Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Science Letters:

Energy harvesting with a slotted-cymbal transducer*

Jiang-bo YUAN†, Xiao-biao SHAN, Tao XIE, Wei-shan CHEN

(*Department of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China*)

†E-mail: yjb0420@126.com

Received Apr. 2, 2009; Revision accepted June 8, 2009; Crosschecked June 10, 2009; Published online June 24, 2009

Abstract: A cymbal transducer is made up of a piezoceramic disk sandwiched between two dome-shaped metal endcaps. High circumferential stresses caused by flexural motion of the metal endcaps can induce the loss of mechanical input energy. Finite element analysis shows that the radial slots fabricated in metal endcaps can release the circumferential stresses, and reduce the loss of mechanical input energy that could be converted into electrical energy. In this letter, the performance of a slotted-cymbal transducer in energy harvesting was tested. The results show that the output voltage and power of the cymbal are improved. A maximum output power of around 16 mW could be harvested from a cymbal with 18 cone radial slots across a 500 kΩ resistive load, which is approximately 0.6 times more than that of the original cymbal transducer.

Key words: Piezoelectric, Cymbal transducer, Energy harvesting
doi:10.1631/jzus.A0920183 **Document code:** A **CLC number:** TM356

INTRODUCTION

The use of wireless sensors and wearable electronics has grown steadily over past few decades. These electronics have all relied on the use of electrochemical batteries for providing electrical energy to the device. However, the increase in power used by the electronics has led to a reduction in battery life and has limited the functionality of the devices. In an effort to extend the life, researchers have begun investigating methods of obtaining electrical energy from the ambient energy surrounding the device (Jiang *et al*., 2005; Priya, 2005; Yoon *et al*., 2005; Jiang and Hu, 2007; Kim *et al*., 2007; Mateu and Moll, 2007). Piezoelectric materials have received the most attention because they can directly convert strain energy into electrical energy. Kim *et al*.(2004; 2005; 2006; 2007) developed a novel circular configuration for power harvesting called a 'piezoelectric cymbal' in which two dome-shaped metal endcaps are bonded on either side of a piezoelectric circular plate. The research was performed on a cymbal with a dimension of Ø29×1 mm^2. The results show that the cymbal transducers are capable of withstanding high force applications while producing useable power. However, high circumferential stresses caused by flexural motion of the metal endcaps can induce the loss of mechanical input energy and decrease the energy transmission coefficient.

In this letter, a new slotted-cymbal structure is presented to set free the circumferential stresses, and the mechanical input energy expended in metal endcaps can be decreased, which will then increase the energy transmission coefficient. The performance containing the output voltage and power of the cymbal transducer with fringe radial slots and cone radial slots was evaluated.

SAMPLE PREPARATION

The original cymbal has avoided the high-stress concentration in the metal endcaps just above the edges of the ceramic metal bonding layers at the edges of cavities (Newnham *et al*., 1994; Newnham

* Project supported by the National Natural Science Foundation of China (No. 50875057) and the Natural Scientific Research Innovation Foundation in Harbin Institute of Technology, China (No. HIT. NSRIF.2008.50)

and Zhang, 2001; Ke *et al*., 2004). However, finite element analysis shows that flexural motion of the metal endcaps could introduce high circumferential stresses, as shown in Fig.1a. The high circumferential stresses result in decrease in the energy transmission coefficient, because some mechanical energy is expended in the metal endcaps, which should be converted into electrical energy. Fig.1b shows that the high circumferential stresses in the metal endcaps are decreased obviously by the radial slots. Same as the non-slotted-cymbal transducer, a slotted-cymbal transducer can be easily fabricated. The only difference between them is the tailoring slots before punching. The form of slots includes fringe radial and cone radial slots, as shown in Fig.2. The metal endcaps were fabricated from phosphor bronze (Liu *et al*., 2002; Chen and Shi, 2007; Li *et al*., 2007). The piezoelectric disk was constructed by PZT5H. The metal endcaps were bonded on the piezoceramic disk by using epoxy colophony and curing at 80 °C for 6 h, and the electrical connections were made on the slotted cymbal by soldering the conductive wires at the edge of the transducer (Kim *et al*., 2006).

