ELECTROMECHANICAL TRANSITION IN A DIELECTRIC ELASTOMER: GIANT LINEAR DEFORMATION AND FAILURE MODES

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Summary An elastomeric membrane can be readily stretched to many times its initial area by mechanical forces. However, voltage-induced deformation may be limited by electromechanical instability, and thus it is difficult to achieve a large voltage-induced deformation. In this paper I will illustrate how a dielectric elastomer membrane survives or eliminates electromechanical instability, and achieves a giant linear deformation, which is important in applications of artificial muscles in soft robots. The membrane is first prestretched along the transverse direction, and then clamped by a rigid bar. Since the transverse stretch is fixed, the membrane can only be actuated along the vertical direction. The theory shows that the actuator may exhibit electromechanical transition and form wrinkles, which is essential in achieving a giant deformation. The experiments confirm the theoretical predictions. For VHB material, the maximum linear strain can be 260%. Different behavior and failure modes are also analyzed in the paper.

INTRODUCTION

An elastomeric membrane can be readily stretched to many times its initial area by mechanical forces, but inducing such a large deformation by voltage is difficult. An important discovery was made about a decade ago that voltage-induced deformation can be greatly enhanced by prestretch [1], which also increases the apparent electric breakdown field more than 10 times [2]. The discovery has led to hundreds of designs of muscle-like actuators, sensors and generators, with promising applications such as soft robots, artificial limbs, adaptive optics, Braille displays, and energy harvesting [3].
The discovery has also led to intense studies of the mechanics and physics of dielectric elastomers [4]. When a membrane of a dielectric elastomer is subject to voltage, the thickness reduces and the electric field increases. This positive feedback can drastically amplify the electric field and thin down the elastomer, leading to electromechanical instability, and ultimately to electric breakdown. In this paper I will illustrate how a dielectric elastomer membrane survives or eliminates electromechanical instability, and achieves a giant linear deformation of actuation.

A CLAMPED DIELECTRIC ELASTOMER MEMBRANE

Fig. 1 illustrates the setup. A membrane of a dielectric elastomer (Fig. 1(a)) is pulled horizontally, fixed to rigid clamps, and pulled vertically by a constant mechanical force P (Fig. 1(b)). The rigid clamps and the mechanical force prepare the membrane in a state of prestretches, $\{\lambda_{1p}, \lambda_{2p}\}$. Subsequently, voltage Φ is applied to actuate the membrane to stretches $\{\lambda_1, \lambda_2\}$ (Fig. 1(c)). The voltage-induced linear stretch is defined by λ_1/λ_{1p}. Large voltage-induced deformations were previously observed in membranes mounted on rigid rings [1]. These setups do not allow direct force coupling to the surroundings, precluding their use as actuators. The clamped membrane allows direct force coupling and linear actuation (which is important in applications of artificial muscles), and is still simple enough for analytical treatment.

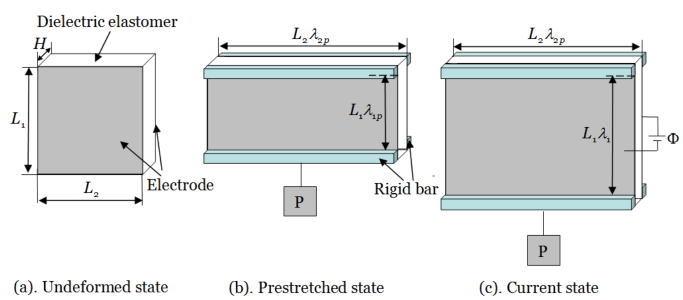

Fig. 1 A clamped dielectric elastomer membrane

Samples were made with VHB4905 (500µm thickness) as the base dielectric elastomer. A free-standing sample has a length of 10 mm ($L_1\lambda_{1p}$) in the direction of actuation and a width of 100 mm ($L_2\lambda_{2p}$) in the transverse direction, as shown in Fig. 2(a). The high aspect ratio ensures that the deformation takes place under clamped conditions, i.e. the prestretch λ_{2p} will not change during subsequent deformations. The free edges were reinforced with narrow strips of thin elastomer (VHB9460, 50µm thickness) to avoid edge cracks propagating into the active region. This narrows the active region to about 95 mm. Stretchable electrodes were made from carbon grease.

EXPERIMENTAL OBSERVATION

Membranes of VHB4905 with prestretches $\{\lambda_{1p}, \lambda_{2p}\}$ are actuated by using a voltage amplifier at a ramp rate of 5 V/s. The slow ramp rate minimizes the effect of viscoelasticity. The membrane is usually smooth in the prestretched state (Fig. 2(a)). Since the membrane is prestretched, the edge is curved. Then the membrane is actuated along the vertical direction, and remains smooth when the voltage is below a critical value (Fig. 2(b)). Since the membrane, subject to a voltage, wants to expand in both vertical and transverse directions, the tensile stress along the transverse direction

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decreases as the voltage increases. As a result, the curvature of the edge decreases. When the voltage exceeds the critical value, the membrane suffers loss of tension and forms wrinkles (Fig. 2(c)). As we can see, the edge becomes straight.

