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# Failure modeling of folded dielectric elastomer actuator

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When subjected to voltage, the dielectric elastomer membrane reduces its thickness and expands its area under the resulting compressive force. This characteristic enables the dielectric elastomer actuators of different structures to be designed and fabricated. By employing the thermodynamic theory and research method proposed by Suo et al., an equilibrium equation of folded dielectric elastomer actuator with two generalized coordinates is established. The governing equations of failure models involving electromechanical instability, zero electric field, electrical breakdown, loss of tension, and rupture by stretch are also derived. The allowable areas of folded dielectric elastomer actuators are described. These results could provide a powerful guidance to the design and performance evaluation of the dielectric elastomer actuators.

**dielectric elastomer, folded dielectric elastomer actuator, failure modes, allowable area**

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## 1 Introduction

Dielectric elastomer is one of the most potential electroactive polymers in fabricating actuators. Dielectric elastomer has some unique properties such as large deformation, high elastic energy density, high efficiency, fast response, and long durability etc [1–7]. In recent years, dielectric elastomer actuators are being studied broadly and deeply [8–15]. Actuators with various structures including folded, rolled, stacked, helical, hemispherical, etc, have been designed and fabricated [16–20]. The essential part of these dielectric elastomer actuators is the dielectric elastomer films coated with compliant electrodes. When voltage is applied on the electrodes, the dielectric elastomer film will reduce its thickness and expand its plane area. Meanwhile the electric energy will be converted into mechanical energy.

At present the performance evaluation of dielectric elastomer actuator mainly limits on destructive test, while the performance test for each actuator is more difficult and impractical, which limited the efficiency and increased the cost. Therefore it is urgent to establish failure modes for actuators with various structures, which can guide us to select the optimized design parameters and evaluate the performance of actuators.

After the nonlinear electromechanical stability analysis theory of dielectric elastomer which is proposed by Suo and Zhao, the electromechanical instability and failure analysis of dielectric elastomer planar actuator are being studied more in-depth, more comprehensive and more specific [21–50].

The coupling of mechanical field and electric field on the dielectric elastomer will cause the electrical breakdown of the dielectric elastomer planar actuator and thus lead to the electromechanical system unstable [21–39]. Zhao and Suo proposed that arbitrary free energy functions could be applied to analyse the stability performance of the dielectric

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elastomer planar actuator. They applied neo-Hookean elastic strain energy function with one material constant to analyse the electromechanical stability behaviour of ideal dielectric elastomer planar actuator. They studied the electromechanical stability of dielectric elastomer actuator with equal biaxial pre-stretch and unequal biaxial pre-stretch respectively. They described the relation between nominal electric displacement and nominal electric field. Their theoretical results first proved that pre-stretch could increase the critical nominal electric field and thus markedly increase the electromechanical stability. Furthermore, the calculated critical electric field of dielectric elastomer planar actuator coincided well with the experiment results.

Norrisa applied Ogden elastic strain energy function model to analyse electromechanical stability behaviour of dielectric elastomer planar actuator [32]. He derived the relation between critical real electric field, nominal stress and stretch. Díaz-Calleja et al. deeply studied the electromechanical stability behaviour of dielectric elastomer planar actuator by using neo-Hookean model [33]. They gave out the Hessian matrix of dielectric elastomer under two specific conditions. The obtained stability area and instability area could help us to understand the electromechanical stability behaviour of neo-Hookean type dielectric elastomer. Liu et al. studied the electromechanical stability area of Mooney-Rivlin type dielectric elastomer planar actuators [42]. They put forward the critical control conditions of actuators and calculated the stability area and instability area with biaxial pre-stretch. Recently they applied elastic strain function model with various material constants to analyse the electromechanical stability of ideal dielectric elastomer planar actuator. Adrian Koh et al constructed the typical failure model of dielectric elastomer thin film energy harvester, and then further worked out its energy density in a working cycle [46].

In the research above the permittivity applied in the electric field energy density function is a constant. In fact, experiments on elastomers have shown that the permittivity varies under large deformation. Recently Zhao and Suo demonstrated that the electromechanical instability can be suppressed when the dielectric elastomer undergoing large deformation [37]. Liu et al. applied the free energy function of thermodynamic system, which contained Mooney-Rivlin elastic strain energy function with two material constants and electric field energy density function combined with linear permittivity, to analyse the mechanical properties and electromechanical stability of incompressible dielectric elastomer planar actuator [41]. In addition, the nominal electric field and nominal electric displacement under two specific conditions were calculated, and the variations of stability parameters were derived. The results showed that stability of dielectric elastomer material was proportional to the material constant ratio $k$ and inversely proportional to the electrostrictive coefficient. Suo group established the state equations of rolled dielectric elastomer actuator with two freedom including electrical breakdown, loss of tension, and rupture by stretch. The optimized design theory of rolled dielectric elastomer actuator was also derived [35].

