

Vibration-based MEMS piezoelectric energy harvesters using cantilever beams

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The simplicity associated with the piezoelectric micro-generators makes it very attractive for MEMS applications, especially for remote systems. The use of piezoelectric materials to capitalize on the ambient vibrations surrounding a system is one method that has seen a dramatic rise in use for power harvesting. In this paper we reviewed the work carried out by researchers during the last three years. The improvements in experimental results obtained in the vibration based MEMS piezoelectric energy harvesters show very good scope for MEMS piezoelectric harvesters in the field of power MEMS in the near future.

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1. Introduction

The flexibility associated with piezoelectric materials is very attractive for power harvesting. They possess more mechanical energy for conversion into electrical energy and can also withstand large amounts of strain. Piezoelectric vibration to electricity or power converters has received much attention, as they have high electromagnetic coupling without any external voltage source requirement. The optimal design and setup of any harvesting system using piezoelectric materials depends on the kind of the surrounding frequency and amplitude as well as on the electrical application to be powered.

Usually energy conversion device includes a vibrating piezoelectric structure combined with an energy storage, an AC to DC rectifier followed by a filtering capacitor is added to smooth the delivered output voltage. Currently used piezoelectric harvesting researches fall mainly into two categories, developing optimal power harvesting structures and highly efficient conversion electrical circuits to store the delivered power.

1.1 Power improvement of MEMS-based micro-generators

There are many methods have been reported to improve the harvested power of MEMS micro-generators.

1.1.1 Proper coupling mode of operation

This method involves two modes of operation. The first mode called 31mode, involves the excited vibration force being applied perpendicular to the poling direction (pending beam). And the other is called 33 mode, in which the force is applied on the same side as the poling direction. The two modes 33 mode and 31 mode are as shown in Fig. 1. 31mode is most commonly used. It

produces a lower coupling coefficient 'k', when compared to the 33 mode.

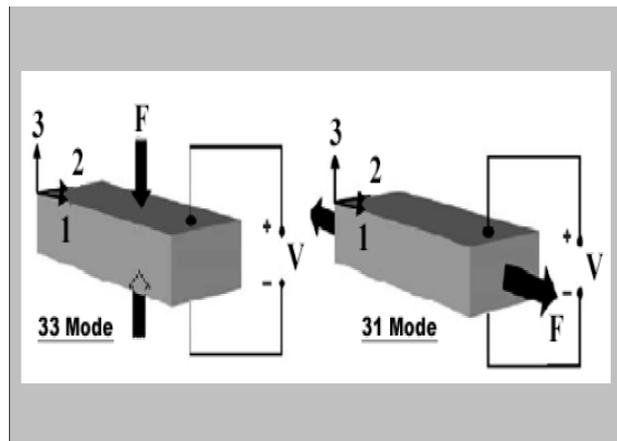


Fig. 1. Piezoelectric coupling modes.

1.1.2 Device configuration of MEMS-based micro-generator

This is accomplished by adding multiple pieces of piezoelectric materials to the harvester.

The uni-morph cantilever beam configuration is as shown in Fig. 2(c). [1] Demonstrated using this configuration that highest power can be generated under lower excitation frequencies and load resistances. Two combinations of bimorph structures are possible, Series Type and Parallel Type.

Series and parallel triple layer bimorph structures represented by [2, 3] are shown in Fig. 2 (a) and (b) respectively.

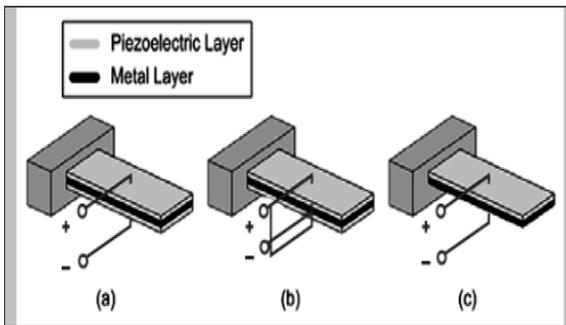


Fig. 2. (a) A series triple layer type cantilever, (b) A parallel triple layer type cantilever, (c) A uni-morph cantilever.

