A constitutive model of polyacrylate interpenetrating polymer networks for dielectric elastomers

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ABSTRACT

A physically based method is proposed to represent interpenetrating polymer networks and their electromechanical behavior. The mechanical behavior of the material is nonlinear elastic and the electromechanical coupling arises from electrostatic effects often called the Maxwell stress effect. Ha et al. have synthesized interpenetrating polymer networks (IPNs) that invalidate the need for an external pre-stretch mechanism in dielectric elastomers. IPNs of acrylic elastomer and 1, 6-hexanediol diacrylate were successfully synthesized to create free-standing films with preserved prestretch. This results in a dual polymer network, with one polymer network in tension and the other in compression. The prestretch is preserved chemically in the dominant network. The internal prestretch is accompanied by an overall stiffening of the dual polymer network leading to compromised actuation strains. A mechanistically simple representation of the networks is proposed by means of a model of two springs in parallel, replaced by an equivalent single spring. A material parameter is introduced to account for the effect of the weight percent of the secondary network. The effect of the additive on the preserved prestretch in the primary network and hence the overall stress strain response is determined. Specifically, a modified Ogden strain energy function is proposed that describes the mechanical behavior of the new interpenetrating polymer network. The electromechanical response of the material is described using a previously presented constitutive formulation that works well for single network polymers. The model results indicate that ideally an interpenetrating polymer network DE should not stiffen when the secondary network is formed to avoid reduced actuation strains.

1. Introduction

Dielectric elastomers are electroactive polymers capable of the largest voltage induced strains (300% areal strain) of any active polymer (Pelrine et al., 1998, 2000a,b; Zhang et al., 1998). They can also be configured for strain and pressure sensing by resistance or capacitance measurements (Son and Goulbourne, 2009). Large strain sensing capabilities (%) have been characterized and modeled for diaphragm configurations and tubular configurations (Rosenthal et al., 2007). There are several technical challenges that remain for realistic implementation of the actuators. Current research efforts include, stabilizing the electrodes, increasing the actuation force output, increasing actuation strains, developing small-scale transducers, and eliminating dependence on a mechanical prestretch mechanism (Brochu and Pei, 2009). Tailoring the properties of a base elastomer (such as polyacrylate or silicone elastomers) to attain improvement in the above mentioned properties has been pursued most notably by Ha et al. (2006a), Mathew et al. (2006), Rosset et al. (2008), Szabo et al. (2003). Matthew et al. added metallic fillers to an elastomer, creating a stiffer polymer that had increased dielectric constant but at the expense of severely compromised actuation strains (Mathew et al., 2006). By embedding the dielectric with metallic particles, the propensity for creating pathways for dielectric breakdown were increased, and the increase in stiffness reduced the capacity for strain generation by means of the electrostatic or Maxwell stress effect.

Of particular interest in this paper is the creation of interpenetrating networks by polymerizing a second network in the presence of a primary network (the base elastomer) creating a new elastomer with hybrid electromechanical properties. Ha et al. synthesized IPNs of silicone and 3 M VHB 4910 and Ha et al. synthesized IPNs of acrylic elastomer and 1, 6-hexanediol diacrylate (Ha et al., 2008, 2006a,b). Whilst the silicone-acrylic hybrid did not provide an appreciable increase in performance, it was proposed that the actuation force output would be higher on account of the increased modulus of the dielectric elastomer. The method employed by Ha et al. yielded a high performance dielectric elastomer (or hybrid elastomer) that does not require an external mechanism to sustain prestretch. This is an important advancement since developing clever ways of mechanically sustaining prestretch is severely limiting. Prestretch is important for two reasons.
Firstly, the voltage-induced deformation response increases due to a shift in the internal molecular arrangement of the polymer to the so-called softening region. Secondly, the breakdown electric field increases with prestretch. Although several explanations for increased breakdown strength with increased prestretch have been proposed, a well-accepted theory does not exist. It would seem that the variable of most interest should be the applied voltage, which is the control parameter from an experimental standpoint.

