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Effect of Polarization and Gravity on Deflection of PZT-5H based Cantilever Actuator

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Abstract

This paper examines the impact of polarization and gravity on piezoelectric actuators operating in various modes (d_{13} and d_{33}). These modes are responsible for two different types of actuations like compressive and tensile. The Finite element analysis (FEA) of unimorph actuator is presented using 3D 20 node coupled element. The two different axial polarization effects are analyzed considering the effect of gravity. The displacement and stress field are studied for PZT-5H (Lead Zirconate Titanate) material. The variation of displacement and stress is presented with respect to thickness of piezoelectric actuator. In addition, the displacement field analysis of bimorph under voltaic gravity loading environment is presented.

Keywords

Piezoelectric actuator, Polarization, Gravity, Coupled element

Introduction

Piezoelectric is one of the best applicable materials for sensor and actuator. In the synthesis of piezoelectric material, polarization is the last step, and its effect must be studied. Electric polarization is defined as the total dipole moment per unit volume. The dipoles align along the applied electric field after polarization. It is done by applying high electric field. The piezoelectric material exhibits piezoelectricity effect only after polarization. The polarization causes different actuation of piezoelectric. Piezoelectric is a material which generates electricity on applying pressure called piezoelectric material. The cause is known as direct effect. Piezoelectric shows indirect effect also i.e., generates strain while applying electric field. The indirect effect has been applied in many domains like mechatronics application, crack repair, micro pump, etc. Based on the domain the literature survey has been done as follows.

Mechatronics application: Many mechatronics applications like car antiskid braking system of piezoelectric actuator has been presented by Janker et al. [1]. He has focused on high amplitude actuators like DWARF. A piezoelectric micro-lens actuator has been developed by Michael and Kwok [2] to change the focal length of lens. Crack Repair: Liu [3] has done crack contact analysis during active repair using piezoelectric multi-layered patches. Wu and Wang [4] focused on repair of a delaminated plate. The stress developed by piezoelectric patch has been applied for repair. Reduction of crack propagation in aluminum panels by using piezo-electric patch has been analyzed by Platz et al. [5]. A modeling approach has been developed for evaluating reduction in stress intensity factor in center-cracked plate by using piezoelectric actuator patch [6]. A brief review of active structural repair and control by using piezoelectric patches has been presented by Abuzaid et al. [7]. Piezoelectric material has been applied for structural health monitoring and repair [8]. In order to analyze the fracture and repair, ephemeral parametric

research was conducted. The effectiveness of repair of the plate with an angular and straight crack was examined under both thermal and mechanical loading using 2D and 3D XFEM (extended finite element method) modelling and simulation. The best repair efficiency was investigated using a variety of patch sizes, shapes, and placements [9]. Analysis was done on experimental research on the best patch placement for a crack repair. The effectiveness of double and single patches in the repair was investigated [10]. FEA modelling was carried out to analyze the repair in the composite plate. Both static and dynamic loads on the repair were evaluated [11]. For the investigation of the fatigue life of repaired structures, XFEM modelling techniques have been employed to model discontinuity [12]. Micro gripper: A micro-gripper [13] has been developed using piezoelectric bimorph. This was based on d_{31} mode. Micropump: Design of pump without valve for micro-fluid devices [14], Development of system to improve mixing of fluids [15], and automatic sensing of flow rate of a pump [16] are the advance application of piezoelectric material. Micro mixing: A review of mixing in microfluidic mixers has been presented by Mansur et al. [17].

All the above discussion is based on two modes (d_{31} and d_{33}) of piezoelectric material. The comparison of displacement under the effect of gravity in all modes has not been reported so far. This paper is focused on the finite element analysis of these modes with two different axial (x and y) polarization. For this an APDL code is written in ANSYS. The displacement and stress field has been analyzed for the parameters like thickness of piezoelectric and applied voltage. Good agreement has been observed between FEA and analytical results. This will help in the application of PZT-5H based actuator in actual environment of gravity.

Experimentation

Problem definition

The deflection of a piezoelectric plate of dimension 76.2 mm x 25.4 mm x 0.5 mm is analyzed for different applied voltage and thickness. The finite element method has been applied to model piezoelectric actuator using 3D 20 Node coupled field element (SOLID 226). The boundary is fixed in all directions at one end and voltage is applied at the top and bottom electrode. The gravitational load is applied in y-direction as shown in figure 1. The same piezoelectric plate is glued to ABS (Acrylic Butadiene Styrene) to form bimorph smart structure. The displacement fields are analyzed under gravity effect and compared with analytical results. The 3D model of bimorph is shown in figure 7.

