High Power Output of L-shape PZT Power Generator Working in Bending-Shear Mode

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***Abstract*—This paper proposes a new L-shape PZT vibration power generator designed to generate electrical power when working in bending-shear mode. The L-shape structure can utilize the linear motion of vibration to generate torsion force on the PZT device attached to the structure for energy generation in both bending and shear motions. At first, a simulation study for evaluating the structure's stress and natural frequency was conducted using Solidworks software. The result shows that the first natural frequency of the structure was at 21 Hz, and it was almost uniformly distributed in terms of distribution of the stress. Next, an experimental analysis was conducted to evaluate the electrical power generation at the first mode of the natural frequency. Lastly, the performance of the proposed power generator was compared to the typical structure of cantilever PZT power generator. The results show that the proposed device was able to produce higher electrical power than the typical cantilever of PZT devices.**

***Index Terms*—PZT Power Generator; Bending-Shear Mode.**

I. INTRODUCTION

The challenges in the development of vibration energy regeneration system are something worthwhile to be taken by researchers in this field because sources of vibrations are unlimited. To generate electrical power from the ambient vibrations is not difficult, but to optimize the output is a challenge. In the past few decades, various techniques and methods have been proposed and presented by researchers on the topic of optimization of the output power of vibration energy harvester. Among the two devices that can convert vibration into electrical power are the theoretical calculation and the experimental evaluation that shows that piezoelectric device is able to produce electrical power with wider range of output voltage [1-2].

Piezoelectric device converts vibrations into electricity through the piezoelectric effect. Generally, it works in three basic operations, namely transverse (d_{31}) mode, longitudinal (d_{33}) mode and shear (d_{15}) mode [3]. The capability of each mode of operation to generate electricity is dependent on the product of two material properties; the piezoelectric strain constant d and piezoelectric stress constant g [4]. Literature that presents vibration energy harvesting in transverse and longitudinal mode operations can be found in [5-9]. However, it has been pointed out that most of the piezoelectric composites have higher d_{15} and g_{15} value when compared to that of the transverse and longitudinal mode [10]. Further study by later researchers has proven that while working in d_{15} mode, the performance of the PZT energy harvester can be improved [12-15]. Hence, this paper presents a new lead zirconate titanate (PZT) vibration power generator device in L-shape, which can utilize the linear motion of vibration to operate in the bending-shear mode for electricity generation. The performance of this power generator was also compared with the typical cantilever PZT power generator.

II. CONCEPT OF POWER GENERATOR

A typical model of PZT power generator in the form of cantilever beam can be found in Figure 1. The model in this figure shows a PZT cantilever is attached to a vibrating structure at one end, while the other end is free. In most of the cases, vibrations in which linear in motion are applied in y-axis so that the piezoelectric cantilever will be deflected in the same axis. The poling direction will eventually be oriented along the thickness of the device. Devices in this structure operate in d_{31} mode, where they utilize the vertical bending vibrations to generate electricity. To allow a bigger deflection to the beam, an auxiliary mass is attached to the free end. The relationship of the auxiliary mass and the deflection and the ability of power generation is another good research theme as well.

As mentioned in the previous section, PZT power generator can be designed and constructed so that it can operate in a specific mode. The basic structure of the proposed power generator is an L-shape of plate made of aluminum, as can be seen in Figure 2. The whole structure of the power generator consists of a vibrating part where one end of the plate is attached to it and an auxiliary mass is attached at the other end of the plate. With this structure, when linear motion vibrations are applied at the vibrating part, the auxiliary mass will vibrate in the same direction. Subsequently, section A of the plate will by forced rolling around the x-axis. As the plate rolls around, it creates a torsional force on the plate's surface. This torsional force can be utilized for the electricity generation, if PZT device is bonded on the plate. Besides the torsional force, section A of the plate will also experience a stress force due to the vertical vibration that comes from the same auxiliary mass.
The characteristic of the forces on the surface of the plate can be observed by performing a stress force analysis using Solidworks software.

