Static stability analysis of dielectric elastomer

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ABSTRACT

Dielectric elastomers (DEs) are compliant electroactive polymers with high energy density and rapid response, making them attractive for soft actuators. Their operational reliability, however, is limited by electromechanical instability (EMI). This study employs the Kelvin–Voigt Generalized Maxwell (KV-GM) model to evaluate steady-state stability under uniaxial, equibiaxial, and non-equibiaxial pre-stretch conditions. The results demonstrate that pre-stretch configuration strongly affects critical voltage and deformation capacity, and that appropriate pre-stretch can suppress EMI and improve the stable operating range of DE actuators.

Keywords: Dielectric elastomers; Static stability; Soft robot.

1. INTRODUCTION

Dielectric elastomers (DEs) are a prominent class of electroactive polymers for soft robotic systems because they combine high energy density, low elastic modulus, rapid response, and large deformation. Structurally, a DE membrane coated with compliant electrodes behaves as a deformable capacitor: an applied voltage generates Maxwell stress, causing thickness contraction and in-plane expansion [1]. These characteristics have enabled applications in artificial muscles [2], energy harvesting [3], biomimetic robots [4], and tunable optical devices [5].

Reliable operation, however, is limited by electromechanical instability (EMI). As the membrane thins under voltage, the electric field increases and produces further thinning, creating a positive-feedback process that may culminate in pull-in, electrical breakdown, or material failure [6-8]. Mechanical pre-stretch is therefore widely used to modify the nonlinear stress–strain response and expand the stable operating range [9, 10]. The resulting stability depends strongly on the pre-stretch magnitude and configuration, as predicted using Neo-Hookean, Ogden, and related constitutive models [11, 12].

Viscoelastic creep and hysteresis further complicate the response because deformation depends on loading time, rate, and voltage frequency [13-17]. Nonlinear rheological models have consequently been developed to characterize the allowable working area of DE actuators [18]. Nevertheless, a concise comparison of zero, uniaxial, unequal-biaxial, and equibiaxial pre-stretch within a consistent equilibrium framework remains useful for actuator design.

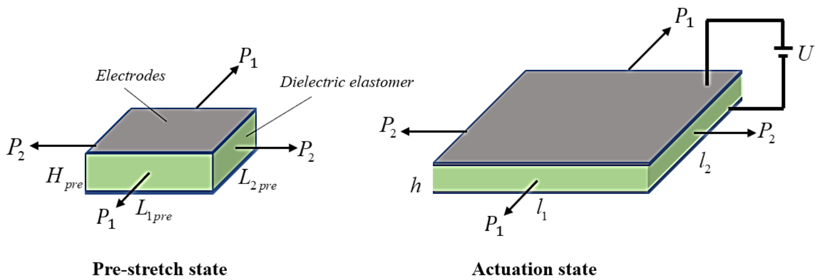


Figure 1. *Deformation mechanism of the dielectric elastomer.*

In this study, the Kelvin–Voigt–Generalized Maxwell (KV-GM) model coupled with Gent hyperelasticity is adopted from the validated formulation in [19]. For static stability analysis, transient viscoelastic contributions are omitted after full relaxation, while the equilibrium elastic response and strain-stiffening effect are retained. The voltage–stretch relationship and critical instability state are evaluated under the four pre-stretch configurations. The results clarify how directional pre-stretch influences critical voltage and deformation capacity and provide a theoretical basis for selecting stable, high-performance DE actuators, including cylindrical and tubular configurations.

