrical energy applies on the piezoelectric crystals may cause deformation on the shape of the crystal. The piezoelectric material is usually applied on mechanical structures, such as cantilever which is designed for accurate inertial measurement [1]. Typically, the direct piezoelectric effect, where piezoelectric material generates electrical energy when mechanical force is applied, allows the piezoelectric structure to act as a generator or a sensor. The piezoelectric cantilever at non-resonant frequency region piezoelectric cantilevers are mostly being utilized as a sensor as the output is dependent to the frequency, while at resonant frequency region is being utilized as power generator since it produces higher power value. Figure 1 shows that the region closer to the resonant frequency will have its linearity influenced [2]. This means that at a frequency far from the resonant the output of the piezoelectric is independent to the frequency, while at a frequency near to resonant the output of the piezoelectric is dependent on the frequency. In order to design an acceleration level sensor using the piezoelectric material, the output of the piezoelectric cantilever needs to be linear even when the frequency of the vibration source varies. The linearity of the output from the piezoelectric cantilever needs to be analyzed and altered to optimize the performance of the designed accelerometer.

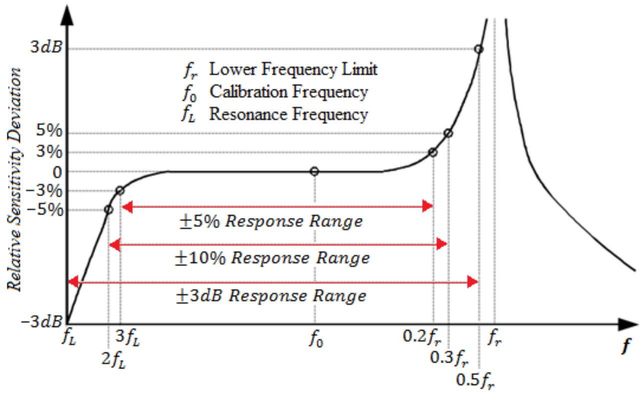
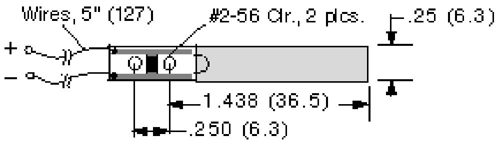


Figure 1. Frequency Response Curve [5]

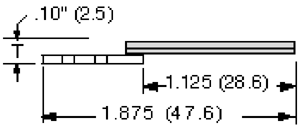
This paper shows the potential of off the shelf piezoelectric cantilever to be tuned or altered in a way to act as a self-powered low-frequency accelerometer which is independent of the frequency of the vibration. Since many of appliances are operating at low-frequency range [3], hence non-resonant frequency range higher than its resonant frequency is not selected in this research. In the other hand, the non-resonant frequency range that is lower than its resonant frequency is narrower. Therefore, it is essential to shift the resonant frequency to the higher region in order to make sure it will not influence the linearity of the piezoelectric cantilever at its operating frequencies. Overall, this paper demonstrates the effect of length reduction of the piezoelectric cantilever towards its resonant frequency [4] and its effect on improving the linearity of the output of piezoelectric cantilever at non-resonant frequency region.

II. Experimental Set-Up

The piezoelectric cantilever used in this paper is a standard quick-mount bending generator with pre-mounted and wired at one end (Q220-A4-303YB) from Piezo Systems, Inc [6]. The piezoelectric cantilever is named CL for reference convenient, and its dimension is as shown in Figure 2. The market available piezoelectric cantilever is used in this research in order to show the potential of the readymade piezoelectric material to be altered to suit the requirement of the designed system. By modifying the length of readymade piezoelectric material, the resonance frequency of the piezoelectric cantilever can be tuned and shift to the exact value to accommodate the desired operating frequency. It is essential that the piezoelectric cantilever is tunable in order to maximize its performance in different operating condition [7].



(a) Top View



(b) Side View

Figure 2. Dimension of Piezoelectric Cantilever (Q220-A4-203YB) [6].

The experiment set-up of this research is as shown in Figure 3, which consists of an oscilloscope, a function generator, a G-link wireless sensor and receiver, a gain amplifier, an electrodynamics shaker, 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 electrodynamic 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 [8].

In order to investigate the linearity of the piezoelectric cantilevers, the output voltage produced by the cantilever is observed when it is excited under vibration produce by the electrodynamics shaker at a fixed frequency but various acceleration level (g-force) from 0.5-g to 5-g. Low acceleration level of 0.5-g to 5-g level is selected because ambient vibration source normally has low acceleration level [3]. Data was collected when the cantilever was excited with vibration from the electrodynamics shaker at a frequency fixed at 100 Hz but varies acceleration level (g-force) of 0.5-g to 5-g to observe the output response of the piezoelectric cantilever toward different acceleration level. The test was continued with the same cantilever, but excited with vibration source of frequency fixed at 150 Hz, 200 Hz, 250Hz and then 300 Hz.

