The effects of width reduction on cantilever type piezoelectric energy harvesters

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ABSTRACT

In this paper, energy harvesting capability is examined by changing the width of cantilever beam and piezoelectric cellulose. It is started from hypothesis that if cantilever piezoelectric energy harvester with given width are split, it would increase power output due to the fact that the divided pieces have smaller damping ratio than the original single piece, in turn, they are supposed to vibrate with high amplitude at resonance frequency.

In the experiment, as a piezoelectric material, cellulose Piezo Paper is prepared with aluminum electrode deposition. By attaching the Piezo Paper on an aluminum beam, a cantilever type piezoelectric energy harvester is made. The given width of the beam is 5cm, and sets of Piezo Papers with different width and number of beams are made as, 5cm x 1, 2.5cm x 2, 1.66cm x 3, 1.25cm x 4, 1cm x 5 and 0.83cm x 6 beams. Cantilever beams are vibrated on a shaker at its resonance frequency and examined their electrical characteristics in terms of output voltage and current. The results are compared with the original beam of 5 cm wide.

Keywords: Piezoelectric energy harvester, Cellulose, Cantilever beam, Damping ratio, Resonance frequency. Power output, Width-splitting method

1. INTRODUCTION

The requirement of low energy consumption in small electric device such as remote and wireless sensing application, the importance of scavenging energy from the ambient vibration has been brought up. Piezoelectric material is one of the appropriate medium to convert external vibration-based energy to electrical energy. Many researches have been implemented cantilever beam type of energy harvester as unimorph and bimorph piezo ceramic[1, 2] because of its simple structure and durability of vibration. Typically, the piezoelectric material on the cantilever beam which is applied dynamic strain generates an alternating electrical output. Piezoelectric ceramics such as PZT have mostly been employed for scavenging ambient power due to the high values of their electro-mechanical coupling constants and energy conversion rate.[3] In addition, PVDF which is film type of piezoelectric polymer was also reported as flexible piezoelectric energy harvester generating output power in a backpack exploiting vibration acceleration.[4]

Recent development has shown that EAPap cellulose exhibit piezoelectric property when it applied mechanical strain.[5] The EAPap cellulose which is based on natural cellulose has been reported a promising smart material. The research shows that various electrode deposited EAPap cellulose attached on the cantilever beam was generated power output and compare power output depending on connection. [3]

With the previous research of EAPap cellulose energy harvester, this paper will suggest the effective energy harvesting method. The width split beam and their connection of EAPap cellulose is considered advanced method to generate high electrical output. From fundamental theory of the vibration, damping ratio of cantilever beam was discovered. The electrical output from the mechanical vibration input was measured and it showed whether the width-split method has validity in EAPap cellulose energy harvester.

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2. EXPERIMENT

2.1 EAPap cellulose

The preparation of EAPap cellulose is well introduced.[7] The EAPap cellulose is made from cotton cellulose with a degree of polymerization of 4500. LiCl(Junsei) and raw cotton cellulose which were dried at 100^{o}C for non-residual water were mixed with DMAc(anhydrous N, N-dimethyl acetamide, sigma aldrich) as a proportion of 2/8/90 (pulp, LiCl, DMAc). The cellulose was dissolved in the solvent using heating and stirring properly so that high viscosity cellulose solution was obtained at room temperature. This solution was poured on clean glass plate, casted uniformly thin by doctor blade. In order to remove residual ion such as Li+(DMAc)x microcations, the casted thin film was cured by deionized water(DI water) and isopropyl alcohol (IPA) solution.

After curing adequately, the mechanical stretching was followed to align the cellulose chain. The stretching was conducted perpendicular direction to casting direction with stretching ratio of 1.6 and dried by infrared heater for 1 hour. Finally, dried EAPap cellulose was obtained. In order to use high piezoelectric property, cellulose was taken orientation of 45 degree from the stretching direction.[5] Aluminum electrode was deposited both side by thermal evaporating method[3] and laminated with transparent laminating film of 50μm to prevent short circuit and preserve electrode and cellulose.

