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Effect of mechanical pre-stretch on the stabilization of dielectric elastomer actuation

Bo Li, Hualing Chen, Junhua Qiang, Shulin Hu, Zicai Zhu and Yongquan Wang

School of Mechanical Engineering, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China
E-mail: hlchen@mail.xjtu.edu.cn

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Abstract

A dielectric elastomer is capable of giant electromechanical actuation but fails at breakdown due to instability under certain conditions with a small deformation. By applying a mechanical pre-stretch, one obtains a stabilized large actuation. In this paper, we measured the dielectric constant and critical voltage of a polyacrylic dielectric elastomer subjected to both equal and unequal biaxial stretch, and modelled its actuation by employing the Gent strain energy function with a microscopic view to characterize the nonlinear stiffening behaviour and the electrostrictive effect in the deformation. The mechanical pre-stretch contributes in several ways to the stabilization of dielectric elastomer, by eliminating the pull-in instability, by generating electrostriction, by improving the breakdown strength, as well as by reducing the membrane thickness which consequently lowers the voltages required for activation.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Electroactive polymers (EAPs) are a class of compliant smart materials, which can generate mechanical response to electric stimuli. Among various EAP materials, dielectric elastomers, a sub-category of EAPs, exhibit promising potential for applications due to their ability of giant deformation over 100% in the presence of an external electric field [1].

A dielectric elastomer is a soft, elastic dielectric, for instance, natural rubber. Sandwiched between compliant electrodes and subjected to a voltage, a dielectric elastomer membrane reduces its thickness due to the Maxwell stress, defined as the attraction of charges accumulated at both surfaces, and then expands its area. The electromechanical actuation of a dielectric elastomer can be considered comparable to that of biological muscles, as actuation strains up to 100% have been observed, and this feature has been explored in practical applications, including soft robots, adaptive optics, Braille displays and electric generators [2–8].

However, a dielectric elastomer is susceptible to modes of instabilities in the actuation process. When the voltage ramps up, the membrane thins down, so the same voltage produces a higher electric field which will further squeeze the membrane as a positive feedback till the electrical breakdown. This failure mode, named pull-in instability, is considered as the key issue that hinders the realization of large stable deformation [9]. After the pull-in instability, the elastomer may survive without electrical breakdown; instead, it may be stabilized in a state of a much smaller thickness, resulting in a snap-through instability [10]. This behaviour is understood by considering the elastomer under tension (figure 1(a)). On approaching the extension limit of the polymer chains, \( \lambda_{\text{lim}} \), the elastomer stiffens sharply. When the deformation is caused by voltage rather than mechanical forces, the voltage–stretch curve may take the form shown in figure 1(b). The voltage attains a local maximum at stretch \( \lambda_c \) (marked by a \( \times \) in figure 1(b)) corresponding to the onset of the pull-in instability. With the voltage ramping up further, the membrane might snap (denoted by the red dashed arrow in figure 1(b)), and be stabilized at a stretch close to \( \lambda_{\text{lim}} \), as long as it survives before electrical breakdown.

Indeed, recent calculations indicate that giant voltage-induced strains, well above 100%, are possible, as long as the instability is eliminated and the elastomer operates in...
This paper aims to study the effect of mechanical pre-stretch on the stabilization of dielectric elastomer actuation. Based on the experimental studies in section 2, we obtained the dielectric property of a deformed elastic dielectric when mechanically loaded, unequal and equal biaxially. Using the free energy model, where we employ the Gent strain energy function in section 3, we characterize the stabilized actuation of the dielectric elastomer with a numerical study combining the discussion on the physical picture of the stabilization from the microscopic view of the soft elastomer. Section 4 discusses the nature of breakdown and how it is related to the instability, followed by a conclusion in section 5.

2. Experiments

A VHB film, produced by the 3M Company, is the most commonly employed dielectric elastomer material for its low cost, large deformation and commercial availability as transparent adhesive tapes. In this paper, we select VHB 4910, whose original thickness is 1 mm, as the dielectric elastomer to be investigated.

2.1. Effect of pre-stretch on the dielectric constant of VHB 4910 films

The deformation is defined in figure 2. The overall deformation is separated into two parts; deformation due to mechanical pre-stretch \( \lambda^p \) and the deformation due to the voltage load (actuation) \( \lambda^a \).