2. CONSTITUTIVE MODELING OF DIELECTRIC ELASTOMERS

The deformation states of the dielectric elastomer membrane are illustrated in Figure 1. In the undeformed state, the membrane is coated with compliant electrodes whose thickness is neglected; its initial thickness and in-plane dimensions are denoted by H , L_1, and L_2, respectively. Following mechanical pre-stretch, an applied voltage generates opposite electrode charges and Maxwell stress, producing thickness contraction and in-plane expansion. The membrane is therefore modeled as a deformable capacitor with coupled electrical and large-deformation responses. This study adopts the Kelvin–Voigt Generalized Maxwell (KV-GM) framework validated in [19], while the detailed derivation is omitted. For static analysis, only the fully relaxed equilibrium state is considered. Consequently, viscoelastic contributions governing transient deformation are removed, whereas the equilibrium elastic and strain-stiffening responses are retained for subsequent stability analysis.

$$\frac{\sigma_{1\mathrm{p}}\lambda_1}{\lambda_{1\mathrm{p}}}+\frac{\varepsilon\lambda_1^2\lambda_2^2U^2}{H^2}=\frac{\mu_\alpha(\lambda_1^2-\lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{\mathrm{lima}}} \quad (1)$$

$$\frac{\sigma_{2\mathrm{p}}\lambda_2}{\lambda_{2\mathrm{p}}}+\frac{\varepsilon\lambda_1^2\lambda_2^2U^2}{H^2}=\frac{\mu_\alpha(\lambda_2^2-\lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{\mathrm{lima}}} \quad (2)$$

The principal stretches λ_1, λ_2 and stresses σ_1, σ_2 describe in-plane deformation and mechanical loading, while (E) and (D) characterize the electrostatic response. Gent parameters represent strain stiffening, whereas KV-GM parameters account for viscoelastic relaxation; detailed definitions are provided in [19]. The validated KV-GM framework is adopted without re-derivation. Its combination with Gent hyperelasticity provides a physically consistent basis for static electromechanical stability analysis under various pre-stretch conditions.

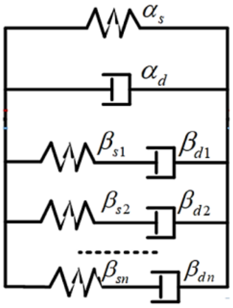


Figure 2. *The Kelvin-Voigt-generalized Maxwell (KV-GM) model [19].*

3. STATIC STABILITY OF DIELECTRIC ELASTOMERS

3.1 Static stability analysis under zero pre-stretch conditions

The electromechanical stability of an isotropic dielectric elastomer membrane is examined without mechanical pre-stretch. Accordingly, the in-plane pre-stresses vanish and the initial principal stretches equal unity. Under high-voltage excitation, both in-plane stretches remain equal. Viscoelastic effects are neglected, yielding the reduced constitutive relation used for static stability analysis.

$$\varepsilon E^2 = \frac{\mu_\alpha(\lambda^2 - \lambda^{-4})}{1-(2\lambda^2+\lambda^{-4}-3)/J_{\mathrm{lima}}} \tag{3}$$

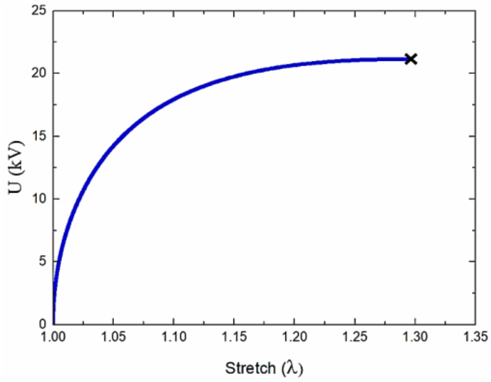


Figure 3. *Voltage-strain curves of dielectric elastomers without pre-stretching.*

Under zero pre-stretch conditions, numerical analysis predicts the onset of electromechanical instability at an applied voltage of 21.15 kV and a corresponding maximum stretch ratio of 1.29, equivalent to approximately 29% deformation. These results indicate premature instability and motivate further evaluation of uniaxial and biaxial pre-stretch configurations.

