International Journal of Advance Research and Innovation
Vol. 8(3), Jul-Sept 2020, pp. 40-45
Doi: 10.51976/ijari.832007
www.gla.ac.in/journals/ijari

Article Info

Received: 11 Jan 2020 | Revised Submission: 29 May 2020 | Accepted: 30 Jul 2020 | Available Online: 15 Sept 2020

Modelling and Simulation of Bending Behaviour of Thermoplastic Polyurethane based Soft Gripper

Ashutosh Singh and Jitendra Bhaskar***

ABSTRACT

Smart polymers are used for designing of soft actuators for soft robotics applications. Performances of actuators depend upon mostly on stimulation environment, design for gripping with required bending moment and bending deflection. Dielectric polymers are one of the important smart polymers that is used grippers for soft robotics. It is actuated under high voltage in the range of kV but consumes less power. In this paper, thermoplastic polyurethane (TPU) is considered for design of gripper. A gripper design using TPU and rubber has been proposed and bending features were analyzed. It was found that thinner layer of TPU with thick layer of rubber is suitable for gripper design.

Keywords: *Dielectric elastomer; Soft robotics; Soft materials; Bending deflection.*

1.0 Introduction

There are various types of smart materials which are used to for smart devices such as actuators and sensors (Bhaskar, J. et al 2020). Many of these show shape change under electric stimulation and are used for robotics grippers. Soft grippers are used for gripping delicate parts which are not suitable with hard grippers. In recent years, soft grippers are also in demand, largely because of the need for flexible robots to interact with a wide range of applications. Medicines, food handling, autonomous robotics and help robotics all require compliant and responsive object handling. Fraś J., Maciaś et.al. discussed the features of soft grippers due to their inherent compliance and a number of other behaviours. There are many smart materials which are directly or indirectly used for Soft grippers as:

- Shape Memory Alloys
- Shape Memory Polymers
- Fluidic Elastomers
- Hydrogels
- Electro-active polymers (EAPs)

Electro-active polymer is classified as shown below in figure 1. Many smart polymers are stimulated under electric field and give response as shape change. Benjamin O'Brien et.al. discussed that EAP based artificial muscle. EAP based muscles are closely comparable to biological muscle. These smart polymers also works as sensor. They are suitable for sensory applications such as observing blood pressure and pulse rate to chemical sensing. These are very useful particularly in areas where high strains and soft material compliance are required.

Samuel Rosset et.al. explained the use of electromechanical coupling in electroactive polymers (EAPs) for actuation. EAPs are a distinctive group of materials with the ability to concur to surfaces of various shapes and low-module high-strains. These characteristics make them suitable for applications including wearable sensors and soft tissue interfaces.

There are various types of EAP materials used for actuation purposes. Ionic EAPs is one of the class of EAPs in which actuation occurs within the polymer due to displacement of ions under actuation by low voltage. However the ionic flow demands higher electrical power and energy to hold the actuator in one certain location. Example Ionic EAPS are conductive polymers, ionic polymer metal (IPMC) composites and responsive gels.

Dielectric is also smart polymer under EAPs which produces electrostatic forces between two electrodes under high voltage in the range of kV. These electrostatic forces compress the polymer layers and responsible for shape change and motion.

**Corresponding author; Department of Mechanical Engineering Department, Harcourt Butler Technical University, Kanpur, Uttar Pradesh, India (E-mail: ashume619@gmail.com)*

***Department of Mechanical Engineering Department, Harcourt Butler Technical University, Kanpur, Uttar Pradesh, India*

Fanghao Zhou et.al emphasized on dielectric elastomers capabilities for producing high stresses between compliant electrodes. Dielectric polymers requires high voltage but consumes very low power. Dielectric EAPs do not need power to maintain a certain location of the actuator.

Electro-active polymer systems can also transform mechanical forces into electrical signals which are desirable and effective for sensors and energy production.

