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COMPARATIVE STUDY OF PIEZOELECTRIC MATERIALS FOR VIBRATION ENERGY HARVESTING

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Abstract

The analysis of commercially available piezoelectric coefficient mono crystalline materials. such as PMN-PT (lead magnesium niobate - lead titanate) helps broaden the gate for silicon-integrated applications (Piezoelectric MEMS) becoming more compatible with micro technology batch processes, further advances are expected in terms of miniaturization, optimization, functionality or integration with electronics, all while reducing manufacturing costs. Subsequently, operating voltage will be lower and devices response time will improve dramatically. Analytical and finite elements modelling (FEM) are performed on three crystals PMNPT and PZT-5A and PZT-5H on Aluminium cantilevers. Comparative results clearly report quantitative improvement of PMNPT on Al design in terms of tip displacement and blocking force, which imply greater potential generation.

Keywords: PMNPT; PZT5A; PZT5H and COMSOL Multi Physics.

1. INTRODUCTION

The piezoelectric effect is often encountered in daily life, for example in lighters, loudspeakers and buzzers. In a gas lighter, pressure on a piezo ceramic generates an electric potential high enough to create a spark. Most electronic alarm clocks do not use electromagnetic buzzers anymore, because piezoelectric ceramics are more compact and more efficient. In addition to such simple applications, piezo technology has recently established itself in the automotive branch. Piezoelectric-driven injection valves in diesel engines require much lower transition times than conventional electromagnetic valves, providing quieter operation and lower emissions.

Piezoelectric materials started being commercially designed and manufactured about four decades ago, spreading our days into an ever increasing spectrum of applications related to positioning and motion control. Piezoelectric devices can perform actuation and micro positioning tasks with resolutions from micrometres down to sub-nanometre scale. Blocking Force can range from several thousand Newton (stacked actuators) to less than Micro Newton (AFM, piezo cantilever, etc.). In static operation the power consumption is extremely small while in dynamic operation, settling time can be far under a millisecond.

Piezo MEMS actuators started to emerge for several years, usually made of deposited films of AlN, BaTiO3 or PZT (Pb[Zr,Ti]O3). New single- crystal materials such as PMN-PT and PZN-PT provide higher piezoelectric properties, energy density and Electro-mechanical coupling factors.

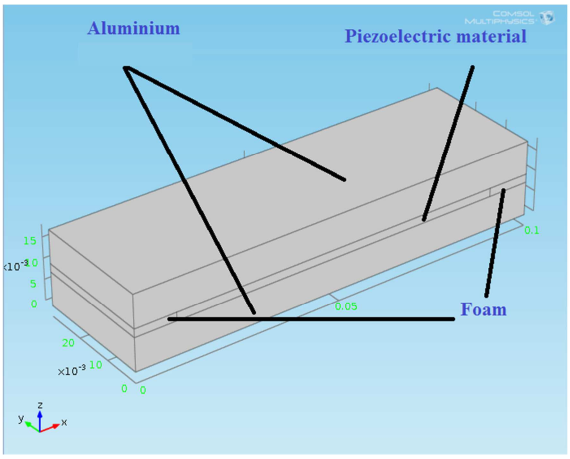
2. Concept &Working Model

The analysis deals with the blocking-force and the displacement at the tip of the cantilever according to its sizes and to the applied voltage. Simulation of theoretical formulations is compared with Finite Elements Method (FEM) results in order to obtain and discuss their performances.

PMN-PT crystals started being employed but especially into ultrasonic transducers. Their potential for actuator designs is yet to be fully revealed. A comparative overview of newer PMN-PT piezoelectric materials is to be presented for composite bimorph actuators. We will consider the classical rectangular blocked-free bender design where the piezoelectric plate (layer) is bonded or deposited on a passive substrate.
Piezo actuators can perform sub-nanometre moves at high frequencies because they derive their motion from solid-state crystalline effects. They have no rotating or sliding parts to cause friction. Piezo actuators can move high loads, up to several tons. Piezo actuators present capacitive loads and dissipate virtually no power in static operation.

2.1 Harvesting Model

The model consists of a 100-mm long sandwiched cantilever beam. This beam is composed of a 2-mm thick flexible foam core sandwiched by two 8-mm thick aluminum layers. Further, the device replaces part of the foam core with a 10-mm long piezo ceramic actuator that is positioned between x = 55 mm and x = 65 mm. as shown in figure.1



. **Figure 1:** The shear bender geometry. Note that a piezoelectric material replaces part of the foam core.