Table 1
Results of natural frequency analysis

Mode	Frequency [Hz]
1st	21.95
2nd	90.43
3rd	214.78
4th	391.57
5th	550.25

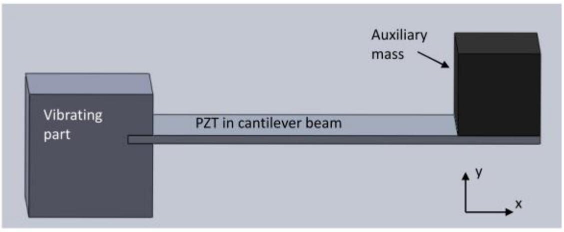

Figure 1: Typical structure of cantilever beam

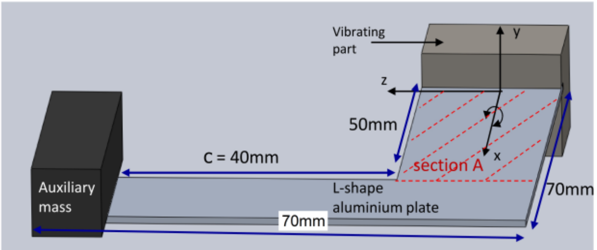

Figure 2: L-shape aluminum plate with auxiliary mass

The simulation result can be used later for the piezoelectric device placement as the target is to place the device on the surface with the highest torsional and stress force distribution.

The parameter of the plate is as shown in Figure 2. The thickness of the plate is 1mm and the weight of the auxiliary mass is 28.0g. For the purpose of analyzing the stress distribution, the vibrating part was set to fix and a total of 2.1N of force was applied uniformly on the top surface of the auxiliary mass in the negative direction of y-axis. The simulation result is shown in Figure 3. As can be seen, the sum of the forces were almost uniformly distributed on the surface of section A. Uniformity in the forces distribution will reduce the charge cancellation which can reduce the output of the power generator [3]. By using the same software, natural frequency analysis was also conducted and their results are listed in Table 1.

Natural frequency data of the structure can be used for the comparison purpose with the experimental results later. It is important to identify the natural frequency of the structure for the matching impedance calculation. Limit of the software in analyzing the natural frequency is up to the 5^{th} mode. In the later experimental analyses, due to the significant effect in the power generation, we focus our work for the output response below than 100 Hz.

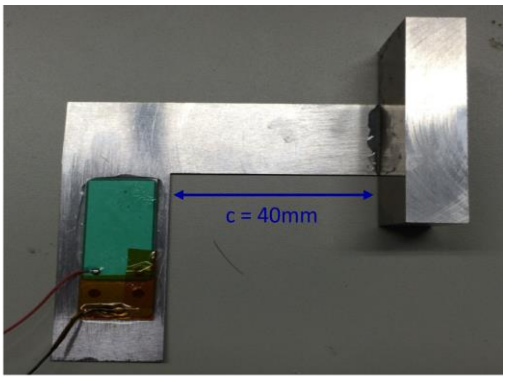

Figure 4: Prototype model of L-shape PZT power generator

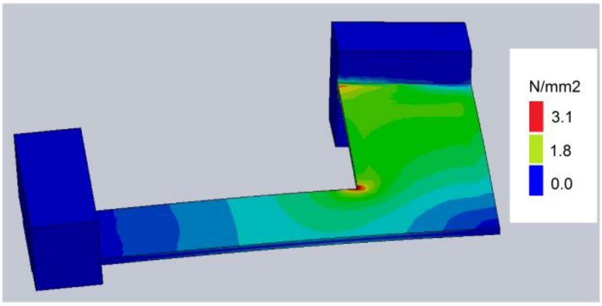

Figure 3: Stress distribution analysis of L-shape aluminum plate with Solidworks software

III. Prototype Model and Impedance Matching Analysis

Prototype model of the power generator is shown in Figure 4. As can be seen, a bimorph PZT device has been bonded to the section A of the aluminum plate. PZT device manufactured by Nihon Ceratec was used as the energy converter and it can be found easily in the market. Capacitance value of the device is 110 nF ± 20%. Dimension of the PZT device is 28 mm × 13.4 mm × 0.2 mm and they are bonded to a 0.2 mm thickness aluminum plate. Both the top and bottom piezoelectric ceramics are connected in parallel connection. The auxiliary mass was attached to the end of L-shape at c = 40 mm. Value of c significantly determines the strength of the torsional force that can be generated on the section A. As c decreases, a smaller torsional force is expected to be generated and as a result, smaller amount of electric power can be harvested.