Kofod's data shows that the breakdown voltage decreases with decreasing thickness, which means that lower maximum voltages can be applied to thinner specimens (Kofod, 2001). The increase in breakdown strength is more an indication of decreased thickness. The fact that the breakdown voltage changes at all though does deserve further consideration. It is not clear from those experiments if the area was maintained constant across the testing conditions. This would be a challenge to implement but would likely provide some insight into how the results should be interpreted.

The purpose of this paper is to present a model that captures the essential characteristics of the electromechanical response of DEs based on IPNs. The dual-network polymer is mechanistically represented as two springs in parallel with different material properties. Based on the polymerization process it appears reasonable to presume as suggested by Ha et al. that the primary network is in compression and the secondary network is in tension. In Section 2, the IPN synthesis for 3 M VHB is briefly described. In Section 3, the constitutive model and briefly summarizes the finite deformation model for DE's. Numerical results are presented in Section 4 and the summary is given in Section 5.

2. DE assembly

A typical dielectric elastomer transducer is a three-layered structure consisting of a soft elastomer sandwiched by compliant electrodes. Polyacrylate or silicone films electroded by carbon or silver grease is the most common assembly. In recent years, electrode printing and vacuum deposition methods have been successfully explored (Rosset et al., 2008). To date, polyacrylate films from 3 M demonstrate the largest actuation strains. The requisite biaxial prestrain for 3 M VHB 4905 ranges between 200% and 400%. Automated and manual prestretch mechanisms are used in practice. In lieu of this, prestretching by hand can be performed, measures should be taken to record the homogeneity of the deformation. Once prestretched, the elastomer is electroded. Depending on the final desired configuration, a clever mechanism is required to maintain the prestretch. For example: plastic picture-frames (minimum-energy structures) (Kofod et al., 2006).

2.1. The ideal IPN dielectric elastomer

Consider the uniaxial behavior of a dielectric elastomer (with Mooney-Rivlin and Ogden model fits) illustrated in Fig. 1. An ideal IPN DE is defined as one whereby the addition of the secondary network causes a shift in the operating region along the constitutive curve. This shift occurs when a mechanical pre-stretch is applied to polyacrylate DE’s and maintained by an external mechanism. The material is mechanically stretched past the initial rise (a pseudo-yield point between a stretch of 2 and 3.5). Thus, when an electric field is applied (post prestretch), large actuation strains are achieved for reasonable applied electric fields. So far, efforts to tailor polyacrylate films by the addition of a secondary network yield a dual polymer network that is stiffer than the primary network. Invariably, this reduces the actuation strains since the ‘soft’ plateau region of the constitutive response is compromised, that is, increases in slope and or is reduced to a more narrow stretch region). In Section 3, a constitutive model for IPN DE’s is presented and numerical results for both ideal and actualized IPN DE electromechanical behavior are discussed in Section 4.

2.2. Interpenetrating polymer networks and preserved prestretch

In this section, Ha et al.'s method for the synthesis of high performance IPN DE’s is summarized (Ha et al., 2006a). Free-standing films are synthesized by thermo-mechanical curing of an additive (1, 6-hexanediol diacrylate) in the presence of a highly prestretched VHB film. Once cured, the dual-polymer network is released from the biaxial stretch mechanism and a free-standing film is created. The free-standing film has a certain % preserved pre-strain depending on the weight percentage of additive used and whether VHB 4905 or VHB 4910 is used. Thus a chemical process has been used to lock in the prestretch. In the event that the two polymers are chemically crosslinked, an interpenetrating network has been created (Fan et al., 2001; Sperling and Mishra, 1995). Likely the networks are individually crosslinked and simply coexist and interact through physical mechanisms but without forming chemical bonds. A schematic of this scenario is shown in Fig. 2.
True interpenetrating polymer networks are actually a single network.