2.2 Aluminum cantilever beam

To deliver mechanical vibration to EAPap cellulose film, aluminum cantilever beam was used. As schematics design of figure 1, the prepared 8cm length EAPap cellulose sample was attached on the aluminum cantilever beam. The laser cutting was used to product the beam, which valid length is 15cm except 5cm fixing part and 1mm thickness. EAPap cellulose was attached by double sided tape. The width difference 6 beam was used : 5cm, 2.5cm, 1.63cm, 1.25cm,

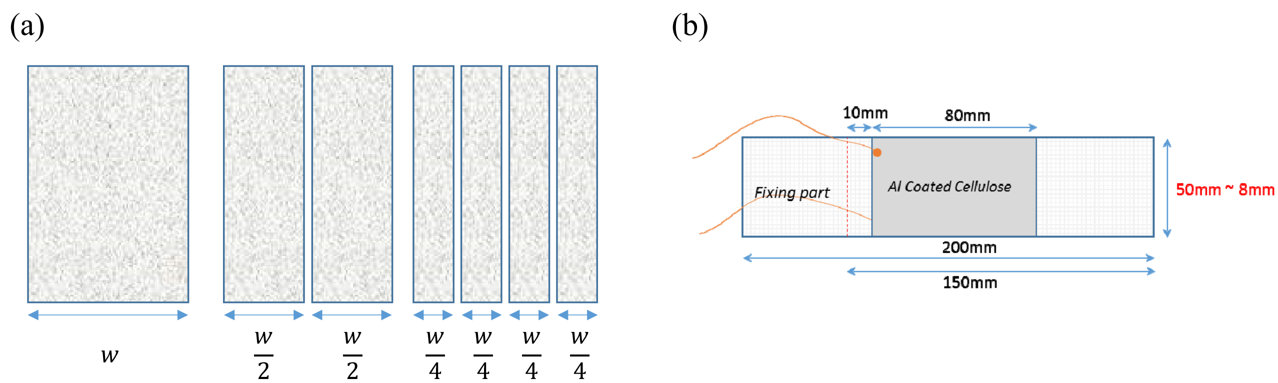

Figure 1. (a) Concept of width split beam (b) Schematics of EAPap cellulose cantilever energy harvester beam

1.0cm, 0.83cm

2.3 Concept of Experiment

Energy harvesting have purpose of generating energy from the variety source efficiently. The idea of this paper has started that width split piezo material would generate more electrical energy. The recent researches reported that connecting together of the piezoelectric cantilever beams divided into several pieces showed generating more power output than single beam has similar total width.[8,9] The reason was believed that width-reduction cause beam to decrease damping ratio, each beam vibrated higher amplitude than before width-reduction therefore the connection of them generate more power output. In other word, combining these smaller beams in parallel result in higher value of total harvested power compared to a single beam with similar total width.

2.4 Experiment set-up

The two experiment was conducted to measure damping ratio and electric power output. First, logarithmic decrement theory equation (1) and (2) was used to verify damping ratio. The equation is based on experimental properties such as peak displacement decay to time and the number of cycle. The experiment was implemented that fixing part was clamped on the stainless jig, applying one small force to the tip for free vibration. Tip displacement was measured by laser displacement (KEYENCE LK-G015). The pulse analyzer (Bruel & Kjaer 35360B-030) is accepted all the necessary data and it was able to plot on the program. The 6 single beam of 15 x 5cm, 15x2.5cm, 15x1.6cm, 15x1.2cm, 15x1.0cm, 15x0.8cm were measured.

$$\delta = \frac{1}{n}\ln\frac{x(t)}{x(t+nT)} \tag{1}$$

$$\zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} \tag{2}$$

Second, the voltage and power output was measured from the cantilever type EAPap cellulose energy harvester using base excitation method. Figure 2 shows set up of experiment. The electro dynamic exciter (Eliezel HEV-50) was mounted on anti-vibration table for applying base excitation. The voltage was measured by pulse analyzer. The load resistance of 1MΩ was connected parallel to EAPap sample to yield power. The EAPap were connected series and parallel connection and two cantilever beam was excited simultaneously.

