Optimizing the Design of Polymer Based Unimorph Actuator using COMSOL Multiphysics

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Abstract: The piezoelectric cantilevers are being extensively used in different configurations such as unimorphs, bimorphs and multimorphs for their application as sensors and actuators. In this study, a unimorph piezoelectric cantilever is chosen as the study element. This piezoelectric unimorph cantilever is designed using COMSOL Multiphysics software. A systematic investigation has been carried out to study the influence of the device dimensions on the deflection of the cantilever. The design parameters are optimized for achieving maximum tip deflection and their role on the tip displacement has been discussed.

Keywords: Piezoelectric, Unimorph, Cantilever, PVDF and elastic substrate.

1. Introduction

Cantilever beam-type transducers have been in great demand and explored widely in the recent years, typically in thin film form because of their sensor and actuator applications[1-4]. The piezoelectric cantilever is the most preferred structure employed in technological applications. These cantilevers are used in different configurations such as unimorph, bimorph and multimorph structures based on the required flexural motion and sensitivities.

The unimorph cantilevers are preferred for their simple structure and easy assembly compared to bimorph and multimorph structures. The polymer based unimorphs and bimorphs are being widely studied for their potential applications in aeronautics, aerospace and industry for their flexibility, durability and light weight structure with high degree of robustness. The piezoelectric ceramics have better electrical response than polymer based cantilevers but are brittle and heavier which limits its use in such technological applications as discussed above. Polyvinylidene difluoride(PVDF) is the most preferred polymer[7].

It is well known that the tip deflection of a unimorph cantilever is dependent on its geometrical dimensions, material properties etc [5,6].Hence, it becomes necessary to optimize the device dimensions in order to achieve maximum deflection in a microactuator. In this work, an attempt has been made to study the effect of device parameters on the deflection of the unimorph cantilever. An optimum design of the cantilever is found by adjusting parameters and device dimensions.

A unimorph cantilever beam consisting of a piezoelectric polymer like PVDF with a non-piezoelectric layer coating of different materials on the other side is considered for the study. The fabrication of such cantilever beam is an expensive affair and hence, it is important to optimize the device parameters before the actual fabrication of beam, In view of this, a piezoelectric cantilever is designed and its response with the electrical signal is simulated with the help of COMSOL Multiphysics software.

2. Use of COMSOL Multiphysics

A 3-dimensional unimorph cantilever is used for simulating the electrical output response with COMSOL Multiphysics Version 4.2[10].

It consists of a nonpiezoelectric layer as substrate with a piezoelectric polymer PVDF layer on the top, poled along the direction of thickness. These layers are rectangular in shape. The piezoelectric polymer PVDF and non-piezoelectric elastic layer are characterized as upper and lower layer respectively. The tried non-piezoelectric elastic layers are Steel, polysilicon and silicon nitride (Si_3N_4).

The structure is divided into two subdomains for the analysis- one for non piezolayer and other one for piezoelectric polymer PVDF layer. The model uses a piezoelectric application module for the simulation of the mechanical and the electrical behavior of the piezoelectric layer whereas structural mechanics module was applied to non-piezo substrate layer. The two physics were coupled together for optimizing the device structure.

2.1 Governing Equations

The piezoelectric unimorph cantilever works in tranverse mode and it is governed by the following equations[11]:

$$D = dE + \varepsilon^{T}E \quad \text{(generator)} \qquad (1)$$

$$S = s^{E}T + dE \quad \text{(motor)} \qquad (2)$$

where S is the mechanical strain vector,
s the elastic compliance tensor (Pa^{-1}),
T the mechanical stress vector (Nm^{-2}),
D the electric displacement vector (Cm^{-2}),
ε the dielectric permittivity tensor (Fm^{-1}),
E the electric field vector (Vm^{-1})
and d the transverse piezoelectric coefficient tensor (CN^{-1}).
The superscripts denote a quantity which is held constant.

For the substrate layer the mechanical behavior was considered using the following stress-strain relationship[12]:
$S = sT$

2.2 Boundary conditions for the Unimorph

In this unimorph model, it is imposed that one end of the cantilever is clamped in relation to mechanical boundary conditions. Hence, fixed constraint condition was applied for the vertical faces of the layers including piezo and non-piezoelectric layers. The other faces were unconstrained and free to move allowing the bending of the unimorph under the application of voltage/force and due to the weight of the beam itself.

The electroding of the top and bottom layers of piezoelectric layer is required for the application of the voltage. However, the effects of the electrode were not considered in the geometry because their mechanical behavior can be neglected due to their thickness. However, the electrical behavior of the electrodes was considered by modeling with the electrostatic boundary conditions of the piezoelectric domain. The voltage of magnitude 100 volts is applied along the Z direction. The lower layer of the PVDF layer was grounded and the voltage was applied on the top layer. Zero charge/ Symmetry constraint was imposed on the other faces.