Theory of piezoelectric indirect effect

Piezoelectricity shows combined behavior of electrical and mechanical. Piezoelectric works on the principle of two effects: direct and indirect. The direct effect is called sensor effect and indirect effect is called actuator effect. The constitutive equation for indirect effect is given by:

$$\{S\} = [s^E]\{T\} + [d^t]\{E\} \quad (1)$$

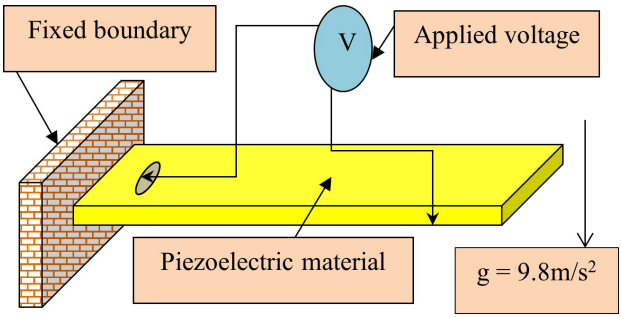

Figure 1: 3D model of piezoelectric actuator with applied voltage.

{S} = Mechanical strain matrix
$[S^E]$ = Compliance matrix at constant electric field
[d]= Piezoelectric coefficient matrix
{E} = Electric field orthogonal matrix
{T} = Mechanical stress matrix

The superscript *E* indicates constant or zero electric field, *T* indicates constant or zero stress, and *t* indicates transpose of a matrix. The 2D model of beam with uniformly distributed load (*w* N/m) is shown in figure 2. In the modeling of beams under gravitational field, the load due to gravity on cantilever beam is considered uniformly distributed. Hence the equation of deflection of cantilever beam due to self-weight can be written as:

$$Max\ Deflection = \frac{wL^4}{8E}; \text{ where,} w = \rho g A \quad (2)$$

ρ (Density) = 7500 kg/m^3
g (Acceleration due to gravity) = 9.8 m/s^2
E (Young's modulus) = 75 GPa
L (Length of the piezoelectric) = 76.2 mm
b (Width of piezoelectric) = 25.4 mm
h (Thickness of piezoelectric) = 0.5 mm
A (Cross section area) = b x h

The analytical result (0.198 mm) of deflection due to self-weight has been validated by finite element result (0.201 mm). Piezoelectric is generally used with host material for generation of smart structure. The 3D model of a bimorph smart structure is shown in figure 7. The deflection of this bimorph under voltaic-gravity effect can be given by [18]:

$$\delta(L) = \frac{3s_1^m s_1^E L^4}{2D} w + \frac{3s_1^m d_3 (t_m + t_p)}{D} V \quad (3)$$

Where, $D = 2s_1^m(3t_m^2 t_p + 6t_m t_p^2 + 4t_p^3) + s_1^E t_m^3$

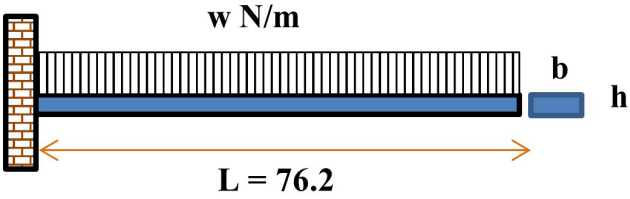

Figure 2: 2D model of piezoelectric with UDL.

In the expressions, superscript '*p*' denotes the piezoelectric, '*m*' denote host; s_{11}^{E} are the compliance coefficient at constant electric field of piezoelectric and d_{31} is the piezoelectric coefficient at constant stress. The other symbols used in the equations are: s_{11}^{m} = flexibility coefficient of host material, t_p = thickness of piezoelectric, t_m = thickness of host structure, L = length of structure, V = applied voltage, and δ = deflection of cantilever.