2.2 Boundary Conditions

2.2.1 Structural mechanics

The cantilever beam is fixed at its surfaces at x = 0; all other surfaces are free.

2.2.2 Electrostatics

The system applies a 20 V potential difference between the top and bottom surfaces of the piezoelectric domain. This gives rise to an electric field perpendicular to the poling direction (x direction) and thus induces a transverse shear strain.

2.2.3 Material Properties

The following table lists the material properties for the aluminum layers and the foam core.

Property	Aluminum	foam
E(young's modulus)	**70GPa**	**35.3 GPa**
μ(poison's ratio)	**0.35**	**0.383**
ρ (density)	**2700kg/m^3**	**32 kg/m^3**

Table 1: General material properties

2.2.4 PMNPT,PZT 5H, &PZT5AMaterial Properties

The material used to sense the vibration is PMN PT,PZT-5A,&PZT5H. The properties of the material are: -

PMNPT

^{C}E MATRIX [Elasticity matrix] = {11.5E10, 10.5E10, 11.5E10, 11.44E10, 11.44E10, 12.6E10, 0, 0, 0, 6.3E10, 0, 0, 0, 0, 6.3E10, 0, 0, 0, 0, 0, 6.5E10} Pascal's

$^{e}E_{S}$ matrix {coupling matrix}={0, 0, -4.69, 0, 0, -4.69, 0, 0, 25.6, 0, 0, 0, 0, 0, 0, 0, 0, 0} C/m^2;

Relative Permittivity =2687;

Density= 8100 kg/m^3;

Poisson's ratio= 0.37;

Young's modulus =72GPa

PZT-5A

^{C}E MATRIX [Elasticity matrix] = {1.20346e+011[Pa], 7.51791e+010[Pa], 1.20346e+011[Pa], 7.50901e+010[Pa], 7.50901e+010[Pa], 1.10867e+011[Pa], 0[Pa], 0[Pa], 0[Pa], 2.10526e+010[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 2.10526e+010[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 2.25734e+010[Pa]}

$^{e}E_{S}$ matrix {coupling matrix}= {0[C/m^2], 0[C/m^2], -5.35116[C/m^2], 0[C/m^2], 0[C/m^2], -5.35116[C/m^2], 0[C/m^2], 0[C/m^2], 15.7835[C/m^2], 0[C/m^2], 12.2947[C/m^2], 0[C/m^2], 12.2947[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2]}:

Relative Permittivity =1730;

Density= 7750kg/m^3;

Poisson's ratio= 0.37;

PZT-5A

^{C}E MATRIX [Elasticity matrix] = {1.27205e+011[Pa], 8.02122e+010[Pa], 1.27205e+011[Pa], 8.46702e+010[Pa], 8.46702e+010[Pa], 1.17436e+011[Pa], 0[Pa], 0[Pa], 0[Pa], 2.29885e+010[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 2.29885e+010[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 0[Pa], 2.34742e+010[Pa]}

$^{e}E_{S}$ matrix {coupling matrix}= {0[C/m^2], 0[C/m^2], -6.62281[C/m^2], 0[C/m^2], 0[C/m^2], -6.62281[C/m^2], 0[C/m^2], 0[C/m^2], 23.2403[C/m^2], 0[C/m^2], 17.0345[C/m^2], 0[C/m^2], 17.0345[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2], 0[C/m^2]}

Relative Permittivity =1704.4

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Density= 7500kg/m^3;

Poisson's ratio= 0.37;

3. FINITE ELEMENT ANALYSIS

Using COMSOL software we have calculated the value of potential difference generated due to application of cyclic load. The result is tabulated as below

3.1 PZT-5H

After the generation of model with PZT-5H layer in between the aluminum layers and fixing it one end , provide a voltage of 20v and compute the model.

After computing we have results in the form of displacements and voltage generted as shown in the figure .2 below