3.2. Electromechanical stability analysis of dielectric elastomers under uniaxial pre-stretch conditions

Uniaxial pre-stretch is applied along one in-plane direction, while the orthogonal direction remains stress-free. Assuming ideal incompressibility and taking the first direction as transverse to the applied pre-stretch, the principal stretches and stress satisfy $\lambda_{1p} = \lambda_{3p} = \lambda_{2p}^{-1/2}, \sigma_{1p} = 0$. Neglecting viscoelasticity, the voltage–strain response is determined from the resulting equilibrium constitutive equations.

$$\varepsilon E^2 = \frac{\mu_\alpha(\lambda_1^2 - \lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{\mathrm{lima}}} \tag{4}$$

$$\frac{\sigma_{2p}\lambda_2}{\lambda_{2p}} + \varepsilon E^2 = \frac{\mu_\alpha(\lambda_2^2 - \lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{\mathrm{lima}}} \tag{5}$$

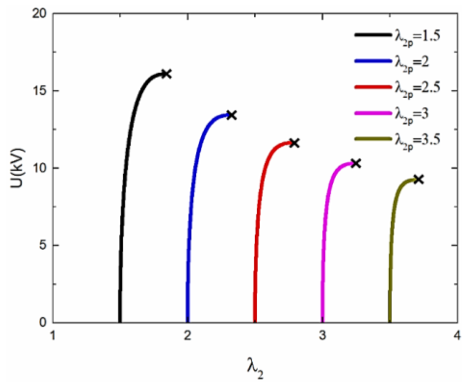


Figure 4. *Electromechanical stability of dielectric elastomers under different uniaxial pre-stretching conditions.*

Solutions of Equations (4) and (5) under varying uniaxial pre-stretch are presented in Figure 4, with black crosses denoting critical instability states. Increasing pre-stretch reduces the critical instability voltage because membrane thinning intensifies the electric field. Consequently, higher pre-stretch causes earlier electromechanical instability under the investigated conditions.

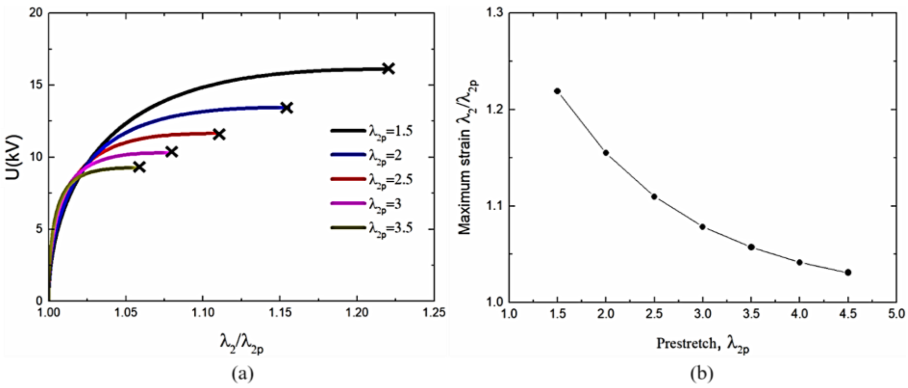


Figure 5. *Electromechanical stability of the dielectric elastomer under uniaxial conditions (a) Voltage-strain curve (b) maximum strain.*

The normalized strain λ_2 / λ_{2p} is used to characterize instability in the second direction. Figure 5 shows that increasing uniaxial pre-stretch reduces the critical voltage and maximum critical strain. Compared with zero pre-stretch, the constrained non-pre-stretched direction limits deformation capacity and increases susceptibility to electromechanical instability under high-voltage excitation.

3.3. Electromechanical stability analysis of dielectric elastomers under equibiaxial/unequal biaxial pre-stretch conditions

This study considers dielectric elastomer materials subjected to pre-stretching in both in-plane directions, with each direction characterized by a different pre-stretch value, thereby forming an unequal biaxial pre-stretch condition. Based on the established constitutive equations for dielectric elastomer materials, the material response and the relationship between excitation voltage and actuation strain can be described by the following expressions:

$$\frac{\sigma_{1p}\lambda_1}{\lambda_{1p}} + \frac{\varepsilon\lambda_1^2\lambda_2^2U^2}{H^2} = \frac{\mu_\alpha(\lambda_1^2 - \lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{lima}} \tag{6}$$

$$\frac{\sigma_{2p}\lambda_2}{\lambda_{2p}} + \frac{\varepsilon\lambda_1^2\lambda_2^2U^2}{H^2} = \frac{\mu_\alpha(\lambda_2^2 - \lambda_1^{-2}\lambda_2^{-2})}{1-(\lambda_1^2+\lambda_2^2+\lambda_1^{-2}\lambda_2^{-2}-3)/J_{lima}} \tag{7}$$

To objectively analyze the response of the dielectric elastomer under various unequal biaxial pre-stretch conditions, the pre-stretch ratio in the first direction was fixed at $\lambda_{1p} = 3$ during the solution of the governing equations. By varying the pre-stretch ratio in the second direction, the resulting excitation voltage-strain relationship is illustrated in Figure 6.