Figure 1: Classification of EAPs

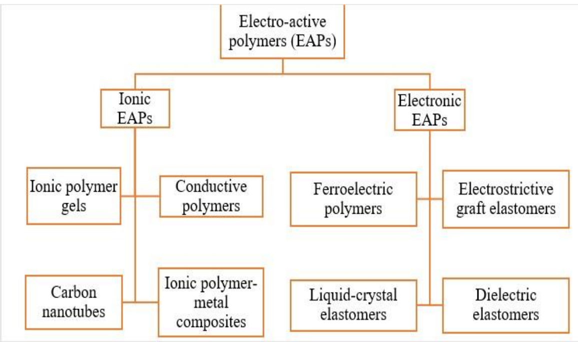
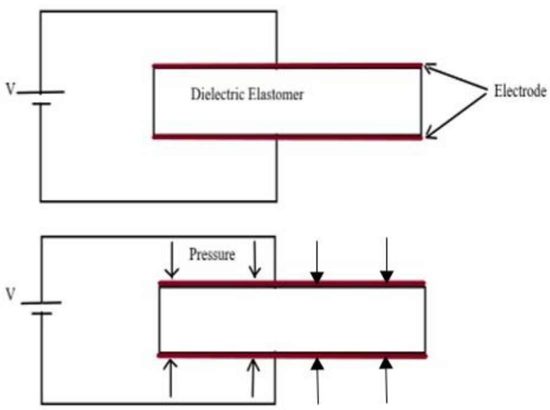


Figure 2: Schematic Diagram of Dielectric Elastomer (a) Not in Active State (b) Activated State



In this study, electromechanical analysis of dielectric polymer based design of soft gripper considering as a beam has been performed applying high voltage in the range of 2.0 kV – 7.0 kV. Bending performance have been analyzed.

2.0 Methodology

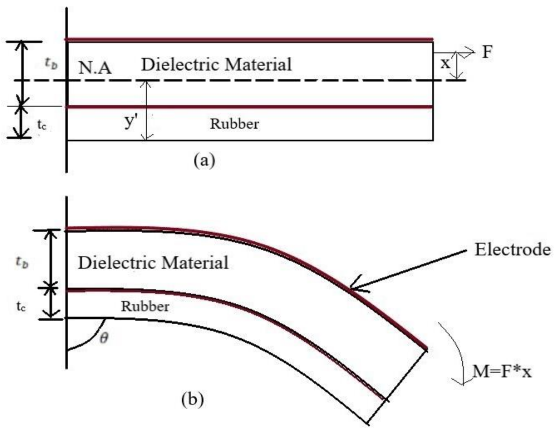
Proposed design of dielectric material consist of two layers. Out which one layer made of non-electrically conductive softer polymeric material which works as passive and other layer, made of dielectric works as active (figure 3 and 4). Compliant electrodes are made on both side of dielectric material. Low Young's Modulus material is selected for passive layer.

Methodology behind the design of bending of gripper is by managing shape change under the pressure developed by high voltage between the electrodes. High pressure compresses the dielectric layer. This dielectric is constrained along the length side so that deformation does not take place along this side. All the stresses developed inside the beam pushes the material to change the shape longitudinally. Due to this stress, an offset force over cross sectional area of beam is applied in longitudinal direction which indirectly develops a bending moment in the beam. In this way beam, end of the beam bends with required amount of tip force to grasp the softer objects.

The analytical model of the working of this proposed design is given here. Euler-Bernoulli model has been used for two layered beam (Kamal et. al) with induced strain.

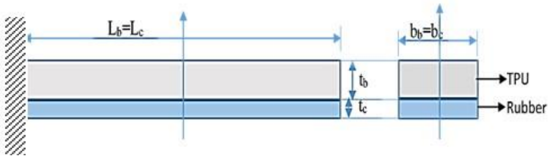
The Euler-Bernoulli model is a consistent strain model and generally gives more accurate results for slender beams than the uniform strain model. So, using this approach for the calculations of extension and bending is obtained.

Figure 3: (a) Schematic Diagram of Two Layer Beam Having TPU and Rubber (b) Extension and Bending Due to Voltage Application on TPU Layer



A generic design for dielectric actuator as a cantilever beam is presented in figure 4. The beam dimensions can be varied according the need of the analysis.