To optimize the output of the power generator, matching impedance need to be used as load. Matching impedance calculation was conducted by firstly performing a system identification experiment. The experimental configuration is shown in Figure 5. Input vibration from the vibrator will deflect the free end of the power generator structure in the vertical direction. Accelerometers at base (input data) and the free end (output data) will collect the acceleration data of the base and the auxiliary mass. The data was recorded in the PC and it was used for bode plot plotting. The result shows that resonant frequency of the power generator is approximately 23 Hz. If compare this result with the simulation data in Table 1, the resonant frequency from the experiment is almost matched with the 1^{st} mode natural frequency of the power generator.

Thus, by using this frequency, matching impedance can be determined from Equation (1).

Table 2
Resonant frequency and matching impedance of device

c [mm]	Resonant frequency [Hz]	Matching impedance [kΩ]
40	21	63
30	23	61
20	27	53
10	30	47

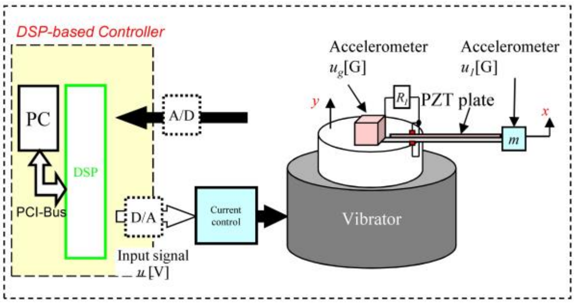

Figure 5: Experimental configuration for system identification experiment

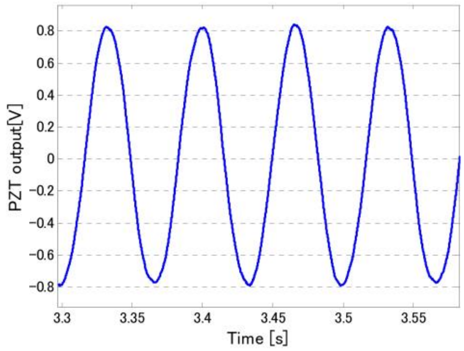

Figure 6: Output voltage of the power generator

$$Z = \frac{1}{2\pi f_{res} C} \tag{1}$$

In this equation, f_{res} represents the resonant frequency of the structure and C is the capacitance of the PZT device. From the calculation, the matching impedance is equal to 63 kΩ. To observe the effect of the auxiliary mass placement to the output response, value of c was reduced from 40mm to 30 mm, 20 mm and 10 mm. Calculation for their matching impedances were carried out and the results are listed in Table 2.

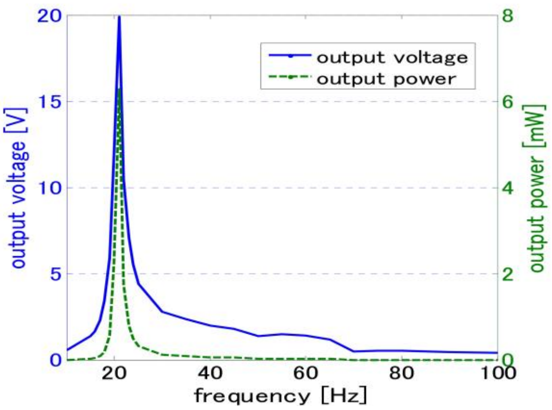

Figure 7: Frequency response of the power generator – peak voltage and power

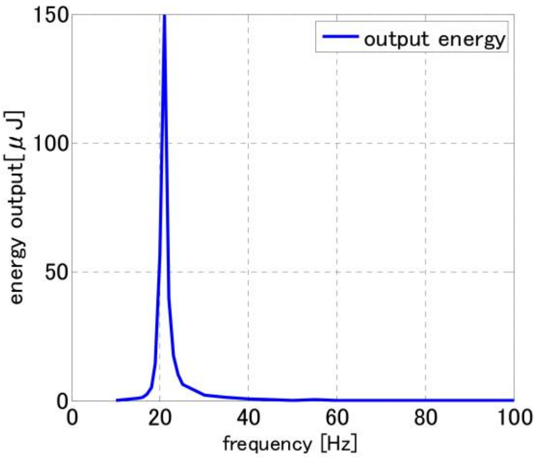

Figure 8: Frequency response of the power generator – peak energy for half cycle of output