In this paper, based on the traditional thermal dynamic equations and Suo's work [35,46], we established the nonlinear condition equation of folded dielectric elastomer actuator with two generalized coordinates at isothermal condition, put forward the control equation when the folded dielectric elastomer actuator failed, and derived the allowable area of folded dielectric elastomer actuator. These results can guide us to design actuators and evaluate the performance of the actuators.

## 2 Basic theory and extension

Folded dielectric elastomer actuator was first designed and fabricated by Carpi et al. [24]. It can be used in actuating artificial muscle, bio-mimetic eye ball, space robot etc. When voltage is applied across the compliant electrodes of dielectric elastomer, the polymer film will shrink in the thickness direction and expand in the area direction. The folded dielectric elastomer actuator is obtained by folding the planar film for several times. When the mechanical force and electric field force are applied on the folded dielectric elastomer actuator, the sum constriction produced in each layer of folded dielectric elastomer actuator can reach the strain of 8%–18%, and can supply enough deformation to be an actuator. Figure 1 is the demonstration of a folded dielectric elastomer actuator. When voltage and mechanical force are applied on the folded actuator, the electric field force and mechanical force are coupled in the thickness direction.

### 2.1 The definition of actuator

In this section, the equilibrium equation of folded dielectric elastomer actuator is derived based on the traditional ther-

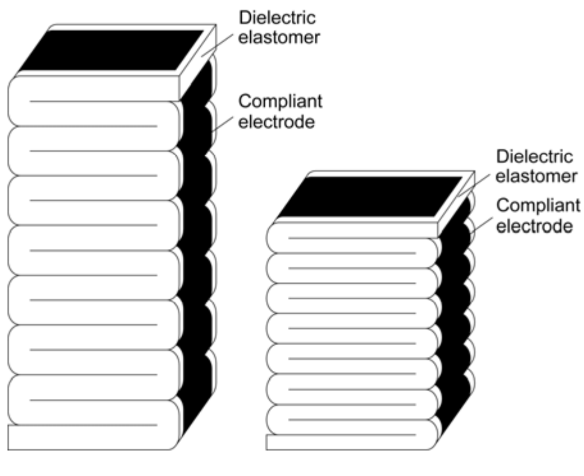


**Figure 1** Folded dielectric elastomer actuator [24].

modynamic equations and Suo's work [20]. In undeformed state, the sides of dielectric elastomer film are $l_1, l_2, l_3$. When the dielectric elastomer film is subjected to the voltage $U$ and mechanical force $F_3$, the three sides deforms to $L_1$, $L_2$, and $L_3$, and the amount of electric charge is $Q$. The principal stretch ratio in three sides are $\lambda_1$, $\lambda_2$, $\lambda_3$, so that $\lambda_1 = L_1/l_1$, $\lambda_2 = L_2/l_2$, $\lambda_3 = L_3/l_3$.

Nominal electric field is defined as the voltage divided by the thickness of dielectric elastomer in the undeformed state, $E^{\sim} = U/l_3$. Nominal electric displacement is defined as the electric charge divided by the area of the electrode in the undeformed state, $D^{\sim} = Q/l_1 l_2$. Meantime, the true electric field of dielectric elastomer is defined as the voltage divided by the thickness in the deformed state, $E = U/\lambda_3 l_3$. The true electric displacement is the electric charge divided by the area of dielectric elastomer in the deformed state, that is $D = Q/\lambda_1 l_1 \lambda_2 l_2$.

## 2.2 Free energy and equilibrium equation of thermodynamic system

Mooney and Rivlin assumed the rubbery polymer is isotropic, so that the strain energy is only function of stretch at both directions. According to the experimental validation, this model is able to capture the stress-strain behaviour when the strain is below 200% [51]. The Mooney-Rivlin type elastic strain energy model with two material constants is shown as follows [14,36]:

$$W(\lambda_1,\lambda_2,\lambda_3,D^{\sim}) = \frac{C_1}{2}(\lambda_1^2+\lambda_2^2+\lambda_3^2-3) + \frac{C_2}{2}(\lambda_1^{-2}+\lambda_2^{-2}+\lambda_3^{-2}-3), \tag{1}$$

$C_1$, $C_2$ are material constants that can be measured by test.

Here the Mooney-Rivlin model is used to describe the elastic performance of folded dielectric elastomer actuator. The dielectric elastomer is taken to be incompressible, so that $\lambda_1\lambda_2\lambda_3 = 1$. Let $\lambda_1 = \lambda_2$, we assume the actuator to be held at a constant temperature, and prescribe the Helmholtz free energy $H$ of the actuator as a function of the two generalized coordinates $\lambda_3$ ($\lambda_1 = \lambda_2 = \lambda_3^{-\frac{1}{2}}$) and $Q$.

$$H(\lambda_3,Q) = \frac{C_1}{2}(2\lambda_3^{-1}+\lambda_3^2-3)l_1 l_2 l_3 + \frac{C_2}{2}(2\lambda_3+\lambda_3^{-2}-3)l_1 l_2 l_3 + \frac{1}{2\varepsilon}\left(\frac{Q\lambda_3}{l_1 l_2}\right)^2 l_1 l_2 l_3. \tag{2}$$

As is shown in the previous paper, in prescribing the free-energy function (2), we have invoked several idealizations. The elastomer is taken to be a cross-linked network of long and flexible polymers, obeying the Gaussian statistics. We assume that the dielectric behaviour of the elastomer is liquid-like, unaffected by the deformation, so that the free energy of the elastomer is the sum of the elastic energy and the electric field energy, with $\varepsilon$ being the permittivity of the dielectric elastomer. Any such deviation can be accounted for by modifying the free-energy function, but should not alter the procedure of analysis described below.