The series triple layer bimorph is constructed out of a metallic layer, sandwiched between two piezoelectrics and the piezoelectric patches are electrically connected in series. In the case of the parallel triple, which is also sandwiched between two piezoelectric layers bimorph, the piezoelectric materials are connected in parallel.

The parallel triple layer bimorph has the highest power under medium excited frequencies and load resistances, whereas the series triple layer bimorph produces highest power when excited under higher frequencies and load resistances. A series connection will increase the device impedance as well as improve the output delivered power at higher loads. Several researchers have carried out studies to improve the bimorph efficiency. [4] studied a bimorph cantilever with a proof mass attached to its end. Their results showed that, by reducing the bimorph thickness and increasing the attached proof mass decreases the harvester resonant frequency and produces a maximum harvested power.

Similarly, [5] found that, by varying the length and width of the proof mass affects the output of the harvested power.

1.1.3 Structure of the cantilever beam configuration

Cantilever geometrical structure also plays an important role in improving the harvester's efficiency. The rectangular shaped cantilever structures are most commonly used in MEMS based piezoelectric harvesters. They are easy to implement and effective in harvesting energy from ambient vibrations.

However, the study proposed by [6], showed that the triangular shaped cantilever beam with a small free end can withstand higher strains and allows maximum deflections, resulting in higher power output when compared to a rectangular beam having width and length equal to the base and height of the proposed triangular cantilever beam.

[7], found that the strain on a trapezoidal shaped cantilever beam can be distributed more throughout its structure, and also observed that, for the same PZT volume a trapezoidal cantilever beam can deliver more than twice the energy than a rectangular shaped beam. Similarly, [8], experimentally tested a nearly triangular trapezoidal shaped cantilever beam along with a rectangular shaped

beam of the same volume, and found that 30% more power can be achieved by using the trapezoidal beam than the rectangular one.

A circular shaped structure called 'cymbal' was developed [9]. This structure consists of two dome-shaped metal bonded on a piezoelectric circular plate, as illustrated in Fig. 3.

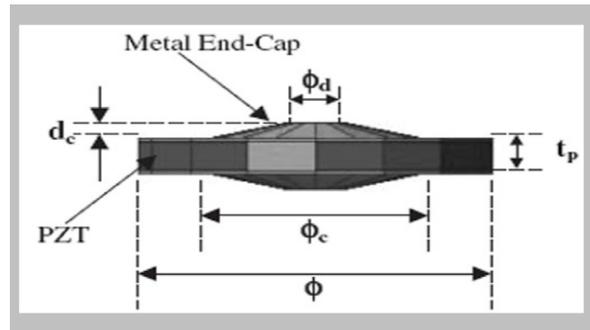


Fig. 3. Piezoelectric 'cymbal' circular shaped cantilever.

1.1.4 Tuning of the MEMS-based micro-generator

This method of improving the efficiency of the power harvester is by tuning the device so that its resonant frequency matches the ambient vibrations resonant frequency. [10, 11], designed a power harvester which resonates at various frequency range and without the need of any adjustments. This device consists of different cantilever beams with different lengths and tip masses attached to its common base frame, such that each cantilever has its own resonant frequency, and this resulted in "mechanical band-pass filter", which led to the increase of size and cost of the device. [12] designed a passive tuning system, which has a two-stage system in which a very low frequency in the range of 0.2 to 0.5 Hz can be converted into potential energy and then transferred to the system with a higher natural frequency. The schematic diagram of the harvester is as shown in Fig. 4.

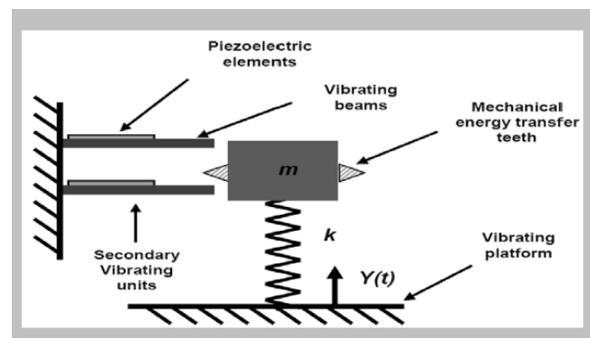


Fig. 4. Schematic of a typical energy harvesting power source using the two-stage design [12].

