Dependence of Actuation Strain of Dielectric Elastomer on Equi-biaxial, Pure Shear and Uniaxial Modes of Pre-stretching

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Abstract. A dielectric elastomer is capable of large deformation under three basic modes of deformation: equi-biaxial, pure shear and uniaxial. Pre-stretching of dielectric elastomer improves the actuation strain appreciably. Experimental results shows that pre-stretching using equal biaxial mode can result to higher actuation strain compared to other two modes of stretching, i.e., uniaxial and pure shear. However, analysis of the experimental results shows that the actuation strain is independent of the modes of pre-stretching rather it is dependent upon the thickness stretch. For same thickness stretch at a particular voltage, the actuation strain is almost similar for all pre-stretching modes. Power trend lines are obtained to predict the actuation strain at any thickness stretch for a particular voltage. The present analysis opens the door to easily design the actuators, sensors and energy harvesting devices.

1. Introduction

Dielectric elastomer (DE) is now-a-days considered as one of the potential materials for sensors, actuators and energy harvesting devices [1]. A thin dielectric elastomer membrane coated with compliant electrodes on both sides expands in area and reduces in thickness when an electric field is applied on it [1-2]. Pre stretch is one of the important conditions that greatly influences the performance of dielectric elastomer actuators by improving the break down strength, actuation efficiency and the electromechanical stability [3-5]. Three modes of deformation (equi-biaxial, pure shear and uniaxial) are generally incorporated in DE to study the mechanical and dielectric properties of the elastomer based on the sample geometry [6-11]. In uniaxial mode of deformation, mechanical force is applied from one direction and lateral direction is free to contract. Rate dependent large uniaxial deformation of DE is generally performed to estimate elastic modulus [7], characterize failure behaviors, stress relaxation and creep phenomena [8-9]. Even most of the visco-hyperelastic models are developed under uniaxial deformation [10]. However, many of the practical DE based devices undergo biaxial or pure shear deformation instead of uniaxial deformation. In equi-biaxial deformation, equal mechanical forces are applied from two mutual perpendicular directions, whereas, in pure shear deformation, mechanical force is applied from one direction and lateral deformation is constrained. The initial reference mode and other three models of deformation are shown in figure 1(a-d). The application areas involving equi-biaxial and pure shear deformation modes are in micro pumps, disk drives, energy generator, pneumatic valve and loudspeaker [12-15] while uniaxial mode of deformation can be applied in inchworm robots and wearable multifunction textiles like smart shirts, life shirts and sensorized sleeves [15-16]. Due to wide application areas of dielectric elastomers in all three deformation modes, many researchers tried to investigate the actuation properties in these modes of deformations.

Uniaxial and equi-biaxial modes were studied by many researchers to characterize DE materials [17-20] and to show increase of actuation strain with increase of pre-stretch [21–26]. Recently pure shear deformation mode was adopted by some of the researchers for actuators, sensors, energy harvesting applications in which actuation strain and electric break down voltage were shown to increase with pre-stretch in pure shear deformation mode [4,27-32]. Most of the researchers well established higher

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actuation stroke for both equi-biaxial and pure shear deformation modes as compare to the uniaxial deformation mode [31-33]. However, no effort has been made earlier to define a common parameter which can be related to actuation parameters under different deformation modes. The present work attempts to relate thickness stretch ratio of different pre-stretching modes (uniaxial, pure shear and equi-biaxial) with actuation strain of planar dielectric elastomer actuators. The results show that at a particular thickness stretch ratio, the actuation strain becomes almost same for equi-biaxial, pure shear and uniaxial modes of pre stretching. Therefore actuation strain defined in terms of thickness stretch ratio can be analyzed independent of the mode of pre-stretching.

2. Experimental Methodology

![Figure 1](image)

**Figure 1.** (a) Reference state (b) Uniaxial stretching (c) Pure shear stretching (d) Equi-biaxial stretching.

The samples were prepared for different pre-stretch conditions such as equi-biaxial, pure shear and uniaxial as shown in the figure 1 for VHB4910. All the pre-stretched samples for equi-biaxial mode are prepared with the help of circular acrylic frames of 8 cm external diameter and 6 cm internal diameter and further coating with 3M carbon conducting grease of 1.5 cm diameter on both sides of the samples. For uniaxial and pure shear samples, the acrylic frames of 10 cm x 8 cm outer dimensions and 8 cm x 6 cm internal dimensions and active area of 3M carbon conducting grease of 1.5 cm x 1 cm are taken. The coating areas for all the deformation modes are almost kept similar. The pre-stretched samples for equi-biaxial, pure shear and uniaxial are shown in figure 2.

Actuation measurement test was carried out using High voltage DC source. The sample was connected to both of the terminal of the High voltage DC source and voltage was applied at the rate of 30- 40 V/s till the breakdown occurs as shown in figure 3. A high resolution camera was used to capture the videos for the calculation of actuation strain. Actuation strain was calculated by using 'Image J' software for different voltages till the breakdown occurs.

