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DESIGN AND SIMULATION OF ENERGY HARVESTING SYSTEM USING PMN-PT AND PZT-5H INTEGRATED WITH SILICA

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ABSTRACT

In this paper, author made an attempt to maximize the power output in the different piezoelectric materials in a unimorph cantilever beam configuration. In the present study, an attempt has been made to macro -scale uni-morph piezoelectric power generator prototypes consists of an active piezoelectric layer, silver substrate and Silca base was designed for frequencies 60 Hz - 200 Hz. An analytical model of a micro power generator is used to obtain displacement, voltage and generated power which are the figures of merit for energy harvesting. This model is presented for three different piezoelectric materials like, PZT-5H and PMN-PT with and without silica base. The designed unimorph piezo energy harvesting system was modeled using COMSOL multi physics and the observed parameters are compared with analytical results.

Keywords: PMN-PT; PZT-5H, integrated silica, voltage, frequency, energy harvesting.

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. Piezo-driven injection valves in diesel engines require much lower transition times than conventional electromagnetic valves, providing quieter operation and lower emissions.

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 PZT-5H provide higher piezoelectric properties, energy density and Electro-mechanical coupling factors.

The Lead Magnesium Niobate - Lead Titanate (PMN-PT) crystal is a new generation of piezoelectric materials. The chemical structural formula of PMN-PT is (1-x) $[Pb(Mg_{1/3}Nb_{2/3})O_3]$-x$[PbTiO_3]$. The PMN-PT is formulated to exhibit high piezoelectric coefficient, large electric-mechanical coupling coefficient, high dielectric constants and low dielectric losses. As a rule, the piezoelectric coefficient is higher than PZT ceramics, and also integrated with silica, which results in improving bandwidth, sensitivity and source level in applications.

2. ANALYTICAL METHOD

A. The piezoelectric cantilever configuration

There are two types of piezoelectric materials, piezoceramics like Lead Zirconate Titanate (PZT) and piezopolymers like Polyvinylidene Fluoride (PVDF). When piezoelectric materials are deformed or stressed, a voltage appears across the material. The mechanical and electrical behavior can be modeled by two constitutive equations [2].

$$S = [S_E]\, T + [d_t]\, E \tag{1}$$

$$D = [d]\, T + [\varepsilon^T]\, E \tag{2}$$

Where S-mechanical strains, T-applied mechanical stress, E-Electric field, D-Electric displacement, S_E - matrix of elasticity under conditions of constant electric field, d-piezoelectric coefficient matrix, ε^T =permittivity matrix at constant mechanical strain. A cantilever type vibration energy harvesting has very simple structure and can produce large deformation under deformation. The cantilever model can be used in two different modes, 33 modes and 31 modes. The 33 mode (compressive mode) means the voltage is obtained in the 3 direction parallel to the direction of applied force. The 31 mode (Transverse mode) means the voltage is obtained in 1 direction perpendicular to the direction of applied force (3). The most useful mode in harvesting applications is 31 mode, because an immense proof mass would be needed for 33 configuration [1].The vibration spectrum shows that the acceleration decreases [1] for higher modes of frequency compared to fundamental mode of frequency. Therefore, the design of the cantilever beam focusses on the fundamental mode of frequency.

B. Governing equation of cantilever beam

The resonant frequency of an cantilever without a proof mass for a simply supported cantilever beam is given by

$$f_n = \frac{v_n^2}{2\pi}\sqrt{\frac{EI}{12AL^4}} \tag{3}$$

where, E-Young's modulus, I-Moment of inertia, A-Area, L-Length of the cantilever beam,v_n=1.875 for fundamental mode, v_n=4.694 for second mode. The simulation is done in comsol and both the frequencies are compared. Different modes are shown below:

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C. Unimorph cantilever configuration

Cantilever beam piezoelectric generator has three types unimorph, bimorph series and parallel congelations. When the beam has only one piezolelectrical layer attached to the substrate, the device is known as unimorph. On the other hand, if a metal shim is sandwiched between two piezoelectric layers, the device is known as bimorph. For energy harvesting an unimorph structure is chosen. One of the most important design parameter in designing a vibration energy harvesting device is resonant frequency. The power density would be maximum when the vibration frequency matches the resonant frequency of piezoelectric generator. It has been proved that power density decreases when resonant frequency deviates from the vibration frequency [1]. The frequency range of common environmental vibrations is between 60 Hz and 200 Hz[1]. Moreover acceleration decreases with higher modes of Frequencies [1]. Therefore fundamental mode is considered in designing the cantilever. The unimorph cantilever configuration looks as in Figure-1.