Figure 3 displays the experimental setup. The VHB 4910 film was fixed on an acrylic frame and stretched, equal and unequal biaxially, up to expected levels after which conductive carbon grease (MG mechanica company) was smeared uniformly on both surfaces of the film as compliant electrodes with a diameter of 10 mm. For each group of measurements, 10 specimens were created under the same condition in order to obtain the average value of the dielectric constant or the critical voltage.

We first obtained the dielectric constant of these deformed VHB films. The capacitance of the specimens was measured by connecting them to two gold tube electrodes of a LCR meter (4991A from Agilent). In order to eliminate the effect of viscoelasticity in the elastomer, all the tests on these specimens were conducted 7 days after the stretch when the residual stress was fully equilibrated at a steady state. The experimental results of the dielectric constant at 0.5 Hz are presented in table 1, which show a strong nonlinear relation between the dielectric constant \( \varepsilon \) and the pre-stretch \( \lambda^p \). \( \varepsilon \) drops with an increase in the pre-stretch in both directions; this coincides with previous reports [7] on the equal biaxial stretch. This phenomenon was also observed in each of these specimens as well as at other frequencies (10 1000 and 1000 Hz).

In the statement of electrostriction [16], where \( \varepsilon \) is a function of deformation, we express \( \varepsilon(\lambda_1, \lambda_2) \) as

\[
\varepsilon = \varepsilon_i [1 + a(\lambda_1 + \lambda_2 - 2) + b(\lambda_1 + \lambda_2 - 2)^2 + c(\lambda_1 + \lambda_2 - 2)^3].
\]
behaviour through modelling and numerical simulation where we calculate the actual thickness in the actuation and hence obtain the electric field. But for the same area expansion, \( \Phi_c \) is not the same as that in an unequal biaxial stretch, as can also be noticed in table 2 (\( \lambda_1^3 \times \lambda_2^3 = 9 \) or \( \lambda_1^3 \times \lambda_2^3 = 16 \)). \( \Phi_c \) differs as the pre-stretch varies under the condition of the same area expansion, where a proportional relation cannot be derived. Here we might ascribe this to the artificial anisotropic property induced by the unequalness. However, in practical applications, in order to attain uniform actuation and stabilization, equal biaxial pre-stretch is widely employed.

3. Free energy model

With reference to figure 5, in the reference state, the dielectric is subjected to no forces and voltage, and is of dimensions \( L_1 \), \( L_2 \) and \( L_3 \). In the current state, subjected to forces \( P_1 \), \( P_2 \) and \( P_3 \), and voltage \( \Phi \), the dielectric is of dimensions \( l_1 \), \( l_2 \) and \( l_3 \); the two electrodes accumulate electric charges \( \pm Q \), and the Helmholtz free energy of the membrane is \( F \).

When the dimensions of the dielectric change by \( \delta l_1 \), \( \delta l_2 \) and \( \delta l_3 \), the forces do work \( P_1 \delta l_1 + P_2 \delta l_2 + P_3 \delta l_3 \). When a small quantity of charge \( \delta Q \) flows through the conducting wire, the voltage does work \( \Phi \delta Q \). In equilibrium, the work done by the forces and voltage equals the increase in the free energy of the dielectric:

\[
\delta F = P_1 \delta l_1 + P_2 \delta l_2 + P_3 \delta l_3 + \Phi \delta Q. \quad (2)
\]

Define the density of the Helmholtz free energy by \( W = F/(L_1 L_2 L_3) \), stretches by \( \lambda_1 = l_1/L_1 \), \( \lambda_2 = l_2/L_2 \) and \( \lambda_3 = l_3/L_3 \), which can be further separated in figure 3, nominal stress by \( \sigma_1 = P_1/(L_2 L_3) \), \( \sigma_2 = P_2/(L_1 L_3) \) and \( \sigma_3 = P_3/(L_1 L_2) \), true stresses by \( \sigma_1 = P_1/(l_2 l_3) \), \( \sigma_2 = P_2/(l_1 l_3) \) and \( \sigma_3 = P_3/(l_1 l_2) \), the nominal electric field by \( E = \Phi/L_3 \), true electric field by \( E = \Phi/l_3 \), nominal electric displacement by \( D = Q/(L_1 L_2) \) and true electric displacement by \( D = Q/(l_1 l_2) \).

