

Linearity Improvement for Cantilever Based Piezoelectric by Using Resonant Shifting Method

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Abstract— Piezoelectric cantilever as a resonant structure can be used both as a sensor as well as an energy harvester. When excited at a frequency near to its resonant, maximum electrical power is generated, therefore it functions as a micro-power generator. When excited to a frequency which is far from the range of the resonant, the voltage signal generated is comparatively linear at the non-resonant region and proportional to the acceleration level; therefore, in this region of frequency it functions as a sensor. This paper demonstrates the potential of the piezoelectric cantilever to be altered in a way to act as a battery-less acceleration sensor which is independent to the frequency. The frequency response of the piezoelectric cantilever is characterized by altering the cantilever length with the intention to shift the resonant frequency region of the piezoelectric cantilevers higher region so it will not influence the output response of the piezoelectric cantilever. The resonant frequency of cantilever at normal condition is 300Hz, 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. After length reduction of 1.5cm, the linear response of the piezoelectric cantilever improved from 90% error deviation to 15% error deviation, which is a major improvement in the linearity of the piezoelectric cantilever's output.

Index Terms— Accelerometer; Energy Scavenger; Linearity; Self-Powered.

I. INTRODUCTION

Piezoelectricity is known as the capability of particular quartz crystals to generate electrical energy when mechanical force is applied on it or vice versa where the application of external electrical energy on the piezoelectric crystals may cause deformation on the shape of the crystal. Piezoelectric material usually integrated into mechanical structures, such as cantilevers which can be configured for accurate inertial measurement [1]. Usually, the direct piezoelectric effect, where piezoelectric material converts mechanical energy into electrical energy effect is accountable for the materials capability to act as a generator or a sensor as demonstrated in many papers [2-4]. Typically, the piezoelectric cantilever at resonant frequency region is being utilized as power generator since it produces higher power value, while at non-resonant frequency region piezoelectric cantilevers are mostly being utilized as a sensor as the output is dependent to the frequency. The region that closes to the resonant frequency will have its linearity influenced [5]. This implies 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 to the frequency. For a piezoelectric cantilever to function as an acceleration level sensor, its output needs to be linear even when the frequency of the vibration source varies. Therefore, in order to design a piezoelectric cantilever based acceleration sensor, the linearity of the output from the cantilever needs to be investigated and altered to optimize the sensor.

This paper demonstrates the potential of the piezoelectric cantilever to be altered in a way to act as a battery-less low-frequency acceleration sensor which is independent to the frequency of the vibration. Since many of appliances are operating at low-frequency range [6], hence non-resonant frequency range higher than its resonant frequency is not selected in this research. The non-resonant frequency range that is lower than its resonant frequency in the other hand is narrower; hence it is necessary to shift the resonant frequency to the higher region in order to make sure it will not influence the linearity of the cantilever at low operating frequencies. This paper shows the effect of length reduction of the cantilever towards its resonant frequency [7] and its effect on improving the linearity of the piezoelectric cantilever's output at non-resonant frequency region [8].

II. EXPERIMENTAL SET-UP

The piezoelectric cantilever used in this research is a standard quick-mount bending generator with pre-mounted and wired at one end (Q220-A4-303YB) from Piezo Systems, Inc [9]. The cantilever is named CL for reference convenient. The dimension of the piezoelectric cantilever is as shown in Figure 1. The off-the-shelf piezoelectric cantilever is used in this research in order to demonstrate the potential of altering the market available piezoelectric material to suit the requirement of the designed application.

The experiment set-up of this research is as shown in Figure 2, which consists of an oscilloscope, a function generator, a G-link wireless sensor and receiver, a gain amplifier, an electrodynamic shaker, and piezoelectric cantilevers. In order to generate a controllable artificial vibration for test purpose, function generator, gain amplifier, electrodynamic shaker, and G-link wireless accelerometer was 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 amplify the power before supplying it to the

electrodynamics shaker.