Figs. 3(a)-3(d) show measured voltage-stretch curves for the membranes prepared in several specific states of prestretches $\{\lambda_{1p}, \lambda_{2p}\}$. For the membrane of prestretches {2,5} (Fig. 3(d)), the vertical stretch attains λ_1=7.2 before failure, corresponding to voltage-induced stretch of λ_1/λ_{1p}, =3.6. All curves show an initial portion with negative curvatures. Some membranes fail on the initial portion (e.g, {2,2}, Fig. 3(a)). In many other cases, however, the stretches increase greatly within small changes in voltage. For example, for the membrane of prestretches {2,4} (Fig. 3(d)), the curve kinks at 2800 V, after which the curve is almost flat from stretch 4.6 to 5.5. In some cases, the jump is cut short by failure (e.g., {2,3}, Fig. 3(b)).

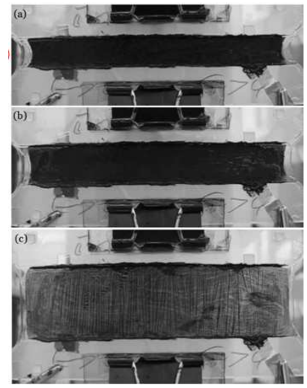

Fig.2 Actuation of a clamped dielectric elastomer

THEORETICAL ANALYSIS

We next interpret the observed behavior by theoretical calculations. The elastomer is taken to be incompressible. To capture the strain-stiffening behaviour of the elastomer, we use the Gent material model. Before loss of tension (Fig. 2(b)), λ_2 is prescribed by the prestretch λ_{2p}. After loss of tension (Fig. 2(c)), the stress in transverse direction vanishes. In Figs. 3(e)-(h), the critical states at loss of tension are marked with black dots, while the modes of failure are marked by red dots.

In the first mode of failure, Fig. 3(e), a membrane fails prior to the global loss of tension. While the clamps hold horizontal stretch fixed at the top and bottom of the membrane, the clamps do not suppress inhomogeneous deformation in the interior of the membrane. Local instability occurs at a point in the membrane where the Hessian becomes singular. Following the method of [5], we calculate the determinant of the Hessian, and predict the state of local instability by setting the determinant to zero. Experiment shows that the membranes of small prestretches fail without forming wrinkles (Fig. 3(a)).

In the second mode of failure, Fig. 3(f), a membrane survives the local instability, suffers the loss of tension, followed by the snap-through instability. The voltage-stretch curve is nearly flat at the failure. Experiment shows that the membrane forms wrinkles when the voltage exceeds a critical value, and fails during a sudden dramatic deformation (Fig. 3(b)).

In the third mode of failure, Fig. 3(g), a membrane survives the local instability, the global loss of tension and the snap-through instability; the membrane only fails after it snaps and reaches the stable state. This theoretical prediction is supported by experimental observations of wrinkles and sudden dramatic deformation (Fig. 3(c)).

In the fourth mode of failure, Fig. 3(h), the voltage-stretch starts with a negative curvature when the horizontal stretch is constrained by the clamps, and switches to a positive curvature upon loss of tension. The entire voltage-stretch curve, however, is monotonic. This theoretical prediction is supported by experimental observations of wrinkles and monotonic voltage-stretch curves (Fig. 3(d)).

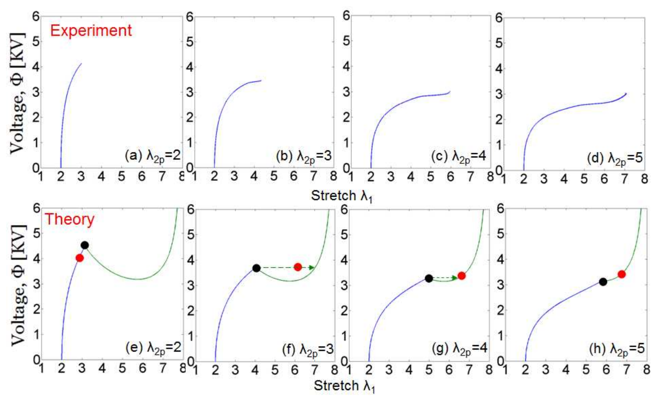

Fig.3 Comparison between theory and experiment

CONCLUSIONS

We have shown that a relatively simple setup—a clamped membrane of dielectric elastomer—displays remarkably rich interplay of nonlinear processes, including local instability, wrinkling, and snap-through instability. Giant voltage-induced stretch of 3.6 is achieved. Snap-through instability itself does not always lead to failure; under certain conditions a membrane can survive the snap and reach a stable state. It is hoped that this understanding of the nonlinear processes and failure modes will inform large-deformation applications such as soft robots and energy harvesting.

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