When the dielectric elastomer is subjected to force $F_3$ and voltage $U$, small changes $\mathrm{d}\lambda_3$ and $\mathrm{d}Q$ will produce on the dielectric elastomer, we do not consider the actuator's gravity here.

Which needs to be emphasised is that the actuators investigated in this paper are folded but not single-layered. From eqs. (3) and (4) we can see obviously that when the folded actuator driving some objects or structures, it suffers from the action of gravity indicated by $F_3$. The following theoretical analysis of the typical failure model is all based on this foundation. On the other hand, the plane actuator usually suffers from the electric field force on the thickness direction only or the effect of prestretching on the direction of plane. Seen from this obvious distinguishment, the research of this paper is focused on the folded actuator rather than the single-layered actuator.

The change in the Helmholtz free energy equals the work done by the applied force and voltage, namely

$$\mathrm{d}H = F_3 l_3 \mathrm{d}\lambda_3 + U\mathrm{d}Q. \tag{3}$$

Consequently, the force and the voltage are the partial differential coefficients of the free-energy function $H(\lambda_3,Q)$. The planar force is work-conjugate to the elongation:

$$F_3 = \frac{\partial H(\lambda_3,Q)}{l_3\partial\lambda_3}. \tag{4}$$

The voltage is work-conjugate to the charge:

$$U = \frac{\partial H(\lambda_3,Q)}{\partial Q}. \tag{5}$$

Insert eq. (2) into eq. (4):

$$F_3 = C_1(\lambda_3-\lambda_3^{-2})l_1 l_2 + C_2(1-\lambda_3^{-3})l_1 l_2 + \frac{Q^2\lambda_3}{\varepsilon l_1 l_2}. \tag{6}$$

From eq. (6) we obtained that the mechanical force $F_3$ of the folded dielectric elastomer actuator is related to the elastic strain energy function and permittivity of the dielectric elastomer. Insert eq. (2) into eq. (5), we obtained the expression of the voltage applied on the dielectric elastomer:

$$U = \frac{Q\lambda_3^2 l_3}{\varepsilon l_1 l_2}. \tag{7}$$

In order to analysis the failure models of folded dielectric elastomer actuator more conveniently, involving electromechanical instability, zero electric field, electrical breakdown, loss of tension, and rupture by stretch in specific, we bring in the material constant ratio $k$, which is related to the dielectric elastomer materials and actuators of different structures. It can measure different dielectric elastomer materials or structures.

Let $C_2 = kC_1$, Dimensionless load parameters $F_3/C_1 l_1 l_2$ and $U\sqrt{\varepsilon/C_1}/l_3$, dimensionless variables $\lambda$ and $Q\sqrt{\mu\varepsilon}/l_1 l_2$ are taken into account, the corresponding eqs. (6) and (7) become

$$\frac{F_3}{C_1 l_1 l_2} = (\lambda_3 - \lambda_3^{-2}) + k(1-\lambda_3^{-3}) + \lambda_3\left(\frac{Q}{\sqrt{C_1\varepsilon} l_1 l_2}\right)^2, \tag{8}$$

$$\frac{U}{l_3}\sqrt{\frac{\varepsilon}{C_1}} = \lambda_3^2 \frac{Q}{\sqrt{C_1\varepsilon} l_1 l_2}. \tag{9}$$

The nonlinear eqs. (8) and (9) show us the mechanical behaviour of folded dielectric elastomer actuator subjected to mechanical force and voltage. According to eqs. (8) and (9), we could study the effect of different mechanical loads and voltage on the actuating performance of folded dielectric elastomer actuator, provide theoretical prediction for designing actuators, and evaluate the electromechanical coupling properties of folded dielectric elastomer actuator. Here the failure modes such as electromechanical instability, zero electric field, electrical breakdown, loss of tension, and rupture by stretch have been taken into account. The allowable area of folded dielectric elastomer actuator is obtained.

In Figure 2, in order to describe the influence of mechanical force to dielectric elastomer folded actuator's electromechanical coupling property we choose some representative parameter values. $F_3/C_1 l_1 l_2 = 0$ represents the circumstance without mechanical force, $F_3/C_1 l_1 l_2 = 2$, 4 represent the relatively small and large tension force while $F_3/C_1 l_1 l_2 = -2, -4$ represent the relatively small and large pressure. Figure 2 shows the relation between stretch ratio and electric displacement of the folded dielectric elastomer actuator with various mechanical forces.