Similar works on the modeling, design and fabrication of MEMS-based piezoelectric power harvesters is being referred in the literature survey [13-23].

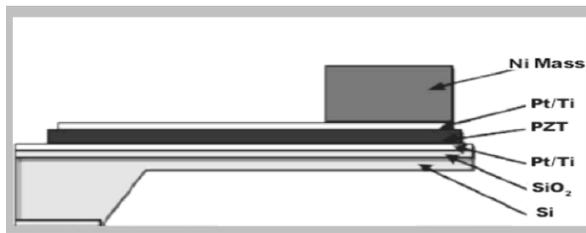


Fig. 8. Schematic configuration of a single cantilever beam [18].

It was found that the output voltage drops off when the excited frequency deviates from the resonant frequency for the available bandwidth of only just 2-3 Hz as described in Fig. 9.

Normally, the derived frequency should be determined first before any design or fabrication of those devices, and this taken as advantageous to design a device that can perfectly operate over a range of frequencies.

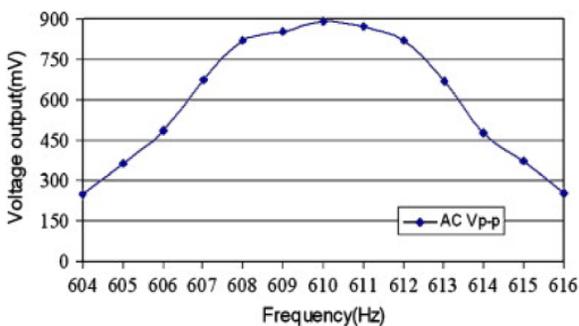


Fig. 9. Output voltage as a function of excited frequency [18].

Cantilevers having closer resonant frequency are designed by considering appropriate structural parameters. The center level of resonance frequency is determined by the target vibration frequency level. The structure parameters are selected from the nodal simulation using ANSYS software.

The frequency bandwidth ranged from 226-234 Hz. This shows that the cantilever array has a wider range of bandwidth than that of a single cantilever.

When the cantilevers are excited under frequency of 229 Hz, the AC output voltage after direct serial connection was found to be only about 3.06 V, which is less than the actual total value of the cantilevers (5.256V). Fig. 10 shows the array performance excited under 229 Hz.

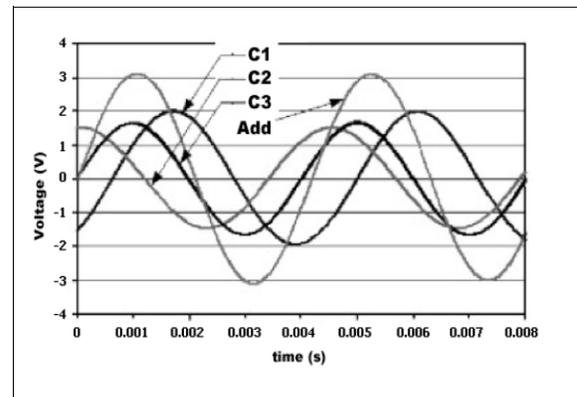


Fig. 10. AC output voltage of three cantilevers and their overall output after serial connection [18].

As shown in Fig. 10, phase difference of about 120° between C1 and C2 is observed. This phase difference impairs the electrical accumulation of the cantilevers and the dc voltage obtained across the capacitor after rectification is only 2.51 V, and the maximum power obtained is about 3.15 μW.

The experimental results showed that the arrayed device is very promising and it improved the operation bandwidth and the output power of the generator. This shows the potential use of the arrayed device in the development of the power generator especially in the wireless/embedded sensor network applications.