The material properties of PVDF, Steel, polysilicon and silicon nitride (Si_3N_4) are taken from material library of Comsol.

3. Results and Discussions

It is well known that the tip displacement of the unimorph cantilever is dependent on its device dimensions and the elastic properties of the substrate layer used. A typical deflection of the cantilever beam in color coded format on the application of electric voltage is shown in figure 1.

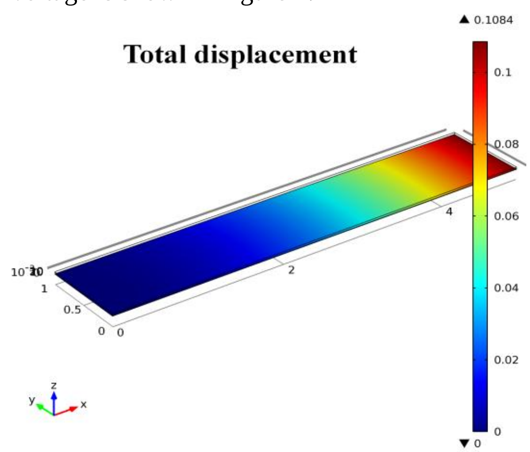

Fig 1.Total deflection of a unimorph cantilever beam.

It is seen from the figure 2 that the tip displacement of the unimorph increases with the increase in length of the piezoelectric layer. It is also seen that the saturation in the tip displacement is reached when the length of piezoelectric and nonpiezoelectric elastic layer becomes equal. This may be attributed to the fact that the bending deformation in this configuration is due to the coupling of converse piezoelectric effect of the active layer and the elastic nature of the passive layer in the beam. [5]. Hence, the length of the PVDF layer should be maintained above 5µm in order to achieve greater tip deflection.

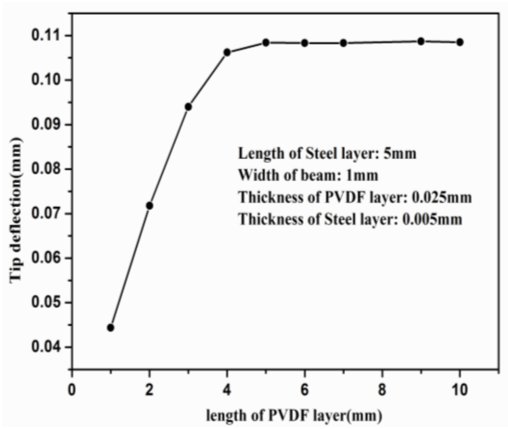

Fig.2. Variation in the tip deflection of the beam with the length of the PVDF layer

It is seen from figure 3 that the width of the cantilever beam has no significant effect on the tip deflection. The variation in the tip displacement from 0.105mm to 0.14mm can be seen when the width of the unimorph cantilever is varied from 1mm to 5mm.

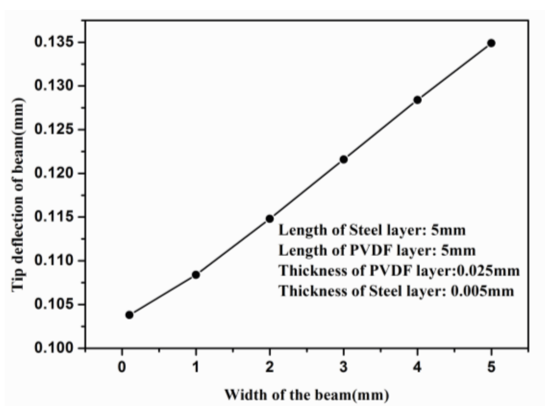

Fig. 3. Variation in the tip deflection of the beam with the width of cantilever

It is known that the moment of inertia of a beam is directly proportional to its width and deflection is inversely proportional to moment of inertia. Hence an increase in width would result in decrease in the tip deflection. However, an increase in width also results in increase the load acting on the beam which overall increases, though not significantly, the tip displacement of the beam[12].