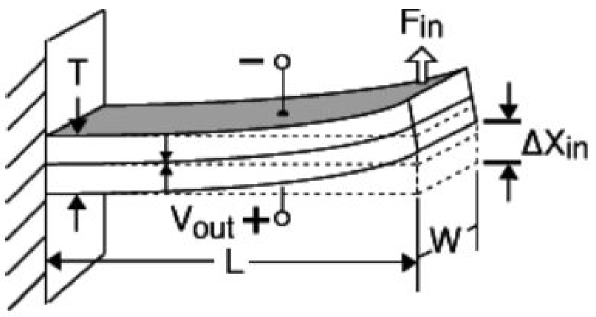

Figure-1. Unimorph cantilever.

The frequency of an unimorph cantilever is given by [3]

$$f = \frac{v_n^2}{2\pi}\sqrt{\frac{0236 D_p \omega}{\left(l-\frac{l_m}{2}\right)^3 (m_e+m_p)}} \quad (4)$$

v_n=1.875

$$m = \rho_p t_p + \rho_s t_s \quad (5)$$

$$m_e = 0.236 m\omega\left(l-\frac{l_m}{2}\right) + m\omega\frac{l_m}{2} \quad (6)$$

$$D_p = \frac{\left(E_p^2 t_p^4 + E_s^2 t_s^4 + 2E_p E_s t_p t_s\left(2t_p^2 + 2t_s^2 + 3t_p t_s\right)\right)}{12(E_p t_p + E_s t_s)} \quad (7)$$

Where
E_s = Young's modulus of substrate,
l_m = length of proof mass, $l_b = l$ = length of beam, E_p = Young's modulus of piezoelectric material, $\omega = \omega_b = \omega_m$ = Width of the beam,
t_p = Thikness of piezoelectric materials, t_s = Thikness of substrate,
m_p = Proof mass,
ρ_p = Density of piezoelectric material, ρ_s = Density of substrate material.

The dimensions of a cantilever are chosen such that the frequency range is between 60Hz and 200Hz. The dimensions and parameters of cantilever are shown in table below:

Table-1. Dimension of cantilever.

$l_b(cm)$	$\omega_b(cm)$	$t_p(cm)$	$l_m(mm)$	$\omega_m(cm)$	$t_s(mm)$
10	3	0.5	25	3	20

The parameters of the cantilever are shown below:

$E_p(Gpa)$ PMN-PT	$E_p(Gpa)$ PZT-5H	$E_{s1}(Gpa)$ Silver	$E_{s2}(Gpa)$ Silca	$E_s(Gpa)$ $=E_{s1}+E_{s2}$
1150	1270	70	150	220

Table-2. Parameter of cantilever.

t_p (mm)	t_s (mm)	$\rho_p\left(\frac{Kg}{m^3}\right)$ PMN-PT	$\rho_p\left(\frac{Kg}{m^3}\right)$ PZT-5H	$\rho_s\left(\frac{Kg}{m^3}\right) = \rho_{s1}+\rho_{s2}$
5	20	8100	7500	19300+2330

C.1 Energy parameters of unimorph cantilever:

$$Q = \frac{-3d_{31} s_s s_p t_s (t_s+t_p)}{B} \quad (8)$$

$$s_s = \frac{1}{E_s},\ s_p = \frac{1}{E_p} \quad (9)$$

$$s_h = s_s t_p + s_p t_s \quad (10)$$

$$V = \frac{-3d_{31} s_s s_p t_s t_p (t_s+t_p) l F}{\varepsilon_{33}^T \omega B\left(1+\left(\frac{3 s_p^2 s_s t_p t_s^2 (t_s+t_p)^2}{s_h B}-1\right)K_{31}^2\right)} \quad (11)$$

$$U = \frac{-9d_{31}^2 s_s s_p^2 t_s^2 t_p (t_s+t_p) l^3 F^2}{\varepsilon_{33}^T \omega B^2\left(1+\left(\frac{3 s_p^2 s_s t_p t_s^2 (t_s+t_p)^2}{s_h B}-1\right)K_{31}^2\right)} \quad (12)$$

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3. DESIGN OF UNIMORPH CANTILEVER USING COMSOL

The different modes of a cantilever beam are shown below:

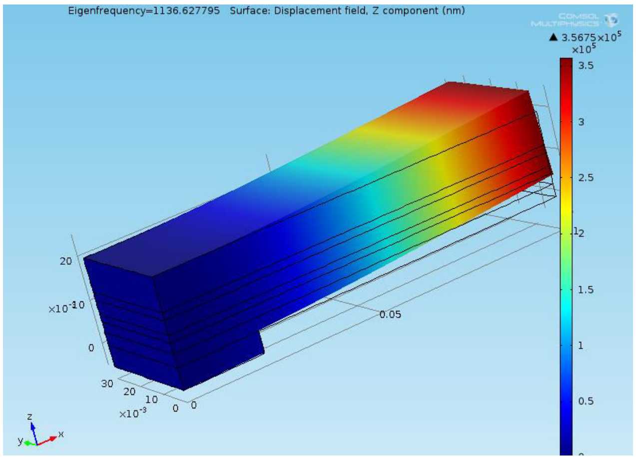

Figure-2(a). First mode of PMN-PT.

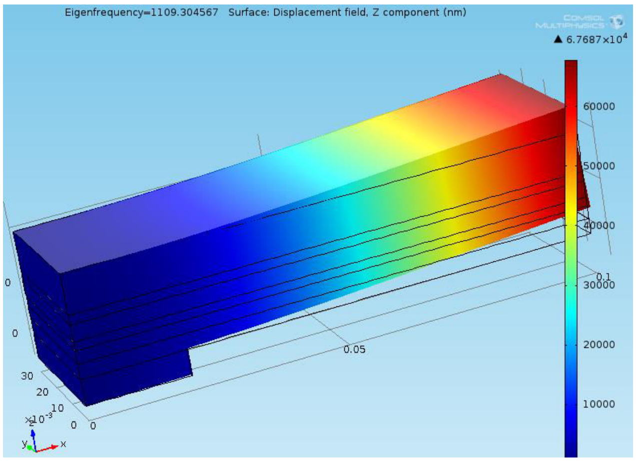

Figure-2(b). First mode of PZT-5H.

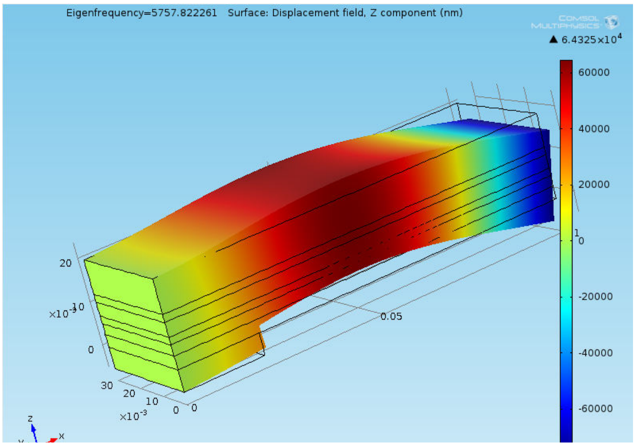

Figure-3(a). Second mode of PMN-PT.

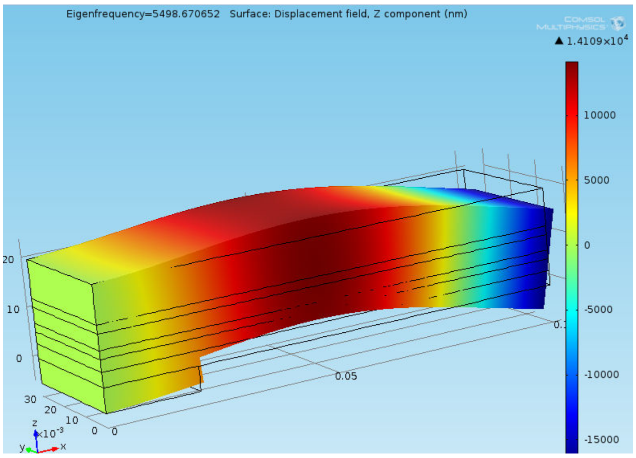

Figure-3(b). Second mode of PZT-5H.

Table-3. Comparison of simulated and analytical for different modes.

