A BIMORPH MULTI-LAYER PIEZOELECTRIC VIBRATION ENERGY HARVESTER

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Abstract: This paper reports a bimorph piezoelectric vibration energy harvester incorporating multiple PZT layers. The advantage of a multi-layer generator is that it produces a higher power than a single-layer generator having the same total thickness. In addition, a lower voltage is required to polarize a multi-layer generator reducing the risk of breakdown during polarization. Moreover, the optimum resistive load of a multi-layer generator is much lower than that of a single-layer generator, which makes it easier to couple to the electrical domain. In this work, it was found, experimentally, that a double-layer generator produces 41.5% and 19.4% more power than a single-layer generator with the same total thickness of PZT and resonant frequency. This was verified theoretically. The generators have been fabricated by screen printing which is attractive for low cost mass production.

Keywords: Piezoelectric, multi-layer, vibration energy harvesting, ANSYS

INTRODUCTION

Over the past decade, research around the world has targeted vibration energy harvesting as a potential alternative to batteries. Common methods of converting mechanical energy to electrical energy include electromagnetic transducers, electrostatic transducers and piezoelectric transducers [1]. Among these methods, 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.

Efforts have been made to increase the output power of piezoelectric energy harvesters. Methods include using more efficient piezoelectric materials (e.g. Macro-Fiber Composite) [2], using different piezoelectric configurations (e.g. mode 31 or mode 33) [3], optimizing the power conditioning circuitry [3], using different mechanical structures [3] and using adaptive energy harvesters [4].

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 [5]. It was found that when 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* [6] 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.

In this paper, the open circuit voltage, maximum output power and optimum resistive loads of bimorph piezoelectric generators with a single layer, a double layer and a triple layer on each side are compared. Each generator has a cantilever structure. The total thicknesses of the PZT layers of these three generators are the same. Experimental results were verified by simulation results in ANSYS.

MULTI-LAYER ENERGY HARVESTERS

Overview

Fig. 1 shows a comparison of cross section view of a single-layer and a multi-layer bimorph piezoelectric generator. 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*.

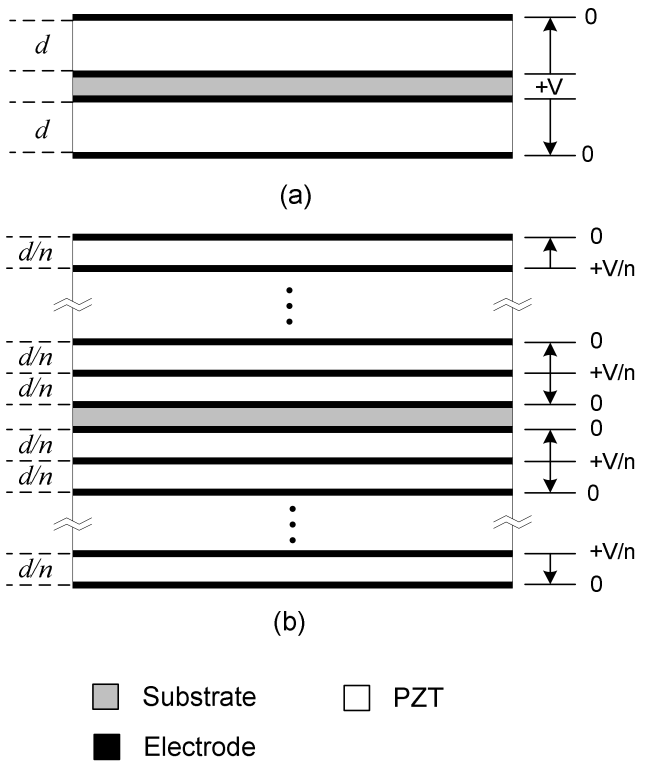


Fig. 1: Comparison of (a) a single-layer and (b) a multi-layer (n layers) bimorph piezoelectric generator.

