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Energy harvesting with piezoelectric cantilever

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Abstract—**Energy harvesting with the piezoelectric cantilever was studied under vibration environment. A theoretical model of piezoelectric cantilever was developed to determine the magnitude of power. The results predicted by the theoretical model were validated by the experimental data. Compared with the rectangular layer piezoelectric cantilever, the trapezoidal piezoelectric cantilever generated higher power with the same force and the volume of PZT. A maximal output power of about 24.2mW can be obtained from the trapezoidal piezoelectric cantilever at the operating frequency of 130Hz across a resistive load of 80kΩ with a cyclic stress of 1N.**

Keywords: **piezoelectric cantilever; self-powered; energy harvesting**

I. INTRODUCTION

The wireless transmission systems need sufficient power to function properly[1-2]. Conventionally, batteries are used as the power sources of the remote sensing systems. However, due to their limited lifetime, replacement of batteries has to be carried out periodically, which is inconvenient. In an effort to extend the life and reduce the volume of the electronics, researchers have begun investigating methods of obtaining electrical energy from the ambient energy surrounding the device. Many environments are subjected to ambient vibration energy that commonly goes unused. Piezoelectric materials are considered it was ideal sources of such energy because they can convert mechanical strain energy into electrical energy or vice versa. Energy can be reclaimed and stored for later use to recharge a battery or power a device through a process called energy harvesting[3-7].

In this paper, the voltage sensitivity of the rectangular and trapezoidal piezoelectric cantilevers were modeled. Power generation from the rectangular and trapezoidal layer piezoelectric cantilevers were investigated, some practical applications such as wireless transmission will be discussed as energy harvester.

II. MODEL OF PIEZOELECTRIC CANTILEVER GENERATOR

A symmetrical cantilever-mounted triple layer bender with an elastic layer sandwiched between two piezoelectric layers will be considered here, as shown in Fig.1. The two piezoelectric layers have opposite polarization direction and are connected electrically in series. The length L is much larger than width w, which is also much larger than total thickness t. If an electrical field E_3 is applied across the thickness direction of the bimorph bender with polarity antiparallel to the upper piezoelectric layer and parallel to the lower piezoelectric layer, the constitutive equations for these two layers will be[8-9]

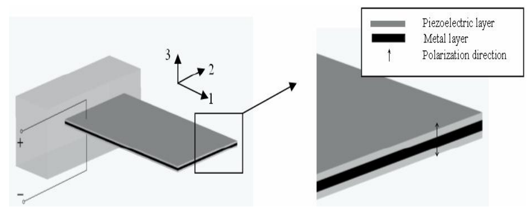

Fig.1 A series triple layer type piezoelectric sensor

$$\begin{cases} s_1^P = s_{11}^E T_1^P - d_{31} E_3 \\ -D_3^P = d_{31} T_1^P - \varepsilon_{33}^T E_3 \end{cases} \quad (1)$$

$$\begin{cases} s_1^P = s_{11}^E T_1^P + d_{31} E_3 \\ D_3^P = d_{31} T_1^P + \varepsilon_{33}^T E_3 \end{cases} \quad (2)$$

where the superscript P denotes the piezoelectric elements; s_1^P and T_1^P are the strain and stress in length direction of piezoelectric elements; D_3^P and E_3 are the electric displacement and electric field; s_{11}^E , d_{31} and ε_{33}^T are the compliance at constant electric field, the transverse piezoelectric coefficient, and the permittivity at constant stress of the piezoelectric layers, respectively. By calculating the internal energy for thermodynamic equilibrium, Wang and Cross[6] derived constitutive equations of a series triple layer type piezoelectric cantilever under a perpendicular tip force F, a uniform load p and a voltage V applied across the cantilever. The charge generated in the series connected triple layer cantilever is in the triple layer bender will be

$$Q = \frac{\partial U}{\partial V} = \frac{3 s_{11}^m d_{31} (t_m + t_p) L^2}{D} F + \frac{Lw}{2t_p} \varepsilon_{33}^T \left(1 - \frac{D - 6 s_{11}^m t_p (t_m + t_p)^2}{D} k_{31}^2\right) V \quad (3)$$

The charge sensitivity of the cantilever can be found by taking derivative of Q with respect to F as follows:

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$$\frac{\partial Q}{\partial F} = \frac{3d_{31}(t_m + t_p)L^2}{Y_m A} \tag{4}$$

The capacitance of the cantilever can be found by taking derivative of Q with respect to V as follows:

$$C_p = \frac{\partial Q}{\partial V} = \frac{Lw}{2t_p}\varepsilon_{33}^T\left(1 - \frac{A - 6t_p(t_m + t_p)^2}{A}k_{31}^2\right) \tag{5}$$

where $A = \frac{2(3t_m^2 t_p + 6t_m t_p^2 + 4t_p^3)}{Y_m} + \frac{t_m^3}{Y_p}$.