The MEMS vibration-based harvesting device has AC output that needs to be rectified. Almost all the rectifying semiconductor devices consume at least 500 mV as dropped voltage. Hence to overcome this high voltage requirement it is proposed to use the inter-digitated electrodes instead of the proposed PZT parallel electrodes [19-21].

[19] developed a {3-3} mode thin film PZT cantilever device with inter-digitated electrodes that can generate 1.0 μW from 10.8 g vibration at 13.9 kHz resonant frequency.

[20], designed and fabricated piezoelectric MEMS micro generator with laminated {3-3} mode PZT cantilever and inter-digitated electrodes that can generate 0.123 μW under 2g ($g = 9.81 \text{ m/s}^2$) acceleration amplitude.

Similarly, [21] developed two piezoelectric MEMS generators with {3-1} mode and {3-3} mode, having a cantilever made by a silicon micromachining process. The experimental results showed that {3-1} mode micro generator could generate output power of 2.765 μW excited at 2.5g amplitude and 255.9Hz resonant frequency, while the {3-3} mode generator could generate an output power of 1.288 μW under 2g amplitude and 214Hz.

The schematic diagram of {3-1} mode and {3-3} mode configuration is illustrated in Fig. 11.

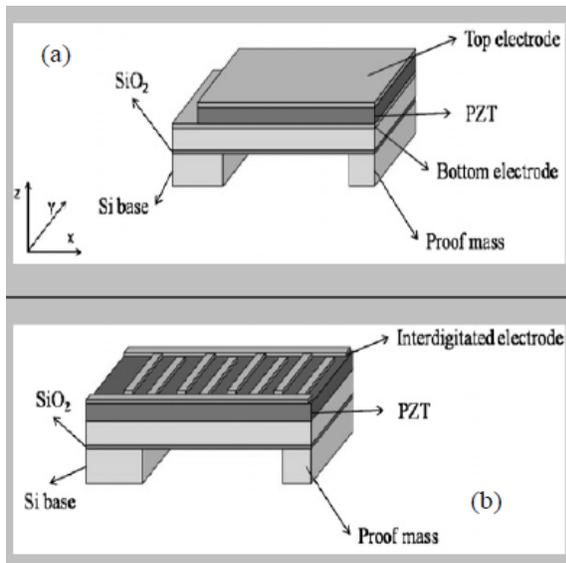


Fig. 11. Schematic diagram of the piezoelectric MEMS generators: (a) {3-1} mode configuration, (b) {3-3} mode configuration.

In the case of {3-3} mode, the inter-digitated electrodes were fabricated with a width of 30µm and gap of 30µm. The proof masses for both MEMS generators were fabricated under the beam structure with dimensions of 500 × 1500 × 500 µm³ and 750 × 1500 × 500 µm³ for the {3-1} and {3-3} modes respectively. A different proof mass dimensions were used to demonstrate the ability of the structure to adjust the resonant frequency. The fabrication process for {3-1} and {3-3} modes configuration are represented in Fig. 12 (a) and (b).

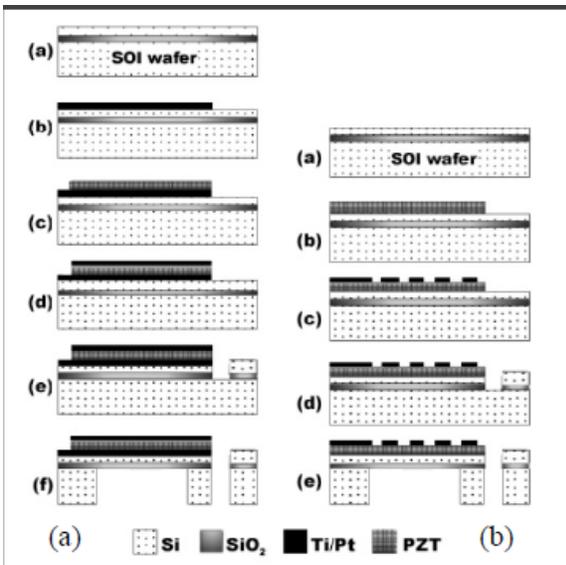


Fig. 12. Fabrication process of the generators in: (a) {3-1} mode, and (b) {3-3} mode [21].

