Modified Electromechanical Model for

Dielectric Elastomer Cylindrical Actuators

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Dielectric elastomers (DEs) based cylindrical actuators are fascinating researchers interest owing applications in biomimetic, robotics and similar intellectual technology. The actuation performance of this actuator significantly depends on dielectric constant and elasticity of DE. However absolute control on electromechanical properties is essentially required towards commercialization of DE actuators. This study reveals the influences of pre-strain on the voltage induced axial deformation of cylindrical actuator. Modified electromechanical model is proposed for thin walled actuator in terms of the strain induced variation in dielectric permittivity. Hypothesis of linear elasticity for small deformation is used to derive the consecutive equation for voltage induced axial strain. Improved axial actuation is achieved with less errors and the values are found in best fit with experimental results, present an efficient model. These study may give path for experimental work towards design and development of cylindrical actuator with high actuation strain.

***Keywords*:** dielectric permittivity, elasticity, axial strain, efficient model

1. **Introduction**

Dielectric elastomers are the electroactive smart materials that illustrate high elastic deformation under stimulation of electric field. Owing the features like high flexibility, low cost, ease in production, inherent softness, etc. DEs acknowledged as feasible material in fabrication of soft actuators, sensors and energy harvester electromechanical system [1]. The electromechanical performance of DE devices is based on principle of Maxwell stress which governs the electrostatic pressure (P) that induces actuation strain (Sz). The expression of Maxwell stress and subsequent field induced strain is as in eq. (1) and (2) respectively [2]. Which reveals the actuation performance dependency on three material parameters namely dielectric permittivity (Ꜫ), film thickness (t) and the elastic modulus (E) of the elastomers.

(1)

(2)

The DE cylindrical actuator, also regarded as tube/ roll actuator, are best suited in emerging field of soft biomimetic instrumentation and development of robotic arms owing the competence of bending and rotational motion [3]. As shown in fig.1. the cylindrical configuration comprises a rolled elastomer film that supposed to deform in axial direction. Further, it is noteworthy that the lateral pre-strain is essential to achieve considerable electromechanical actuation strain [4]. The applied pre-strain prevents electromechanical pull-in instability and is known to improve actuation performance by regulating dielectric and mechanical properties [5][6].

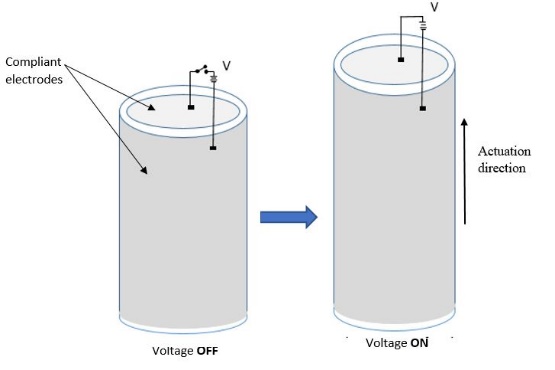


Fig.1. Schematic diagram for dielectric elastomer cylindrical actuator configuration.

Earlier, an experimentally validated electromechanical model proposed for DE cylindrical actuator assumed dielectric permittivity as constant (i.e. not vary either with strain or with voltage) and underline the influences of voltage per unit thickness on axial actuation strain [7]. Unfortunately, the extension of this work is yet not found in available literature, although it is well recognized that applied pre-strain significantly influences the permittivity of dielectric.

In order to improve the effectiveness of existing model, this analytical work propose a modified electromechanical model considering variation in dielectric permittivity as a function of strain. The results are observed in good agreement with available set of experimental data and comparatively reduced error ensures the reliability on improved model for high actuation strain.

1. **Analytical Modelling**

Modifying the existing model, electrostatic pressures generated across the electrodes are considered to be constant and dielectric permittivity is varied in respect to pre-strain. Consideration of a pure electrical analysis enable to define geometrical parameter () in expressions of pressure generated by electrically charged electrodes [7]. Hence, for cylindrical configuration with and inner and outer radii respectively the induced pressure are;

(3)

(4)

For small strain in material with linear elastic, homogeneous and isotropic features, mechanical analysis can be done to establish the relation between stresses and respective pressure induced actuation strain on the surfaces of the cylindrical actuator. Pressure-induced strains of the actuator can be obtained after the identification of the related displacements. To evaluate the displacement in absence of body forces in static condition, Navier’s equation for cylindrical actuators are;

(5)

(6)

(7)

*Where and are the Lame’s constant, defined as:*

(8)

(9)

Assuming actuator constrained for deformation in axial and radial direction the displacements dependency on the r and z coordinates are;

(10)

(11)