3. Finite deformation model of IPN DEs

In the proposed model, the IPN is treated as a ‘single network’ in that the current configuration of the synthesized polymer is taken as the reference configuration. The hybrid material undergoes affine deformations only. Each of the networks is individually treated as a hyperelastic network in the volume preserving sense; a future treatment will consider viscoelastic effects. Although, it is not unreasonable to suppose that inelastic and viscoelastic effects occur, it is not the focus of the current treatment.

3.1. A constitutive model for interpenetrating polymer networks

A mechanistic representation of the dual-network polymer is shown in Fig. 3. Springs A and B refer to each network. The newly synthesized polymer with preserved prestretch in the primary/secondary network is taken as the initial configuration (prestretch kinematics and network formation are not explicitly considered in this phenomenological approach). The total stress \( T \) in the elastomer is given by the additive decomposition,

\[
T = T^A + T^B, \tag{1}
\]

where \( T^A \) is the Cauchy stress in the primary network \( (A) \) and \( T^B \) is the stress in the secondary additive network \( (B) \).

The deformation gradient \( F \) is identical in both polymers \( F_A, F_B \), hence

\[
F = F_A = F_B. \tag{2}
\]

Each polymer network is modeled as a hyperelastic material and hence the stress can be related to a suitable strain energy function. Network A could be represented with say an Ogden material model and network B represented with a Neo-Hookean model. Therefore, if the individual properties are known, the hybrid properties could be represented in terms of the volume fraction, and material parameters of the two strain energy functions. The dual-polymer network strain energy is the additive strain energy of the two components such that

\[
W_{\text{IPN}} = W_A + W_B, \tag{3}
\]

where \( W \) is the strain energy of the IPN, network A, or network B, per the subscript used. A natural selection of the form of the strain energy function accounting for the volume fraction \( \psi \) of the secondary network is

\[
W_{\text{IPN}} = (1 - \psi)W_A + \psi W_B. \tag{4}
\]

Indeed this form has been in the description of particle-filled materials. See for example, formulations employed by Bergstrom and Boyce (1998), Lion (1996). See Suo and Zhu for the application of this approach for interpenetrating networks (Suo and Zhu, 2009) and analysis of snap-through instabilities using the IPN model developed there. The representation lends itself to incorporation of the prestretch of the overall network. Stretches in each network are introduced although it is not clear how the overall prestretch is decomposed in each network for numerical validation with experimental results. The formulation presumes that the properties of the insitu thermocured polymer are known, as they are needed to solve for the preserved prestretch. Whereas planar equibiaxial deformations are analysed there, the present work considers out of plane deformations of IPN membranes. Here, we propose an alternate formulation used to numerically determine the material properties of the IPN. This approach includes the observation that the in situ cure in the presence of the prestretched VHB network leads to unknown properties of the cured additive and affects the VHB network leading to different interchain and intrachain interactions. The approach is amenable to numerical calculations. The approach is strictly phenomenological and does not describe the preparation kinematics, which is treated elsewhere.

Considering the interpenetrating polymer network after release from the prestretch mechanism, we introduce a material parameter \( \phi \), and supposing an Ogden representation, propose the following strain energy function for the new material (Ogden, 1972).

The strain energy is a function of the usual invariants (principal stretch) and the new material parameter \( \phi \)

\[
W_{\text{IPN}}(\lambda_1, \lambda_2, \lambda_3) = (1 + \phi) \left( \left( \frac{\lambda_1^{1/2} + \lambda_2^{1/2} + \lambda_3^{1/2}}{3} \right)^{2/3} - \frac{q}{k_1} \left( \frac{\lambda_1^{1/2} + \lambda_2^{1/2} + \lambda_3^{1/2}}{3} \right) \right) + 2 \left( \frac{\lambda_1^{2/3} + \lambda_2^{2/3} + \lambda_3^{2/3}}{q_2} - 3 \right), \tag{5}
\]