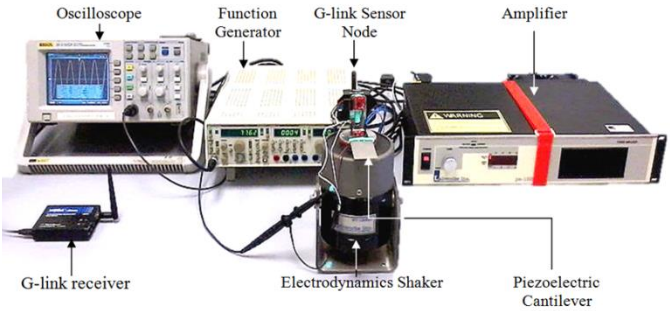


Figure 3. Experimental Set-up

With the intention to shift the resonant frequency of the cantilever away from the selected operating frequencies, to a higher region, the experiment continues by reducing the effective length of the piezoelectric cantilever [9-10]. The length of the cantilever is reduced by clamping the cantilever over than its clamping base, towards its flexible beam as illustrated in Figure 4. Then, based on the frequency response of the piezoelectric cantilever, the cantilever with most suitable clamping over length is selected.

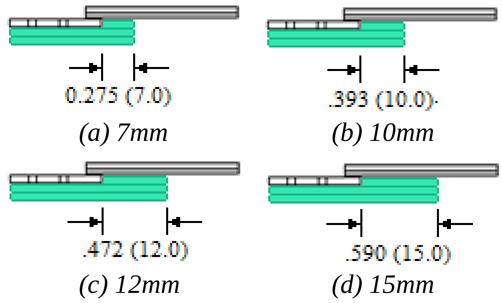


Figure 4. Illustration for Reducing Cantilever Length by Clamping Over

With the selected clamping over length, the linear response of the cantilever is observed again. The output voltage of the cantilevers was recorded when they were excited with vibration from the electrodynamics shaker at a frequency fixed at 100 Hz but various acceleration level (g-force) of 0.5-g to 5-g. The test was then repeated with vibration frequencies of 150 Hz, 200 Hz, 250 Hz, and then 300 Hz.

The relative sensitivity deviation is calculated in order to recreate the graph shown in Figure 1 [5]. The frequency response curve of cantilever CL at the reference frequency of 200 Hz at 1 g-level is plotted for further analysis. Since, the voltage output is used as the acceleration level indicator signal in this paper and voltage sensitivity is the voltage value per unit of acceleration [5], hence the relative sensitivity deviation in dB can be calculated using Equation 1 and Equation 2.

$$Relative\ Sensitivity\ Deviation = 20\,log_{10}\left(\frac{\left(\frac{V}{g-level}\right)}{\left(\frac{V_{ref}}{g-level}\right)}\right) \quad (1)$$

$$= 20\,log_{10}\left(\frac{V}{V_{ref}}\right) \quad (2)$$

where, in this case, V_ref is the voltage value when the frequency is 200Hz. The frequency of 200Hz is chosen in this case, because it is the middle point of the testing frequency range which is from 100Hz to 300Hz.

III. EXPERIMENTAL RESULTS

The output response of cantilever CL, when placed under vibration source with vary range of acceleration level, is shown in Figure 5. The result shows that the linearity of the cantilevers at a frequency range from 100 Hz to 500 Hz is undesirable as it is dependent on the frequency of the vibration. Even though the vibration acceleration level remains constant, the output voltage increases significantly when the frequency increased. Even when the result obtained for 300 Hz in Figure 5 is excluded in Figure 6, the percentage of deviation still showing a high number of 90% deviated from the trendline which is the mean of the collected data. This is undesirable because a single acceleration level would give varies output value at different frequencies. Hence, in order to design an acceleration sensor with high accuracy, it is essential to minimize the difference.

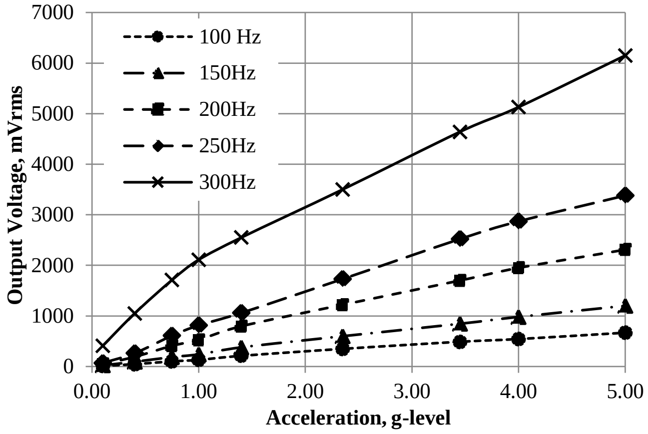


Figure 5. Output Voltage obtained under Variation of Acceleration Level.