When an elastomer undergoes large deformation, the change in the shape is typically much larger than the change in the volume. Consequently, the elastomer is often taken to be incompressible—that is, the volume of the material remains unchanged during deformation, \( l_1 l_2 l_3 = L_1 L_2 L_3 \), so that

\[
\lambda_1 \lambda_2 \lambda_3 = 1. \quad (3)
\]

This assumption of incompressibility places a constraint among the three stretches. We regard \( \lambda_1 \) and \( \lambda_2 \) as independent.
variables, so that $\lambda_3 = \lambda_1^{-1}\lambda_2^{-1}$, and $\delta\lambda_3 = -\lambda_1^{-2}\lambda_2^{-1}\delta\lambda_1 - \lambda_1^{-1}\lambda_2^{-2}\delta\lambda_2$. Divide both sides of equation (2) by the volume of the membrane, $L_1L_2L_3$, and using equation (3), we obtain that

$$\delta W = \left(\bar{\sigma}_1 - \frac{\bar{\sigma}_3}{\lambda_1^2\lambda_2}\right)\delta\lambda_1 + \left(\bar{\sigma}_2 - \frac{\bar{\sigma}_3}{\lambda_2^2\lambda_1}\right)\delta\lambda_2 + \tilde{E}\delta\tilde{D}. \quad (4)$$

The free energy density is a function of stretch and nominal electric displacement, $W(\lambda_1, \lambda_2, \tilde{D})$, so that

$$\bar{\sigma}_1 = \frac{\bar{\sigma}_3}{\lambda_1^2\lambda_2} = \frac{\partial W(\lambda_1, \lambda_2, \tilde{D})}{\partial \lambda_1}, \quad (5a)$$
$$\bar{\sigma}_2 = \frac{\bar{\sigma}_3}{\lambda_2^2\lambda_1} = \frac{\partial W(\lambda_1, \lambda_2, \tilde{D})}{\partial \lambda_2}, \quad (5b)$$
$$\tilde{E} = \frac{\partial W(\lambda_1, \lambda_2, \tilde{D})}{\partial \tilde{D}}. \quad (5c)$$

According to Suo [3], the free energy model takes the form

$$W(\lambda_1, \lambda_2, \tilde{D}) = W_s(\lambda_1, \lambda_2) + \frac{\lambda_1^{-2}\lambda_2^{-2}}{2\varepsilon_0\varepsilon(\lambda_1, \lambda_2)}\tilde{D}^2. \quad (6)$$

Here $\varepsilon_0$ is the permittivity of vacuum. Once $W_s(\lambda_1, \lambda_2)$, energy due to stretch, and $\varepsilon(\lambda_1, \lambda_2)$ are known for a specific dielectric, specializing equation (6) with respect to equations (5a)–(5c), one obtains the equations of state.

The free energy due to the stretching of the elastomer, $W_s(\lambda_1, \lambda_2)$, may be selected from a large menu of well-tested functions in the theory of rubber elasticity. To account for the extension limit, here we adopt the Gent model [18], which is based on the non-Gaussian distribution and features its parameters with microscopic interpretations:

$$W_s = -\frac{\mu J_m}{2} \log \left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}{3}\right). \quad (7)$$

Combining (6) and (7), specializing (5a)–(5b), we obtain the equation of state as

$$\frac{P_1}{\mu L_2L_3} = \frac{P_3}{\mu L_1L_2\lambda_1^2\lambda_2} = \frac{\lambda_1^{-2} + \lambda_2^{-2} + \lambda_3^{-2} - 3}{J_m}$$
$$-\lambda_1\lambda_2^2\varepsilon_0\varepsilon \left(\frac{\Phi}{L_3}\right)^2 - 1 = \frac{1}{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3}$$
$$\times [a + 2b(\lambda_1 + \lambda_2 - 2) + 3c(\lambda_1 + \lambda_2 - 2)^2], \quad (8a)$$

$$\frac{P_2}{\mu L_2L_1} = \frac{P_3}{\mu L_1L_2\lambda_1^2\lambda_2} = \frac{\lambda_2 - \lambda_2^{-2}\lambda_1^{-3}}{J_m}$$
$$-\lambda_1\lambda_2^2\varepsilon_0\varepsilon \left(\frac{\Phi}{L_3}\right)^2 - 1 = \frac{1}{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3}$$
$$\times [a + 2b(\lambda_1 + \lambda_2 - 2) + 3c(\lambda_1 + \lambda_2 - 2)^2], \quad (8b)$$

Here by prescribing $P_i (i = 1, 2, 3)$, we defined the levels of pre-stretch as the boundary condition, the passive region without electrode in figure 2.