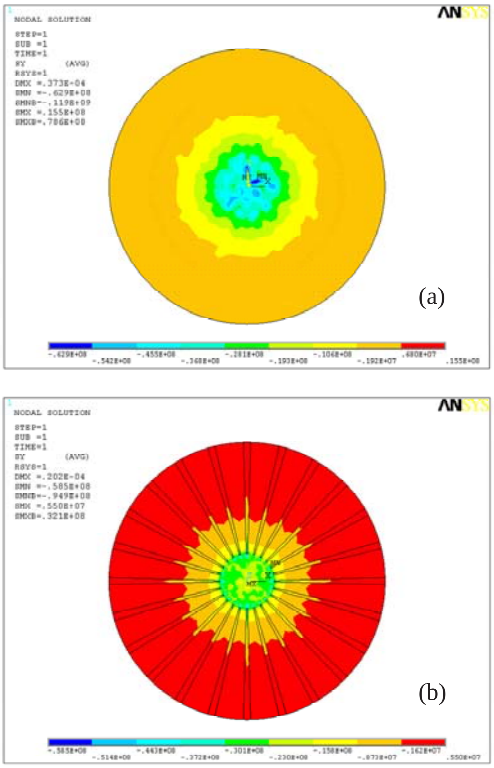

Fig.1 (a) Circumferential stresses in the original cymbal under 30 N; (b) Circumferential stresses in the slotted cymbal under 30 N

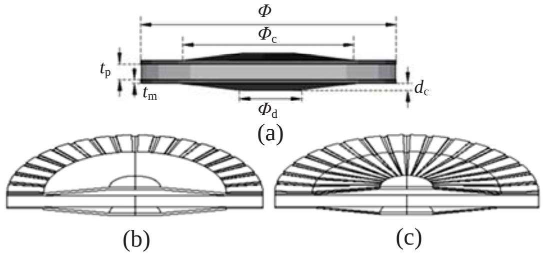

Fig.2 (a) Schematic diagram of the original cymbal transducer; (b) Fringe radial slots in the cymbal endcaps edge; (c) Cone radial slots in the cymbal endcaps

PZT disk diameter, same as the diameter of brass endcaps, Φ=35 mm; depth of cavity, d_c=1 mm; apex diameter of cavity, Φ_d=7 mm; base diameter of cavity, Φ_c=25 mm; sheet thickness of PZT disk, t_p=2 mm; sheet thickness of endcap, t_m=0.5 mm

EXPERIMENTAL RESULTS AND DISCUSSION

Fig.3 shows the picture of experimental setup. A mechanical shaker (HEV-50) was controlled by a high-power amplifier and a function generator (HEAS-5). This shaker can provide a maximum force of 50 N in a frequency band of 5~3000 Hz. The output voltage from the slotted cymbal was measured using an oscilloscope (DS-5000). In order to avoid any interference from the noise in the surrounding environment, all experiments were performed on an isolated bench (Kim *et al*., 2004).

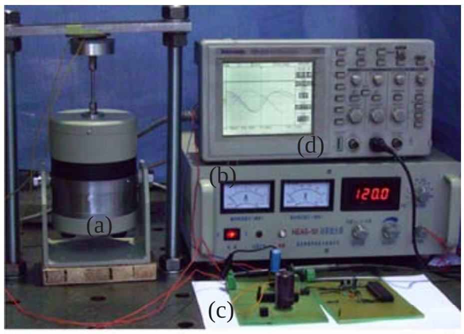

Fig.3 Experiment setup: (a) shaker; (b) an arbitrary function generator and an amplifier; (c) energy harvesting circuit; (d) digital oscilloscope

Fig.4 shows the schematic diagram of the electronic circuit. The equivalent circuit of the cymbal transducer is modeled as a current source in parallel with a capacitance C_p (Wang *et al*., 2007). The rectification circuit including a diode rectifier bridge and a filter capacitor is used to store the electrical energy generated from the slotted-cymbal transducer, and the magnitude of the filter capacitor is 10 μF. A large capacitor is selected as the storage medium because of two prime reasons: (1) a capacitor can be easily charged by various methods such as pulses of current or constant current, and (2) capacitors have an extremely long lifetime (Kim *et al*., 2006). The performance containing the output voltage and power of the cymbal transducer was measured with the circuit directly across the load resistor without any amplification (Wang *et al*., 2007). The output power would reach maximum at an optimum resistive load which is equal to the equivalent impedance of the cymbal transducer. The resonance frequency of the cymbal transducer is usually more than 10 kHz; however, it works at low frequency. The effect of slots on the resonance frequency of the cymbal transducer is ignored. In all the measurements the magnitude of the mechanical vibrations was kept constant at 120 Hz under 30 N.