Figure 4: Different Views of Beam with Dimensions



The voltage is applied to the electrodes which causes the strain to bend with the thickness of the Dielectric beam. The bending stress along the electrode's length is assumed to have no change.

2.1 Maxwell's stress for dielectric beam

$$\sigma_c = \epsilon\epsilon_\circ \left(\frac{V}{t}\right)^2 \quad \text{....(1)}$$

Force due to stress will be:

$$F_c = \sigma_c \times A \quad \text{....(2)}$$

So, longitudinal stress in the beam:

$$\sigma_{axial} = \frac{F_C}{A_b} \quad \text{....(3)}$$

Let, location of neutral axis is at y_1 from bottom.

$$M_\wedge = F_c \times h \quad \text{....(4)}$$

where $h = \frac{t_b}{2} + t_c - y_1$

Figure 5: Specimens Used in Modelling

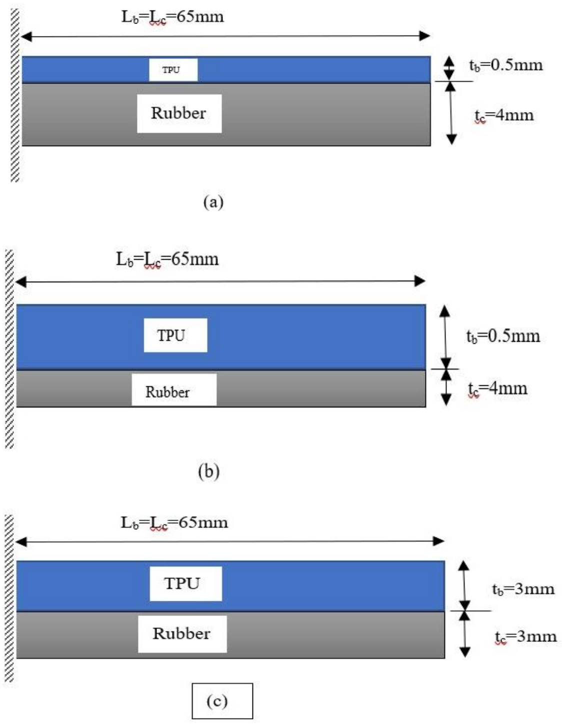


Figure 6: Voltage vs Mid Plane Strain on Varying Thickness of Materials

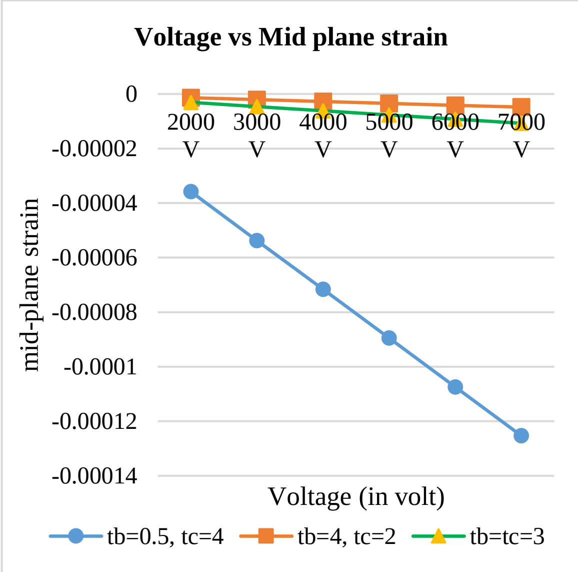
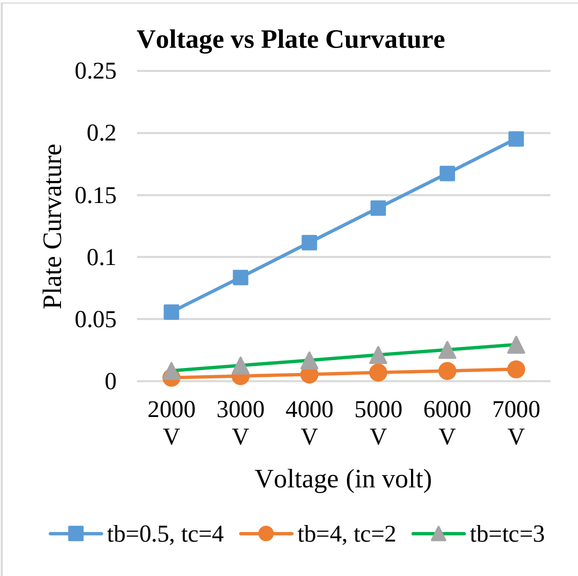