	Analytical	Simulated	Error %
First [PMN-PT]	1098.015	1136.620	3.5
First [PZT-5H]	1050.056	1109.304	5.3
Second[PMN-PT]	5742.234	5757.822	2.7
Second[PZT-5H]	5426.481	5468.670	7.7

The model is designed in comsol. A 2 dimensional unimorph cantilever is used for the simulation in comsol. Piezoelectric material PMNPT and PZT-5H is used as a piezoelectric and silver and Silicais used as substrate. It has been proved that cantilever beam with higher effective mass and less damping factor gives high output power. The proof mass not only increases effective mass but decreases damping. So the cantilever beam with proof mass has the power 10 times of the power of the cantilever beam without proof mass [4]. Therefore, a proof mass made of silican is used. The power is maximum when non-piezoelectric length and piezoelectric lengths are equal [5]. So the lengths of substrate and piezomaterial are made equal. Using solid mechanics module, one end of the model is fixed and the other end is made to move freely. The eigen frequency analysis is done. The frequency of 163.2Hz is designed using comsol. The analytical and simulated results vary by 1.82%. The designed model is shown below. The model consists of non piezoelectric material made of Silver, piezoelectric

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material made of PMNPT and PZT-5H and proof mass made of silican.

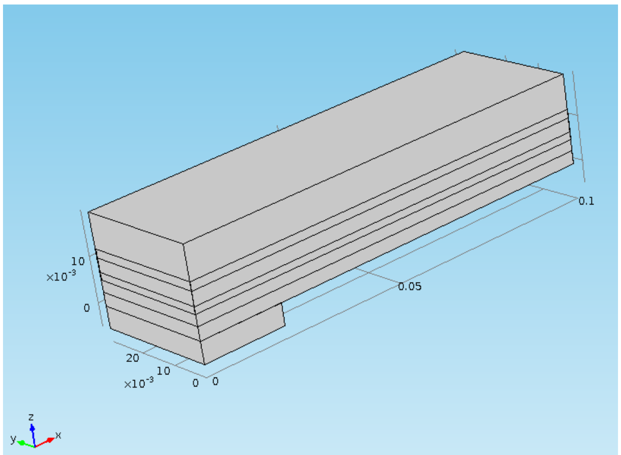

Figure-4. Designed model in COMSOL.

Meshing: The model is meshed with physics controlled mesh and element size fine. The meshed model looks as follows:

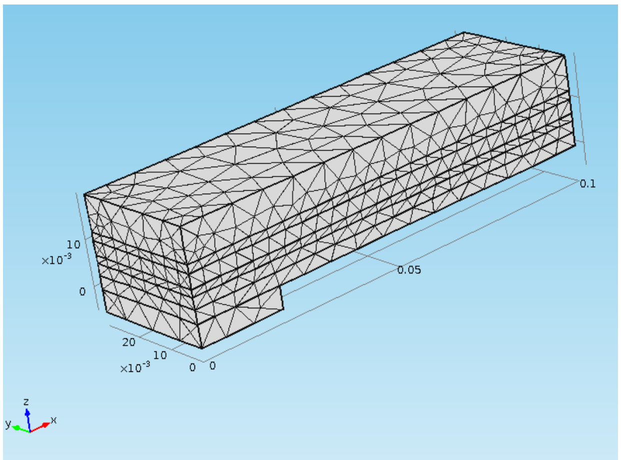

Figure-5. Meshed model in COMSOL.

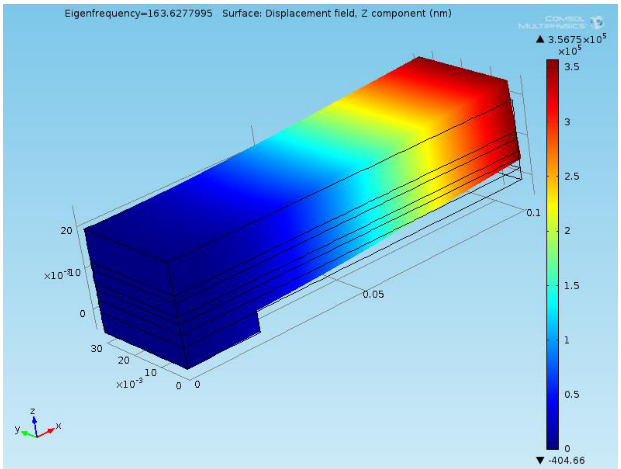

Figure-6(a). PMNPT model in COMSOL frequency of 163.62Hz.