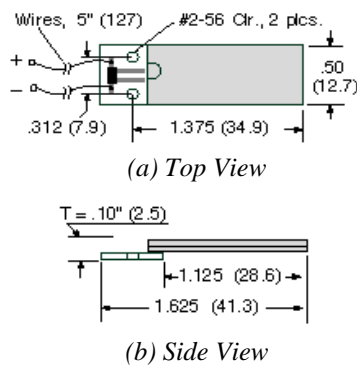


Figure 1: Dimension of Piezoelectric Cantilever (Q220-A4-303YB) adapted from Piezo Inc [9].

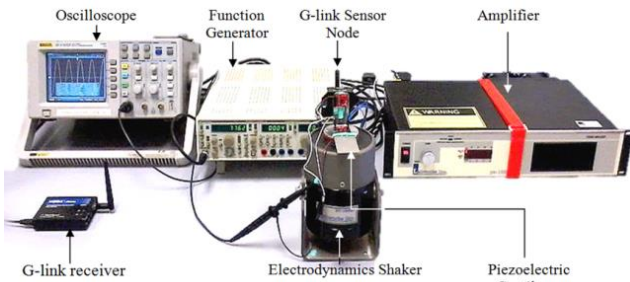


Figure 2: Experimental Set-up

In order to investigate the linearity of the piezoelectric cantilevers, the output voltage produced by the cantilever is recorded when it is excited with vibration from the electrodynamic 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 [6]. Data were collected when the cantilever was excited with vibration from the electrodynamic 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, 250 Hz and then 300 Hz.

In order to shift the resonant frequency of the cantilever away from the selected operating frequencies, the experiment continues by reducing the effective length of the piezoelectric cantilever. The length of the cantilever is reduced by clamping the cantilever over than its clamping base, towards its flexible beam as illustrated in Figure 3 [10]. Then, based on the frequency response of the piezoelectric cantilever, the cantilever with most suitable clamping over length is selected.

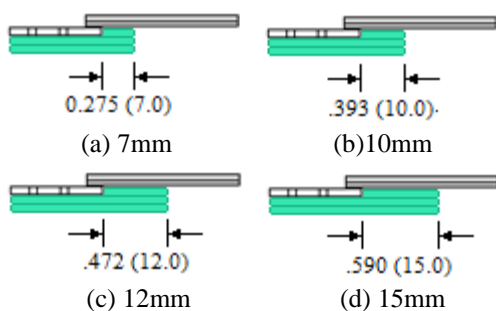


Figure 3: Illustration for Reducing Cantilever Length by Clamping Over

With the selected clamping over length, the linear response of the cantilever is tested again. The output voltage of the cantilevers was recorded when they were excited with vibration from the electrodynamic 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.

III. EXPERIMENTAL RESULTS

The output response of cantilever CL when exposed to vibration source with varies acceleration level is shown in Figure 4. The result shows that the linearity of the cantilevers is not desirable. The output voltage increased drastically when the frequency increased even though the acceleration level remains constant. Even if the result obtained from 300 Hz in Figure 4 is excluded as shown in Figure 5, the percentage of error deviation is still showing a high number of 90%. This is undesirable because a single acceleration level would give different output value at different frequencies. Hence, it is essential to minimize the difference in order to design an acceleration sensor with high accuracy.

Researches show that the output of the piezoelectric cantilever is independent to the frequency when it is at a frequency far away from its resonant frequency. The further it is from its resonant frequency; the output would be more linear. In this case, an acceleration sensor for low-frequency application is needed. However, the resonant frequency of the cantilever, 300 Hz is too near to the operating frequency. The result obtained in Figure 4 and Figure 5 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 increase the linearity of the output produced at operating frequency. One of the methods to shift the resonant frequency higher is to reduce the length of the cantilever. This can be done by clamping the cantilever even more toward the beam of the cantilever.