In Figure 3, we use the continuing increasing electric field force (described by $U/l_3\sqrt{C_1/\varepsilon}$) to describe the influence to the electromechanical coupling property of dielectric elastomer folded actuator. Figure 3 shows the relation between stretch ratio and electric displacement with various voltages.

In the analysis, we assume the material constant ratio $k = 0$, 1, 2, 3 [36,52]. In Figure 2, when the mechanical force is fixed, electric displacement $\tilde{D}$ increases with voltage and stretch ratio $\lambda_3$ decreases. Meanwhile, in

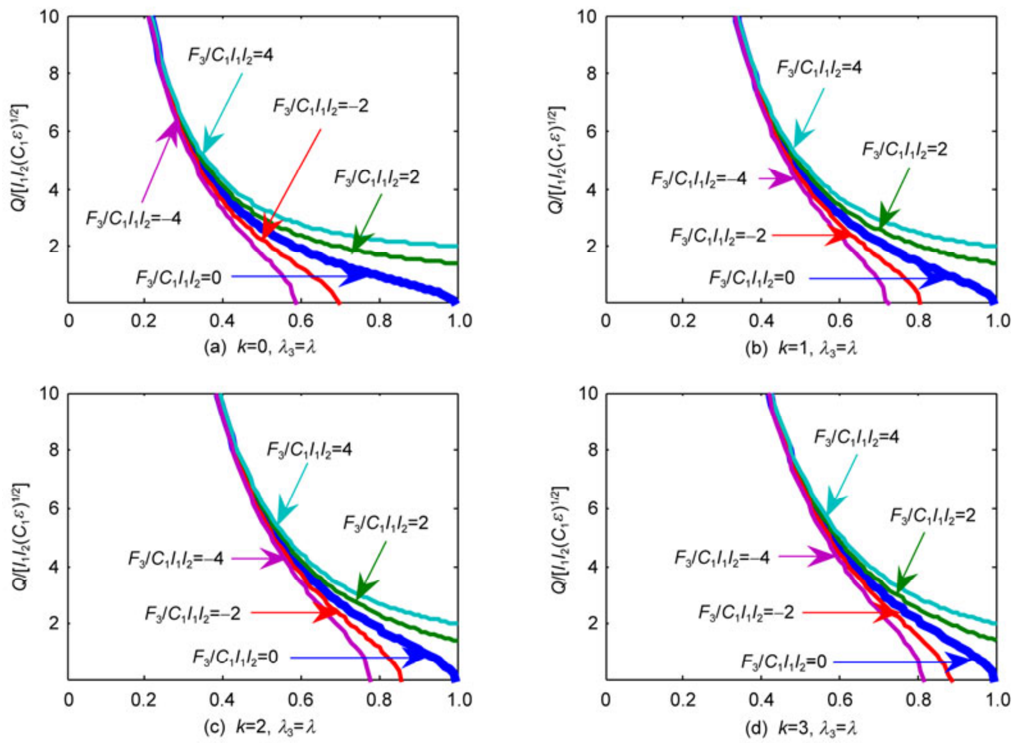


**Figure 2** (Color online) Relations between stretch ratio and the nominal electric displacement with various mechanical forces.