Actuation strain (%) is calculated from the following relation

\[
\left\{(A_f - A_i)/A_i\right\} \times 100
\]

where, \(A_f\) = Final coated area in the actuated state.
\(A_i\) = Initial coated area.
The final and initial coated areas were calculated by ‘Image J’ software by measuring the pixels of the samples before and after application of voltages as shown in the figure 4. The unactuated image of the sample is shown in figure 4 (a) while actuated state image is shown in figure 4 (b). The initial $A_i$ and final area $A_f$ can be calculated easily from the images.

3. Results and Discussions
Uniaxial, pure shear and equi-biaxial samples are prepared under different pre stretch conditions. Thickness stretch can be calculated by using the relation from equation 2.
where, \( \lambda_i = t_f / t_i \) \hspace{1cm} (2)

Final thickness, \( t_f \) can be obtained for incompressible material from the following relation

For equi-biaxial, \( t_f = 1 / \lambda_p^2 \)

For pure shear, \( t_f = 1 / \lambda_p \)

For uniaxial, \( t_f = 1 / \lambda_p^{0.15} \)

Where, \( \lambda_p \) = Pre-stretch ratio for equi-biaxial, pure shear and uniaxial deformation modes.

The area is calculated from ‘Image J’ software as discussed in section 2. Actuation strains (in %) against voltage are plotted for different pre-stretching (\( \lambda_p \)) ratios of equi-biaxial, pure shear and uniaxial deformation modes and as shown in figure 5. From the figure 5 it is observed that equi-biaxial mode of deformation can produce very large actuation strain as compared to pure shear and uniaxial deformation modes at any particular voltage. This has been reported in earlier work by Huang and Suo [27].

**Figure 5.** Variation of actuation strain with voltage for different pre-stretch ratios for (a) equi-biaxial (b) pure shear and (c) uniaxial deformation mode.
This work attempts to determine a common parameter to relate actuation strain under different modes of deformations and tries to understand why does equi-biaxial deformation mode is actually produce higher actuation strain. Different values of pre-stretch ratios of different modes of deformation were first converted in terms of thickness stretch ratio and actuation strain is plotted against this parameter at different applied voltages. From figure 6 (a), actuation strain versus thickness stretch \((\lambda_3)\) is plotted at three different voltages for different pre-stretching \((\lambda_p)\) under equi-biaxial, pure shear and uniaxial deformation modes of pre-stretching. It can be observed that for same thickness stretch ratio, different modes of pre-stretched dielectric elastomer produce almost same actuation strain. For example, at a thickness stretch of 0.32, it is seen that actuation strain for equi-biaxial pre-stretch \((\lambda_p = 1.75)\), pure shear pre-stretch \((\lambda_p = 3.06)\) and uniaxial pre-stretch \((\lambda_p = 9.37)\) is almost equal to 5\% at 10 kV and 3\% at 2.9 kV. At another thickness stretch of 0.44, it is seen that actuation strain for equi-biaxial pre-stretch \((\lambda_p = 1.5)\), pure shear pre-stretch \((\lambda_p = 2.25)\) and uniaxial pre-stretch \((\lambda_p = 5.06)\) is almost same equal to 3.8\% at 10 kV and 2\% for 8 kV. At these two thickness stretch, it is clearly seen that actuation strain is same irrespective of pre-stretch deformation modes \(\lambda_p\).

Power trend lines are obtained for different voltages of 6 kV, 8 kV and 10 kV after fitting in the data for actuation strain versus thickness stretch plot as shown in figure 6 (b). These trend lines may be used to predict the actuation strain at any thickness stretch irrespective of any pre-stretch deformation modes, \(\lambda_p\). However, actuation strain for equi-biaxial pre-stretching case is shown to achieve higher value as very low thickness stretch ratio can be obtained in this case compared to that of pure shear and uniaxial modes of pre-stretching.
Figure 6. (a) Variation of actuation strain with thickness stretch for different pre-stretch ratios for equi-biaxial (●), pure shear (×) and uniaxial (■) modes of deformation at different voltages of 6kV, 8kV and 10kV (b) Trend lines between actuation strain (%) and thickness stretch (λ₃) obtained after fitting equi-biaxial, pure shear and uniaxial data at different voltages of 6kV, 8kV and 10kV.

Figure 7. Actuation strain versus voltage plot for different thickness stretch under equi-biaxial, pure shear and uniaxial mode of deformation.

From figure 7, actuation strain versus voltage graph is obtained for same thickness stretch under all three deformation modes. It is seen that with the decrease in thickness stretch, the actuation strain...
increases appreciably. It is also shown that actuation strain for a particular thickness stretch increases with voltage.

4. Conclusion
From the experimental results of actuation strain for equi-biaxial, pure shear and uniaxial deformation modes at different pre stretch values, it has established that actuation strain is independent of pre-stretch modes of deformation (equi-biaxial, uniaxial and pure shear) rather it depends upon the thickness stretch ratios. The actuation strain can be successfully predicted at different thickness stretch for different voltages using the power law proposed in this work. Experimental results also show very high value of actuation strain in case of equal-biaxial pre-stretching. This may be due to very low thickness stretched value achievable in case of equal-biaxial pre-stretching. This works also shows nonlinear relationship between actuation strain and applied voltage for all deformation modes.

Acknowledgement:
The reported study was partially supported by DST, Govt. of India, research project No. INT/SIN//P-03.

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