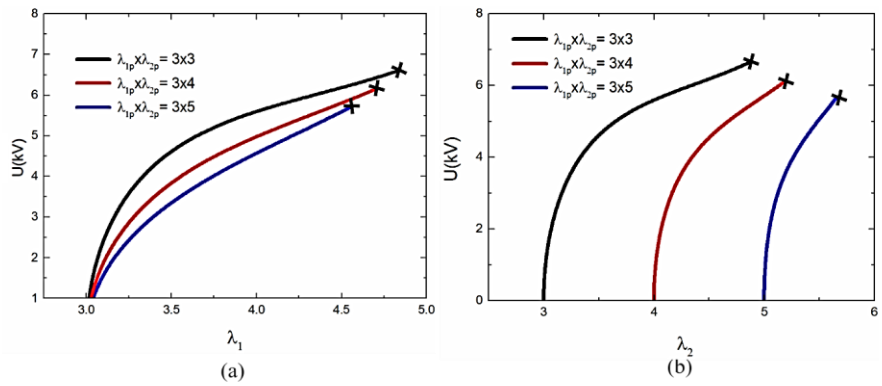
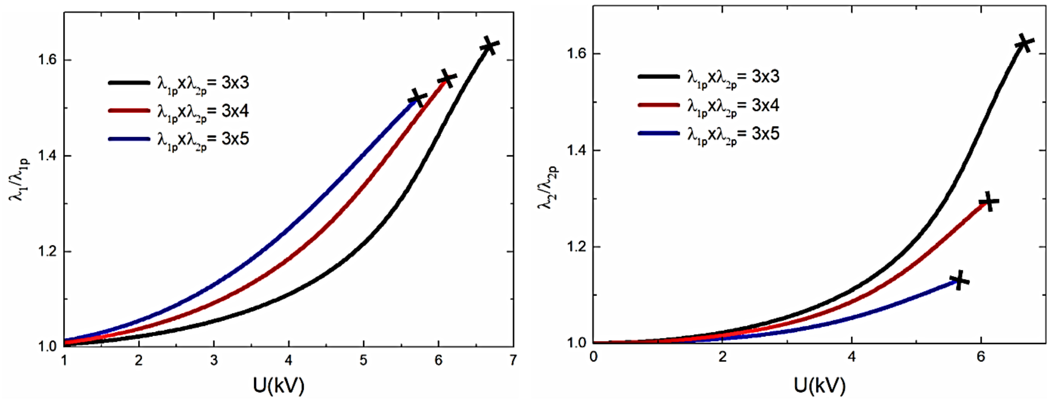


Figure 6. *Electromechanical stability of dielectric elastomer materials under unequal axial pre-stretching (a) first in-plane direction (b) second in-plane direction.*