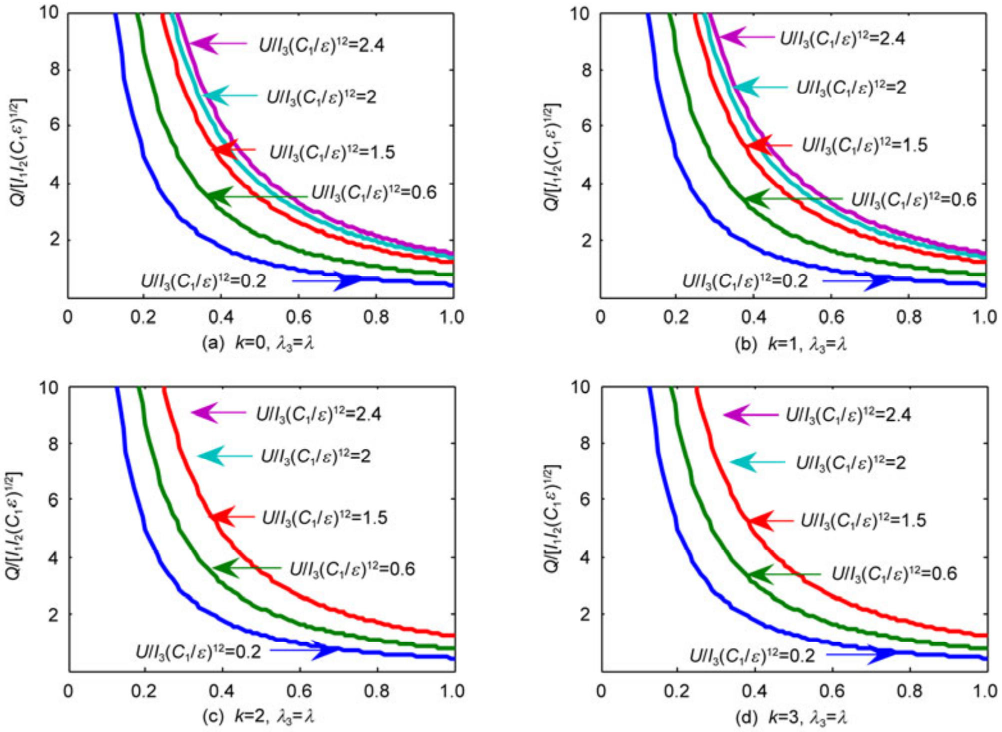


**Figure 3** (Color online) Relations between stretch ratio and the nominal electric displacement with various voltages.

Figure 3, when the voltage is fixed, electric displacement $D^{\sim}$ increases with mechanical force and the stretch ratio $\lambda_3$ decreases. Figures 2 and 3 can confirm the state of the folded dielectric elastomer actuator subjected to mechanical force and voltage.

## 3 Typical failure modes of the actuator

### 3.1 Electrical breakdown of the folded dielectric elastomer actuator

When the folded dielectric elastomer actuator is subjected to a voltage, as shown in Figure 4, when the applied voltage exceeds to the breakdown voltage of the dielectric elastomer, the electrical breakdown (EB) will cause the failure of the actuator.

From eq. (9) we obtained

$$E_{\mathrm{EB}}\lambda_3^{-1}\sqrt{\frac{\varepsilon}{C_1}} = \frac{Q}{\sqrt{C_1\varepsilon}\,l_1 l_2}, \tag{10}$$

where $E_{\mathrm{EB}}$ is the breakdown voltage of dielectric elastomer.

The eq. (10) corresponds to the curve marked by EB in Figure 5. Here the representative values $E_{\mathrm{EB}} = 10^8$ V/m [14,35,46], $\varepsilon = 3.54\times 10^{-11}$ F/m [37,41] and $C_1 = 1$ MPa [29,36,42] are used in plotting the figure. When the state of folded dielectric elastomer actuator belongs to the below region of the EB curve, the electrical breakdown will occur, while above the EB curve, the actuator will not suffer the electrical breakdown.

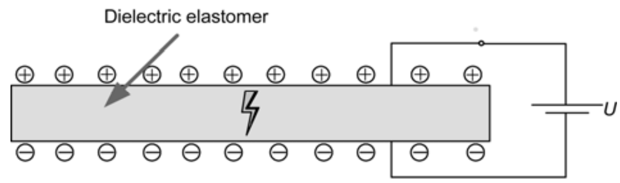


**Figure 4** Electrical breakdown mode of dielectric elastomers.

### 3.2 Electromechanical instability of the folded dielectric elastomer actuator

When the folded dielectric elastomer actuator is subjected to voltage and mechanical load, the dielectric elastomer film will decrease in thickness and expand in area. The decrease in thickness will induce a higher electric field. This positive feedback may cause the dielectric elastomer film thins down drastically. This process is called the electro-mechanical instability (EMI) [29,36,40,41,44,45]. As shown in Figure 6, when the electric field exceeds the critical electric field, the resulting electrical breakdown will cause the electromechanical instability of the folded dielectric elastomer actuator.

According to previous study [40], the actuator is in an equilibrium state when the Hessian is positive definite. The Hessian of the folded dielectric elastomer actuator is