[22], designed and fabricated a micro power generator of thin film PZT laminated cantilever with proof mass and inter-digitated electrodes which could generate about 1.6 V and 1.4 µW when excited under 2g at 870 Hz resonant frequency.

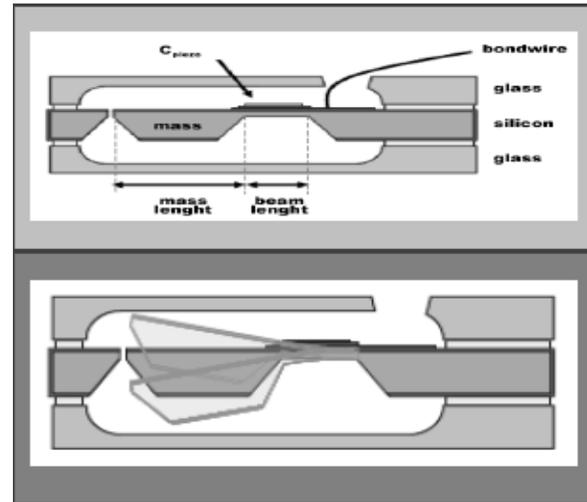


Fig. 13. (Top) Vibration energy harvester packaged in between glass substrates at the rest position. (Bottom) The movement of the proof mass [23].

[23], designed and fabricated a MEMS-based AlN piezoelectric cantilever micro generator, that can generate an output power of 60 µW under 2g (g =9.81m/s²) acceleration at 572 Hz resonant frequency. Devices with different cantilever beams and mass geometries were produced. Glass wafers were used for the top and bottom covers. Fig. 13(Top) shows the generator design and its package configuration at the rest position, while Figure 13(Bottom), shows the movement of the mass when the generator is at resonance [23].

The devices were packaged with top and bottom glass substrates within the cavities to allow mass displacement up to about 400 µm.

3. Results and conclusions

Various designs of harvesters and their experimentally obtained results during the last 3 years have been summarized in Table 1.

According to the literature reviewed thus far, it appears that the delivered power output of those MEMS-based devices is still inadequate to be used as dc power supply to power mobile electronic devices as well as remote sensors and other medical monitoring devices. However, the prospect for improvement looks positively inclined.

Table 1. Summarizes MEMS piezoelectric micro generators with different structures.

Ref.	Material	Cantilever type	Amplitude (g=9.81)	Frequency Hz	Delivered Power μ W
[14]	AlN	D31, thin film	4.0 g	1368	1.97
[15]	PZT	D31, thin film	2.0 g	461.15	2.15
[16]	PZT	D31, thin film With integrated mass	1.9 g	1800	40
[17]	PZT	D31, thin film With non-integrated mass	1 g	609	2.16
[18]	PZT	Thin film array	0.5 g	229	3.98
[19]	PZT	D33, thin film With interdig. electrodes	10.8 g	13900	1
[20]	PZT	D31, thin film With interdig. electrodes	2 g		0.123
[21]	PZT	D31 and d33 thin film With interdig. electrodes	2.5 g	255.9	2.765
			2 g	214	1.288
[22]	PZT	D31, thin film With mass and interdig. electrodes	2 g	870	1.4
[23]	AlN	Different Beams and masses	2 g	572	60

The following two observations were derived from this study. The first observation was that, the maximum output power harvested was about 60 microwatts without any interface power conversion circuit. This produced power losses in the form of consumption power and also resulted in the reduction of the delivered power. Secondly, the absence of the vibration source control affected the delivered output power.

Our future work is to design and fabricate a novel vibration-based MEMS micro power harvesting device consisting of piezoelectric cantilever type together with interface power conversion circuitry. This is expected to provide the optimal desired dc output power characteristics with high efficiency satisfying all the desired parameters and also maintain an output power that can be used to power wireless sensor networks instead of the conventional batteries.