IV. Experimental Analysis and Results

Experimental analyses were performed with the prototype model of the power generator as shown in Figure 4. The same experimental configuration for the system identification experiment was used in this analysis. Input signal for the vibrator is denoted by equation (2). It is noted here that the increment in the frequency results in the increment in the acceleration of the base too. Thus, base acceleration starts with 0.56 g when input frequency is 10 Hz and gradually increased as the frequency reached 100 Hz. Output voltage across the load impedance was measured and recorded in the PC. Sample of the output voltage can be observed in Figure 6. From the figure, we can see that the output voltage of the power generator is an AC voltage.

$$y(t) = Y\cos(\omega t) \tag{2}$$

To analyze the frequency response of the power generator when c = 40 mm, input frequency was varied from 10 Hz to 100 Hz. The experimental time was set to 5 s. The peak voltage, V_{peak} between 4 s to 5 s of the output was recorded and its frequency response was plotted in Figure 7. In the same figure, the peak power value derived by V_{peak}^2 / R against the frequency is also plotted. It can be seen from the plot that the peak voltage and power output were recorded at input frequency of 21 Hz. These results matched with the natural frequency simulation results and the system identification result in the previous section where the output voltage is maximum at the frequency of about 21 Hz. For the energy plot, it is shown in Figure 8. Based on these results, the output obviously peaked when the system is vibrated at resonant frequency only. At other than the resonant frequency, the output of the power generator reduced drastically almost to the zero level.

Table 3
Maximum output power and energy with variation in c

c [mm]	Maximum power [mW]	Maximum energy [μJ]
40	6.29	149.66
30	6.43	141.13
20	3.34	63.22
10	3.76	63.92

