



Proc. Eurosensors XXV, September 4-7, 2011, Athens, Greece

## Improving Output Power of Piezoelectric Energy Harvesters using Multilayer Structures

Dibin Zhu\*, Steve Beeby, John Tudor, Neil White and Nick Harris

*School of Electronics and Computer Science, University of Southampton, UK*

---

### Abstract

This paper studies the feasibility of increasing the output power of vibration piezoelectric energy harvesters using multilayer structures. In this study, single-layer, double-layer and triple-layer devices with the same resonant frequency were compared. Two design cases were studied:- In the first case, the overall thickness of all PZT layers is fixed and each PZT layer has the same thickness. In the second case, the thickness of one PZT layer is fixed. The output power of these generators was studied and compared for the conditions where all the PZT layers were connected in parallel and in series. In all cases, the multilayer structure increased the output power over the single layer structure in piezoelectric energy harvesting.

© 2011 Published by Elsevier Ltd.

*Keywords:* Piezoelectric energy harvesters, multilayer structure;

---

### 1. Introduction

Among transducers in vibration energy harvesting, the piezoelectric transducer has received the most attention due to its simplicity in structure, which makes it easy to integrate in a self-powered system. Methods have been developed to increase the output power of piezoelectric energy harvesters, such as using more efficient piezoelectric materials (e.g. Macro-Fiber Composite) [1], using different piezoelectric configurations (e.g. mode 31 or mode 33) [2], optimizing the power conditioning circuitry [2], using different mechanical structures [2] and using adaptive energy harvesters [3].

Using piezoelectric energy harvesters with a multi-layer structure is also a potential method to increase output power. Multi-layer structures were previously studied for actuators [4]. It was found that when

---

\* Corresponding author. Tel.: +44(0)238-059-5161; fax: +44(0)238-059-2901.  
*E-mail address:* [dz@ecs.soton.ac.uk](mailto:dz@ecs.soton.ac.uk).

compared with the same equivalent total thickness single layer, the multi-layer devices can be driven at a lower voltage to give the same displacement. Recently, the application of multi-layer structures in vibration energy harvesting was also reported. Song *et al* [5] compared piezoelectric energy harvesters with single layer, two layers and five layers. It was claimed that output power of the generators decreased with the increase of the number of layers. However, their experimental results were not verified by theory.

Zhu *et al* [6] compared output power of single-layered, double-layered and triple-layered piezoelectric energy harvesters with the same total PZT thicknesses. It was found in simulation as well as in experiments that piezoelectric energy harvesters with multilayer structures did improve the output power by a maximum 40% when all PZT layers were connected in parallel.

In this paper, a more detailed study of bimorph piezoelectric energy harvesters with multilayer structures will be presented. In this study, single-layer, double-layer and triple-layer devices with the same resonant frequency were compared. Two cases will be presented. In the first case, overall thickness of all PZT layers is fixed and each PZT layer has the same thickness. In the second case, the thickness of one PZT layer is fixed. Output power of these generators when all PZT layers are connected in parallel and in series was studied and compared.

## 2. Multilayer structures

### 2.1. Overview

Fig. 1 shows comparisons of cross-section view of a single-layer and a multi-layer bimorph piezoelectric generator. In the first case, PZT layers of the single-layer and the multi-layer generator have the same total thickness,  $d$ . Assuming that each PZT layer in a multi-layer generator has the same thickness, for a device with  $n$  layers, the thickness of each PZT layer is  $d/n$  as shown in Fig. 1(b).

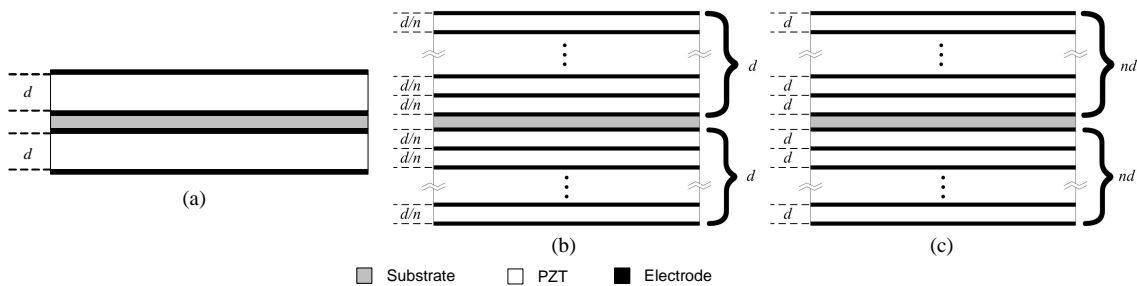


Fig. 1. (a) single layer; (b) multilayer case 1 (total same thickness); (c) multilayer case 2 (total same thickness)

In the second case, thickness of each PZT layer is the same in the single-layer and the multi-layer generators as  $d$ . For a device with  $n$  layers, the total thickness of all PZT layers in a multilayer generator is  $nd$  as shown in Fig. 1(c). In this study, single-layer, double-layer and triple-layer devices with the same resonant frequency were compared under the same vibration level.

### 2.2. Connections of PZT layers

Fig. 2 shows connections of multilayer piezoelectric generators, both in parallel and in series. Different methods of connection can result in different device capacitances and thus different optimum load resistances. Furthermore, generated electrical charge has different distribution when PZT layers are connected differently, which affects output power of the generator.