Finite element analysis

A piezoelectric actuator is modeled by FEA. The dimensions of the actuator are t = 0.3 mm, w = 10 mm, and l = 20 mm for the thickness, width, and length, respectively. PZT-5H is considered for the actuator analysis. Table 1 and table 2 shows material properties of PZT-5H and ABS. Figure 3 shows the displacement contour plot. The displacement of piezoelectric actuator can be calculated by equation (4).

$$\Delta l_p = S_p l_p \tag{4}$$

$$= \frac{3}{} \tag{5}$$

Where, S_p is strain in piezoelectric, l_p is length of piezoelectric patch, d_{31} is piezoelectric coupling coefficient, V is applied voltage, and t_p is thickness. The maximum displacement obtained from FEA found to U_{max} = 1.40 µm at the free end of cantilever. This shows good match with the analytical result of U_{max} = 1.40 µm. It is also in good agreement with the reference result Platz et al. [5] U_{max} = 1.43 µm. In this, the polarization axis is in z-direction.

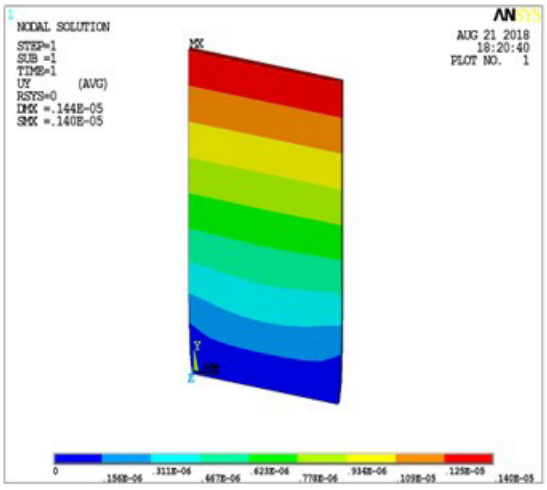

Figure 3: Piezoelectric linear actuator in d_{31} mode at 10 V.

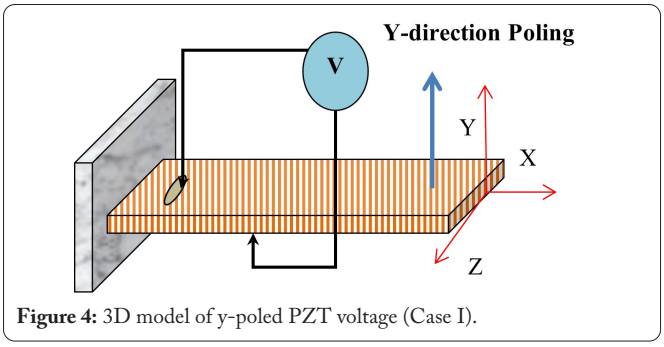

Figure 4: 3D model of y-poled PZT voltage (Case I).

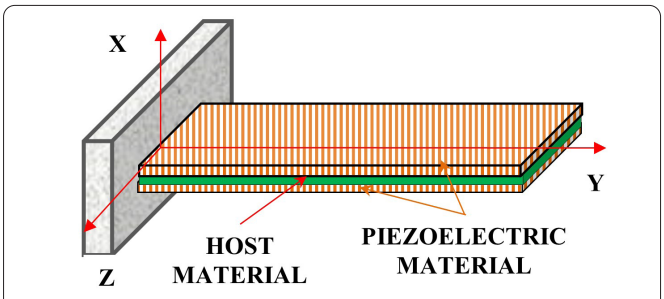

Figure 5: 3D model of y-poled bimorph (Case II).

Polarization in y-direction

Case I

In this PZT-5H of dimensions 76.2 mm x 25.4 mm x 0.5 mm (L x w x tp) is taken for the FEA. The piezoelectric is polarized in the y-direction. The voltage applied to piezoelectric is across the thickness. Figure 6 and figure 7 show

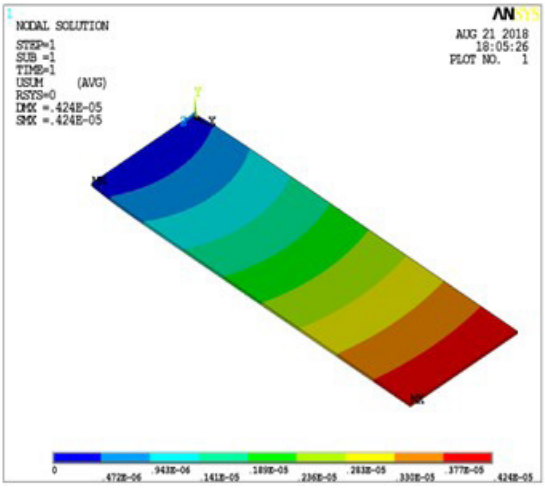

Figure 6: Displacement contour plot of piezoelectric compressive actuator in d_{31} mode at 100 V.