(12)

Thus, in terms of boundary conditions, the displacement in θ direction (eq. 6) becomes null, and expression as for r and z direction are;

(13)

(14)

On applying boundary condition for stresses (i.e. and and solving for the constants:

(15)

(16)

(17)

Further in relation with constitutive equations, the stresses ( and) and strains (and) are related and represented by the Hooke’s law in terms of the Lame’s constants:

(18)

(19)

(20)

Strains in terms of stresses by using Hooke’s law:

(21)

(22)

(23)

These expressions for actuator that include the strains induced on axial (along lateral direction) and the radial direction (inner and outer radii) define percentage variation based on parameters and can be calculated as:

(24)

(25)

(26)

Finally, the property of constant volume of the elastomer implies a value of for its Poisson’s ratio, which gives:

(27)

(28)

(29)

The change in the relative permittivity with uniaxial pre-strain is referred to experimental data of widely investigated VHB 4910 dielectric elastomer [5]. At frequency of 1MHz the variation of the relative permittivity as a function of strain is found to be:

(30)

Where represents the induced strain in the system on the application of the voltage across the electrodes. The induced strain varies with changes in relative permittivity and consequently affect the pressure in inner and outer wall.

1. **Result and Discussion**

In purely electrical analytical analysis of a 50 mm long cylindrical actuator is carried out. The actuator having initial inner radius, ri = 0.8 mm and outer radius, ro = 1 mm is pre-strained for 5 % elongation along axial direction. Due to symmetry the respective decrease in inner and outer is presumed to be equal and resultant change is calculated based on constant volume condition;

(31)

Table 1. represents the parameters used in respect to similar testing condition as used for experimental validation of existing model [7].

Table 1. Actuator parameters

|  |  |
| --- | --- |
| Initial parameters | |
| Inner radius | 0.8 mm |
| Outer radius | 1 mm |
| Pre-strain | 5 % |
| Length | 50 mm |
| Poisson’s ratio | 0.5 |
| Young’s modulus | 5 MPa |
| After pre-strain | |
| Inner radius | 0.781 mm |
| Outer radius | 0.976 mm |

To get the initial result, MATLAB simulation is performed using equations of solid mechanics for small strain in isotropic material. The attained result is shown in fig. 2. It is found that the behviour of voltage induced deformation is in good agreement with existing result. Meanwhile, it fitted best with experimental data used to validate earlier model [7]. The attribution to close fit with experimental data is obviously the consideration of dielectric permittivity in consecutive model, as performance influencing material parameters. Furthermore, the comparative root mean square error is observed to decrease from 31.59 % to 10.56 %. Thus, relative decrease in absolute error confirm the improved efficiency of modified electromechnical model for actuation performance of cylindrical actuator.



Fig.2. Relative axial deformation with voltage per unit thickness



Fig.3. Absolute error as compare to the existing experimental data

1. **Conclusion**

Existing electromechanical model for DE cylindrical actuator is modified to improve its effectiveness in evaluation of actuation strain in axial direction. Pre-strain regulated dielectric permittivity of VHB 4910 elastomer is implemented in revised model and actuation behaviour is compared with existing data for cylindrical actuator. Model results indeed best fit with experimental data, significantly reduced absolute error ensured improved efficiency. However, the elastomer weight, energy dissipation in radial direction, and performance under load are a few considerations in future prospect.

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**References**

[1] R. Shankar, T. K. Ghosh, and R. J. Spontak, Soft Matter, vol. 3, pp. 1116–1129, 2007.

[2] R. Pelrine, R. Kornbluh, J. Joseph, R. Heydt, Q. Pei, and S. Chiba, Mater. Sci. Eng. C, vol. 11, pp. 89–100, 2000.

[3] F. Carpi, R. Kornbluh, and P. Sommer-larsen, Bioinspiration & Biomimetics, vol. 6, no. 045006, pp. 1–10, 2011.

[4] F. Carpi, P. Chiarelli, A. Mazzoldi, and D. De Rossi, Sensors Actuators A, vol. 107, pp. 85–95, 2003.

[5] R. K. Sahu, B. Pramanik, K. Patra, A. K. Pandey, and D. K. Setua, in 2012 IEEE 10th International Conference on the Properties and Applications of Dielectric Materials July 24-28, 2012, Bangalore, India Experimental, 2012, vol. 2, no. 1, pp. 1–4.

[6] S. M. A. Jiménez and R. M. Mcmeeking, Int. J. Non. Linear. Mech., pp. 1–8, 2013.

[7] F. Carpi and D. De Rossi, Mater. Sci. Eng. C, vol. 24, no. 4, pp. 555–562, 2004.