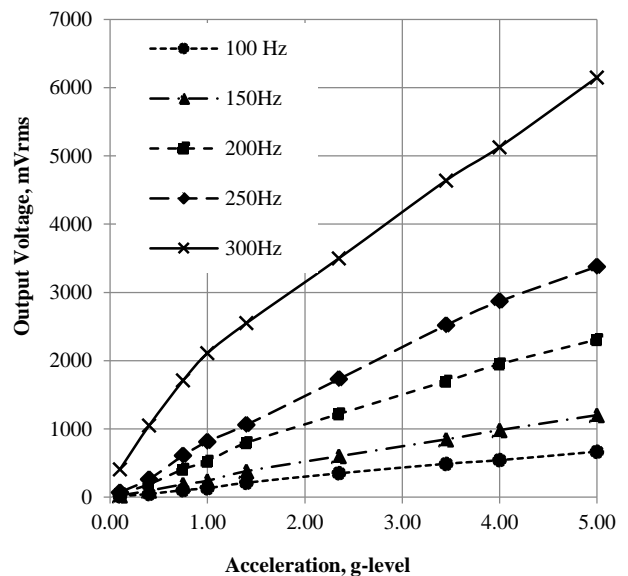


Figure 4: Output Voltage obtained under Variation of Acceleration Level

The length of the cantilever, CL is reduced 0.7cm, 1.0cm, 1.2cm and 1.5cm from the actual length and the new frequency response of the length reduced cantilever shows in Figure 6. The result shows that decreasing in cantilever length increased the resonant frequency of the cantilever. The resonant frequency of cantilever at normal condition is 300Hz, 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.

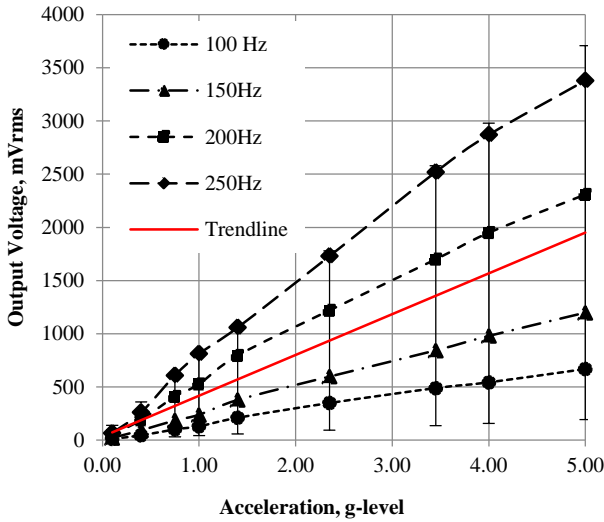


Figure 5: Output Voltage obtained under Variation of Acceleration Level with Trendline and Error Bar

Notice that 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 increase of the resonant frequency. This in fact is not desirable as with its output voltage too low, it might not be sufficient to act as a signal to indicate the acceleration level.

The result in Figure 6 shows that the cantilever with 1.5cm reduction shows high linearity in its output for frequency ranging between 10Hz to 500Hz, with the minimum voltage output of 0.87V and a maximum voltage of 1.34V. Hence, a cantilever with a 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 7. Based on the result after length reduction, the linearity of the cantilever definitely improved as compared to the result obtained in Figure 4 and 5.

The result improved from 90% error deviation even after excluding the result from 300Hz before length reduction, to 15% error 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 5-g acceleration level, would produce 0.67V for 100Hz, 1.20V for 150Hz, 2.31V for 200Hz, 3.38V for 250Hz and 6.15V for 500Hz. After length alteration, when the cantilever exposed to vibration of 5-g acceleration level, would produce 0.32V for 100Hz, 0.34V

for 150Hz, 0.36V for 200Hz, 0.38V for 250Hz and 0.39V for 500Hz. The deviation error reduced from between 0.67V and 6.15V to between 0.32V and 0.39V after length alteration.