Table 1: Electromechanical properties of PZT-5H [19].

Sr. No.	Material	Piezoelectric Coefficient (10^{-12} m²/N)			Dielectric Constant (10^{-12} C/N)		Density (Kg/m³)
1.		$d_{31} = d_{32}$	d_{33}	$d_{15} = d_{24}$	ε_{11}	ε_{33}	ρ
	PZT-5H	-274	593	741	3130	3400	7500
2.		Young's Modulus (GPa)			Poisson Ratio		Density (Kg/m³)
	ABS	2.5			0.35		1052

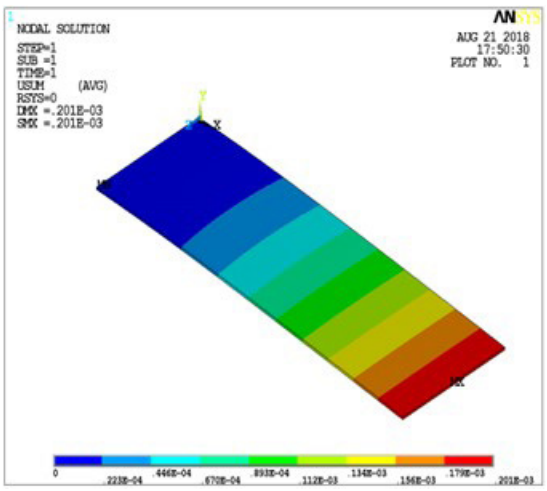

Figure 7: Displacement contour plot of piezoelectric compressive actuator in d_{31} mode at 100 V under gravity load.

the displacement contour plot without and with gravity load respectively for y-direction polarization. An increase of factor 47.40 in displacement has been observed due to gravity.

Case II

In this case host material (ABS) is sandwiched by piezoelectric material (PZT-5H). The PZT-5H of dimensions 76.2 mm x 25.4 mm x 0.5 mm (L x w x tp) is used and glued to an ABS strip of dimension 76.2 mm x 25.4 mm x 1.0 mm (L x w x tm). The piezoelectric is polarized in the y-direction. The voltage applied to piezoelectric is across the thickness. Figure 8 and figure 9 show the deflection contour plot of bimorph structure without and with gravity effect respectively. An increment of factor 1.04 in the maximum deflection is observed.

Polarization in x-direction

Case I

The PZT-5H of dimensions 76.2 mm x 25.4 mm x 0.5 mm (L x w x tp) is taken. The piezoelectric is polarized in x-direction. The voltage applied to piezoelectric is across the length. Figure 12 and figure 13 show the displacement contour

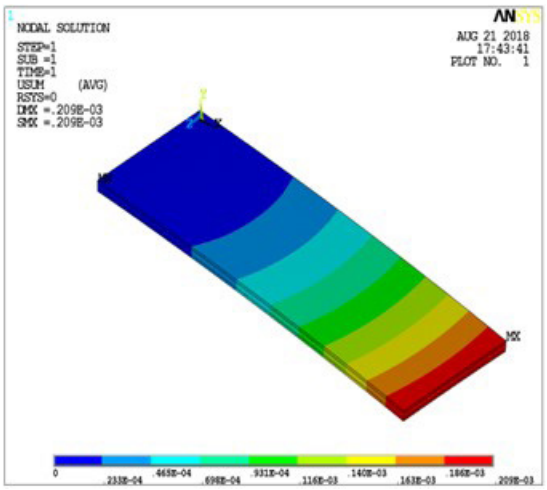

Figure 8: Displacement contour plot of bimorph in d_{31} mode at 100 V (Case I).

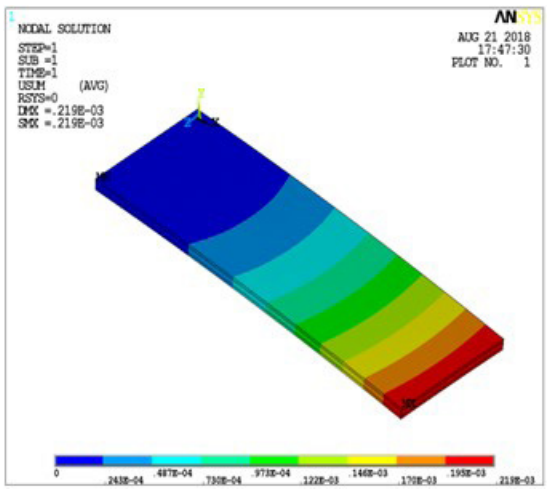

Figure 9: Displacement contour plot of bimorph in d_{31} mode at 100 V under gravity load (Case II).

plot without and with gravity load respectively for x-direction polarization. An increase of factor 4637.93 in displacement has been observed due to gravity.