where \( \phi, q_1, q_2 \) are material parameters determined from best fits to the experimental data. Note that the elastomer considered here is incompressible so \( W \) is actually a function of two invariants (hence, two principal stretch components). Physically speaking, the parameter \( \phi \) represents the effect that the secondary network has on the IPN response such that when \( \phi \) is zero – the primary network material response is recovered. Thus the purpose of the new material parameter is to stiffen the primary network, whilst still permitting facile application of prestretch boundary conditions to the primary network. Ha et al.’s experiments reflect a strong dependence of recovered prestretch with the amount of additive used. There is an initial percolation region (critical additive weight for the secondary network to spontaneously polymerize is between 15% and 20%), followed by a quick rise in preserved prestretch with increasing amounts of additive, leading to a plateau-like region at greater than 50% weight percentage of poly (1, 6-hexanediol diacylate), where the preserved prestretch is near 100%. Results for weight percentages greater than 60% were not reported.

The new constitutive model is used to describe the electromechanical response of the high performance IPN DE’s. Previously, Goulbourne et al. proposed a finite deformation model for predicting the electromechanical response of dielectric elastomers (Goulbourne et al., 2005). The model postulates the total stress as an additive composition of a purely elastic stress and an electrostatic stress (commonly referred to as the Maxwell stress). Later, Suo et al. used a variational approach and determined an identical expression suitable for dielectric elastomers that provided a dielectric constant remains constant. This implies that electrostriction is nonexistent or negligible, a specific case referred to as the ideal dielectric elastomer within the generalized framework for electromechanical coupling in isotropic elastic dielectrics (Suo and Zhu, 2009). To solve boundary value problems, a modified membrane theory (Rivlin and Green and Adkins) is used to describe the electromechanical response of a dielectric elastomer in the presence of an electric field (Adkins and Rivlin, 1952; Goulbourne et al., 2007; Green and Adkins, 1970). Using this theoretical kernel, numerical

![Fig. 3. Mechanistic model of dual-polymer network.](image)
results for the electromechanical response of IPN DE's consistent with experimental results are presented in Section 4.

4. Numerical results

The proposed strain energy function in the previous section is incorporated into a numerical model for membrane inflation based on a modified finite deformation membrane theory. The modified theory for elastic membranes subject to a simultaneous electric field has been presented elsewhere (Goulbourne et al., 2005). Four coupled nonlinear first order differential equations in each of the variables: the horizontal distance from the axis of symmetry $\rho$, the meridional stretch $\lambda_1$, the vertical displacement from the axis $y$, and the intermediary variable $\omega = \rho'$, where primes refer to derivatives taken with respect to the dependent variable $s$ (namely the undeformed arc length) are obtained in final form by manipulating the two equilibrium equations and two elementary geometrical relations for the surface. The resultant membrane stresses $T_1$ and $T_2$ using the Ogden material model are obtained by integrating the principal stresses over the membrane thickness. The equilibrium equations are

$$\frac{d(T_1 \rho)}{d\rho} = T_2,$$

$$k_1 T_1 + k_2 T_2 = p,$$

and the geometrical Codazzi equations are

$$\frac{d}{ds} (k_2 \rho) = \kappa \frac{d\rho}{ds},$$

$$k_1 k_2 \rho \lambda_3 = \frac{d\rho}{ds} \frac{d\lambda_3}{ds} - \lambda_1 \frac{d^2 \rho}{ds^2},$$

From the modified Ogden strain-energy function, the principal stress components are given by

$$T_1 = \lambda_1 (1 + \phi) (\lambda_1^{\gamma_1-1} + 2\lambda_1^{\gamma_2-1}) - p,$$

$$T_2 = \lambda_2 (1 + \phi) (\lambda_2^{\gamma_2-1} + 2\lambda_2^{\gamma_1-1}) - p,$$

$$T_3 = \lambda_3 (1 + \phi) (\lambda_3^{\gamma_3-1} + 2\lambda_3^{\gamma_4-1}) - p,$$

where $p$ is the unknown hydrostatic pressure.