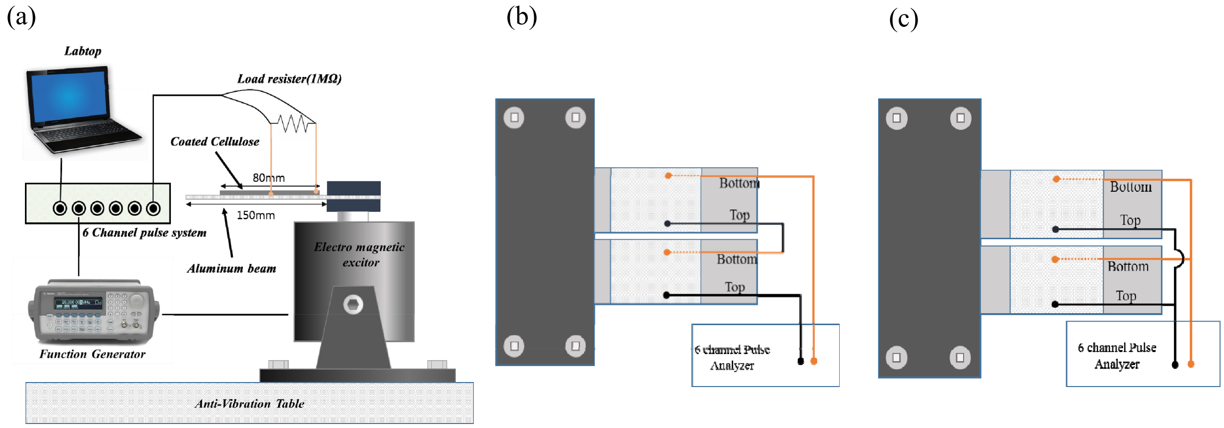

Figure 2. (a) Schematic diagram of experiment setup (b) Two cantilever beam series connection (c) Two cantilever beam parallel connection

3. RESULT & DISCUSSION

3.1 Damping ratio

The damping ratio was determined by the logarithmic decrement equation (1) and (2) and the experiment result. The beam's peak displacement was used and selected the 20 cycles. It was observed that the width reduction was influenced the decreasing damping ratio. The damping ratio of 5cm width beam was 0.00679, 2.5cm was 0.00499, 1.6cm was 0.00461, 1.2cm was 0.00363, 1.0cm was 0.00328 and 0.8cm width was 0.002995. It showed almost linear relationship. The estimated resonance frequency is 36Hz, and the experiment of all the beam showed approximately 36Hz in spite of gap caused by damping ratio and stiffness change. Low damping ratio means the high amplitude of their excitation.

3.2 Voltage and power output

The experiment was conducted to prove the electrical power output increasing. First, two 15 x 0.8cm sample and one 15 x 1.6cm beam were compared. Two 15 X 0.8cm EAPap cantilever beam was fixed to base clamp as it can be seen figure 2(b), (c). The exciter was subjected 100mV sine wave from function generator (Agilent 33220A). Before the excitation, the resonance frequency was checked and it was identified 34.4Hz which present high amplified voltage. It seems that there is a discrepancy of the resonance frequency from identified in the damping ratio experiment. It is because of the environment of experiment was changed, it showed a little differences in two experiment.

The alternating voltage was generated and the power output was computed, the result showed in Table 1. For the simplicity, the maximum peak to peak voltage (with 1MΩ load resistance) presented here. Each single beam showed that V_{p-p} was 41.8mV and 40.8mV and RMS power output was 0.218nW and 0.208nW. When the beam connected series, it showed V_{p-p} was 58.4mV, P_{rms} was 0.426nW. It was about twice increase of power than single beam. Parallel connection was measured 49.5mV and 0.306nW 40~47% higher power than single beam. 15 x 1.6cm case was measured 51.2mV and 0.327μA. It seemed that the series connection has a benefit to voltage gain and power output gain rather than non-split single beam. Parallel connection showed higher value than single beam but not that of 15 x 1.6cm.

Table 1. Voltage(p-p) and RMS power output of 15 x 0.8cm single beam case, connection case and 15 x 1.6cm sample case (Load resister 1MΩ)

	15 x 0.8cm (#1)	**15 x 0.8cm (#2)**	**Series connection**	**Parallel connection**	**15 x 1.6cm (#1)**
V_{p-p} (mV)	41.8	40.8	58.4	49.5	51.2
P_{rms} (nW)	0.218	0.208	0.426	0.306	0.327

For the expanding to another case, two 15 x 1.24 cm cantilever beam was compared with 15 x 2.5cm as well. The resonance frequency of this beam was identified 33.9Hz. Each single 15 x 1.25cm beam showed 30.8mV, 26.6mV and 0.118nW, 0.090nW peak to peak respectively. The result of the series connection and parallel connection was 47.8mV, 32.1mV and 0.286nW, 0.129nW respectively. The power output of series connection was over twice more than single split-width beam. 15 x 2.5cm case showed 47.7mV and 0.284nW, it was lower than series connection.