Case II

In this case host material (ABS) is sandwiched by piezoelectric material (PZT-5H). The PZT-5H of dimensions 76.2 mm x 25.4 mm x 0.5 mm (L x w x tp) is used and glued to an ABS strip of dimension 76.2 mm x 25.4 mm x 1.0 mm (L x w x tm). The piezoelectric is polarized in x-direction as shown in figure 13. The voltage applied to piezoelectric is across the length. As seen in figure 14 and figure 15, an increase of factor 188.84 is observed due to gravity. This value is large and will greatly affect the displacement of bimorph.

Results and Discussion

Figure 16 shows the logarithmic displacement vs. thickness

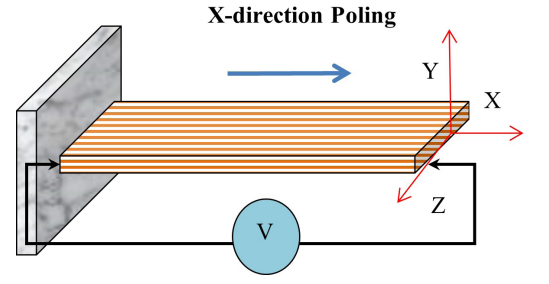

Figure 10: 3D model of x-poled PZT (Case I).

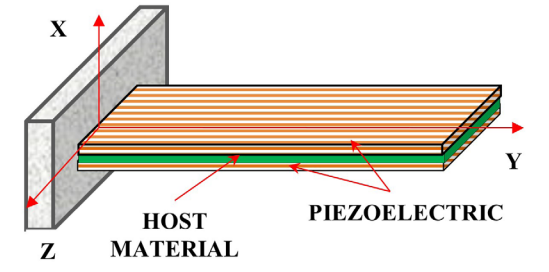

Figure 11: 3D model of x-poled bimorph (Case II).

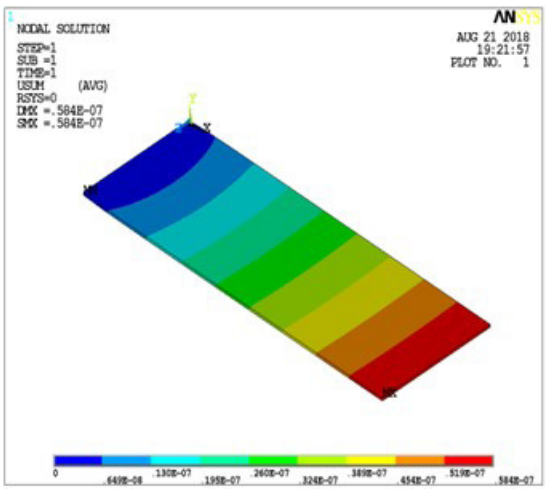

Figure 12: Displacement contour plot of tensile actuator in d_{33} mode at 100 V (Case I).

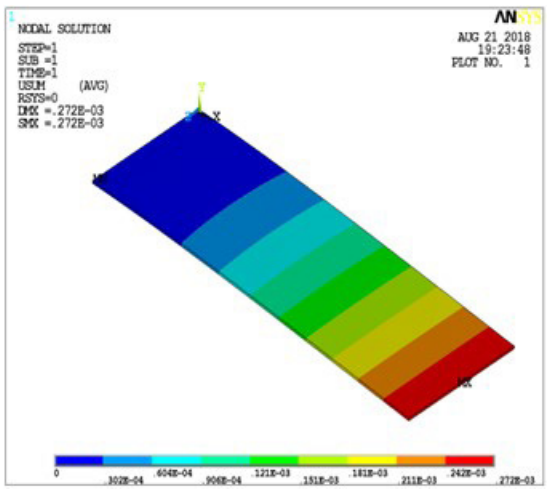

Figure 13: Displacement contour plot of tensile actuator in d_{33} mode at 100 V under gravity load (Case II).