Polarizing voltage

For the same polarizing electric field, the polarizing voltage for the generator with n-layers is only *1/n* of that for the single layer generator, which reduces the risk of breakdown during polarization.

Capacitance of the generator

Assuming that the area of the PZT layer is A, the capacitances of one PZT layer of a generator with a single layer (C_1) and n layers (C_i) are given by:

$$C_1 = \varepsilon \frac{A}{d} = C \tag{1}$$

$$C_i = \varepsilon \frac{A}{d/n} = nC \tag{2}$$

, respectively, where ε is the dielectric constant of PZT.

In a multi-layer generator, all the PZT layers on one side of the cantilever are connected in parallel. Therefore, the overall capacitance of one side of the multi-layer generator (C_{n_1}) is:

$$C_{n\_1} = \sum_{i}^{n} C_i = n^2 C \tag{3}$$

When PZT layers on both side of the cantilever are connected in parallel, the overall capacitances of a single-layer (C_{s_p}) and an n-layer generator (C_{n_p}) are:

$$C_{s\_p} = 2C \tag{4}$$

$$C_{n\_p} = 2n^2 C \tag{5}$$

When PZT layers on the two side of the cantilever are connected in series, the overall capacitances of a single-layer (C_{s_s}) and an n-layer generator (C_{n_s}) are:

$$C_{s\_s} = \frac{C}{2} \tag{6}$$

$$C_{n\_s} = \frac{n^2}{2} C \tag{7}$$

In both cases, the overall capacitance of an n-layer generator is always n^2 times greater than that of a single-layer generator.

Optimum load resistance

Theoretically, the optimum load resistance is inversely-proportional to the capacitance of the piezoelectric generator [7] as follows:

$$R_{opt} = \frac{1}{\omega C_{PZT}} \cdot \frac{2\zeta}{\sqrt{4\zeta^2 + k^4}} \tag{8}$$

where ω is the resonant frequency, C_{PZT} is the overall capacitance of the generator. ζ and k are damping ratio and piezoelectric coupling coefficient, respectively.

Substitution of Eq. 4 to 7 into Eq. 8 leads to the conclusion that the optimum resistive load of a single-layer generator is n^2 times that of an n-layer generator.

ANSYS MODEL

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. Details of this method can be found in [8].

FABRICATION OF GENERATORS

The generators tested in this research were fabricated using a screen printing process. Details can be found in [9]. Fig. 2 shows an illustration of the bimorph generator.

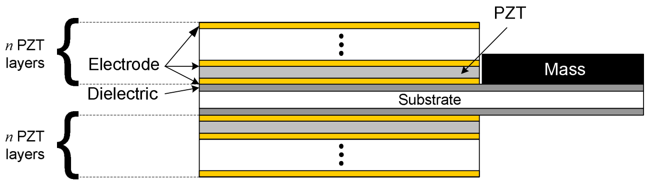


Fig. 2: Illustration of the bimorph generator.

The piezoelectric area of each generator is 22 mm long and 23 mm wide. Tungsten blocks were manually attached to the free end of the cantilever so that all the different generators had the same resonant frequencies to allow a comparison of multi-layer generators. However, the tungsten mass can also be directly screen printed if required [9].

Fig. 3 shows a photograph of a single-layer, double-layer and triple-layer generators. They have the same dimensions and same total PZT layer thickness of 150 µm.

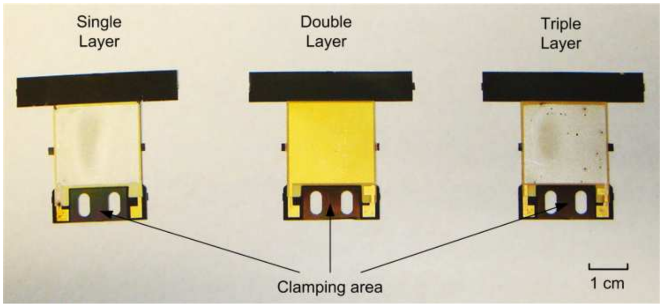


Fig. 3: Fabricated piezoelectric energy harvesters.