The further it is from its resonant frequency, the output would be more constant. In this paper, a self-powered accelerometer is designed for low-frequency application. However, the original resonant frequency of the cantilever, 290Hz is too near to the desired operating frequency. The result obtained in Figure 5 and Figure 6 show that piezoelectric cantilever with a resonant frequency near to the operating frequency is not ideal for acceleration level sensor application. The resonant frequency of the cantilever needs to be shifted further away from the operating frequency in order to improve the linearity of the accelerometer output produced at operating frequency. One of the methods to shift the resonant frequency higher is by increasing the stiffness of the cantilever. This can be done by reducing the effective length by clamping the cantilever even more toward the beam of the cantilever.

In this paper, the length of the cantilever, CL is reduced 0.7cm, 1.0cm, 1.2cm and 1.5cm from the actual length. The new frequency response of the altered cantilever is as shown in Figure 7. The result shows that reducing in cantilever length indeed increased the resonant frequency of the cantilever. The resonant frequency of cantilever at normal condition is 290Hz, increased to 320Hz after length reduction of 0.7cm, increased to 400Hz after length reduction of 1.0cm, 500Hz for reduction of 1.2cm, and lastly 780Hz for reduction of 1.5cm.

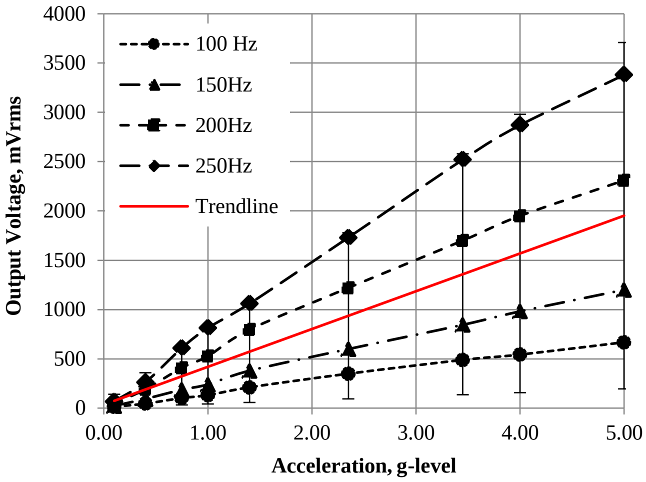


Figure 6. Output Voltage obtained under Variation of Acceleration Level with Trendline and Deviation Bar.

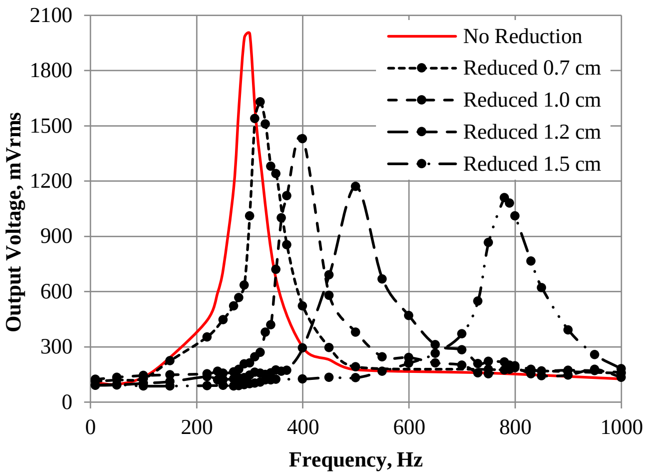


Figure 7. Frequency Response of the Cantilever after Length Reduction.

When the resonant frequency of the cantilever is increased, the output value produced by the cantilever before their resonant frequency is getting linear. This is desirable as it would help in producing an even more accurate value when acting as a sensor. However, note that the output value of left-sided tail of the graph also decreased with the increasing of the resonant frequency. This, in fact, is undesirable as with low output voltage, might be not sufficient to act as a signal to indicate the acceleration level of the vibration. The result in Figure 7 shows that the cantilever with 1.5cm has a lower deviation in its output for frequency ranging in between 10Hz to 500Hz, with the minimum voltage output of 0.87V and a maximum voltage of 1.34V. Hence, a cantilever with 1.5cm reduction in length is selected to act as an acceleration sensor in this research.

