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Challenges and Improvement of Electrostriction based Elastomers

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ABSTRACT

Dielectric elastomer is one of the important electroactive polymer used as actuator in adaptive structures due to its outstanding ability to generate very large deformations under the influence of an external electric field. In this paper the role of compliant electrodes for enhancement of dielectric response has been discussed. Due to significant electrostrictive and mechanical characteristic of the elastomer, it has a great potential for electromechanical applications in actuators, transducers, artificial muscles and sensors. In most of the recent experiment for the determination of electrostrictive parameters in elastic dielectrics, several researchers have used in correct formulae without considering the contributions from lateral stresses, proper boundary conditions and edge effect. In this paper I identify some of the challenges associated with its development, and examine the main focus of research with key parameters affecting the performance in some of the potential applications.

Key words: Electrostriction, Elastomer, Electroactive polymer, Dielectric materials

INTRODUCTION

An actuator is an electro-mechanical device for controlling the mechanism of a system used in wide range of industrial applications. Traditional actuators include pneumatic actuators, electronic actuators, motors, and hydraulic cylinders. The weight, limited size, complex transmission, and restrictive shape of such actuators have led researchers to investigate alternative technologies for various applications [1-3]. Under the influence of an external electric field, the displacement of charge produces electrically induced strain inside the material. If the strain depends quadratically on the electric field, then two phenomena, namely (a) Maxwell's electrostatic effect and (b) Electrostriction effect (Fig. 1), are responsible for producing induced strain. An elastomer (elastic dielectrics) has an excellent dielectric response property apart from its mechanical flexibility and stability. Most of the recent researchers are trying to exploit its excellent dielectric properties (electrostriction) for various applications in actuators, artificial muscles and sensors.

The compressive induced stresses in polymer [4] under the influence of large potential differences is given as -

$$p = \varepsilon\varepsilon_0 E^2 \tag{1}$$

where p is the compressive stress, ε is the relative dielectric constant of polymer, ε_0 is the permittivity of free space, E is the applied electric field.

However the selection of appropriate materials with high dielectric breakdown strength (to prevent disruptive electrical discharge), relatively high dielectric constant (a larger dielectric constant will result in greater movement) and low elastic modulus (smaller the modulus, the more would be the movement) is the major task faced by the scientists in the past for various applications. The other problem is to use the compliant electrode [5] to increase the electrostriction response of the material. The choice and type of electrodes depend on the nature of interaction between the compliant electrodes and the elastomer film. Various researchers [6-7] used thin metallic films directly evaporated on both side of sample (elastomer) to reduce the effect of higher young modulus of these materials, very thin metallic films are recommended. Kloos [8] showed a constraint of 81% for an unprestrained isotactic polypropylene film electrode with silver of 5× 10^{-6} m thick. However to reduce the substantial loss of conductivity under influence of high field, compliant electrodes [9-10] like a graphite powder, polymeric elastomer filled with carbon black and silver particles, electrolyte polymer solutions and conductive polymer have been used for getting more conductivity, durability and stiffness. Some of the researchers used liquid layer between electrodes and the elastomer to decrease frictional force [6]. However the researchers [7, 8] have not considered the contribution from lateral stress in electrostriction.

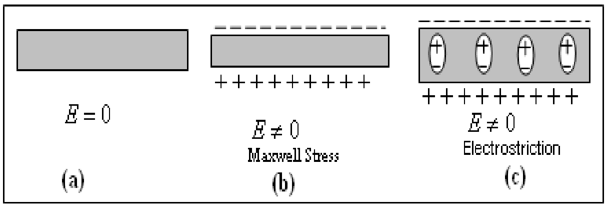

Fig. 1 Schematic diagrams illustrating (a) Pure linear elastic response governed by Hooke's law, (b) Maxwell stress produced by surface charge & governed by Coulomb's law, and (c) electrostriction stress due to dipoles alignment

ELECTRICALLY INDUCED STRAINS

If the sample is placed between the compliant electrodes or with very thin metal layer, the repulsion between like charges on the same electrode enhances more or less electrostrictive effect. The contribution of the pure electrostriction [7] can be expressed as

$$S_p = -A\varepsilon_0^2 (\varepsilon - 1)^2 E^2 \tag{2}$$

where S_p denotes induced strain, E is the electric field strength, ε relative dielectric constant and A is the pure electrostrictive coefficient.