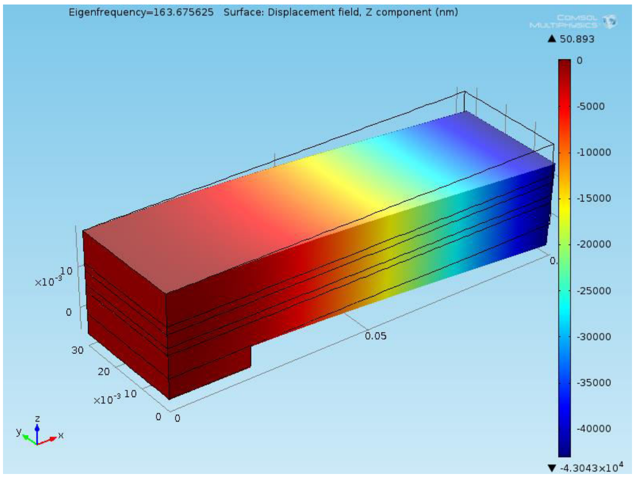

Figure-6(b). PZT-5H model in COMSOL frequency of 163.67Hz.

4. RESULTS AND DISCUSSIONS

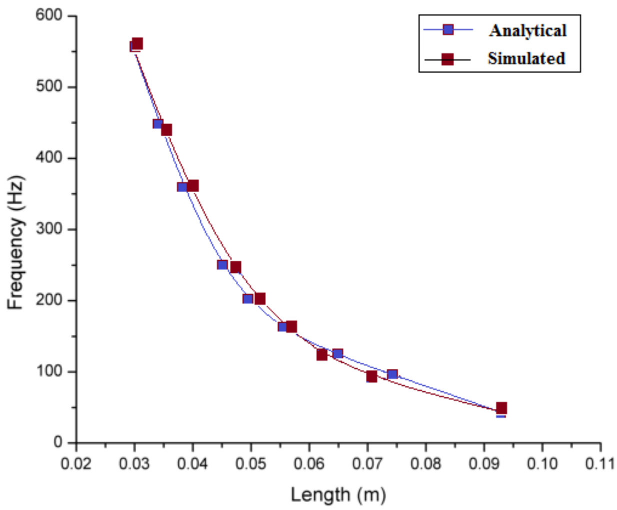

Figure-7(a). Variation of frequency with the length of the beam [PMNPT].

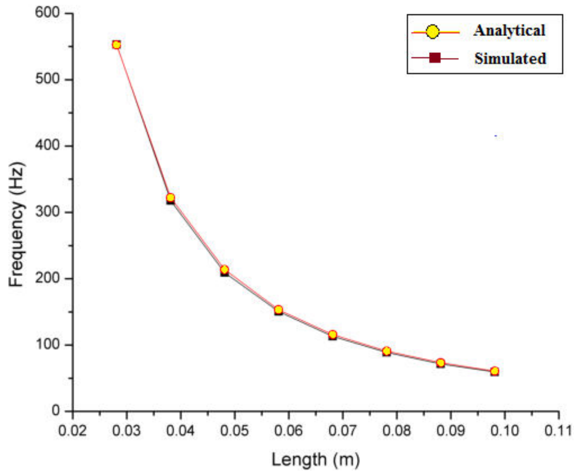

Figure-7(b). Variation of frequency with the length of the beam [PZT-5H].

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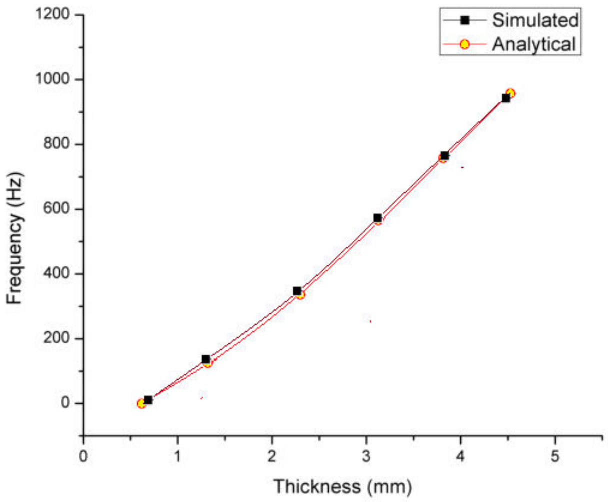

Figure-7(c). Variation of frequency with the thickness of the beam PMNPT.

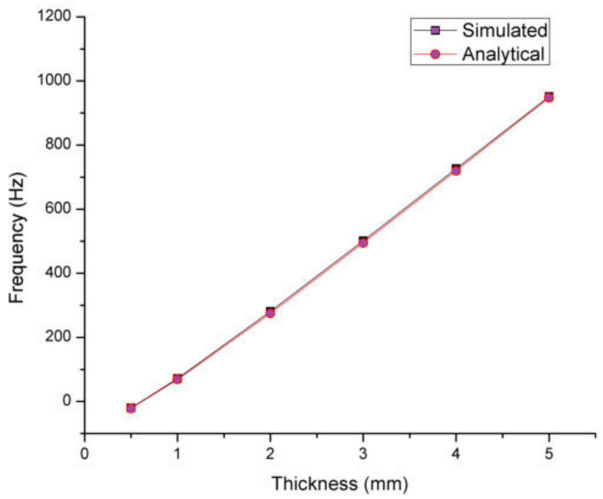

Figure-7(d). Variation of frequency with the thickness of the beam PZT-5H.

