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Simulation and Analysis of MEMS based Multistep Piezoelectric Actuator

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***Abstract*— The work presents the performance enhancement of Piezoelectric actuators using Multistep stack configuration. The structural optimization of the PZT actuator results in the reduction of the driving voltage with an increase in the displacement and force per unit area. We find the displacement of the multistep piezoelectric micro actuator is 50% more compared to the multilayered piezoelectric actuator made from the same volume of Lead Zirconate Titanate. We also further investigate the design and analysis of multistep piezoelectric stack configuration of this micro actuator for significant characteristic improvisation using COMSOL Multiphysics. The analysis of the evaluated parameters can be used for design and optimization of these MEMS-based actuators for various manipulating and microfluidic devices with low-voltage actuation. The obtained results for displacement of Multistep arrangement at 100V was 60nm as compared to 40nm and 25nm for Multilayered and Single layered configuration respectively.**

***Keywords*—COMSOL, Lead Zirconate Titanate, MEMS, multistep actuators, Piezoelectric**

I. INTRODUCTION

Piezoelectric actuators work on the principle of Inverse Piezoelectric effect. The equations governing the inverse piezoelectric effect can be given as [1, 2]

$$S = s^E T + d_t E$$

$$D = dT + \varepsilon^T E$$

Due to rapid time response, high displacement resolution, increased operating frequency bandwidth and enhanced stability these piezoelectric actuators are employed in various micro and nano manipulating applications. The displacement of the actuator is proportional to the voltage applied [3]. The frequency bandwidth is proportional to the stiffness and inversely proportional to the damping constant and mass [4]. Piezoelectric effect can be used to develop sensors and ultrasonic sound wave while inverse piezoelectric effect can be used to develop actuators and vibrators [3]. The most important benefit of piezoelectric substance are micro displacement and stumpy power utilization [5]. A significant research is done in developing displacement amplification mechanism in these piezoelectric actuators. Lead Zirconate Titanate is one of the promising materials of various micro actuating mechanisms. Simulation and Analysis of these PZT actuators provide the essential prerequisite for designing novel actuating mechanisms for MEMS (Micro Electro Mechanical Systems) applications.

II. MATHEMATICAL MODELING

A system level actuator description with forces, in the presence of an external mechanical load F_0, is shown in figure 1. The equation of motion can be written as [6]

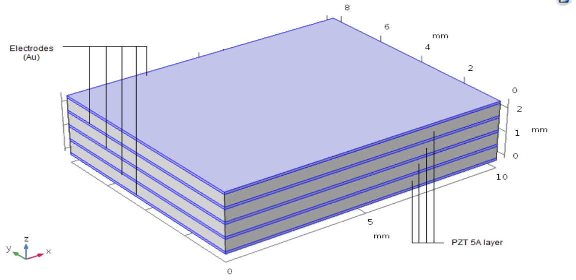


Figure 1 Multilayered Piezoelectric actuator model

$$\left(M + \frac{m_a}{3}\right)\ddot{x_a} + F_a + F_0 = 0$$

where M is the load mass, m_a is the mass of the actuator, and F_a is the force exerted by the actuator. The pressure model of the actuator is given by

$$P = Y_{33}\left(\frac{x_a}{nd} - \frac{d_{33}}{d}v_a\right)$$

where Y_{33} is the elastic modulus of PZT, x_a is the actuator displacement, n is the number of layers, d is the thickness of each layer, d_{33} is the electromechanical coupling coefficient and v_a is the actuator voltage.

The model for the multilayered piezoelectric actuator is given in the figure 1. The z-axis is chosen to be the axis of displacement of the actuator. The other axes are considered arbitrary. The displacement when no load is connected to the actuator is given by

$$\Delta z_{PZT} = N_{film} d_{33} V$$

where N_{film} is the number of layers of PZT material along the axis of actuation, d_{33} is the piezoelectric constant and $V(> 0)$ is the driving voltage given to each PZT layer. The piezoelectric coefficient, d_{33} is not a constant; it may vary significantly as strain gets larger [7]. In this paper, however, it is assumed to be constant. The force generated by the multilayered PZT actuator during displacement Δz_{PZT} is given by [8]

$$f_{PZT} = k_{PZT}(\beta V - \Delta z_{PZT})$$

where $\beta = N_{film} d_{33}$ and stiffness $k_{PZT} = E_{PZT} h_{PZT} w_{PZT} / l_{PZT}$, where E_{PZT} is the elastic modulus of PZT material. The variables h_{PZT}, l_{PZT} and w_{PZT} are the height, length and width of the actuator respectively.

III. Simulation and Analysis

The configurations proposed were multilayered and multistep configuration of the piezoelectric material against the single layered piezoelectric material. The piezoelectric material used was Lead Zirconate Titanate (PZT 5A) along with Au electrodes.