The contribution of pure Maxwell strain is given as

$$S = -\frac{1}{2Y} \varepsilon_0 \varepsilon E^2 \tag{3}$$

where S is the thickness strain along the direction of applied field, and Y is the Young modulus. For an ideal compliant electrodes this contributions (equations 3) is doubled [8-10].

Total strain considering contribution from electrostriction and the Maxwell strains is

$$S_T = S_p + S \tag{4}$$

this exhibits experimental dependence of a strain response of the material on the applied electric field.

CHALLANGES

Selection of Electrostrictive Materials

While selecting the materials for various applications, attention has to be given on its density (weight), performance (efficiency), size (compactness), process ability and its electrical & mechanical toughness. For example, for aerospace applications, there is a requirement of light weight actuators with high performance & compact in size. Polyurethane elastomer [6, 7 and 10] and silicon rubbers [9, 10] are traditional exiting material used for various actuating & sensing purposes. The electrostrictive polymeric elastomers have demonstrated high electric field induced strain with high mechanical energy density. Materials must exhibits smaller modulus of elasticity and a larger dielectric constant for greater strain & flexibility, movement, and high dielectric strength to prevent disruptive electrical discharge at a large potential difference.

Among the widely used elastic dielectric materials i.e. VHB-4910, TC-5005 and CF19-2186, VHB 4910 exhibits high viscoelastic behaviour with low modulus of elasticity (i.e. higher strain & flexibility) and lower dielectric breakdown strength with significant creep effects than TC-5005. Due to sticky nature of VHB 4910, it is preferred for compliant electrodes. Generally conductive carbon grease is used as compliant electrode. The negative property of VHB 4910 is its lower dielectric strength, which can be improved by prestraining the materials [4]. The VHB-4910 shows superior properties than TC-5005 if the applied electric field is less than the breakdown strength of VHB-4910. However TC-5005 exhibits higher dielectric breakdown strength but it has lower mechanical flexibility & tolerance than VHB-4910.

Role of Compliant Electrodes

In order to sustain very large surface strains of dielectric EAPs, the electrodes with the same amount of strain are required to prevent damages. This is more challenging, because the conductive materials are generally not compliant and compliant materials are generally not conductive [4]. The electromechanical performance of dielectric elastomer is mainly dependent on the material of electrode.

APPLICATION OF DIELECTRIC ELASTOMER

In a move to illustrate the potential of dielectric elastomer actuators, we take a look at some applications. Pelrine et al [4] at SRI reported high-speed, giant-strain, electrically actuated elastomers with unprecedented electromechanical transduction performance. These materials were demonstrated for so-called dielectric elastomer actuators, deformable capacitors made of a film of a soft insulator (such as acrylic, polyurethane, or silicone elastomer), with compliant electrodes. When subjected to an external electrical field, purely electrostatic forces cause the elastomer film to undergo substantial thickness compression and surface expansion [11]. The exceptional performance of these dielectric elastomer actuators gives rise to a scientific and technological revolution in the field of building of new models of gene expression regulation (Fig. 2 & 3). The main benefit of dielectric elastomer is to show how a muscle like actuators can operate without the rigid support of a skeleton, just like worms do in nature.

Fig. 2 Dielectric elastomers could be used for human prostheses and make the six million dollar man a reality [11]

Fig. 3 In touch screen dielectric elastomer actuators could produce effects that enhance the user's experience with such devices

DISCUSSION: ERRORS IN ESTIMATION

Errors are often committed in the derivation of suitable expression for the interpretation of experimental results. The above expressions (equations 2-3) have been derived on the sole assumption that permittivity changes with longitudinal strain only but the permitivity also changes with respect to the lateral strain-stress in the capacitor depending on the crystal structure of elastic dielectric medium. If an electric field is parallel to the Z-axis (unidirectional field as in case of parallel plate capacitor), the stress tensor T_{ij} in terms of dielectric tensor ε_{ij} is given [12] by

$$T_{ij}(0,0,E_z) = \begin{bmatrix} -\frac{1}{2}\varepsilon_{33}E_z^2 & 0 & 0 \\ 0 & -\frac{1}{2}\varepsilon_{33}E_z^2 & 0 \\ \varepsilon_{13}E_z^2 & \varepsilon_{23}E_z^2 & \frac{1}{2}\varepsilon_{33}E_z^2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \varepsilon_{13}E_z^2 & \varepsilon_{23}E_z^2 & \frac{1}{2}\varepsilon_{33}E_z^2 \end{bmatrix} - \frac{1}{2}\varepsilon_{33}E_z^2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (5)$$