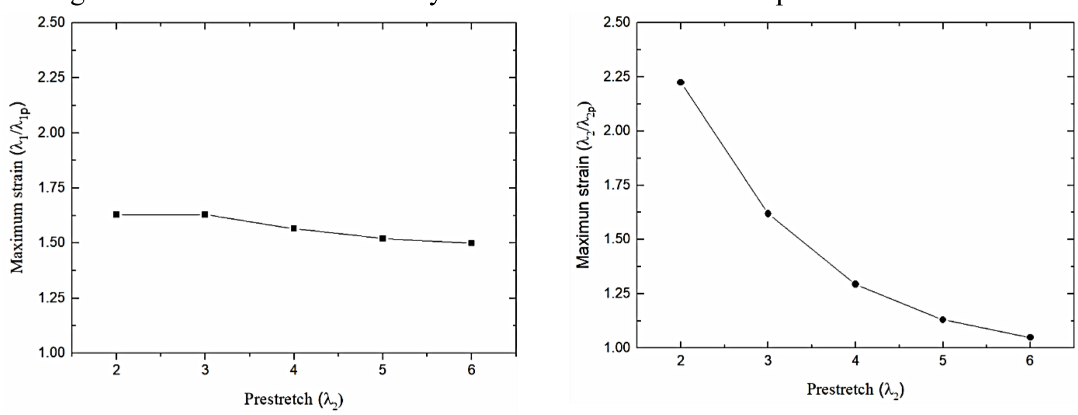
Equations (6) and () were solved to evaluate unequal biaxial pre-stretch, for which deformation in both in-plane directions was considered. The first-direction pre-stretch was fixed at $\lambda_{1p} = 3$, while λ_{2p} was varied. Figure 6 shows that increasing λ_{2p} enhances first-direction deformation. At the same excitation voltage, the corresponding deformation increases with pre-stretch in the orthogonal direction. At 4 kV, $\lambda_{2p} = 3, 4, 5$ produces $\lambda_1 = 3.3,\ 3.5,\ 3.7$, respectively. This response is attributed to reduced internal stress. Figure 7(a) indicates minor variations in the critical instability points. The maximum occurs at $\lambda_{2p} = 3$; at 6.5 kV, the strain in the first direction can reach 1.62 before instability occurs.



(a) (b)

Figure 7. *Voltage-strain rate curves of dielectric elastomers under different unequal pre-stretching conditions (a) first in-plane direction (b) second in-plane direction.*

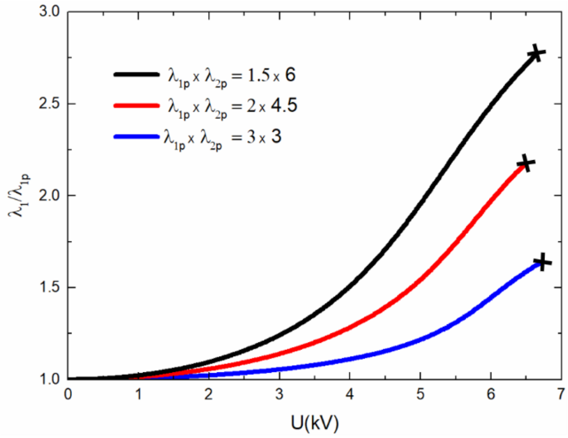
Figures 7(b) and 8(b) characterize the second-direction response under unequal biaxial pre-stretch. Increasing the pre-stretch ratio reduces the critical instability voltage because membrane thinning intensifies the electric field. For a fixed minimum equibiaxial pre-stretch, increasing the stretch in one direction also reduces its critical strain rate as the material approaches the strain-hardening regime and becomes stiffer. Consequently, the second-direction deformation capacity decreases rapidly: at $\lambda_{2p} = 2$, the critical strain rate is 125%, whereas at $\lambda_{2p} = 6$, it decreases to 4%. These results demonstrate the combined effects of electric-field amplification and strain hardening on electromechanical stability under increased directional pre-stretch.



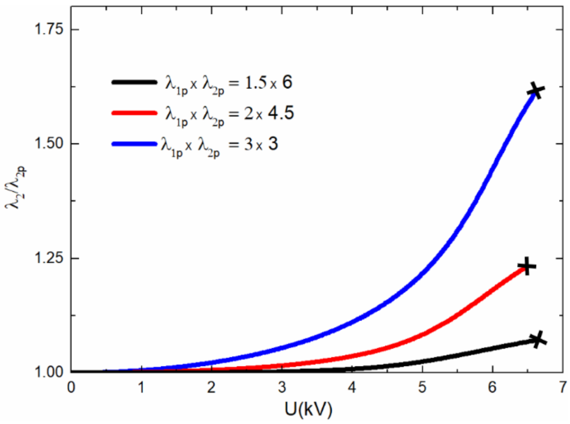
(a) (b)