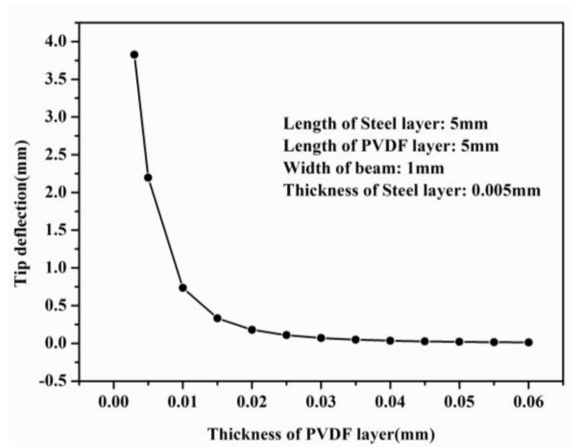

Fig 4. Variation in the tip deflection of the beam with the thickness of PVDF layer

It is known that the thickness of the cantilever beam has great influence on the deflection. The tip deflection of the composite beam will hence depend on the thickness of both piezoelectric and nonpiezoelectric layers of the beam. Hence, a systematic approach has been made to study the influence of piezoelectric and nonpiezoelectric layers by keeping the thickness of one layer constant and varying the thickness of the other layer one by one.

The variation of the thickness of the PVDF layer on the tip deflection of the beam is shown in figure 4. It is seen from the figure that the thickness of PVDF layer has great impact on the tip deflection of the beam. It is concluded from the graph that lesser the thickness of the piezoelectric layer, greater is the tip deflection of the beam. With the decrease in the thickness of the piezoelectric layer, the electric field across it increases as the applied potential remains the same. Hence, the strain along the length of the piezoelectric layer increases resulting in significant bending deformation of the beam. The tip displacement of the beam is almost uniform for thickness of piezoelectric layer above 20μm. Hence, the thickness of piezoelectric layer plays an important role in determining the performance of such cantilevers. It can be stated from the figure that the thickness should be maintained below 5μm in order to achieve maximum tip displacement[6,11].

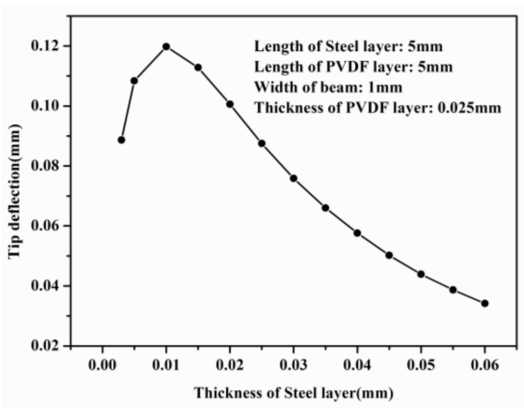

Fig 5. Variation in the tip deflection of the beam with the thickness of steel layer

The influence of the thickness of non-piezoelectric layer on the deflection of the beam is shown in figure 5. It is seen from the graph that the optimum value for which maximum tip deflection is achieved is for 10μm for which the maximum value of tip displacement is obtained[12].

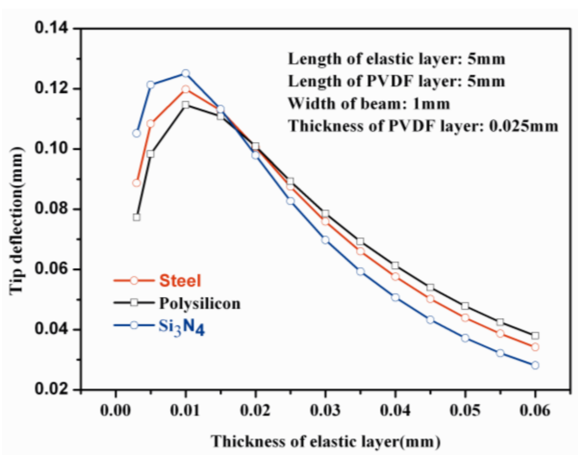

Fig. 6. Variation in the tip deflection of the beam with thickness for three different materials

The three different materials studied for non-piezoelectric layer were silicon nitride (Si_3N_4), Polysilicon and Stainless Steel. The variation in the tip deflection with thickness of these materials is shown in figure 6. It is seen from the figure that the material, which is best suited as a non-piezoelectric layer in the unimorph cantilever beam, is Si_3N_4 which gives maximum tip displacement of 0.1219mm for 9μm thickness of Si_3N_4 layer.

4. Conclusions

A piezoelectric unimorph cantilever beam is designed with the help of COMSOL Multiphysics software. The optimization of the dimensions of the device is done by adjusting different parameters and dimensions. It is found from the study that the length of the piezoelectric layer should be maintained equal to or greater than the length of non-piezoelectric elastic layer. The study revealed that the thickness of piezoelectric layer plays a dominant role in determining the tip deflection of the beam compared to the thickness of nonpiezoelectric layer. The lesser the thickness of the piezoelectric layer, higher is the deflection. The optimum value obtained for the thickness of PVDF is 5μm. It is also observed that tip displacement for Si_3N_4 layer is maximum as compared to polysilicon and stainless steel being chosen as passive layer.

5. References

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