The single layer of 125µm was later substituted by 5 layers of 25µm each in the multilayered and multistep configurations. In the multistep configuration, the PZT layers of the multilayered stack configuration were given a dimensional shift of 5 microns alone the x axis to get a step like arrangement for performance enhancement by displacement amplification.

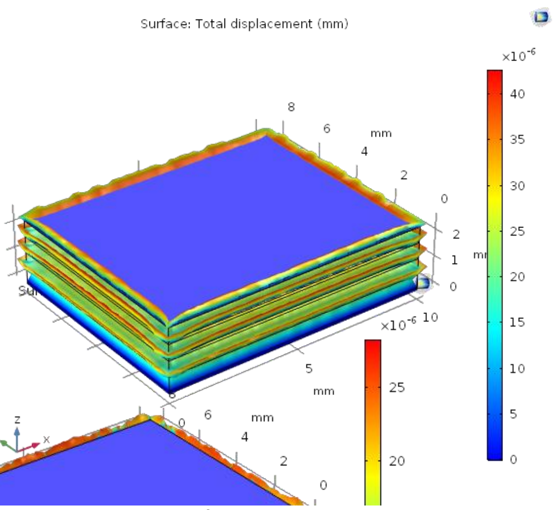


Figure 3 Displacement of Multi layered piezoelectric actuator at 100V

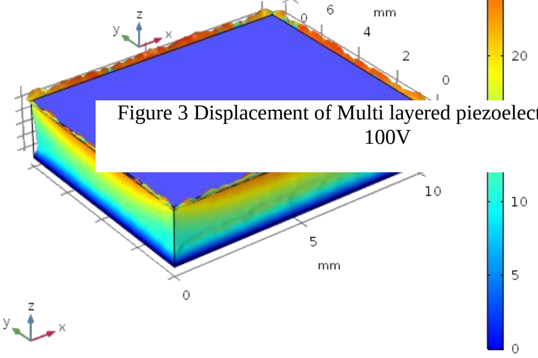


Figure 2 Displacement of Single layered piezoelectric actuator at 100V

Material	Energy Density (J/m^3)	Piezoelectric constant d_{33} (m V^{-1})	Young's Modulus (GPa)	Electric field (kV cm^{-1})
Lead Zirconate Titanate	1.2x10^5	500x10^{-12}	63	40

Table 1: Properties of Lead Zirconate Titanate

The actuator was simulated using the Piezoelectric Devices module in COMSOL Multiphysics. The PZT layers were stacked between the Au electrodes. The electric potential was the given to the electrodes whereas the PZT layers were connected to the ground. The characteristics such as displacement, strain, and pressure were evaluated at varying voltages ranging between 25-300 volts.

At 100V, the following results were obtained, in the order: Single layered, Multilayered and Multistep.

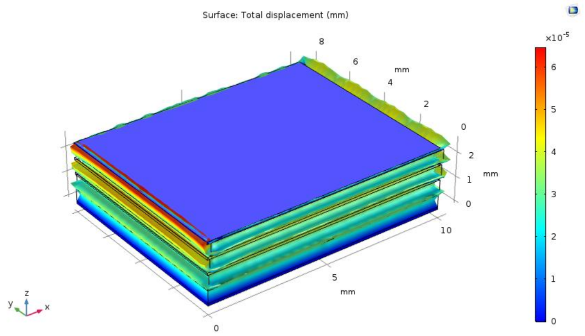
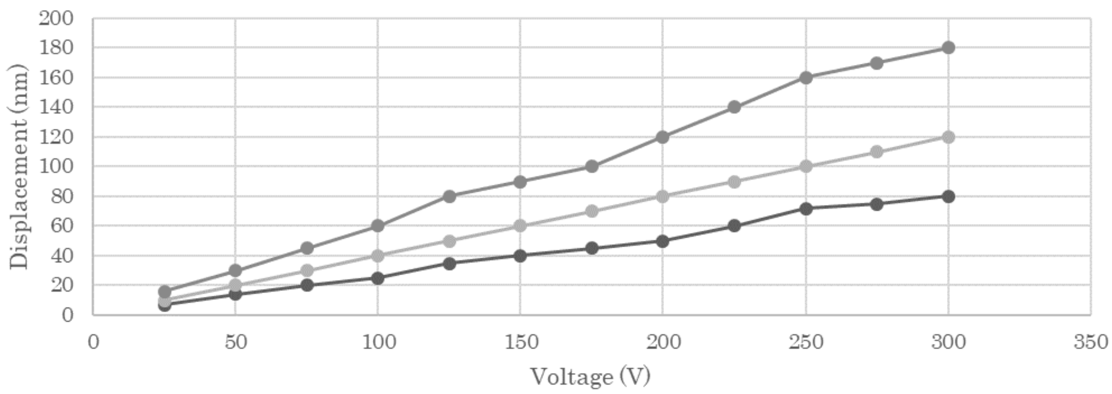


Figure 4 Displacement of Multi step piezoelectric actuator at 100V

Based on the simulation, the following graphs were calculated and plotted.