Table 2. Voltage(p-p) and RMS power output of 15 x 1.25cm single beam case, connection case and 15 x 2.5cm sample case (Load resister 1MΩ)

	15 x 1.25cm (#1)	**15 x 1.25cm (#2)**	**Series connection**	**Parallel connection**	**15 x 2.5cm (#1)**
V_{p-p} (mV)	30.8	26.6	47.8	32.1	47.7
P_{rms} (nW)	0.118	0.090	0.286	0.129	0.284

From the case of 15 x 0.8cm, the connection of split-width beam definitely increase the power output. The power output showed almost twice than single split-width beam, and 30% higher than whole single beam. Parallel connection also showed increasing in power than single split-width beam but it was lower than whole single beam. Likewise case of 15 x 0.8cm, voltage and power output of series connection was twice more than single split-width beam. But the power output was not much difference between series connection and 15 x 2.5cm. Two sample are almost analogous with each other.

4. CONCLUSION

Through this experiment, the relationship of damping ratio vs beam width and electrical output of single beam vs connection beam was investigated.

Theoretically, the damping is a factor affected by stiffness and mass of whole material or system. Damping ratio showed dissimilar since the properties of width-split beam is different depending on their shape. In this paper, it was verified a wide width beam had high damping ratio resulted in low amplitude and rapid decrement. A narrow beam had relatively low damping ratio and the entire result was represented damping ratio and the width had almost linear relationship. Followed experiment was demonstrated voltage and power output gain from the connection of the EAPap cellulose energy harvester. The series connection of two EAPap energy harvester indicate advantage of voltage. It seems that series connection is more suitable for the high voltage usage and scavenge more power. On the basis of this result, further research will be considered. The power output changes depending on load resistance, the effect of three or four beam connection, modeling of EAPap cellulose energy harvester will be implemented. That would be beneficial for the advances in EAPap cellulose as energy harvester.

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REFERENCES

[1] Erturk, A. and Inman, D. J., "An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations," Smart Mater. Struct. 18(2), 025009 (2009).

[2] Sodano, H. A., Park, G. and Inman, D. J., "Estimation of Electric Charge Output for Piezoelectric Energy Harvesting," Strain 40(2), 49–58 (2004).

[3] Abas, Z., Kim, H. S., Zhai, L., Kim, J., and Kim, J.-H., "Electrode effects of a cellulose-based electro-active paper energy harvester," Smart Mater. Struct. 23(7), 074003 (2014).

[4] Granstrom, J, Feenstra, J, Sodano, H. A. and Farinholt, K., "Energy harvesting from a backpack instrumented with piezoelectric shoulder straps," Smart Mater. Struct. 16(5), 1810 (2007).

[5] Kim, H. S., Li, Y. and Kim, J., "Electro-mechanical behavior and direct piezoelectricity of cellulose electro-active paper," Sensor Actuat. A-Phys. 147, 304–309 (2008).

[6] Kim, J., Yun, S. and Ounaies, Z. "Discovery of Cellulose as a Smart Material," Macromolecules, 39(12), 4202–4206 (2006).

[7] El Seoud, O. A., Marson, G. A., Giacco, G. T. and Frollini, E., "An efficient, one-pot acylation of cellulose under homogeneous reaction conditions," Macromol. Chem. Physic. 201(8), 882-889 (2000).

[8] Chow, M, Dayou, J. and Liew, WYH "Increasing the output from piezoelectric energy harvester using width-split method with verification," Int. J. Precis. Eng. Manuf. 14, 2149-2155 (2013).

[9] Dayou J., Liew, WYH and Chow, M., "Increasing the bandwidth of the width-split piezoelectric energy harvester," Microelectr. J., 43, 484–491 (2012).