Investigation of the performances of PZT vs rare earth ($BaLaTiO_3$) vibration based energy harvester

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Abstract. This study proposes the investigation of two piezoelectric material namely PZT and Lanthanum Doped Barium Titanate ($BaLaTiO_3$) performance as a vibration based energy harvester. The piezoelectric material when applied mechanical stress or strain produces electricity through the piezoelectric effect. The vibration energy would exude mechanical energy and thus apply mechanical force on the energy harvester. The energy harvester would be designed and simulated using the piezoelectric material individually. The studied outputs are divided to frequency response, the load dependence, and the acceleration dependence whereby measurement are observed and taken at maximum power output. The simulation is done using the cantilevers design which employs d_{31} type of constants. Three different simulations to study the dependence of output power on the resonant frequency response, load and acceleration have found that material that exhibit highest power generation was the $BaLaTiO_3$.

1 Introduction

The piezoelectric energy harvester is one of the most promising devices to generate electric energy from renewable energy sources. In particular, it is of interest in wireless and mobile devices as an alternative energy supply since the feature size of the devices becomes smaller and power consumption increases with diversified functions. In order to extract the maximum power from the environment, the resonant frequency of such device has to match the dominant frequency in the surroundings and this research delves into the investigation of the performance of two piezoelectric based energy harvesters. Vibrations based energy harvesting usually employs an electromagnetic, electrostatic or piezoelectric transduction mechanism [1]. For the design of a structure to convert mechanical vibration to electricity, the cantilever is one of the basic structures since displacement can be easily generated in a transverse direction upon vibration. A piezoelectric transduction device normally consists of an elastic cantilever supporting a piezoelectric layer with metal electrodes on either side. The electrical output energy attains a peak value if the vibration frequency of the environment matches the resonant frequency of the cantilever, and dies out dramatically when it deviates from the resonant frequency of the device [2]. The advantage of choosing a cantilever structure is that the cantilever has the lowest stiffness for a given size, and therefore it is easier to design a low frequency system that can generate highest average strain for a given load, the d_{33} mode PEH has the advantage in obtaining higher voltage while the d_{31} mode can be superior in large current generation. In the case of output power determined by the product of voltage and current, better performance was reported from d_{31} mode PEH than the d_{33} mode device due to low capacitance in the d_{33} mode device

2 Design and material characteristic

The relative permittivity of the material especially for the Lanthanum doped barium Titanate is one of the defining features that sets it apart from the likes of Barium Titanate due to fact that doping of the rare earth (Lanthanum) causes a change in the grain size of the Barium Titanate due to the smaller lanthanum ion stabilizing the cubic form of the crystal after the ion substitution between the rare earth and Barium Titanate. With the large number of holes means a large surface area with dangling bonds of the ceramic particles that tend to absorb species and water. These bonds absorb electrical energy [3]. This reaction can be described as in equation 1 [4]:

$$Ba^{2+}Ti^{4+}O_3^{2-} + xLa \rightarrow (Ba_{1-x}^{2+}La_x^{3+})Ti_{1-x}^{4+}(Ti^{4+}e^{1-})_xO_3^{2-} \quad [1]$$

Fig. 1 shows the design architecture used to simulate power generation out of the piezoelectric material.

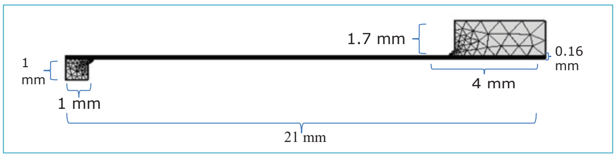

Fig. 1. The dimensions of meshed cantilever

It is noted that Lanthanum doped barium Titanate possess twice the relative permittivity than that of PZT and the following Table 1 shows the material properties of a PZT material.

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Table 1. Material properties of PZT

Properties		Notation	Value
✓	Density	Rho	7750 [kg/m^3]
✓	Elasticity matrix	cE	{1.20346e+011}[Pa]
✓	Coupling matrix	cES	{0[C/m^2],
✓	Relative permitttivity	epsilonrS	{919.1,919.1,826.6}
	Relative permitttivity	epsilonr	{919.1,919.1,826.6}
	Compliance Matrix	sE	{1.64e-011[1/Pa]}

The calculation for piezoelectric constant, d_{31} and power generation, P_{31} are based on the equations 2-6 where ω, C_{p31}, d_{31}, g_{in}, k, and ζ are the resonance frequency, capacitance of piezoelectric layer, piezoelectric constant, vibration input, electromechanical coupling coefficient, and damping ratio, respectively.