the first term of this equation represents tension along X and Y direction, the second term implies a compression along Z- direction. Generally compression along longitudinal axis (Z-axis) is always accompanied by extension along transverse plane (X-Y plane) as in (Fig. 2) and vice –versa. It is also clear from the above equation (5) that the stress tensor with electric field in Z-direction has affected only the components $\varepsilon_{33}, \varepsilon_{13}$ & ε_{23} of dielectric tensor ε_{ij} corresponding to the strain component S_{33}, S_{13} & S_{23} of strain tensor S_{ij} respectively and other components become zero. The lateral strains S_{13} & S_{23} exist in the capacitor electrode. So the contribution from lateral strains should not be neglected for the correct estimation of results.

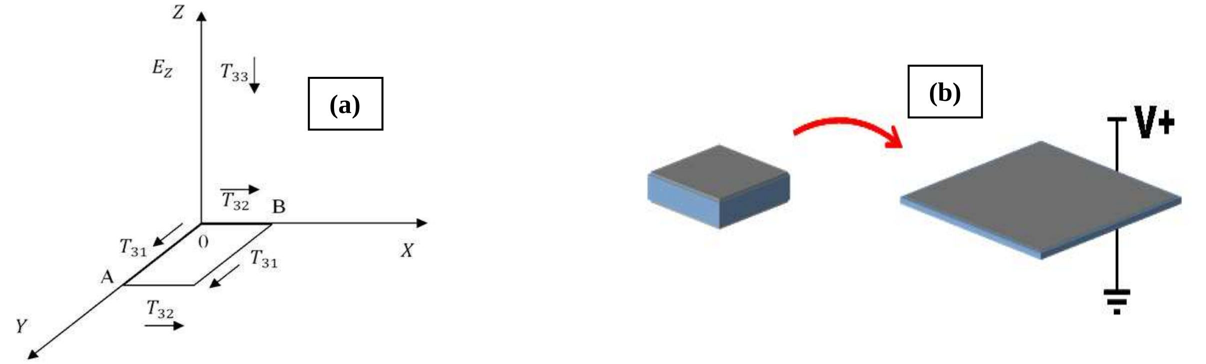

Fig. 4 (a) Schematic diagram indicating compression due to normal stress along Z-directions and is accompanied by the extension due to shear stresses along X-Y plane. (b) Schematic diagram indicating expansion of lateral dimension and compression along the applied field

So the correction due to lateral strain & corresponding change in lateral permittivity must be incorporated to get correct mathematical modelling. The researchers has stopped the change in lateral strain by considering constrained situation (considering sides of capacitor fixed & rigid) but fail to understand that the change in lateral permittivity is also due to lateral electrostatic stresses.

Researchers [9-10] use non-tensor form of stresses & strains for experimental determination of induced strains in the case of Polyurethane elastomers (DOW 2103-80AE) and the relative change in thickness of the dielectric slab of a parallel plate capacitor is considered by using equation 3. In case of an elastomer or an elastic dielectric material with large Poisson's ratio $\sigma \approx 0.5$, the neglect of shear stresses/strains leads to incorrect estimation [15-17] of induced strain. A lot of work has been performed for mechanical characterization of the elastomers [11-14], however a lot of work has to be performed on electromechanical coupling. It is very difficult to predict the exact boundary conditions taking place at the interface between the electrodes and the dielectric or between two regions with different permittivity. If the field is applied exactly along Z direction then the strains components, S_{33} (normal/bulk strains along Z), and S_{31} & S_{32} (shear strains along X & Y directions) play the major role in the electromechanical phenomena exhibited by the interface in nanometric dielectrics [16-18].

CONCLUSION

While much research and development still remains to be done, EAP technology is already emerging from the laboratories. A number of companies e.g. TRS Technologies (USA), Akzo Nobel (Denmark), Wacker (Sweden), are offering commercial products based on EAP. The selection of appropriate compliant electrodes requires a thorough understanding of material structures particularly its properties at and near the interface between the electrodes and the sample. Also the selection of material is very significant for getting good response with higher mechanical & electrical sensitivity & better compliant with the electrodes. The contribution from shear or lateral stresses should not be ignored for the determination of electrically induced strains particularly for elastomers with higher Poisson's ratio.

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