Therefore, the voltage sensitivity of the series triple layer piezoelectric cantilever can be obtained form (4) and (5)

$$\frac{\partial V}{\partial F} = \frac{\partial Q / \partial F}{C_p} = \frac{6d_{31}t_p(t_m + t_p)L}{wY_m A\varepsilon_{33}^T\left(1 - \frac{Y_m A - 6t_p(t_m + t_p)^2}{Y_m A}k_{31}^2\right)} \tag{6}$$

Similarly, we can get the voltage sensitivity of the trapezoidal Piezoelectric cantilever

$$\frac{\partial V}{\partial F} = \frac{2t_p L d_{31}(a + 2w)(t_m + t_p)}{Y_m A w \varepsilon_{33}^T (a + w)\left(\frac{6(t_m + t_p)^2 t_p - Y_m A}{2s_{11}^E Y_m Y_p A}k_{31}^2 + \frac{1}{2}\right)} \tag{7}$$

By assuming only a perpendicular tip force is acting at the end of the cantilevers, with the parameters shown in Table 1. And voltage sensitivities of bending cantilevers versus the thickness (tm) and Young's modulus (Ym) of the middle metal layer are shown in Fig. 2.

Table 1. Cantilever parameters.

$d_{31}(m/V)$	2.74e-10
$Y_p(N/m^2)$	1.1e11
k_{31}	0.44
L(mm)	45
w(mm)	20
t_p(mm)	0.3

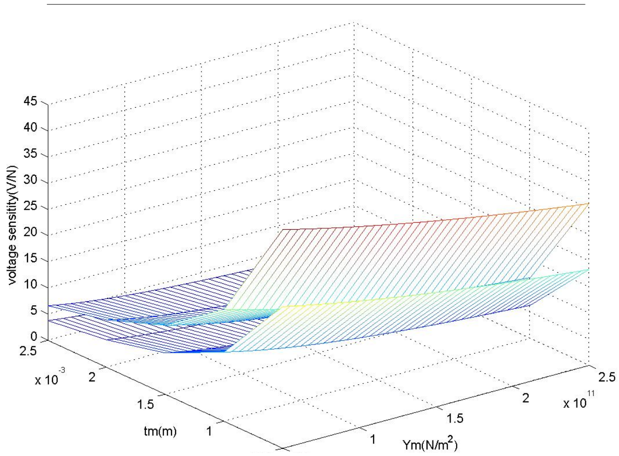

Fig.2. Voltage sensitivity of two types cantilevers

III. Experiments

The experimental setup is shown in Fig. 3. The mechanical shaker(HEV-50) was used here for supplied dynamic conditions. The shaker can apply a maximum of 50 N force within a wide frequency range of 5–3000 Hz. The shaker was driven at various driving voltages and frequencies by using an arbitrary function generator and an amplifier(HEVS-50) to produce a cyclic force of the desired magnitude and frequency. The output voltage from the piezoelectric cantilever was monitored by a digital oscilloscope. In order to avoid any interference from the noise in the surrounding environment, all the experiment was performed on an isolated bench.