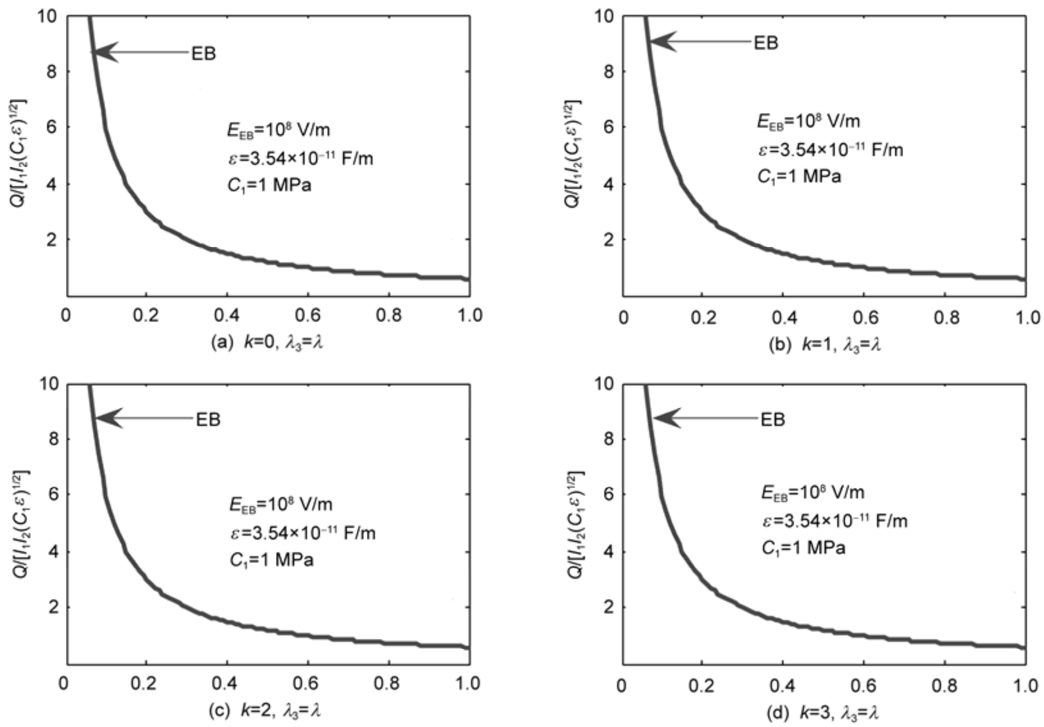


**Figure 5** Electrical breakdown of folded dielectric elastomer actuator.

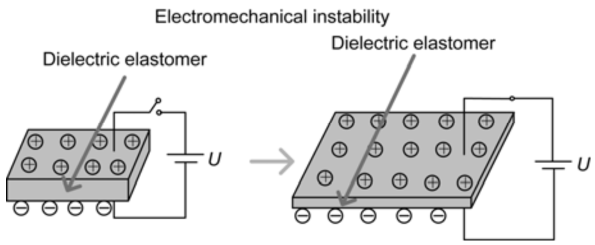


**Figure 6** Electromechanical instability mode of dielectric elastomers.

$$He=\begin{bmatrix}\dfrac{\partial^2 H(\lambda_3,Q)}{\partial\lambda_3^2} & \dfrac{\partial^2 H(\lambda_3,Q)}{\partial\lambda_3\partial Q}\\ \dfrac{\partial^2 H(\lambda_3,Q)}{\partial\lambda_3\partial Q} & \dfrac{\partial^2 H(\lambda_3,Q)}{\partial Q^2}\end{bmatrix}$$
$$=\begin{bmatrix}C_1(1+2\lambda_3^{-3})l_1l_2l_3+3kC_1\lambda_3^{-4}l_1l_2l_3+\dfrac{Q^2l_3}{\varepsilon l_1l_2} & \dfrac{2Ql_3}{\varepsilon l_1l_2}\lambda_3\\ \dfrac{2Ql_3}{\varepsilon l_1l_2}\lambda_3 & \dfrac{l_3}{\varepsilon l_1l_2}\lambda_3^2\end{bmatrix}. \tag{11}$$

To meet the Hessian positive definite, the first and second order principal minors need to be greater than 0, that is

$$C_1(1+2\lambda_3^{-3})l_1l_2l_3+3kC_1\lambda_3^{-4}l_1l_2l_3+\frac{Q^2l_3}{\varepsilon l_1l_2}>0$$

and

$$\frac{l_3}{\varepsilon l_1l_2}\lambda_3^2>0,$$

$$C_1(1+2\lambda_3^{-3})l_1l_2l_3+3kC_1\lambda_3^{-4}l_1l_2l_3-\frac{3Q^2l_3}{\varepsilon l_1l_2}>0. \tag{12}$$

In order to facilitate our analysis, we suppose $C_1>0$, $k>0$. The electromechanical stability critical condition of folded dielectric elastomer actuator can be expressed as follows:

$$\frac{Q}{\sqrt{C_1\varepsilon}l_1l_2}=\sqrt{\frac{(1+2\lambda_3^{-3})+3k\lambda_3^{-4}}{3}}. \tag{13}$$

From eq. (13) we can plot the electromechanical instability critical curve of the folded dielectric elastomer actuator. As shown in Figure 7, the plane is divided into two regions by the EMI critical curve. Above the EMI curve, the electromechanical instability will take place by the electric breakdown. While below the EMI curve, the folded dielectric elastomer actuator is in a stable state.

### 3.3 Loss of tension of folded dielectric elastomer actuator

As shown in Figure 8, loss of tension can cause the folded dielectric elastomer actuator to buckle out of the plane.