$$P_{31} = \frac{1}{\omega^2} \cdot \frac{R_O C_{p31}^2 \left(\frac{E_p d_{31} t_p b^*}{\varepsilon_0 \varepsilon_r} g_{in} \right)^2}{(4\zeta^2 + k^4)(R_O C_{p31}\omega)^2 + 4\zeta k^2 (R_O C_{p31}\omega) + 4\zeta^2} \quad (2)$$

$$R_O = \frac{1}{\omega C_{p31}} \frac{2\zeta}{\sqrt{4\zeta^2 + k^4}} \quad (3)$$

$$b^* = \frac{3b}{l_c} \frac{\left(2l_c + l_{pm} - l_e\right)}{\left(2l_c - \frac{3}{2} l_{pm}\right)} \quad (4)$$

$$b = t_s + \frac{t_p}{2} - n_s \quad (5)$$

$$n_s = \frac{\left(\frac{E_s}{E_p}\right)\frac{t_s^2}{2} + t_p\left[t_s + \frac{t_p}{2}\right]}{\left(\frac{E_s}{E_p}\right) t_s + t_p} \quad (6)$$

4 Results and discussion

The results that were obtained can be analysed by the three different type of output based on the simulation namely frequency response (Voltage and Power), Load dependence and lastly Acceleration dependence. The resonant frequency of the material is determined based on the frequency response towards voltage and power. The highest power is obtained by the cantilever when it resonated at the resonant frequency. As shown in Fig. 2 and Fig. 3, the resonant frequencies of the cantilever are 75.5 Hz and 102.5 Hz for PZT5A and $BaLaTiO_3$ respectively. Once the resonant frequency is determined, that frequency would be sampled for the following two studies load dependence and lastly acceleration dependence. The reason behind this is because at resonant frequency the material would vibrate at its maximum and thus this translates to the maximum output and can be proven based on the simulation output of the frequency response.

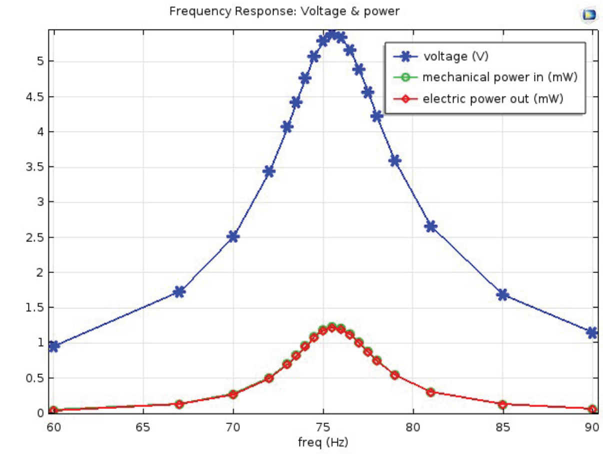

Fig. 2. Frequency responses for voltage and power of PZT at 75.5 Hz

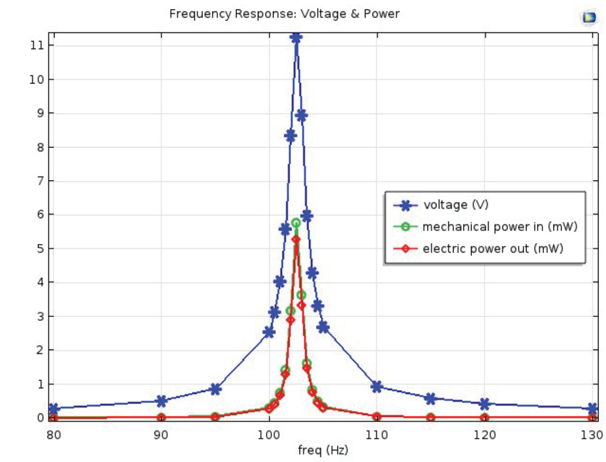

Fig. 3. Frequency responses for voltage and power of BaLaTiO3 at 102.5Hz

Table 2 has summarized the results of power when both materials were simulated with variety load values. It was found that the maximum power is obtained when the applied load is 5623.4 Ω for PZT5A and 1000 Ω for $BaLaTiO_3$. As for the acceleration dependence, 1.2 mW of output power is obtained from PZT5A and 5.02 mW from the $BaLaTiO_3$ when 1g of acceleration is applied onto the structure.

Table 2. Summary of simulation results

PZT5A	Specification	$BaLaTiO_3$
1.228 mW at 75.5 Hz	Frequency Response : Voltage & Power	5.395 mW at 102.5 Hz
1.4436 mW at 5623.4 Ω	Load Dependence : Voltage & Power	17.15 mW at 1000 Ω
1.2 mW	Acceleration Dependence : 1g	5.02 mW

5 Conclusion

In conclusion the piezoelectric cantilever that doped with rare earth material i.e. $BaLaTiO_3$ generates for a higher power than the PZT. Application of Lanthanum doped Barium Titanate as energy harvester would be of positive impact to the environment and consumer in comparison to PZT as the future material for vibration based energy harvester utilising a greener piezoelectric would seem very possible in the near future. The performance of the energy harvester can be made more stable with the inclusion of polyvinyl material due to its robust properties thus enabling longer shelf life of the energy harvester since piezo-ceramics can undergo fatigue crack when submitted to high frequency cyclic loading [5]. Such example is that a complete energy harvester system installed within the car's engine that produces vibration energy as a side effect of the engine combusting within is a great source to harvest the wasted energy.

References

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