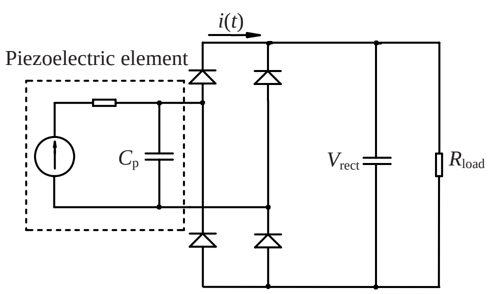

Fig.4 Schematic diagram of the energy harvesting circuit

Fig.5 shows the results of the cymbal with fringe radial slots as a function of the resistive load with various slots. A maximum power of around 14.5 mW can be harvested from the 18-fringe slotted-cymbal transducer across a 520 kΩ resistor. It is shown that the voltage of the slotted cymbal increases with the load resistance. The voltage reaches about 112 V across the 1000 kΩ resistor. However, the output power will decrease with increase in the resistive load when the resistive load is larger than the optimum resistive load. The experimental results show that more slots cause the larger voltage and power across the same resistive load, because more slots can release more circumferential stresses and increase the energy transmission coefficient. However, too many more slots will cause difficulties in fabrication and reduce the rigidity of the cymbal metal endcaps (Ke *et al*., 2004).

Fig.6 shows the results of the cymbal transducer with cone radial slots as a function of the resistive load with various slots. A maximum power of around 16 mW can be harvested from the 18-cone radial slotted-cymbal transducer across a 500 kΩ resistive

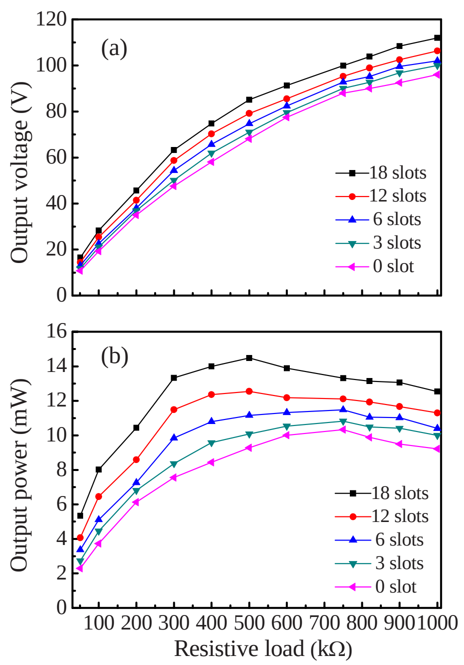

Fig.5 Output voltage (a) and power (b) of the fringe radial slotted-cymbal transducer as a function of resistive load with various slots

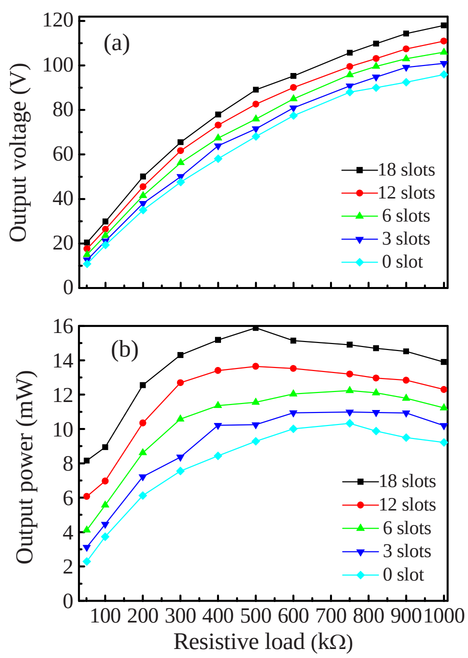

Fig.6 Output voltage (a) and power (b) of the cone radial slotted-cymbal transducer as a function of resistive load with various slots

load. A 90 V voltage was obtained when the output power was 16 mW. Comparison of Figs.5 and 6 shows that the output voltage and power of the cone radial slotted-cymbal transducer are larger than those of the fringe radial slotted-cymbal transducer across the same resistive load. It means that the output voltage and power of the slotted cymbal increase as the slot length increases.