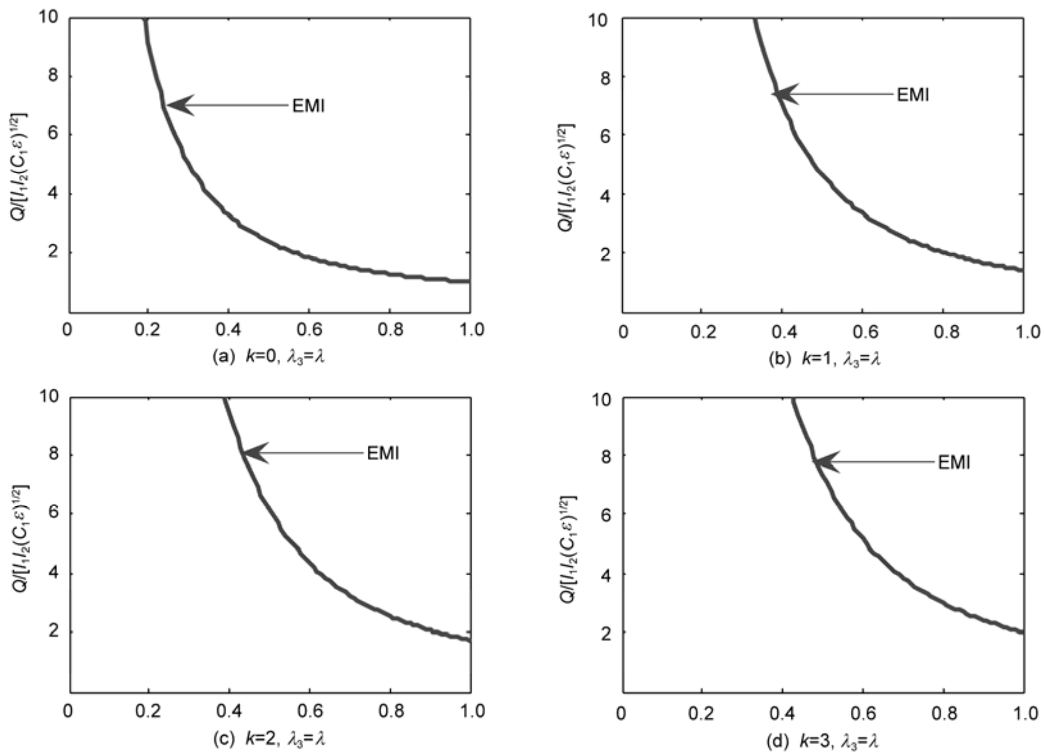


**Figure 7** Electromechanical instability of folded dielectric elastomer actuator.

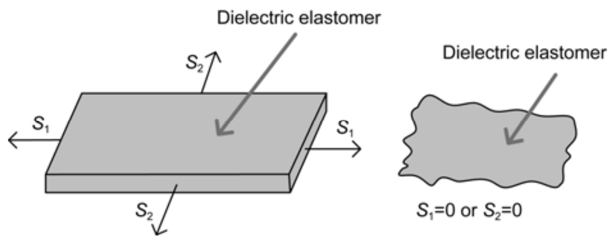


**Figure 8** Loss of tension mode of dielectric elastomers.

Therefore the dielectric elastomer will no longer work as an actuator.

The nominal stress of the actuator is defined as $s = \partial H(\lambda_3, Q)/\partial\lambda_3$. Insert it into eq. (2):

$$\frac{s}{C_1} = (\lambda_3 - \lambda_3^{-2}) + k(1 - \lambda_3^{-3}) + \left(\frac{Q}{\sqrt{\mu C_1} l_1 l_2}\right)^2 \lambda_3. \tag{14}$$

Let $s = 0$

$$\frac{Q}{\sqrt{\mu C_1} l_1 l_2} = \sqrt{(\lambda_3^{-3} - 1) + k(\lambda_3^{-4} - \lambda_3^{-1})}. \tag{15}$$

The critical condition for loss of tension of folded dielectric elastomer actuator, $s = 0$ is plotted in Figure 9. Similar to the EMI curve, when the state of folded dielectric elastomer actuator is above the curve, loss of tension will cause the dielectric elastomer actuator to buckle. Below the curve is the stable area of the actuator.

### 3.4 Rupture of folded dielectric elastomer actuator

The stretch ratio of dielectric elastomer material in the planar direction is in the range of $\lambda_1 \leqslant 5$, $\lambda_2 \leqslant 5$ [14]. As shown in Figure 10, when the stretch ratio of dielectric elastomer exceeds the critical condition, the rupture will cause the failure of dielectric elastomer. For the folded dielectric elastomer actuator, let $\lambda_1^C = \lambda_2^C = 5$, due to incompressibility the stretch in the direction of thickness is given by $\lambda_3^C = \dfrac{1}{25}$.

### 3.5 Allowable area of folded dielectric elastomer actuator

All the failure modes above are plotted in Figure 11. From the figure we can see that the shaded region is the allowable area of the folded dielectric elastomer actuator. The allowable area depends on the critical condition of various failure modes of the actuator. If new failure mode adds to the diagram, the allowable area may decrease.