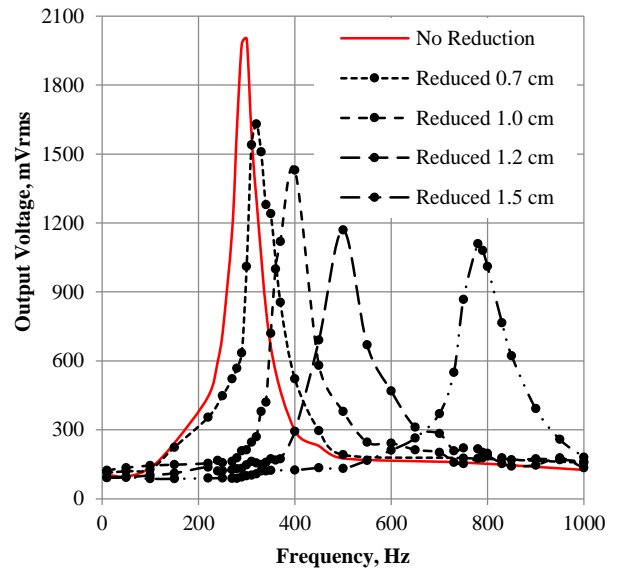


Figure 6: Frequency Response of the Cantilever after Length Reduction

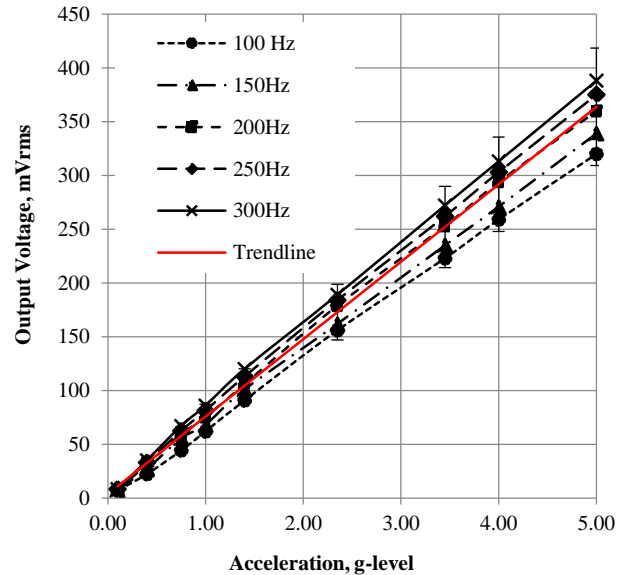


Figure 7: Output Voltage obtained under Variation of Acceleration Level after Resonant Frequency Alteration with 1.5 cm cantilever length reduction.

IV. DISCUSSION AND CONCLUSION

This paper demonstrates the potential of the cantilever-based piezoelectric material to be altered in a way to produce an optimum battery-less acceleration level sensor. For a piezoelectric cantilever to function as an acceleration level sensor, its output needs to be linear even when the frequency of the vibration source varies. Researches show that the output of the piezoelectric cantilever is independent to the frequency when it is at a frequency far away from its resonant frequency. Hence, in this paper the resonant frequency of the cantilever is shifted toward the right frequency region in order to make use of its left tail frequency region as an acceleration sensor. The resonant frequency of the cantilever is increased by reducing the length of the cantilever. This is due to the fact that the stiffness of the cantilever increases when its length is reduced, hence its resonant frequency shifted to a higher

region. Length reduction of 1.5cm is selected as the resonant frequency is furthest. Further length reduction is not recommended as the output produced by the cantilever at low frequencies would decrease and will not be sufficient to act as a voltage signal or significantly reduce the sensitivity of the piezoelectric cantilever as an accelerometer. After length reduction of 1.5cm the deviation reduced from 90% between the frequency range of 100Hz and 250Hz to 15% between the frequency range of 100Hz and 300Hz. This means after the increase in the resonant frequency of the cantilever, the output of the cantilever will not deviate so much from the same acceleration level even though its frequency is changing. It is crucial to minimize the difference in order to design an acceleration sensor with high accuracy.

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