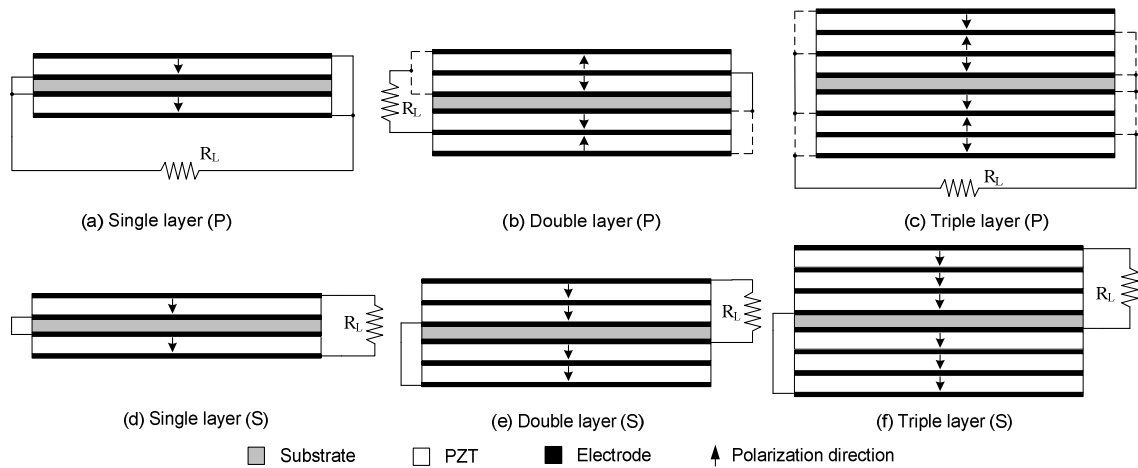


Fig. 2. Connections of PZT layers: (a)(b)(c) Parallel connection; (d)(e)(f) Series connection

### 3. Simulation in ANSYS

Simulation was conducted in ANSYS with direct coupled field analysis between the mechanical and piezoelectric domain. Together with coupled physics circuit simulation in ANSYS, the performance of the piezoelectric generator can be fully simulated.

In the simulation, the coupled-field element SOLID 5 was used for the piezoelectric material and linear structural element SOLID 45 was used for non-piezoelectric materials. The piezoelectric circuit element CIRCU94 was connected with the piezoelectric element to simulate electrical loads, in this case a resistive load. Harmonic analysis was performed. To simulate a sinusoidal vibration, a constant base displacement was applied to the clamped area.

### 4. Results

Tables 1 to 3 compare simulation results of output power, optimum load resistance and open circuit voltage in different cases, respectively. It was found that output power increases with the number of PZT layers except in parallel connection case one where double-layer generator has higher output power than triple-layer. In most cases, the piezoelectric generator with series connection has higher output power. Furthermore, optimum load resistance is inversely proportional to the device capacitance. Open-circuit voltage is proportional to the effective thickness between the two main electrodes that connect to the electrical load.

Table 1. Normalized output power (output power of parallel case 1 of single-layer is defined as 1)

	Parallel connection		Series connection	
	Case 1	Case 2	Case 1	Case 2
Single-layer	1	1	1	1
Double-layer	1.37	2.22	1.17	3.42
Triple-layer	1.18	4.56	1.4	6.63

Table 2. Normalized optimum load resistances (optimum load resistance of parallel case 1 of single-layer is defined as 1)

	Parallel connection		Series connection	
	Case 1	Case 2	Case 1	Case 2
Single-layer	1	1	4	4
Double-layer	1/4	1/2	4	8
Triple-layer	1/9	1/3	4	12

Table 3. Normalized open-circuit voltage (open-circuit voltage of parallel case 1 of single-layer is defined as 1)

	Parallel connection		Series connection	
	Case 1	Case 2	Case 1	Case 2
Single-layer	1	1	2	2
Double-layer	1/2	1	2	4
Triple-layer	1/3	1	2	6

## 5. Conclusions

This paper studies the feasibility of increasing the output power of vibration piezoelectric energy harvesters using multilayer structures. Simulation results show that output power of piezoelectric energy harvester can be improved by using multilayer structure regardless how PZT layers are connected. Optimum load resistance in parallel connection is lower while open-circuit voltage is higher when PZT layers are connected in series. Some part of the simulation has been verified by experiments [6]. More tests will be done to prove rest of the simulation results.

## Acknowledgements

This work is supported by the European Union Seventh Framework Programme (FP7) research project TRIADE (<http://triade.wscrp.com/>).

## References

- [1] Anton SR, Sodano HA. A review of power harvesting using piezoelectric materials (2003–2006) *Smart Mater. Struct.* 2007; **16**:R1-R21.
- [2] Goldschmidtboeing F, Woias P. Characterization of different beam shapes for piezoelectric energy harvesting. *J. Micromech. Microeng.* 2008; **18**:104013.
- [3] Zhu D, Tudor MJ and Beeby SP. Strategies for increasing the operating frequency range of vibration energy harvesters: a review. *Meas. Sci. Technol.* 2010; **21**(2):022001.
- [4] Harris NR, Hill M, Torah R, Townsend R, Beeby S, White NM, Ding J. A multilayer thick-film PZT actuator for MEMs applications. *Sens. and Actu.* 2006; **132**:311-6.
- [5] Song HC et al. Multilayer piezoelectric energy scavenger for large current generation. *J. Electroceram.* 2009; **23**:301-4.
- [6] Zhu D, Almusallam A, Beeby SP, Tudor J, Harris NR. A bimorph multi-layer piezoelectric vibration energy harvester. *Proc. PowerMEMS 2011.*