Figure 8. *Maximum strain rates of dielectric elastomers in two plane directions under different un-pre-stretching conditions (a) first in-plane direction (b) second in-plane direction.*

For an ideal isotropic dielectric elastomer, non-equibiaxial pre-stretch modes with a constant product $\lambda_{1p} \times \lambda_{2p}$ produce identical relaxed thicknesses and initial electric fields. Three cases, $\lambda_{1p} \times \lambda_{2p} = 1.5 \times 6,\ 2 \times 4.5,\ 3 \times 3$, were examined. Figure 9 shows nearly identical critical instability points, confirming that membrane thickness governs instability. Figure 9(a) shows decreasing first-direction deformation with increasing corresponding pre-stretch, whereas Figure 9(b) shows the opposite response. For $\lambda_{1p} \times \lambda_{2p} = 1.5 \times 6$, the highly stretched second direction reaches only 6% deformation, whereas the first direction, with $\lambda_{1p} = 1.5$, achieves 175% before instability. Thus, coupled pre-stretch can optimize asymmetric actuators, including cylindrical, tubular, and rhombic configurations.



(a)



(b)

Figure 9. *Voltage-strain rate curves in two plane directions of the dielectric elastomer under unequal axial pre-stretching (a) first in-plane direction (b) second in-plane direction.*

3.4. Electromechanical stability analysis of dielectric elastomers under equibiaxial pre-stretch

Equibiaxial pre-stretch of dielectric elastomers is a specialized pre-stretching process where identical pre-stretch ratios are applied in both in-plane directions. The applied pre-stress in these directions is also inhibitory. In the current constitutive model, we consider $\lambda_{1p} = \lambda_{2p} = \lambda_p$ and pre-stress $\sigma_{1p} = \sigma_{2p} = \sigma_p$. After pre-processing, the film is brought to a fully relaxed state. Assuming the material is ideally isotropic, the resulting deformations under voltage excitation in both directions are $\lambda_1 = \lambda_2 = \lambda$. By substituting these boundary conditions into the constitutive model of the dielectric elastomer, the governing equations for this specific case can be derived.

$$\frac{\sigma_p \lambda}{\lambda_p} + \frac{\varepsilon \lambda^4 U^2}{H^2} = \frac{\mu_\alpha(\lambda^2 - \lambda^{-4})}{1-(2\lambda^2 + \lambda^{-4} - 3)/J_{\mathrm{lim}\alpha}} \tag{8}$$

By solving the governing equation, the excitation voltage-strain relationship is obtained. In Figure 10, black cross points represent EMI critical points, and E_b denotes the dielectric breakdown threshold (set at 250 MV/m). To minimize strain-hardening effects, equibiaxial stretch ratios below 5 are prioritized. Results show that equibiaxial pre-stretch significantly enhances deformability, though EMI remains unavoidable.

As shown in Figure 11, as the pre-stretch ratio increases, the instability voltage initially decreases until $\lambda_p = 3.5$ before rising. Similarly, the maximum critical strain increases until $\lambda_p = 2.5$ and then decays rapidly. This is because low pre-stretch ratios soften the material by reducing internal stress, whereas higher ratios trigger strain-hardening, increasing hardness and limiting deformation.