4. Numerical simulation and results

4.1. Equal biaxial pre-stretch

Assume the dielectric elastomer is subjected to fixed forces $P_1 = P_2 = P$ and $P_3 = 0$, as well as voltage $\Phi$. Write the stretches as $\lambda_1 = \lambda_2 = \lambda$, and specializing (8a)–(8c), we obtain that

$$\frac{P}{\mu L_2L_3} = \frac{\lambda - \lambda^{-5}}{1 - \frac{2\lambda^{-2} + \lambda^{-4} - 3}{J_m}} - \frac{3\varepsilon_0\varepsilon}{2\Phi \lambda^4} \left(\frac{\Phi}{L_3}\right)^2$$
$$- \frac{1}{2} \frac{3\varepsilon_0\varepsilon}{\mu} \left(\frac{\Phi}{L_3}\right)^2 [a + 2b(\lambda - 2) + 3c(\lambda - 2)^2]. \quad (9)$$

We may use the normalized voltage as $\Phi/(L_3\sqrt{\mu/\varepsilon})$, where $\varepsilon = \varepsilon_0\varepsilon$, and the pre-stretch force as $P/(\mu L_2L_3)$, and take $J_m = 72$ as a representative value for VHB films [3]. Figure 6 plots the voltage–stretch curves, and as a comparison, we also plot the actuation curves taking the dielectric constant
Table 2. Critical breakdown voltage of the pre-stretched dielectric elastomer.

<table>
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<tr>
<th>$\lambda_p$</th>
<th>2</th>
<th>3</th>
<th>2.25</th>
<th>2</th>
<th>4</th>
<th>3.2</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>$\lambda_c$</td>
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<td>3</td>
<td>4</td>
<td>4.5</td>
<td>4</td>
<td>5</td>
<td>5.3</td>
<td>2.25</td>
</tr>
<tr>
<td>$\Phi_c$ (kV)</td>
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<td>6.41</td>
<td>6.31</td>
<td>6.29</td>
<td>6.53</td>
<td>6.5</td>
<td>6.57</td>
<td>6.31</td>
</tr>
</tbody>
</table>

Figure 5. A membrane of a dielectric elastomer sandwiched between two compliant electrodes. (a) In the reference state, the dielectric is subjected to no forces and voltage. (b) In the current state, subjected to forces and voltage, the membrane deforms, and charge flows from one electrode to the other through the external conducting wire.

Figure 6. Voltage–stretch curves of the equally biaxially pre-stretched dielectric elastomer with invariable (red) and variable (blue) dielectric constants.

Figure 7. Voltage–stretch curves of the equally biaxially pre-stretched dielectric elastomer using two models: Gent model with a variable dielectric constant and Neo-Hookean model with a constant dielectric permittivity.

Both groups of these curves exhibit stiffening behaviour at large strain but differ at their extension limit. For ideal dielectric elastomers, whose dielectric constant is independent of deformation, the extension limit is identical to that of experimental report, $\lambda_{lim} \approx 6$, from a pure mechanical stretch [7]. The pull-in instability takes place without pre-stretch ($\lambda_p = 1$) and is eliminated by increasing pre-stretch, which agrees well with the previous study by Zhao and Suo [22]. The other group of curves combining the electrostriction due to the change in the dielectric constant show that the dielectric elastomer stiffens earlier at a lower extension limit. This is due to the mechanism of electrostriction; unlike the Maxwell stress which squeezes the membrane, the electrostriction will thicken the film as a result of the elongation of polarizable dipoles [16], and hence offsets the thinning process in the vertical direction.