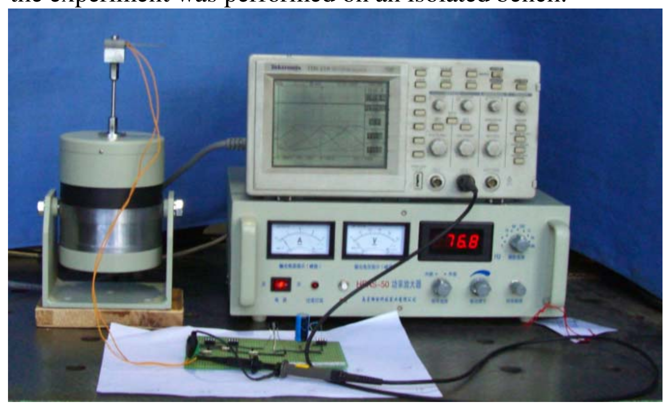

Fig.3. Experimental setup for device testing

The schematic diagram of the electronic circuit is shown in Fig.4. The equivalent circuit of the piezoelectric cantilever is modeled as a current source in parallel with its capacitance C_p. The rectifier and a capacitor were used for storing the generated electrical energy of the piezoelectric cantilever. The piezoelectric transducer charges up the large energy storage capacitor through a full wave rectifier bridge. The functions of different parts in the electronic circuit are described as follows. The full wave rectifying bridge circuit consists of the four small signal Schotty diodes. The storage capacitor is a $10\,\mu F$ with a very low leakage current. The performance including the output voltage and the output power of the transducer were initially characterized with the circuit directly across the resistive loads without any amplification. When the impedance of the load resistor, R_{load}, is matched to the equivalent impedance of the transducer, the energy harvested would be the maximum. Note that the open circuit voltage (Voc) generated by the vibration source showed almost constant as function of the frequency, because the dynamic force from the vibration source was almost constant with changing the frequency determined for three different types of PZT materials[10]. The magnitude of Voc of cantilevers was 18V. It can be seen that the result of the theoretical model of Voc are agree with the experiment.

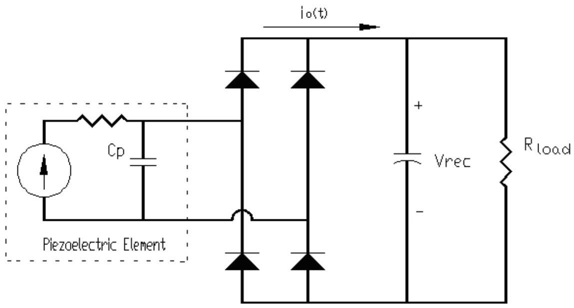

Fig.4. Schematic diagram of the energy harvesting circuit.

As shown in Fig 5and Fig 6, a maximal output power of about 8.6mW can be obtained from the rectangular piezoelectric cantilever at the operating frequency of 180 Hz across a resistive load of 72kΩ. It was shown that the output voltage of the piezoelectric cantilever increases with the resistive load. The voltage approaches15V when the resistive load is 72kΩ with around dynamic force 1 N. Nevertheless, the electrical power decreases when the load resistance is further increased. In Fig.7 and Fig.8, a maximal output power of 24.2mW can be harvested from the trapezoidal piezoelectric cantilever at 130 Hz across the resistive load of 80kΩ while the voltage of 23.5 V can be generated under the same condition. Compared with the rectangular layer piezoelectric cantilever, the trapezoidal piezoelectric cantilever generated higher power with the same force and the volume of PZT.