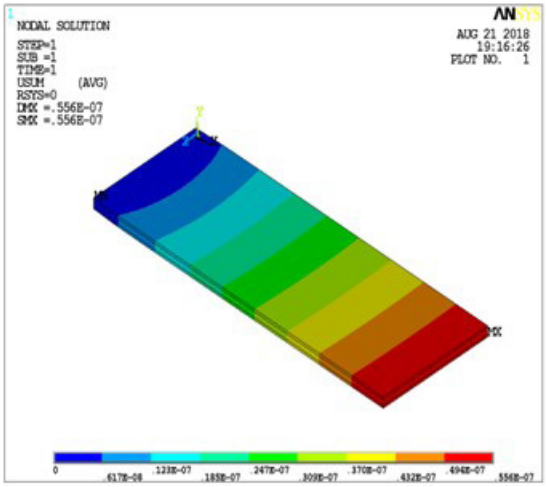

Figure 14: Displacement contour plot of bimorph in d_{33} mode at 100 V.

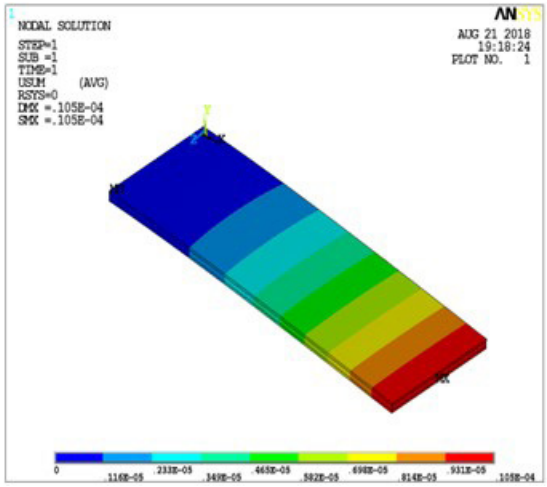

Figure 15: Displacement contour plot of bimorph in d_{33} mode at 100 V under gravity load.

for y-polarization. The displacement decreases as the thickness of piezoelectric increases. A large gap in the displacement has been observed in the plot due to gravity. Figure 17 shows the logarithmic von Mises vs thickness for y-polarization. The von Mises stress also decreases as the thickness increases. Figure 18 and figure 19 shows logarithmic displacement vs length and logarithmic von Mises stress vs length plot, respectively. The displacement decreases as the length increases in the case of without gravity and increases in the case of gravity. A similar pattern has been observed for von Mises stress. Figure 20 shows the comparison of deflections calculated by finite element and analytical method under voltaic and voltaic gravity loading effect. In this y-poled piezoelectric is taken.

Conclusion

The FEA has been performed for piezoelectric actuator in d_{13} and d_{33} mode. The actuator displacement has been evaluated for PZT-5H because of its high piezoelectric coefficient. The result shows that thin piezoelectric plate produces large displacement and von Mises stress. The maximum displacement of 0.201 mm and 0.00424 mm has been obtained with and without gravity, respectively, for 0.5 mm thick piezoelectric plate. It is observed that the displacement has increased by a factor of 47.40 due to gravity in case of y-polarization. Similarly, an increase of factor 4637.93 in displacement has been observed due to gravity in case of x-polarization. The maximum displacement of 0.201 mm has been observed in the

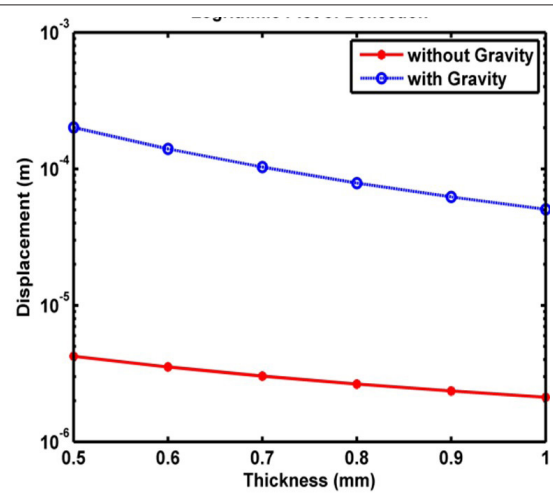

Figure 16: Displacement contour plot of piezoelectric compressive actuator (x-polarized) in d_{31} mode.