Since we employ the Gent model to characterize the limited chain extension, the snap-through instability is also plotted at the onset of pull-in instability, as marked and interpreted physically in section 1. Figure 7 compares our model with the Neo-Hookean model. Unlike the Neo-Hookean model, the Gent model benefits from its ability...
of characterizing the stiffening process of the rubbery material at large strains, either caused by mechanical force or by voltage load. This is due to the feature of the Gent model based on the non-Gaussian distribution when the polymer molecular chain end–end distance is comparable to its full length scale. At small strains, the molecular chains of the polymer are uncoiled slightly, exhibiting a low resistance, which is observed macroscopically as the low elastic modulus. However, when the chains are fully stretched, the external stress fights against the tension of the backbone for further extension, requiring a sharp increase in the force. Since the Neo-Hookean model is concerned mainly on the deformation at small strains, it fails to predict the stiffening process when the material is completely stretched, also plotted in figure 7.

4.2. Unequal biaxial pre-stretch

For unequal biaxial pre-stretch, define $\lambda_2^p = k\lambda_1^p$, and equations of state are reduced to

$$\frac{P_i}{\mu L_2} \frac{L_1}{L_2}$$

$$= \frac{\lambda_2^p \lambda_1^p - k^{-3} (\lambda_1^p)^2 (\lambda_2^p)^{-2} (\lambda_1^p)^{-5} (\lambda_2^p)^{-3}}{1 - \frac{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2}{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2 + k^{-2} (\lambda_2^p)^{-2} (\lambda_1^p)^{-4}} - 3}$$

$$- k^2 (\lambda_2^p)^3 (\lambda_1^p)^2 \frac{\epsilon_{\text{EF}}}{\mu} \left( \frac{\Phi}{L_3} \right)^2$$

$$- \frac{1}{2} \frac{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2}{2} \frac{\epsilon_{\text{EF}}}{\mu} \left( \frac{\Phi}{L_3} \right)^2$$

$$\times [a + 2b (\lambda_2^p \lambda_1^p + k \lambda_2^p \lambda_1^p - 2) + 3c \lambda_2^p \lambda_1^p + k \lambda_2^p \lambda_1^p - 2^2],$$

(10a)

$$\frac{P_2}{\mu L_3} \frac{L_2}{L_1}$$

$$= \frac{k \lambda_2^p \lambda_1^p - k^{-2} (\lambda_2^p)^{-2} (\lambda_1^p)^{-5} (\lambda_2^p)^{-3}}{1 - \frac{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2}{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2 + k^{-2} (\lambda_2^p)^{-2} (\lambda_1^p)^{-4}} - 3}$$

$$- k (\lambda_2^p)^3 \lambda_2^p \frac{\epsilon_{\text{EF}}}{\mu} \left( \frac{\Phi}{L_3} \right)^2$$

$$- \frac{1}{2} \frac{k^2 (\lambda_2^p)^3 (\lambda_1^p)^2}{2} \frac{\epsilon_{\text{EF}}}{\mu} \left( \frac{\Phi}{L_3} \right)^2$$

$$\times [a + 2b (\lambda_2^p \lambda_1^p + k \lambda_2^p \lambda_1^p - 2) + 3c \lambda_2^p \lambda_1^p + k \lambda_2^p \lambda_1^p - 2^2].$$

(10b)

Here, we plot the actuation curves at the area pre-expansion of 9 and 16, respectively, in figure 8, where the electrostrictive effect is involved. For the same area pre-expansion, the equally biaxially pre-stretched dielectric elastomer exhibits a better performance in stability than the unequally stretched one. This numerical result agrees with the tendency observed experimentally for the critical voltage in section 2, which we also marked with circles • in figure 8 to illustrate the maximum actuation. The unequalness in the pre-stretch complicates the material property. On the one hand, it introduces anisotropy, where the dielectric fails in the weak direction, i.e. material being less pulled along one direction has a lower stiffness, and instability occurs, leading to the overall failure; on the other hand, some local failure, e.g. crack’s propagation, is also induced by the inequality and hence degrades partly the stabilization brought about by the pre-stretch as has been expected.