To solve these equations, the mechanical stress-stretch response for a hyperelastic incompressible material, they must be augmented to account for the stress incurred from the application of an electric field. To this end, within a continuum mechanics framework the total Cauchy stress in the membrane in the presence of an electric field can be sufficiently approximated as the sum of the mechanical stress and the electrical stress:

$$\tau = \tau_M + \tau_e,$$

where $\tau_M$ is the Maxwell stress or electrostatic stress, and $\tau_e$ is the mechanical portion of the stress with principal components given in Eq. 10. The electrostatic stress is proportional to the square of the electric field. For a uniform electric field applied in the thickness direction of the membrane, the surviving principal stress components of the Maxwell stress tensor with diagonal components of the form

$$\epsilon_e E_0 V^2$$

where $\epsilon_e$ is the relative dielectric constant, $\epsilon_0$ is the permittivity of free space, $V$ is the applied voltage, $\lambda_3$ is the stretch in the thickness direction, and $h_0$ is the original membrane thickness. Note here that the $\lambda_3 h$ term in the denominator is equivalent to the instantaneous material thickness. Eqs. 6–9, a set of coupled nonlinear differential equations, are solved using a shooting method in Mathematica™. Noting the symmetry of the problem, the stretch at the center of the membrane is prescribed and as the membrane is clamped at the edge, the latitudinal stretch is set equal to the prestretch.

The mechanical response of the membrane is considered for the two loading configurations described by Ha et al. In the first configuration, the IPN membrane is inflated without releasing the external prestretch mechanism. In the second configuration, the membrane is released from the prestretch mechanism and subsequently subject to pressure inflation. The numerical results are consistent with Ha et al’s experimental results. Every effort has been made to use available numerical parameters in the model consistent with the experimental results. Some numerical variance is expected since the material properties of the elastomers used in their study and the recovered geometrical dimensions are not reported. The model is sensitive to the material parameters.

4.1. Mechanical response of IPN membranes

Fig. 4 shows the mechanical inflation pressure as a function of membrane pole stretch for a membrane that has not been released from the biaxial prestretch frame. The pressure versus pole stretch response of an IPN dielectric elastomer is calculated for varying values of the material parameter, $\phi$ between 0 and 0.4. All films are subject to equi-biaxial prestrain of 400%. Model parameters are given in Table 1. The trends are consistent with the experimental results of Ha et al. The membrane becomes increasingly stiff with increased % volume fraction of the added secondary network eventually transitioning to a Mooney-Rivlin elastomer without the defined inflection typical of Ogden solids. The nonlinear dependence of the mechanical response on increasing volume fractions of the secondary network (represented by the parameter $\phi$) is accurately captured in the model.

In Fig. 5, the mechanical response of an IPN membrane with preserved prestretch is given. Each of the curves corresponds to the weight percent of poly (1, 6-hexanediol diacrylate) in the Membrane inflation pressure as a function of pole stretch for a membrane that has not been released from the biaxial prestretch frame. (The membrane has not been released from the biaxial prestretch frame.)

**Table 1**

<table>
<thead>
<tr>
<th>Summary of model material and geometrical parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material model parameters: 3-parameter Ogden model</td>
</tr>
<tr>
<td>$\mu_1$</td>
</tr>
<tr>
<td>28.9 kPa</td>
</tr>
<tr>
<td>Radius</td>
</tr>
<tr>
<td>25.4 mm</td>
</tr>
</tbody>
</table>
al.’s data. The following material parameters are employed:

\[ \text{Numerical results are generated by using the preserved prestretch reported for that level of additive in the composite and fitting the material parameter } \phi \text{ to Ha et al.’s data. The following material parameters are employed: } \]

\[ \mu_1 = 12.1 \text{ kPa}, q_1 = 2.07, \text{ and } q_2 = 7.64. \]