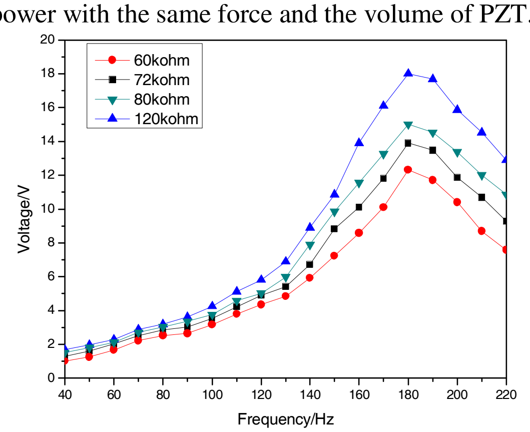

Fig.5. Output voltage of the rectangular piezoelectric cantilever

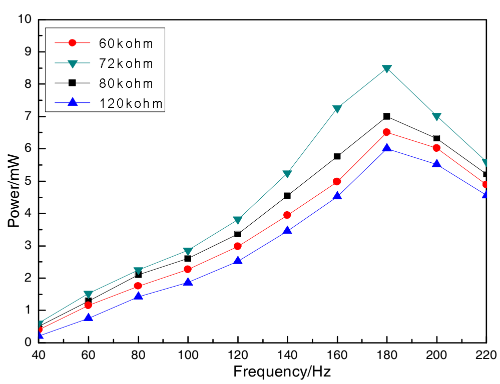

Fig.6. Output power of the rectangular piezoelectric cantilever

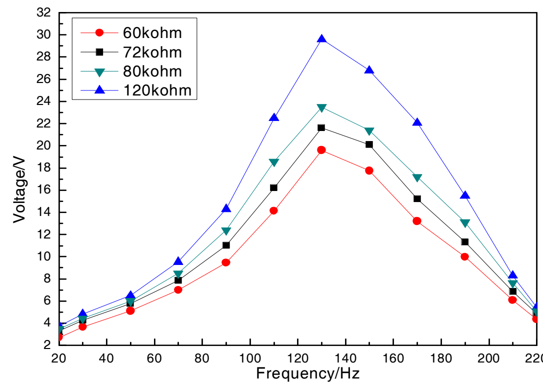

Fig.7.Output voltage of the trapezoidal piezoelectric cantilever

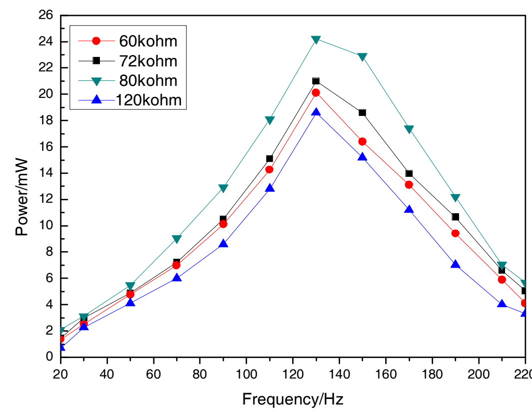

Fig.8. Output power of the trapezoidal piezoelectric cantilever

IV. CONCLUSION

A piezoelectric cantilever generator is investigated. The theoretical model was developed to determine the magnitude of power. The results predicted by the theoretical model were validated by the experimental data. An excellent consistency was found between the theoretical and experimental results. Power generation from the rectangular and trapezoidal piezoelectric cantilevers were investigated. The results show the trapezoidal piezoelectric cantilever generated higher power with the same force and the volume of PZT compared with the rectangular layer piezoelectric cantilever. The useful power output of the piezoelectric cantilever can power itself as energy harvester, it also is potential to use the cantilever here to power a wireless sensor network. Indeed, this power level is already enough for some wireless communication systems.

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REFERENCES

[1] S. Roundy, P.K. Wright, and J. Rabaey, "A Study of Low Level Vibrations as a Power Source for Wireless Sensor Nodes," *Computer Communications*, **26**(11), pp. 1801-1144 ,2003.

[2] M.G. Taranowski, D.L. McClanahan, D.S. Totten, and J.J. Kinsella, "Self-Powered Wireless Transducer," *US Patent*, 6,259,372 B1 ,2001.

[3] J. Kymissis, C. Kendall, J. Paradiso and N. Gershenfeld, ‘‘Parasitic Power Harvesting in Shoes,’’ Proceedings of the Second IEEE International Symposium on Wearable Computing, pp. 132-139 ,1998.
[4] S. Wang., Kwok, H.L., C, L.Sun., et al, ‘‘Energy harvesting with piezoelectric drum transducer,’’ APPLIED PHYSICS LETTERS, 90(11), pp.180506 ,2007.
[5] S. Kim, W.W. Clark, and Q.M. Wang, ‘‘Piezoelectric Energy Harvesting Using a Diaphragm Structure,’’ Proceedings of SPIE Conference on Smart Structures and Materials, 5055, pp. 307-318 ,2003.
[6] H.S. Yoon, G. Washington, A. Danak, ‘‘Modeling, optimization, and design of efficient initially curved piezoceramic unimorphs for energy harvesting applications,’’ Journal of Intelligent Material Systems and Structures, 16(10),pp.877-888 ,2005.
[7] H. W. Kim, S. Priya, K. Uchino, H. Stephanou and Ken, J.U, ‘‘Consideration of Impedance Matching Techniques for Efficient Piezoelectric Energy Harvesting,’’ IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 54(9),pp.1851-1859 ,2007.
[8] P.K. Liu, L.N. Sun, Y.H., Zhu, and Y.F. Zhao, ‘‘Analysis on Piezoelectric Bimorph Actuator for In-Pipe Micro Robot,’’ PIEZOELECTRIC &ACOUSTOOPTICS, 24(2),pp.111-115 ,2002.
[9] M. Wang and L.E. Cross, ‘‘Constitutive Equations of Symmetrical Triple Layer Piezoelectric Benders,’’ IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 46(6), pp. 1343-1351,1999.
[10]H.W. Kim, S. Priya and K. Uchino, ‘‘Modeling of Piezoelectric Energy Harvesting Using Cymbal Transducers,’’ Japanese Journal of Applied Physics, 45(7),pp.5836–5840 ,2006.