CONCLUSION

The objective of this paper was to improve the performance of the cymbal in energy harvesting by setting free the circumferential stresses in metal endcaps. The performance of the cymbal transducer including output voltage and power with fringe radial slots and cone radial slots was tested. The results show that the performance of the cymbal can be improved by fabricating radial slots in the metal endcaps, and that the energy transmission coefficient of the cymbal transducer can be increased as well. The output power of the 18-cone radial slotted cymbal can reach about 16 mW, which is approximately 0.6 times more than that of the original cymbal transducer, and the output voltage and power of the slotted cymbal increase with the growth of the number and length of the radial slots.

References

Chen, W.S., Shi, S.J., 2007. A bidirectional standing wave ultrasonics linear motor based on Langevin bending transducer. *Ferroelectrics*, **350**:102-110. [doi:10.1080/00150190701369958]

Jiang, S.N., Hu, Y.T., 2007. Analysis of a piezoelectric bimorph plate with a central-attached mass as an energy harvester. *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, **54**(7):1463-1469. [doi:10.1109/TUFFC.2007.407]

Jiang, S.N., Li, X.F., Guo, S.H., Hu, Y.T., Yang, J.S., Jiang, Q., 2005. A piezoelectric analysis of a vibrating ceramic bimorph for power harvesting. *Smart Mater. Struct.*, **14**(4):769-774. [doi:10.1088/0964-1726/14/4/036]

Ke, Y.L., Guo, T., Li, J.X., 2004. A new-style, slotted-cymbal transducer with large displacement and high energy transmission. *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, **51**(9):1171-1177. [doi:10.1109/TUFFC.2004.1334850]

Kim, H.W., Batra, A., Priya, S., Uchino, K., Markley, D., Newnham, R.E., Hofmann, H.F., 2004. Energy harvesting using a piezoelectric "cymbal" transducer in dynamic environment. *Jpn. J. Appl. Phys.*, **43**(9):6178-6183. [doi:10.1143/JJAP.43.6178]

Kim, H.W., Priya, S., Uchino, K., Newnham, R.E., 2005. Piezoelectric energy harvesting under high pre-stressed cyclic vibrations. *J. Electroceram.*, **15**(1):27-34. [doi:10.1007/s10832-005-0897-z]

Kim, H.W., Priya, S., Uchino, K., 2006. Modeling of piezoelectric energy harvesting using cymbal transducers. *Jpn. J. Appl. Phys.*, **45**(7):5836-5840. [doi:10.1143/JJAP.45.5836]

Kim, H.W., Priya, S., Stephanou, H., Uchino, K., 2007. Consideration of impedance matching techniques for efficient piezoelectric energy harvesting. *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, **54**(9):1851-1859. [doi:10. 1109/TUFFC.2007.469]

Li, X., Chen, W.S., Xie, T., Liu, J.K., 2007. Novel high torque bearingless two-sided rotary ultrasonic motor. *J. Zhejiang Univ. Sci. A*, **8**(5):786-792. [doi:10.1631/jzus.2007.A0786]

Liu, P.K., Sun, L.N., Zhu, Y.H., Zhao, Y.F., 2002. Analysis on piezoelectric bimorph actuator for in-pipe micro robot. *Piezoelectric & Acoustooptics*, **24**(2):111-115 (in Chinese).

Mateu, L., Moll, F., 2007. System-level Simulation of a Self-powered Sensor with Piezoelectric Energy Harvesting. Int. Conf. on Sensor Technologies and Applications, p.399-404. [doi:10.1109/SENSORCOMM.2007.92]

Newnham, R.E., Zhang, J., 2001. Cymbal Transducer: A Review. Proc. 12th IEEE Int. Symp. on Applications of Ferroelectrics, p.29-32.

Newnham, R.E., Xu, Q.C., Yoshikawa, S., 1994. Metalelectroactive Ceramic Composite Actuators. US Patent 5 276 657.

Priya, S., 2005. Modeling of electric energy harvesting using piezoelectric windmill. *Appl. Phys. Lett.*, **87**(18):184101. [doi:10.1063/1.2119410]

Wang, S., Lam, K.H., Sun, C.L., Kwok, K.W., Chan, H.L.W., Guo, M.S., Zhao, X.Z., 2007. Energy harvesting with piezoelectric drum transducer. *Appl. Phys. Lett.*, **90**(11):113506. [doi:10.1063/1.2713357]

Yoon, H.S., Washington, G., Danak, A., 2005. Modeling, optimization, and design of efficient initially curved piezoceramic unimorphs for energy harvesting applications. *J. Intell. Mater. Syst. Struct.*, **16**(10):877-888. [doi:10.1177/1045389X05055759]