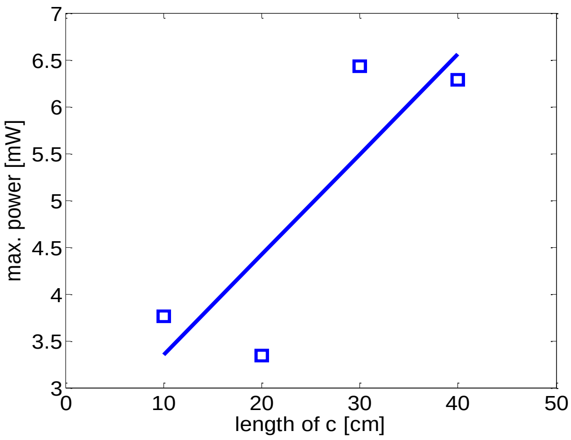

Figure 9: The length of *c* against the maximum output power

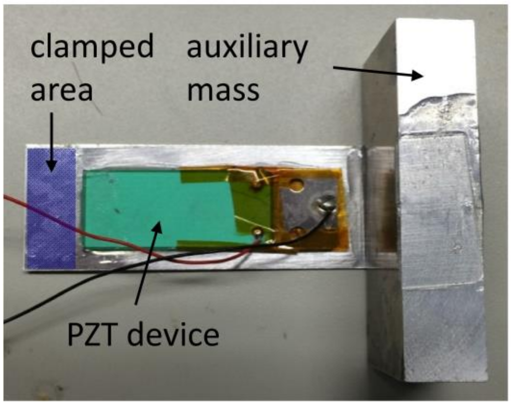

Figure 10: Typical cantilever beam with PZT device bonded on the top surface

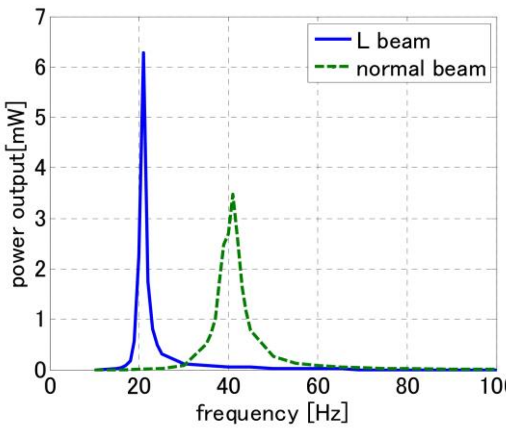

Figure 11: Output power of L-shape and typical cantilever beam piezoelectric power generator

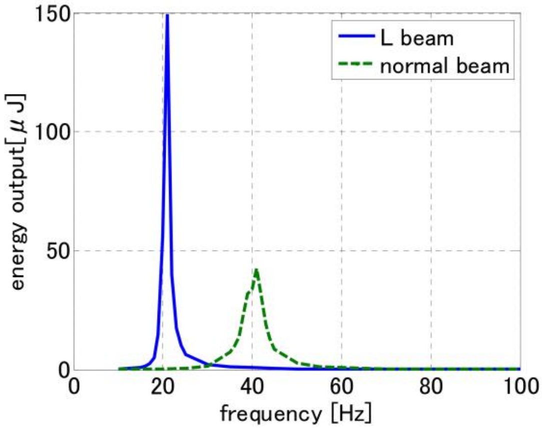

Figure 12: Output energy of L-shape and typical cantilever beam piezoelectric power generator

The same experimental analyses were conducted with variation in *c*. The results of the maximum power and energy output are listed in Table 3 and it is plotted in Figure 9. It can be seen from both the table and figure that power and energy output increased as *c* increased. Increment in *c* eventually increases the vertical displacement of the auxiliary mass at each resonant frequency. As has been discussed earlier, the vertical vibration of the auxiliary mass can create torsional force on the surface of section A. Higher displacement will result in the higher torsional force and subsequently a higher output response can be expected.

V. COMPARISON WITH TYPICAL CANTILEVER BEAM PZT POWER GENERATOR

A comparison of the performance of the designed power generator with the typical cantilever beam power generator, which operates in the longitudinal mode, aluminum plate with the dimension of 70 mm × 20 mm × 1 mm was made. This structure of power generator is shown in Figure 10. The dimension was chosen so that the dimension of the main structure is equal to the L-shape power generator. Based on the analysis, stress distribution of rectangular shape of cantilever beam with an auxiliary mass attached on the free end will gradually increase as it goes closer to the clamped area [11]. Therefore, for the optimum output, the same PZT device is bonded on the aluminum plate closer to the clamped area. This can be seen in Figure 10. To validate the performance of the power generator, same experimental conditions were used. Results from the system identification experiment shows that the resonant frequency of the power generator is about 41 Hz. Thus, matching impedance for this frequency is approximately 40 kΩ. The experimental result which compares the output of both power generator are shown in Figs. 11 and 12. Results in Figure 11 show that the maximum output power of the L-shape power generator that experienced a bending-torsional force is higher than that of generated by the typical cantilever beam power generator, where in this figure it is regarded as normal beam.

The advantage of the proposed power generator can be seen here, even though a higher matching impedance was used as the load. In terms of energy, it can be seen from Figure 12 that the proposed power generator can achieve 3 times maximum energy if compared to the typical cantilever beam power generator.

VI. CONCLUSION

PZT power generator in L-shape was developed and experimentally analyzed. Based on the experimental results, by applying the linear motion of vibrations, torsional stress can be developed on the surface of the power generator. As the PZT device was bonded on the surface of the plate, torsional stress deformed the device in shear mode and eventually allowed the device to generate electricity. Besides the torsional stress, vertical vibration of the auxiliary mass also produces bending stress on the plate. Thus, combination of the bending-torsional stress developed on the plate has resulted in bending-shear mode of operation for the power generator. Comparison with the typical cantilever beam power generator also shows the effectiveness of the structure in generating higher output power when their effective surface is equal.

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