The variation of frequency with length, width and thickness of beam are shown above. The thickness of the beam has great impact on the frequency of the cantilever. It is concluded from the graph that the frequency is directly proportional to the thickness of beam. As the thickness increases, stiffness increases which in turn increases the frequency. The width of the beam has no significant effect on the frequency compared to length and thickness of beam. The frequency increased from 100 to 200 Hz as width increased from 0.01 to 0.05 metre. The length is inversely proportional to the frequency. After some point, the change in frequency is reduced. The desired frequency can be obtained for the unimorph cantilever structure considering these variations in design parameters.

Sensitivity of a unimorph cantilever:

The design parameters of a cantilever would affect the charge, voltage and energy produced by a unimorph cantilever. The variations are shown below.

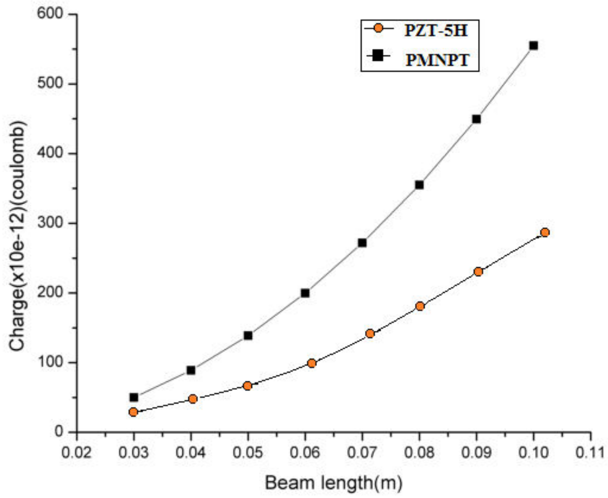

Figure-8(a). Variation of charge with length of beam.

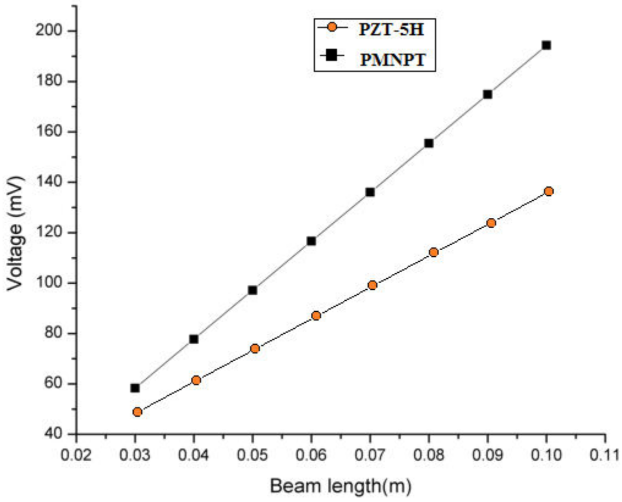

Figure-8(b). Variation of voltage with length of beam.

The width of the beam does not affect the charge produced. As the length of the beam increases, the charge produced also increases. While length is directly proportional, width is inversely proportional to the voltage produced. The length of the beam increases the energy produced. The width of the beam decreases the energy produced.

Comparison of different piezoelectric materials:

The comparison of sensitivities of different materials is done. The table below illustrates the comparision between these materials [7] [8].

Table-4. Comparison of Different parameters for Different Materials.

parameters	PMNPT	PZT-5H
Capacitance(Cp)	0.564nF	0.548nF
Charge(Q)	39.17x10^{-9}C	52.39 x10^{-9}C
Voltage(V)	1209.7mV	123.2mV
Energy(J)	3.3x10^{-5}J	5.815 x10^{-75}J

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5. CONCLUSIONS

From the above results, compared to PZT-5H and PMNPT.

PMNPT is chosen to be an appropriate material for unimorph energy harvesting system. And also these preliminary results were presented showing successful PiezoMEMS applications based on bulk PMN-PT on silicon substrate. The electro-mechanical characterization clearly shown a net performance improvement with respect to the classical designs based on PZT ceramics.

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