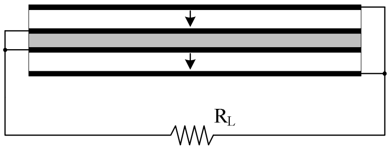
Table 1 lists material or printing pastes used for each layer and their respective thicknesses.

Table 1: Properties of the generator.

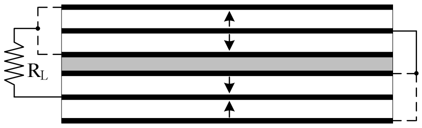
Layer	**Material/Paste**	**Thickness (μm)**
Substrate	Stainless Steel 430S17	120
Dielectric	ESL4924	20
Electrode 1	ESL8836	10
PZT	University of Southampton [9]	150^{*}, 75^{**}, 50^{***}
Electrode 2	ESL1901-S	10

* single layer, ** double layer, *** triple layer

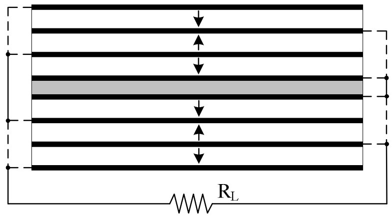
Fig. 4 illustrates the polarization direction of each of the PZT layers in the three generators, and their connections. Note that dashed lines are connections made by printing and solid lines are wire connections. In this research, only the case where PZT layers on both sides of the cantilever are connected in parallel was reported.



(a) Single layer



(b) Double layer



(c) Triple layer

▨ Substrate ☐ PZT

■ Electrode ↑ Polarization direction

Fig. 4: Parallel connection of PZT layers in (a) a single-layer generator (b) a double-layer generator and (c) a triple-layer generator.

All generators were polarized with an electric field of 4 MV·m^{-1}. The polarizing voltages for the three generators are 600 V for the single-layer generator, 300 V for the double-layer generator and 200 V for the triple-layer generator. The piezoelectric coefficients, d_{33}, of all three generators were measured to be around -150pC/N.

The total capacitances of the three generators when the PZT layers on both sides of the cantilever were connected in parallel were measured at 18.9 nF for the single-layer generator, 76.4 nF for the double-layer generator and 176.4 nF for the triple-layer generator.

EXPERIMENTS AND RESULTS

The generators were tested on a shaker table with a programmable resistance box and a PC with LabVIEW software collecting the data. This system is suitable for fully characterizing the generator over a wide range of acceleration levels, load resistances and frequencies. The acceleration level used in this test was 0.29 $\boldsymbol{g}_{\mathrm{rms}}$ (1$\boldsymbol{g}$ = 9.8 m·s^{-2}), i.e. 2.84 m·s^{-2}.

Fig. 5 and 6 compare the open circuit voltage and optimum output power of the three generators, respectively.

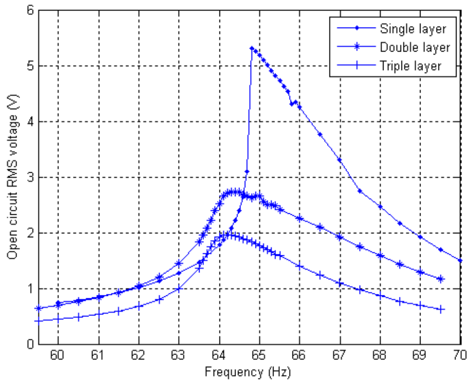


Fig. 5: Comparison of open circuit voltage.

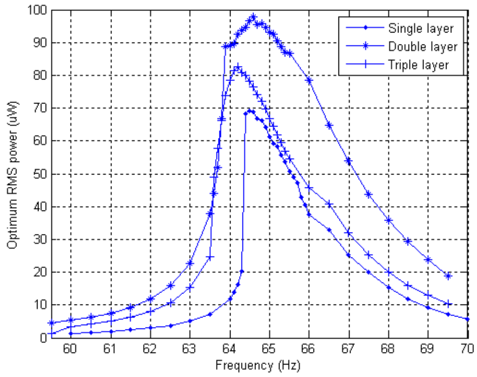


Fig. 6: Comparison of optimum output power.

