Giant voltage-induced deformation in dielectric elastomers

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Summary Large voltage-induced deformation has been a major challenge in the practical application of Dielectric elastomers (DEs). We model the actuation of DEs, study their loading path effect and introduce various methods to achieve giant deformation in dielectric elastomer. Giant voltage-induced deformation (area strain 1692%) is achieved with commonly used experimental setups. Varying the parameters in experiment changes the electromechanical behavior of the DE membrane.

ABSTRACT

Dielectric elastomers (DEs) are capable of large deformation by applying voltage. The deformation of dielectric elastomer is restricted by electromechanical instability (EMI) and electric breakdown. Large voltage-induced deformation has been a major challenge in the practical application of Dielectric elastomers. We study the loading path effect of dielectric elastomer and introduce various methods to achieve giant deformation in dielectric elastomer: Pre-stretch a dielectric elastomer to suppress the electromechanical instability; place a dielectric elastomer near the verge of snap-through instability, trigger the instability with voltage, and bend the snap-through path to avert electric breakdown. We demonstrate these principles of operation in experiments. Varying the parameters in experiment changes the voltage-deform behavior of the DE membrane. We use a computational model to analyze the actuation of DE and guide the experiment.

Introduction

Dielectric elastomers are being widely used as artificial muscles for diverse applications, including soft robotics, adaptive optics and energy harvesting [1]. Desirable attributes include large voltage-induced deformation, high energy density, fast response, quiet operation, light weight, and low cost. Figure 1 shows the mechanism of actuating dielectric elastomers.

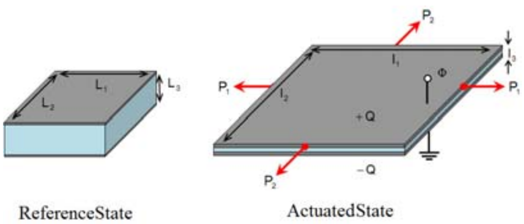

Figure 1. A membrane of a dielectric elastomer is sandwiched between two compliant electrodes. In the reference state, the membrane is subject to neither force nor voltage, and is undeformed. In the actuated state, the membrane is subjected to biaxial forces and voltage.

Voltage-induced deformation by suppressing EMI

For an ideal dielectric elastomer, the stress-stretch relations take the form [2]:

$$\sigma_1 + \varepsilon E^2 = \lambda_1 \frac{\partial W_{stretch}(\lambda_1, \lambda_2)}{\partial \lambda_1}, \quad (1)$$

$$\sigma_2 + \varepsilon E^2 = \lambda_2 \frac{\partial W_{stretch}(\lambda_1, \lambda_2)}{\partial \lambda_2}, \quad (2)$$

where $W_{\mathrm{stretch}}(\lambda_1, \lambda_2)$ is the free energy associated with the stretching of the elastomer. $W_{\mathrm{stretch}}(\lambda_1, \lambda_2)$ is determined by the mechanical property of DE material, which can be modified by material engineering. E is the true

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electric field on the DE membrane. During actuation, the relation between the true electric field, the stresses applied on the DE membrane with the stretch, $\sigma_1(\lambda_1,\lambda_2)$, $\sigma_2(\lambda_1,\lambda_2)$, $E(\lambda_1,\lambda_2)$ can be designed by certain loading path.

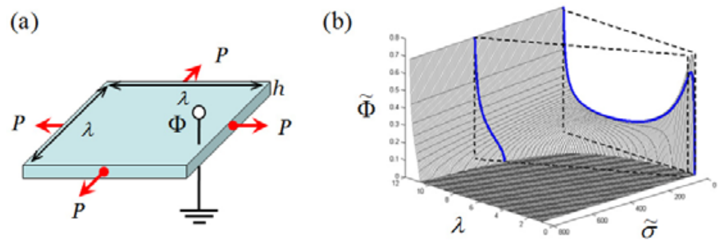

Figure 2. DE under equal biaxial tension: (a) Schematics, (b) states of equilibrium and loading path, dashed surface shows the different loading path , the blue curves are the intersections between loading paths and surface of states of equilibrium.

Different loading paths highly affect the electromechanical behavior of the DE membrane. Large voltage induced deformation has been investigated both by designing new material [3] and structures [4], [5]. We identify the mechanisms of large actuation strain in the reported experiments: Pre-stretch and certain stress-strain relation of the DE material suppress or eliminate the electromechanical instability. The voltage-stretch response of DE material is modified. DE membrane achieves large deformation without electric breakdown.

Giant voltage-induced deformation by harnessing EMI

Rather than causing failure, the instability can be a feature for large deformation. We have recently demonstrated a method to harness EMI instead of suppressing it to achieve large voltage-induced deformation. We place a dielectric elastomer in a state near the verge of snap-through instability, trigger the instability with a voltage, and bend the snap-through path to avert electric breakdown [6]. We use a computational model with the nonlinear theory of dielectric elastomer to demonstrate the mechanism of giant voltage-induced deformation.

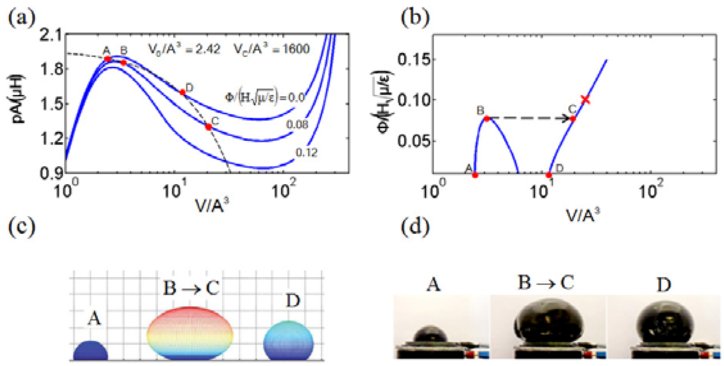

Figure 3. Numerical results for a membrane mounted on a chamber of volume . The membrane is pressurized to a balloon of initial volume . Simulation results [7]: (a) Pressure-volume curves of the membrane at several values of voltage. The dashed line is the pressure-volume curve of the air. (b) Voltage-volume curve. (c) simulated balloon shapes correspond to the states in (a),(b). Experimental results [6]: (d) balloon shapes correspond to the states in (a),(b).

CONCLUSIONS

The voltage-induced deformation of DE is restricted by electromechanical instability and electric breakdown. The instability often leads to electric breakdown. We can either suppress the EMI or harness it to achieve giant voltage-induced deformation. We demonstrate the loading path effect during DE actuation with commonly used experimental setups. The electromechanical behavior can be dramatically changed by varying the loading path during actuation.

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