Figure 7: Voltage vs Plate Curvature on Varying Thickness of Material



The bending deflection of the beam can be calculated from the bending moment, which is assumed constant within the length of the beam covered by the Dielectric material.

The cross-section of the beam with the different layer positions. An electric field causes the beam to bend and extend. The balance of strength and moment achieved by the cross-section integration provides the control equations.

$$\begin{Bmatrix} F + F_{\wedge} \\ M + M_{\wedge} \end{Bmatrix} = \begin{bmatrix} EA_{tot} & ES_{tot} \\ ES_{tot} & EI_{tot} \end{bmatrix} \begin{Bmatrix} \epsilon_o \\ w'' \end{Bmatrix} \quad \ldots(5)$$

In the absence of external loads $F = 0$ & $= 0$, equation (5) can be for general bending case:

$$\begin{Bmatrix} F_{\wedge} \\ M_{\wedge} \end{Bmatrix} = \begin{bmatrix} EA_{tot} & ES_{tot} \\ ES_{tot} & EI_{tot} \end{bmatrix} \begin{Bmatrix} \epsilon_o \\ w'' \end{Bmatrix} \quad \ldots(6)$$

Where $w'' = \frac{\partial^2 w}{\partial x^2}$

$$EA_{tot} = E_b b_b t_b + E_c b_c t_c$$

$$ES_{tot} = E_c b_c t_c \left(\frac{t_c}{2} + \frac{t_b}{2}\right)$$

$$EI_{tot} = \frac{1}{12} E_b b_b t_b^3 + \frac{1}{12} E_c b_c t_c^3 + E_c b_c t_c \left(\frac{t_c}{2} + \frac{t_b}{2}\right)^2$$

The forces and moments due to free strain of dielectric material are given by

$$F_{\wedge} = E_c b_c t_c \wedge \quad \ldots(7)$$

$$M_{\wedge} = -E_c b_c t_c \left(\frac{t_c}{2} + \frac{t_b}{2}\right) \wedge \quad \ldots(8)$$

So, assuming pure bending case $ES_{tot} = 0$ in equation (7)

$$F_{\wedge} = EA_{tot} \, \epsilon_o \quad \ldots(9)$$

Mid plane strain $(\epsilon_o) = \frac{F_{\wedge}}{EA_{tot}}$ …(10)

The bending deflection ‘w’ for cantilever beam at $0 \le x \le (L_c = L_b)$ and at neutral axis where mid plane strain $\epsilon_o = 0$, and putting boundary condition $\left(\partial w / \partial x\right) = 0$ and $w = 0$ both at $x = 0$:

$$M_{\wedge} = EI_{tot} \frac{\partial^2 w}{\partial x^2}$$

$$\frac{\partial^2 w}{\partial x^2} = \frac{M_{\wedge}}{EI_{tot}}$$

$$w = \frac{M_{\wedge}}{EI_{tot}} \frac{x^2}{2} \quad \ldots(11)$$

3.0 Materials Selection and Design

The thermoplastic polyurethane was taken as dielectric material and rubber as softer material. Flexible TPU offers high mechanical characteristics and versatility. Solid and durable performance components can be designed with extremely good surface quality and specific level.

Rubber has lower Young’s Modulus than Thermoplastic polyurethane because as the upper layer starts elongating under applied voltage, the lower layer will not elongate. This will give bending. The three specimens with dimension is shown in figure 5(a,b) and (c).