Fig. 7 shows a comparison of output power with variation of normalized resistive load between simulation results in ANSYS and the test results. The load resistance of the single-layer generator was set as a reference.

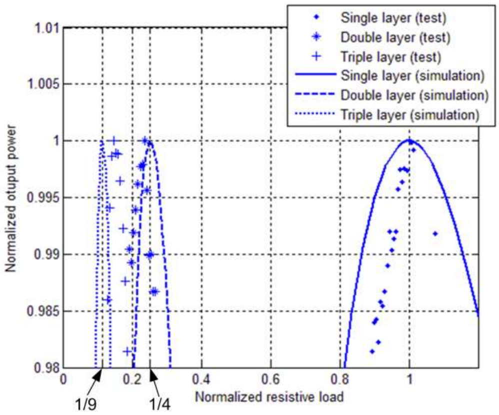


Fig. 7: Comparisons of simulation and test results (output power vs. optimum resistive loads).

DISCUSSION

Table 2 summarizes the test results shown in Fig. 5 to 7. Experimentally, the three generators had similar resonant frequencies. The open circuit voltage of the single-layer generator was measured at 1.94 and 2.7 times greater than that of the double-layer and the triple-layer generator, respectively. Theoretically, the open circuit voltage of the single-layer generator is 2 and 3 times greater than that of the double-layer and the triple-layer generator, respectively.

In addition, the optimum load of the single-layer generator is experimentally 4.27 and 9.29 times greater than that of the double-layer and the triple-layer generator, respectively. Theoretically, the open circuit voltage of the single-layer generator is 4 and 9 times greater than that of the double-layer and the triple-layer generator, respectively. The experimental results agree with the theoretical analysis mentioned above and simulation results from ANSYS. Most importantly, it was found experimentally that the double-layer generator produced 41.5% (37% in simulation) more power than the single-layer generator while the triple-layer generator had slightly more output power as the single-layer generator (19.4% in the test and 18.6% in simulation).

Table 2: Summary of test and simulation results.

Generator	Single layer	Double layer	Triple layer
Resonant frequency (Hz)	64.5 (64.47)*	64.5 (64.45)	64.2 (64.41)
Open circuit voltage (V)	5.304 (5.258)	2.731 (2.729)	1.958 (1.661)
Optimum load resistance (kΩ)	158 (150)	37 (37.5)	17 (16.8)
Maximum output power (µW)	69.18 (67.08)	97.9 (91.89)	82.61 (79.56)

* Figures in brackets are simulation results.

CONCLUSION

This paper compares performance of bimorph piezoelectric energy harvesters with one, two and three PZT layers. These generators have the same total thickness of PZT layers and the same resonant frequency.

When all PZT layers are connected in parallel, the following conclusions can be drawn from this research:

- The overall capacitance of an n-layer generator is n^2 times greater than that of a single-layer generator.
- Optimum resistive load of a single-layer generator is n^2 times greater than that of an n-layer generator.
- Open circuit voltage of a single-layer generator is n times greater than that of an n-layer generator.
- Maximum output power of a double-layer generator is about 40% more than that of a single-layer generator while a triple-layer generator has about 20% more output power than a single-layer generator.
- It is not worth fabricating triple (or more) layer piezoelectric generator unless low input impedances are required.

The higher open circuit voltage of a single-layer generator is due to its low total capacitance. However, although the modeling and the experimental results confirm that there is a significant increase in the output power of a multi-layer device over a single-layer device, the reason for this increase is not immediately apparent, and the effect of stress distribution in the different devices is under investigation to clarify the reasons. This will be reported later in a full journal publication.

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