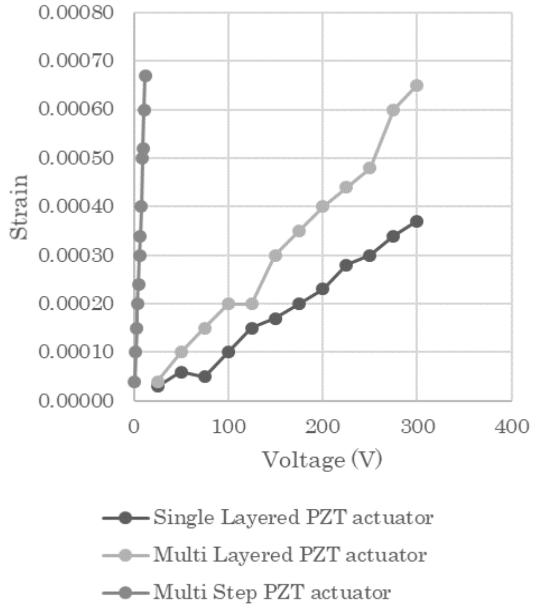


Figure 6 Strain Characteristics at varying voltages in the PZT actuators

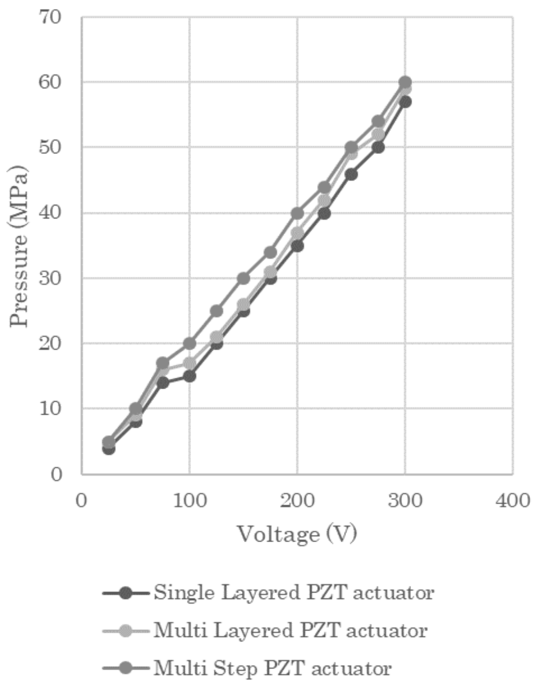


Figure 7 Pressure Characteristics at varying voltages

RESULTS

Potential (V)	Single Layered PZT actuator			Multi Layered PZT actuator			Multi Step PZT actuator		
	Displacement (nm)	Pressure (MPa)	Volumetric strain	Displacement (nm)	Pressure (MPa)	Volumetric strain	Displacement (nm)	Pressure (MPa)	Volumetric strain
25	7	4	0.00003	10	5	0.00004	16	5	0.00004
50	14	8	0.00006	20	9	0.00010	30	10	0.00010
75	20	14	0.00005	30	16	0.00015	45	17	0.00015
100	25	15	0.00010	40	17	0.00020	60	20	0.00020
125	35	20	0.00015	50	21	0.00020	80	25	0.00024
150	40	25	0.00017	60	26	0.00030	90	30	0.00030
175	45	30	0.00020	70	31	0.00035	100	34	0.00034
200	50	35	0.00023	80	37	0.00040	120	40	0.00040
225	60	40	0.00028	90	42	0.00044	140	44	0.00050
250	72	46	0.00030	100	49	0.00048	160	50	0.00052
275	75	50	0.00034	110	52	0.00060	170	54	0.00060
300	80	57	0.00037	120	59	0.00065	180	60	0.00067

Table 2 Comparison of various Displacement, Pressure and Strain at different voltages

V. CONCLUSION

The characteristics of the single layered, multilayered and multistep stack PZT actuators were studied and the it can be concluded that the displacement can be amplified using the multistep configuration. The displacement amplified was as much as 60% in the multistep configuration compared to the multilayered actuator. The displacement amplification can prove to be useful in the performance enhancement of various micro and nano manipulators. The obtained characteristics prove the effectiveness of multistep PZT stack actuators in the field of micro actuation by further reducing the driving voltages of these actuators with enhanced characteristics.

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