Ogden material parameters are given in Table 1 and the physically equivalent values for the material parameter as it relates to the weight percentage additive is given in Table 2. It should be noted that the following assumptions have been made: (i) For fitting the numerical parameters, it is considered that changes in the dimensions of the membrane due to the additive are negligible. (ii) At these high prestretch levels, it is likely that the membrane will relax. Thus the exact prestretch may indeed be lower, but taken as the reported experimental values in the model since changes in the initial prestretch were not reported. (iii) Ha et al. calculated the pole stretch by measuring the height and radius of the deformed membrane and comparing the arc length to the undeformed membrane diameter. This assumes that the stretch is uniformly distributed from edge to pole. This is a clear approximation that may deviate at small stretch values where there is little to no out of plane displacement. (iv) The membrane was loaded with a fluid (water). This is modeled as a constant pressure in the numerical simulations. The pressure will actually vary as the membrane deforms since the fluid pressure will be a function of depth. (v) The material parameters for the VHB should ideally be calculated from both uniaxial and biaxial data. Notwithstanding these points, the numerical fit is good.

The results are similar to the response of the unreleased membranes (Fig. 4). The preserved biaxial prestrain is always less than 400%. Ha et al.’s results indicate that at smaller stretch ratios, the films are much softer than the polycrylate films without poly (1, 6-hexanediol diacylate). This result differs from the numerical results obtained here. It is possible that the samples were not conditioned. These types of elastomers typically soften and stabilize after a few low load cycles, sometimes referred to as a type of Mullins effect in particle filled elastomers. The phenomenon also occurs in unfilled elastomers hence the mechanisms used to describe the behavior do not apply but the nomenclature remains. This preload cycle is called pre-conditioning and may account for the uncharacteristically stiff response observed by Ha et al. Alternatively, for a mildly stretched network, the additive may function as a plasticizer, facilitating polymer chain motion through chain slippage or due to recovery of secondary network precompression.

### Table 2

<table>
<thead>
<tr>
<th>Material model parameter ( \phi ) and corresponding weight % additive</th>
<th>( % ) additive</th>
<th>Preserved prestretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>0.05</td>
<td>18.33%</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>20.16%</td>
</tr>
<tr>
<td></td>
<td>0.17</td>
<td>21.91%</td>
</tr>
<tr>
<td></td>
<td>0.23</td>
<td>23.58%</td>
</tr>
<tr>
<td></td>
<td>3.75</td>
<td>4.07</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
<td>4.41</td>
</tr>
</tbody>
</table>

4.1. Ideal IPN dielectric elastomers

It is useful to compare the mechanical response of the new composite membranes with the desired response. An ideal IPN DE would preserve or better yet augment the response of current polycrylate dielectric elastomers. The ideal IPN DE is described in Section 2.1. If the composite membrane preserved prestretch without shifting the constitutive response of the primary network (effectively moving along the same stress–strain curve) then a large region of softening would be preserved. It is the lack of preserving this mechanical region that leads to compromised actuation strains (discussed in Section 4.2 in more detail). Fig. 6 shows numerical results for the inflation response of an ideal IPN DE. The target operating region identified in the figure refers to the range where largest actuation strains would be obtained if an electric field were applied. This qualitative analysis refers to the analogous mechanical effect that the electric field has on deforming the solid. By operating in the so-called target region, lower electric fields can be used to cause very large actuation strains. This example also illustrates the main disadvantage of these electroactive polymers, the low force output that accompanies large actuation strains. Using the model equivalence between preserved prestretch and addition of the secondary network, the results show the desired effect of maintaining a soft, plateau-like region for increasing % preserved prestretch.