## 4 Conclusions

In this paper we established the free energy function of

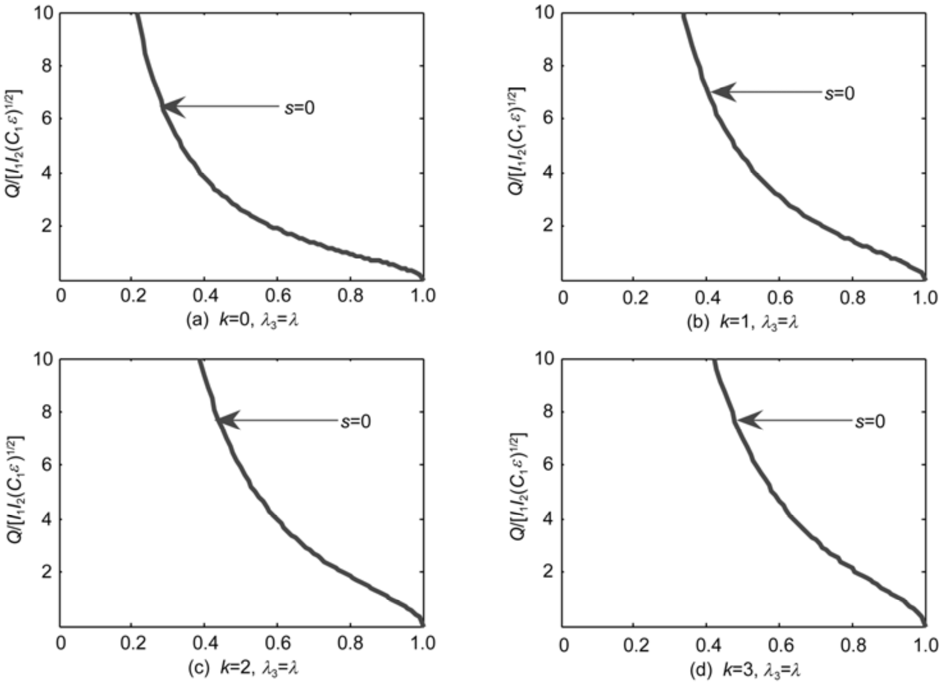


**Figure 9** Loss of tension of folded dielectric elastomer actuator.

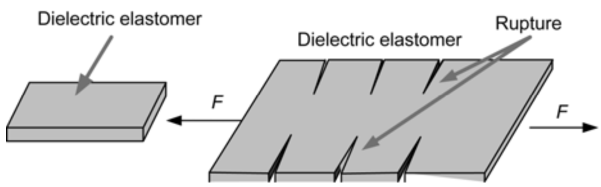


**Figure 10** Rupture mode of dielectric elastomers.

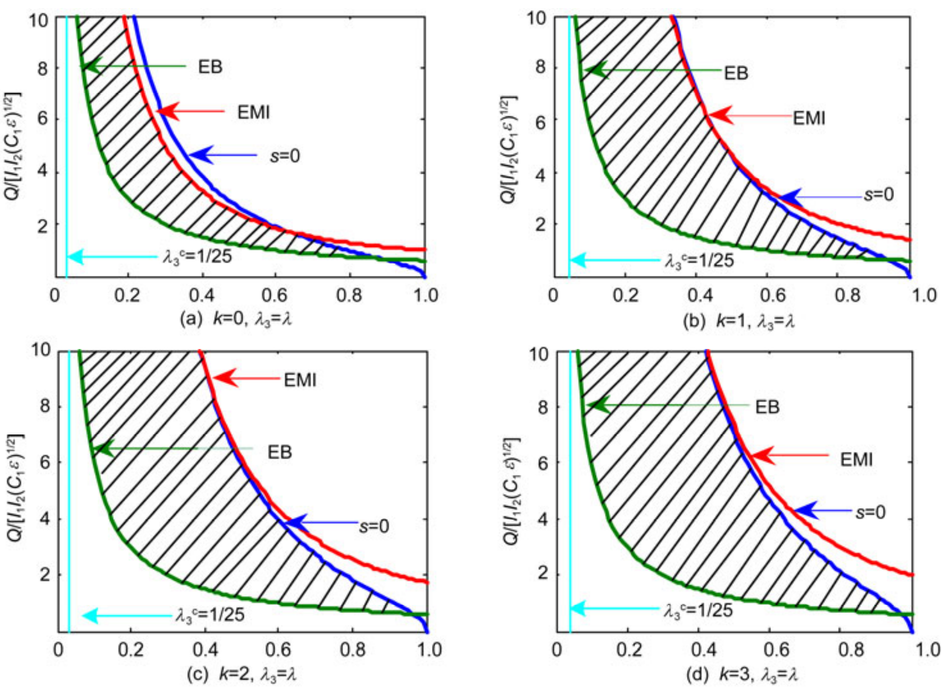


**Figure 11** (Color online) Allowable area of folded dielectric elastomer actuator.

folded dielectric elastomer actuator, analyzed the effect of mechanical force and electric force in thickness direction on the actuating performance of the folded dielectric elastomer actuator, and derived the controlling equations of typical failure models, including loss of tension, rupture by stretch, zero electric field condition, electrical breakdown, and electromechanical instability. We further described the allowable areas of folded dielectric elastomer actuators. We think these results can be used to facilitate the design and manufacture of folded dielectric elastomer actuators.

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