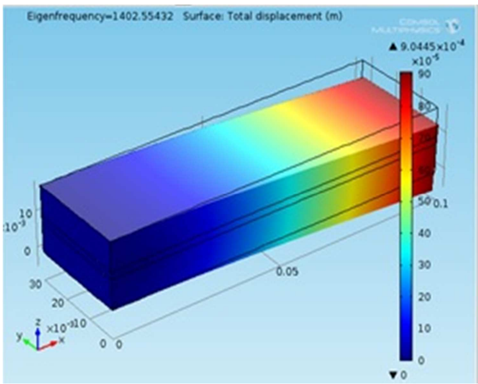


Figure 2: Deflection for the PZT-5H

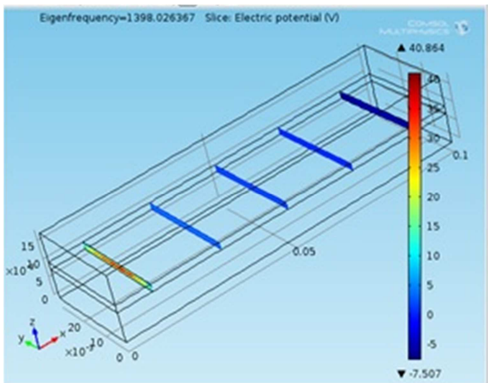


Figure 3: potential generation for the PZT-5H

This figure.2 depitcs the deflection of the cantilever beam under the load with an eigen frequency of 1402.55432 hz and figure.3 shows the static electric potential developed by the beam under the eigen frequency of 1398.026367 hz.

3.2 PZT-5A

After the generation of model with PZT-5A layer in between the aluminum layers and fixing it one end , provide a voltage of 20v and compute the model. After computing we have results in the form of displacements and voltage generted as shown in the figure below

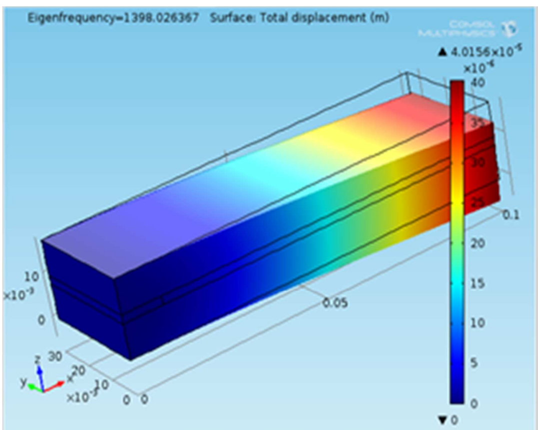


Figure 4: Deflection for the PZT-5A

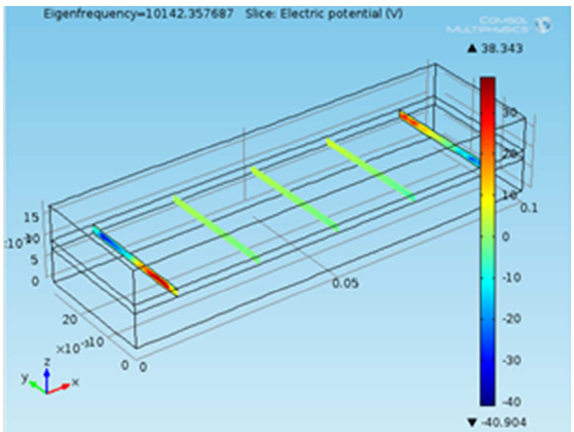


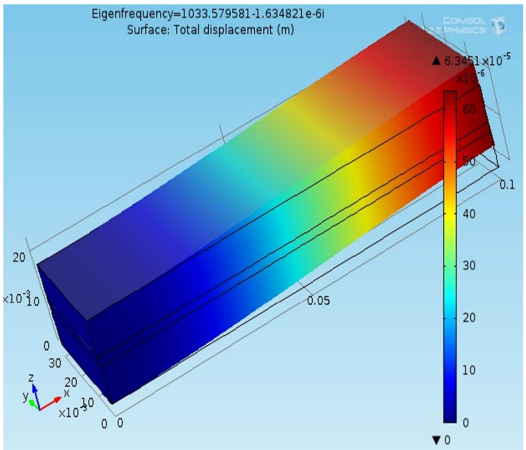
Figure 5: potential generation for the PZT-5H

This figure.4 depitcs the deflection of the cantilever beam under the load with an eigen frequency of 1398.02637 hz and figure.5 shows the static electric potential developed by the beam under the eigen frequency of 1398.026367 hz.

3.3 PMN PT

After the generation of model with PZT-5A layer in between the aluminum layers and fixing it one end , provide a voltage of 20v and compute the model.