4.3. Electrical strength at different pre-stretch levels

Both in figures 6 and 8, we show the maximum actuation by substituting the critical voltage into equations (9) and (10a) and (10b) to get $(\lambda_2^p \lambda_1^p)_{\text{max}}$ and $(\lambda_2^p \lambda_2^p)_{\text{max}}$; then we may write the critical electric field, or the dielectric strength, as

$$E_c = \frac{(\lambda_2^p \lambda_1^p)_{\text{max}} (\lambda_2^p \lambda_2^p)_{\text{max}}}{L_3} \Phi_c$$

(11)

We plot in figure 9 the critical electric field by taking our experimental data along with the computational result of the maximum strain and express the nonlinear dielectric strength of the elastic dielectric undergoing deformation by power law fitting. This expression agrees well with previous prediction [3] and together with equations (9) and (10a) and (10b), they offer a valid method to estimate the actual actuation strain at a given pre-stretch.

5. Mechanism of stabilization enhancement by mechanical pre-stretch

An elastomer is a three-dimensional network of long and flexible polymer chains, held together by crosslinks. Each polymer chain consists of such a large number of monomers that the crosslinks affect polarization of the monomers negligibly. That is, the elastomer can polarize nearly as freely as a polymer melt. As an idealization, we may assume that the dielectric behaviour of an elastomer is exactly the same as that of a polymer melt, which is unaffected at a natural or small strain state. However, actually as the chains are being further
stretched, the movements of dipoles are gradually constrained by the mechanical force at the expense of freedom of dipole rotation. Therefore a decrease in dielectric constant is observed experimentally, a material property representing the ability of polarization in a dielectric subjected to an external electric field.

Dielectric elastomers are also capable of giant deformation as has been studied as their hyperelasticity [17]. At finite deformation or large strain state, the molecular chains constituting the polymeric network become more and more untangled, thus the resistance from the chain network is composed mainly of the strong stiffness of the molecular chain backbone. Therefore, the stiffening effect at moderate strain is observed experimentally, as illustrated in figure 1(a). The elastomer may also stiffen when subjected to an unequal biaxial stretch, but may have anisotropic elasticity. Therefore the material fails mechanically or electrically in the introduced weak direction and behaves with less stability than an equally biaxially stretched specimen at the critical voltage.

Pull-in instability has been the key issue blocking the exploration of the giant deformation of dielectric elastomers, and limits the maximum strain in the thickness direction at 30% [19]. Electrically speaking, the pull-in instability occurs when the mechanical stress, due to the squeezing force from the attraction of the electrodes, exceeds a critical value which is unbalanced by the dielectric’s elasticity [20]. Other dielectric elastomers may survive after the pull-in instability, and exhibit a coexistence of two states at a constant voltage: thick and thinner, which is interpreted as snap-through instability upon stiffening of soft matter at large strains [9]. Therefore, it consequently explains the mechanism that the mechanical pre-stretch stabilizes the actuation by increasing the stiffness and hence dielectric elastomers operate in a thinner and stiffer region to generate a continuous deformation of over 100% until breakdown. However, in the later case of actuation, where the dielectric possesses a greater stiffness, the breakdown mechanism is still within electromechanical mode, for the elastomer keeps deforming under a voltage load till the unbalance in the stress [21].

A recent report has revealed that the breakdown strength of a soft elastomer is dependent on the mechanical stiffness [14], and the critical voltages are of the same magnitude as our experimental data. When the pre-stretched dielectric elastomer benefits from a significantly enhanced breakdown strength, let us say infinite for an extremely thin film, it can continue deforming till the extension limit, where the molecular chains are broken under the load, and in the sense of this statement, its hyperelasticity is completely explored. By setting $\partial \Phi(P, \lambda)/\partial \lambda > 0$ in equations (9) and (10a) and (10b), one attains the minimum requirement of mechanical pre-stretch for a stabilized deformation.

6. Conclusion

Unlike a rigid dielectric, a dielectric elastomer fails at a critical voltage which results from the electromechanical coupling deformation. A mechanical pre-stretch contributes to the stabilization of the material, by eliminating the pull-in instability, by improving the breakdown strength and by reducing the membrane thickness, which consequently lowers the voltages required for activation. On eliminating the instability, the pre-stretched dielectric membrane stiffens to block the thinning down under a voltage and a continuous deformation is attainable; meanwhile, it generates electrostriction to offset the squeezing stress, which both stabilize the actuation.

Acknowledgments

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