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References

- [1] T. J. Johnson, D. Charnegie, W. W. Clark, M. Buric, G. Kusic, 2006. In: Proceedings of the Smart Structures and Materials Conference, Proc.SPIE 6169 61690D.
- [2] T. H. Ng, W. H. Liao, Smart Structures and Materials **5**, 377-88 (2004).
- [3] T. H. Ng, W. H. Liao, Journal of Intelligent Material Systems and Structures **16**, 785-97 (2005).
- [4] S. N. Jiang, X. F. Li, S. H. Guo, Y. T. Hu, J. S. Yang, Q. Jiang, Smart Materials and Structures, **14**, 769-74 (2005).
- [5] T. A. Anderson, D. W. Sexton, Smart Structures and Materials **6174**, 621-29 (2006).
- [6] L. Mateu, F. Moll, Journal of Intelligent Material Systems and Structures **16**, 835-45 (2005).
- [7] S. Roundy, E. S. Leland, J. Baker, E. Carleton, E. Reilly, E. Lai, et al., Pervasive Computing **4**, 28-36 (2005).
- [8] J. Baker, S. Roundy, P. Wright, Proceedings of 3rd International Energy Conversion Engineering Conference, San Francisco; August 15-18 (2005).
- [9] H. W. Kim, A. Batra, S. Priya, K. Uchino, D. Markley, R. E. Newnham, et al, Japanese Journal of Applied Physics **43**, 6178-83 (2004).
- [10] S. M. Shahruz, Journal of Sound and Vibration **292**, 987-98 (2006).
- [11] S. M. Shahruz, 2006. Journal of Sound and Vibration; 293: 449-61.
- [12] J. Rastegar, C. Pereira, H. L. Nguyen, In proceeding of Smart Structures and Materials conference; proc. SPIE 6171 617101 (2006).
- [13] M. Marzencki, B. Charlot, S. Basrou, M. Colin, L. Valbin, 2005. DTIP7'05-Symp. On Design Testing Integration and Packaging of MEMS/MOEMS, Switzerland; 299-302.
- [14] M. Marzencki, Y. Ammar, S. Basrou, 2007. International conference on solid-state sensors, actuators and micro systems, transducers. p. 887-90.
- [15] D. Shen, J. H. Park, J. Ajitsaria, S. Y. Choe, H. C. Wickle, D. J. Kim, Journal of Micromechanics and Micro-engineering; 18, (2008).
- [16] M. Renaud, K. Karakaya, T. Sterken, P. Fiorini, C. Van Hoof, R. Puers, Sensors and Actuators a-Physical; **145**, 380-6 (2008).
- [17] H. B. Fang, J. Q. Liu, Z. Y. Xu, L. Dong, L. Wang, D. Chen, et al, Microelectronics Journal **37**, 1280-6 (2006).
- [18] J. Q. Liu, H. B. Fang, Z. Y. Xu, X. H. Mao, X. C. Shen, D. Chen, H. Liao, et al, Microelectronics Journal **39**, 802-6 (2008).
- [19] Y. B. Jeon, R. Sood, J. H. Jeong, S. G. Kim, Sensors and Actuators a-Physical **122**, 16-22 (2005).
- [20] B. S. Lee, W. J. Wu, W. P. Shih, D. Vasic, F. Costa, IEEE Ultrasonics Symposium Proceedings **1-6**, 1598-1601 (2007).
- [21] B. S. Lee, S. C. Lin, W. J. Wu, X. Y. Wang, P. Z. Chang, C. K. Lee, J. Micromech. Microeng **19**, 8 (2009).
- [22] P. Muralt, M. Marzencki, B. Belgacem, F. Calame, S. Basrou, Procedia Chemistry **1**, 1191 - 4 (2009).
- [23] R. Elfrink, T. M. Kamel, M. Goedbloed, S. Matova, D. Hohlfeld, R. van Schaijk, et al, 2008 Proceedings of the powermems workshop, Sendai; November 10-11, p. 249-52. Einstein A., 2007. Paper templates.

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