After computing we have results in the form of displacements and voltage generted as shown in the figure below



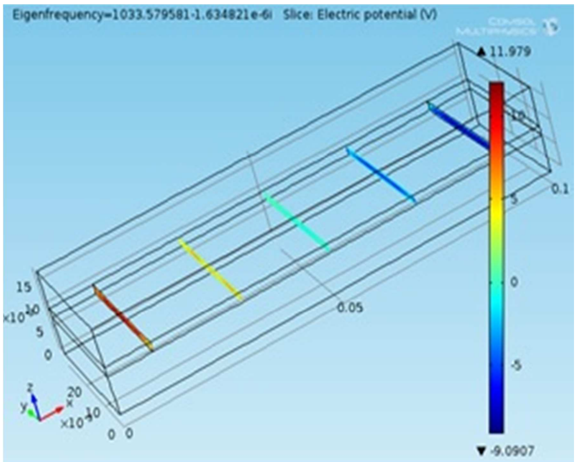


Figure 6: Deflection for the PZT-5A

Figure 7: potential generation for the PZT-5H

This figure.6 depitcs the deflection of the cantilever beam under the load with an eigen frequency of 1033.579 hz and figure. 7 shows the static electric potential developed by the beam under the eigen frequency of 1033.5798 hz.

3.4 Numerical Results

Hence these results show that PMN-PT crystal gives a higher voltage besides PZT-5A and PZT-5H crystals.

The deflections of the beams are as follows:

PZT-5A: $4.1056*10^{-5}$m

PZT-5H: $9.044*10^{-4}$m

PMN-PT: $6.435*10^{-5}$m

The voltages generated by each crystal are as follows:

PZT-5A: 0.88v

PZT-5H: 0.98v

PMN-PT: 1.67v

4. Theoretical Calculations

Now at open circuit,the formula for calculating the value of voltage and power are given by

Voltage V_{OC}= $-(d_{31}.h/E^s).T_1$ (1)

Power $P= V_L^2 / R_L$ (2)

4.1. PZT-5A

Discrete values,

d_{31} = -190 CN^{-1}

Thickness (h)= 0.03m

Relative permittivity E^s =1700

Temperatre $T_1 = 25^0C$

Using these values substituting in equation (1) we have the voltage as **0.99volts**

4.2. PZT-5H

Discrete values,

d_{31} = -265 CN^{-1}

Thickness (h)= 0.08m

Relative permittivity E^s =3400

Temperatre $T_1 = 25^0C$

Using these values substituting in equation (1) we have the voltage as **1.558volts**

4.3. PMN-PT

Discrete values,

d_{31} = -1200 CN^{-1}

Thickness (h)= 0.08m

Relative permittivity E^s =7900

Temperatre $T_1 = 25^0C$

Using these values substituting in equation (1) we have the voltage as **3.03volts**

4.4 COMPARISION

The results from the sections 4.1, 4.2 and 4.3 shows that the voltages generated by the crystals PZT-5A, PZT-5H and PMN-PT are 0.99v, 1.558v and 3.03v.

This clearly depicts that the voltage generated by PMN-PT crystal is the highest and shows that it is the most efficient material among the best available piezoelectric materials. Hence this theoretical analysis proves that PMN-PT is the best available crystals for energy harvesting.

5. CONCLUSION

Hence we have presented a comparative study of performances of PMN-PT and PZN-PT single crystals and PZT materials based piezo cantilever actuators. The analysed performances concern the blocking force and the tip displacement, and for this purpose both analytical constitutive expressions and FEM simulations were employed. A significant difference between the two types of simulation was noticed and explained; FEM method is more reliable for high coupling factor materials.

PMN-PT and PZN-PT are three to five times more piezoelectric than PZT. On the other hand, blocking forces for these single crystal materials are comparable to that of PZT. As seen, relating on specific application and geometry restrictions, there are different rate-offs privileging displacement range or blocking force. The results and discussions show that PMN-PT and PZN-PT materials are very attractive for designing silicon integrated micro actuators, providing high range of displacement and high resolution.

Compared to PZT ceramics, PMN-PT and PZN-PT single crystal materials are around three to five times more piezoelectric, making actuation range increasing substantially. Comparative results were related to a similar geometry, dimensions and same applied voltage. Maximum applicable voltage however differs. As an average, manufacturers usually restrict maximum bipolar working fields for soft PZTs to 8 kV/cm while PMN-PT+ 25 kV/cm (TRS Technologies). This means that PMN-PT may be driven up to 68%more voltage than PZT, allowing a theoretical increase of the actuating range.

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15. Elastic, piezoelectric, and dielectric properties of 0.58Pb.Mg1Õ3Nb2Õ3.O3-0.42PbTiO3 single crystal Hu Caoa) and V. Hugo Schmidt *Department of Physics, Montana State University, Bozeman, Montana 59717* Rui Zhang and Wenwu Cao *Material Research Institute, The Pennsylvania State University, University Park, Pennsylvania 16802*Haosu Luo *Shanghai Institute of Ceramics, Chinese Academy of Sciences 215 Chengbei Road, Jiading, Shanghai 201800, People's Republic of China*