4.2. Electromechanical response of IPN DE membranes

The electromechanical coupling is described by a quadratic dependence on the electric field and is characterized by the dielectric constant of the material. The dielectric constant measured by Ha et al. is used in the numerical calculations, 3.27. Polycrylate films (3 M VHB 4910) have a reported dielectric constant of 4.7. The reduction is expected since the additive polymer has a dielectric constant on the order of 2. The predicted electromechanical response of free standing IPN DE’s are summarized in Fig. 7. As expected, the actuation strains are lower for a given applied voltage than the response of unmodified polycrylate films. For the specified voltage range, the actuation strains increase with increasing % weight poly (1, 6-hexanediol diacylate for a fixed chamber pressure of 3600 Pa. The actuation strains are strongly dependent on the bias pressure supplied and the preserved prestretch, and the dependence is nonlinear. Fig. 8 shows the electromechanical...
response of IPN DE’s for a bias pressure of 4200 Pa, where the actuation strains increase with decreasing weight percent additive (consistent with the experimental trends reported). (The bias pressure was not reported in that work.) Figs. 7 and 8 demonstrate the effect that the preserved prestretch has on the electromechanical response for two different levels of bias pressure.

The calculated actuation strains for an applied voltage of 2000 V are between 20 and 70% for a given amount of residual prestretch in the free standing films (Fig. 8). This is much greater than the more modest strain level achieved (5–15%) for a bias pressure of 3600 Pa (Fig. 7). To illustrate why this occurs, consider Figs. 9 and 10 that show the relationship between mechanical bias pressure and pole stretch for a preserved prestretch of 2.5 and 3.75. In both figures, the individual curves correspond to a different applied voltage. The applied voltage has the effect of causing an apparent decrease in membrane compliance. It is clear that the dependence on the preserved prestretch and the voltage is nonlinear (because the elastomer is nonlinear as is the electromechanical coupling). The pole stretch has been normalized by the preserved prestretch. In Fig. 9 the material response is initially steeply linear, softening for a long stretch range, and eventually transitioning to hardening. In Fig. 10, the material has a more pronounced initial inflation before the plateau-like softening region. It is interesting to consider the membrane response for a prestretch of 2.5 actuated at a fixed pressure of 3600 Pa and 4200 Pa in Fig. 10. It is clear that the actuation response is finite for 3600 Pa for the voltage range considered (horizontal shift to the right from 0 V curve to any one of the actuated curves). If however, \( P = 4200 \text{ Pa} \), the strain increases drastically and uncontrollably (unstable branch), the membrane is susceptible to geometric instabilities in this range. Indeed, these simulations suggest that the IPN DE’s are susceptible to electric field induced uncontrollable inflation as observed in unmodified polyacrylate DE’s. The actuated IPN films also carry significant surface wrinkling with periodicity in the circumferential direction. Major failure modes and instabilities of dielectric elastomers were discussed by Plante in (Plante and Dubowsky, 2006). Fox and Goulbourne described the onset of wrinkling and geometric deviations (the membrane no longer inflates as a section of a sphere as evidenced by the formation of a symmetric and sometimes asymmetric bulge) (Fox and Goulbourne, 2008, 2009). Neither wrinkling nor shape variations are described by the present model.

5. Summary

In this paper, a mechanistic constitutive model is proposed to describe the response of new high performance dielectric elastomers. The composite membranes are interpenetrating polymer networks that invalidate the need for an external pre-stretch mechanism in dielectric elastomers. The finite deformation electromechanical model previously developed by the author has been used to describe the inflation response of the new materials in the presence of an electric field. The numerical results are consistent with experimental results. The model results illustrate that there is a trade-off between obtaining free-standing films and actuation
strains. Electric field induced finite strains in elastomers can give way to material and geometric instabilities. Although very large actuation strains can be obtained by operating under these conditions, unstable phenomena such as wrinkling are likely undesirable and will severely compromise the lifetime of the polymers. This work illustrates the applicability of the electromechanical model as a framework for describing the response of IPN DE’s.

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