Properties of Thermoplastic Polyurethane:

- Young’s Modulus = 2410 MPa
- Poison’s ratio = 0.38
- Shore A Hardness = 60
- Relative Permittivity = 6.5
- Electric Potential Range = 4 kV to 7 kV
- Permittivity of Space = 8.85 * 10^{-12} F/m

Properties of Rubber:

- Young’s Modulus = 50 MPa
- Poison’s ratio = 0.47

Dimensions of Specimens

- $L_b = 65\ mm$
- $L_c = 65\ mm$
- $b_b = 15\ mm$
- $b_c = 15\ mm$
- $t_b = 0.5\ mm\ and\ 2\ mm$
- $t_c = 2\ mm\ and\ 4\ mm$
- $A_c = 30\ mm^2$
- $E_b = 2410\ MPa$
- $E_c = 50\ MPa$

4.0 Results

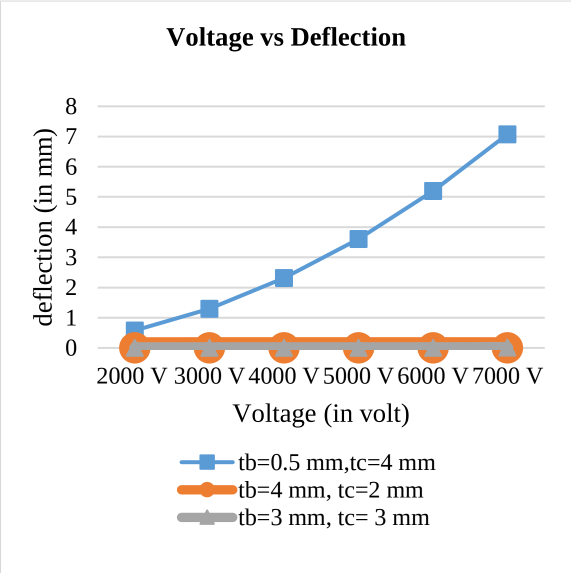
With the help of MATLAB programming, the following results are obtained, fig 4.1 shows the variation on mid plane strain, on varying voltage with changing the thickness of TPU and rubber beam and fig. 4.2 shows the variation on plate curvature on varying voltage with changing the thickness of TPU and rubber beam.

Above graph (fig 6) shows that when thickness of TPU is 0.5 mm and Rubber is 4 mm, then mid plane strain varies on changing voltage as compared to other specimens having thickness of TPU is equal to Rubber thickness or more than rubber thickness.

Above graph (figure 7) shows that when thickness of TPU is 0.5 mm and Rubber is 4 mm, then Plate curvature varies on changing voltage as compared to other specimens having thickness of TPU is equal to Rubber thickness or more than rubber thickness.

Now, the maximum bending deflection in beam is calculated on varying voltage from 2.0 kV to 7.0 kV with changing the thickness of TPU and Rubber, having 3 specimens (TPU = 0.5 mm and Rubber = 4.0 mm), (TPU = 4mm and Rubber = 2.0 mm) and (TPU = 3.0 mm and Rubber = 3.0 mm). The figure 8 shows that when the thickness of TPU is 0.5mm, bending deflection in beam is clearly observed. As thickness in TPU is increased, the deflection reduced.

Figure 8: Voltage vs Bending Deflection Graph



5.0 Conclusions

In this research work, bending behaviour of dielectric based gripper was simulated using Euler-Bernoulli model for layered beam. Voltage and thickness of layers was taken as independent parameters. It was observed from simulation that bending deflection increase with voltage 2.0 kV to 7.0 kV. It was obserevd that thinner layer of TPU with thick layer of rubber is suitable for gripper design.

Nomenclature

$_b$	For showing properties dielectric part
$_c$	For showing properties of rubber part
t	Thickness
b	Width
A	Rectangular cross-sectional area
κ	Bending curvature
w	Bending deflection
Δl	Axial deflection
E	Modulus elasticity
EA_{tot}	Extensional stiffness
ES_{tot}	Coupling stiffness
EI_{tot}	bending stiffness
M_{Λ}	Bending moment due to induced strain
M	Bending Moment
EI_b	Bending stiffness of the Dielectric material
EI_c	Bending stiffness of the Rubber
F	Axial force in the Dielectric material beam
d_c	Dielectric constant

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