The linearity of the cantilever after length reduction of 1.5cm was tested under variation of acceleration level again. The result is shown in Figure 8. Based on the result after length reduction, the linearity of the cantilever definitely improved as compared to the result obtained in Figure 5 and 6. The result improved from 90% deviation even after excluding the result from 300Hz before length reduction, to 15% deviation including the result from 300Hz after length reduction, which is a major improvement in linearity. For example, before length alteration, the piezoelectric cantilever exposed to vibration of 1-g acceleration level, would produce 0.131V for 100Hz, 0.240V for 150Hz, 0.409V for 200Hz, 0.61V for 250Hz and 2.11V for 500Hz. After length alteration, when the cantilever exposed to vibration of 5-g acceleration level, would produce 0.062V for 100Hz, 0.068V for 150Hz, 0.076V for 200Hz, 0.081V for 250Hz and 0.086V for 500Hz. The deviation reduced from between 0.131V and 2.11V to between 0.062V and 0.086V after length alteration.

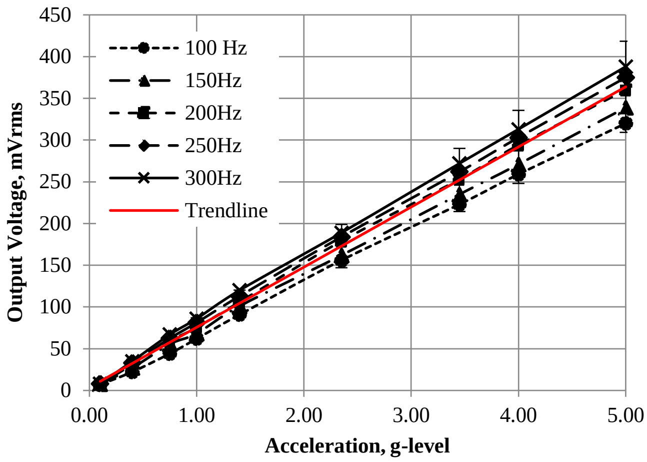


Figure 8. Output Voltage obtained under Variation of Acceleration Level after Resonant Frequency Alteration with 1.5 cm cantilever length reduction.

The frequency response curve of the designed generator was calculated based on the reference voltage of the sensor in order to observe the difference of the output from generator compared to output from the sensor. The frequency response curve in Figure 9 shows that the maximum relative sensitivity deviation of CL before alteration is 14dB and reduces to 1dB after alteration at a frequency range of 100Hz to 300Hz. This shows that the linearity of the piezoelectric cantilever improved after the resonant frequency is shifted to a higher region.

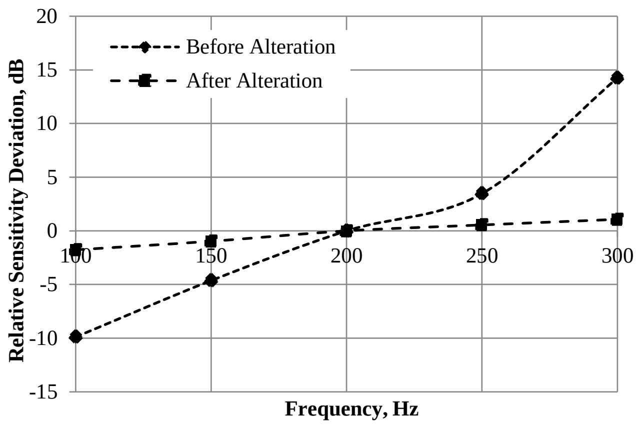


Figure 9. Frequency Response Curve for CL Before and After Alteration.

IV. CONCLUSION

This paper shows the potential of the market available piezoelectric cantilever to be altered in a way to produce an optimum self-powered acceleration level sensor. In order for a piezoelectric cantilever to function as an acceleration level sensor, its output needs to be constant even when the frequency of the vibration source is varied. A number of researchers show that the output of the piezoelectric cantilever is independent to the frequency when it is at a frequency far away from it resonant frequency. Therefore, in this paper, the resonant frequency of the piezoelectric cantilever is tuned to the higher frequency region in order to design a low-frequency accelerometer. The resonant frequency of the cantilever is shifted to the higher region by reducing the length of the cantilever. When the length of the cantilever is reduced, its stiffness increased. Hence its resonant frequency shifted to higher region. Length reduction of 1.5cm is selected as the resonant frequency is furthest. Further length reduction is not recommended as the output at low frequencies would decrease and will not be sufficient to act as a voltage signal. Beside that, the sensitivity of the piezoelectric cantilever as accelerometer would also greatly reduces. After the alteration, the output deviation of the piezoelectric cantilever reduced from 90% between the frequency range of 100Hz and 250Hz to 15% between the frequency range of 100Hz and 300Hz. By converting the result to response curve, its shows that the maximum relative sensitivity deviation of CL before alteration is 14dB and reduces to 1dB after alteration at frequency range of 100Hz to 300Hz. This demonstrates that after the alteration, the output of the cantilever will not deviate so much for the same acceleration level anymore even though its frequency is varying. It is important to minimize the deviation in order to design an accelerometer with high accuracy.

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