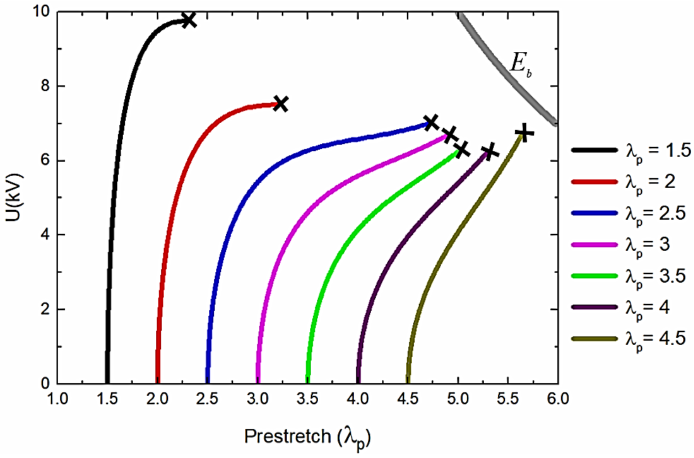
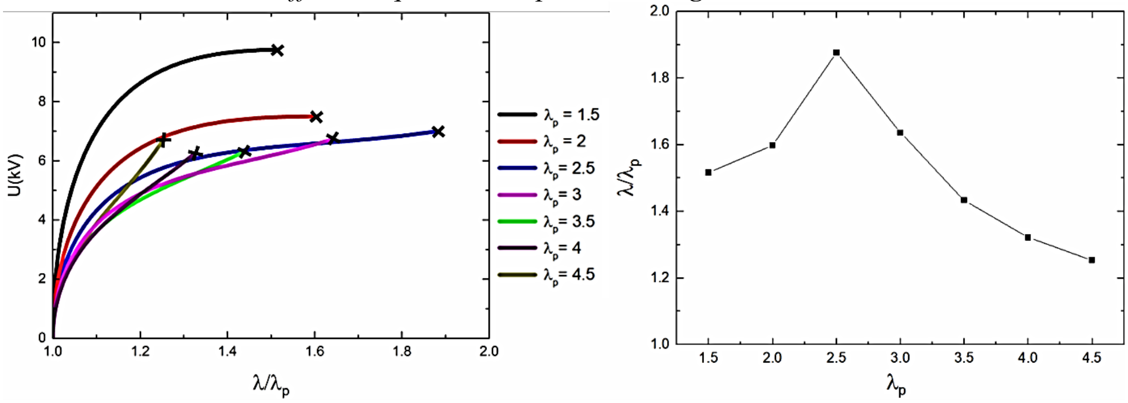


Figure 10. *Voltage-strain curves of the dielectric elastomer under different equal biaxial pre-stretching conditions.*



(a) (b)

Figure 11. *Electromechanical stability of the dielectric elastomer under equal biaxial pre-stretching (a) Voltage-strain rate curve (b) maximum strain rate.*

4. CONCLUSIONS

The electromechanical stability of dielectric elastomers was quantitatively evaluated under zero, uniaxial, unequal-biaxial, and equibiaxial pre-stretch conditions. Without pre-stretch, instability occurs at approximately 21.15 kV, with a maximum stretch ratio of 1.29. Increasing uniaxial pre-stretch reduces the critical voltage and achievable strain because of membrane thinning and transverse constraint. Unequal-biaxial pre-stretch enhances orthogonal deformation, yielding a maximum stretch ratio of approximately (1.62) before instability. Under equibiaxial pre-stretch, deformation initially increases and subsequently decreases with increasing pre-stretch, indicating an optimal range. Overall, the pre-stretch configuration governs electromechanical stability and can be selected to maximize stable actuation and expand the safe operating range of dielectric elastomer actuators.

REFERENCES

[1]. Zhigang Suo, Xuanhe Zhao and William H. Greene, "*A nonlinear field theory of deformable dielectrics*", Journal of the Mechanics and Physics of Solids, Vol. 56, No. 2, pp. 467–486, (2008).