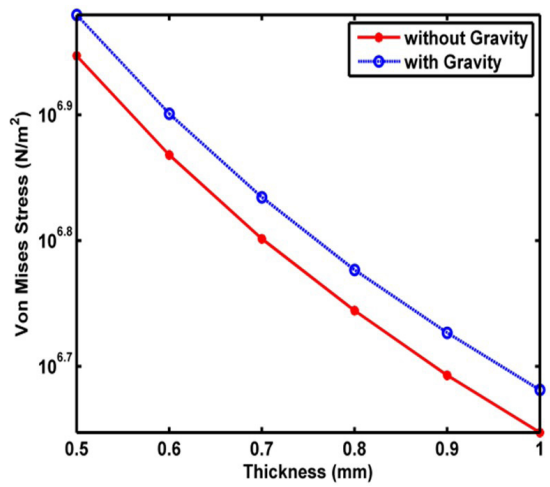

Figure 17: von Mises stress of piezoelectric compressive actuator (x-polarized) in d_{31} mode.

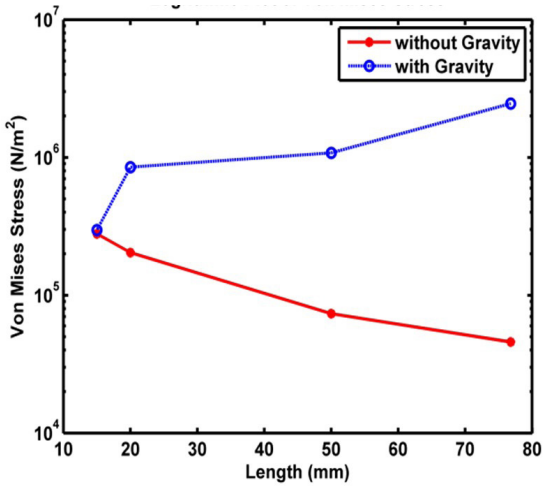

Figure 19: von Mises stress of piezoelectric tensile actuator (x-polarized) in d_{33} mode.

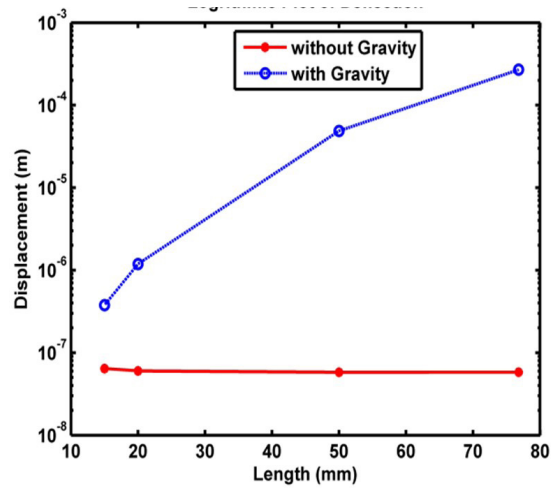

Figure 18: Displacement vs length of piezoelectric tensile actuator (x-polarized) in d_{33} mode.

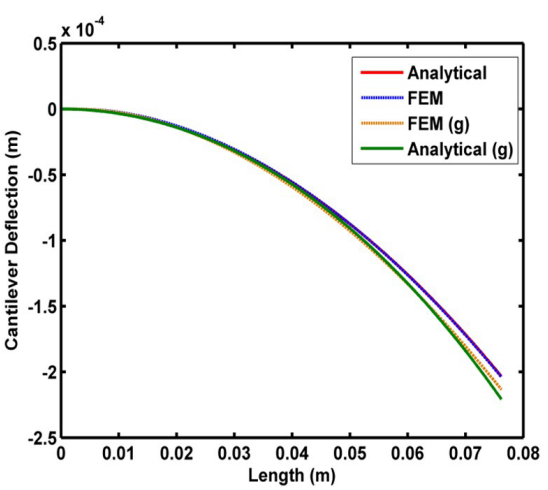

Figure 20: Deflection of bimorph in d_{31} mode.

case of y-polarization and 0.272 mm in the case of x-polarization under gravity. So, large increase in displacement is found in x-poled piezoelectric. In the case of bimorph, an increase of factor 4637.93 in case of y-polarization and 188.84 in case of x-polarization. The gravity effect shows a large increase in the displacement. So, the experimental error can be minimized by performing the finite element analysis under gravitational environment.

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Conflict of Interest

The authors declare no conflict of interests that are relevant to the content of this article.

Credit Author Statement

Ritesh Kumar: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft preparation; Naresh Kumar Vemula: Resources, Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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