[2]. Xiaotian Shi et al., "*Semiseparated biphasic bicontinuous dielectric elastomer for high-performance artificial muscle*", Science, Vol. 390, No. 6777, pp. 1044–1049, (2025).
[3]. Giacomo Moretti et al., "*A review of dielectric elastomer generator systems*", Advanced Intelligent Systems, Vol. 2, No. 10, p. 2000125, (2020).
[4]. Yanju Liu et al., "*An investigation on electromechanical stability of dielectric elastomers undergoing large deformation*", Smart Materials and Structures, Vol. 18, No. 9, p. 095040, (2009).
[5]. Zhuoqun Hu et al., "*Tuneable Lenses Driven by Dielectric Elastomers: Principles, Structures, Applications, and Challenges*", Applied Sciences, Vol. 15, No. 12, p. 6926, (2025).
[6]. Chen Hualing et al., "*Research on Electroactive Polymer Materials and Their Applications in Actuators*", Journal of Mechanical Engineering, Vol. 49, No. 6, pp. 10–21, (2013).
[7]. Ron Pelrine et al., "*High-speed electrically actuated elastomers with strain greater than 100%*", Science, Vol. 287, No. 5454, pp. 836–839, (2000).
[8]. Michael Wissler and Edoardo Mazza, "*Modeling of a pre-strained circular actuator made of dielectric elastomers*", Sensors and Actuators A: Physical, Vol. 120, No. 1, pp. 184–192, (2005).
[9]. Xuanhe Zhao and Zhigang Suo, "*Method to analyze programmable deformation of dielectric elastomer layers*", Applied Physics Letters, Vol. 93, No. 25, (2008).
[10]. R. Huang et al., "*Electromechanical phase transition in dielectric elastomers*", Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, Vol. 468, pp. 1014–1040, (2012).
[11]. J. S. Plante and S. Dubowsky, "*Large-scale failure modes of dielectric elastomer actuators*", International Journal of Solids and Structures, Vol. 43, No. 25, pp. 7727–7751, (2006).
[12]. E. M. Mockensturm and N. C. Goulbourne, "*Dynamic response of dielectric elastomers*", International Journal of Non-Linear Mechanics, Vol. 41, No. 3, pp. 388–395, (2006).
[13]. J. X. Zhou, W. Hong and X. H. Zhao, "*Propagation of instability in dielectric elastomer*", International Journal of Solids and Structures, Vol. 45, No. 13, pp. 3739–3750, (2008).
[14]. J. Zhu, S. Cai and Z. G. Suo, "*Resonant behavior of a membrane of a dielectric elastomer*", International Journal of Solids and Structures, Vol. 47, No. 24, pp. 3254–3262, (2010).
[15]. Tuan Dung Nguyen et al., "*Solution for suppressing viscoelastic creep in cylindrical dielectric elastomer actuator*", Journal of Military Science and Technology, Vol. 101, pp. 148–154, (2025).
[16]. B. X. Xu, R. Mueller, A. Thesis et al., "*Dynamic analysis of dielectric elastomer actuators*", Applied Physics Letters, Vol. 100, p. 112903, (2012).
[17]. W. Kaal and S. Herold, "*Electroactive polymer actuators in dynamic applications*", IEEE/ASME Transactions on Mechatronics, Vol. 16, No. 1, pp. 24–32, (2011).
[18]. P. Dubois et al., "*Voltage control of the resonance frequency of dielectric electroactive polymer membranes*", Journal of Microelectromechanical Systems, Vol. 17, No. 5, pp. 1072–1081, (2008).
[19]. Tuan Dung Nguyen et al., "*Viscoelasticity modeling of dielectric elastomers by Kelvin Voigt-generalized Maxwell model*", Polymers, Vol. 13, No. 13, p. 2203, (2021).

TÓM TẮT

Phân tích ổn định tĩnh của vật liệu điện môi đàn hồi

Vật liệu điện môi đàn hồi (DEs) là các polyme kích thích điện mềm, có mật độ năng lượng cao và đáp ứng nhanh, nên phù hợp cho các cơ cấu chấp hành mềm. Tuy nhiên, độ tin cậy trong vận hành bị giới hạn bởi hiện tượng mất ổn định cơ điện (EMI). Nghiên cứu này sử dụng mô hình Kelvin–Voigt Generalized Maxwell (KV-GM) để đánh giá độ ổn định ở trạng thái xác lập dưới các điều kiện kéo giãn trước đơn trục, hai trục đều và hai trục không đều. Kết quả cho thấy cấu hình kéo giãn trước ảnh hưởng đáng kể đến điện áp tới hạn và khả năng biến dạng; việc lựa chọn cấu hình phù hợp có thể hạn chế EMI và mở rộng vùng làm việc ổn định của cơ cấu chấp hành DE.

Từ khoá: Điện môi đàn hồi; ổn định tĩnh; Robot mềm.