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Giant voltage-induced deformation in dielectric elastomers near the verge of snap-through instability

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ABSTRACT

Dielectric elastomers are capable of large voltage-induced deformation, but achieving such large deformation in practice has been a major challenge due to electromechanical instability and electric breakdown. The complex nonlinear behavior suggests an important opportunity: electromechanical instability can be harnessed to achieve giant voltage-induced deformation. We introduce the following principle of operation: 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 this principle of operation with a commonly used experimental setup—a dielectric membrane mounted on a chamber of air. The behavior of the membrane can be changed dramatically by varying parameters such as the initial pressure in the chamber, the volume of the chamber, and the prestretch of the membrane. We use a computational model to analyze inhomogeneous deformation and map out bifurcation diagrams to guide the experiment. With suitable values of the parameters, we obtain giant voltage-induced expansion of area by 1692%, far beyond the largest value reported in the literature.

1. Introduction

Dielectric elastomers are being developed as artificial muscles for diverse applications, including soft machines, adaptive optics, haptic surfaces, and energy harvesting (Brochu and Pei, 2010; Carpi et al., 2010; Kornbluh et al., 2012). Desirable attributes include large voltage-induced deformation, high energy density, fast response, quiet operation, light weight, and low cost. In such an artificial muscle, a membrane of a dielectric elastomer is sandwiched between two compliant electrodes typically made of carbon grease (Fig. 1). When the electrodes are subject to a voltage, electrons flow through the external circuit from one electrode to the other. Charges of opposite signs on the two electrodes attract each other, so that the membrane reduces its thickness and expands its area. The dielectric elastomer enables electromechanical transduction: the voltage can deform the membrane, and the deformation changes the capacitance of the membrane.

Large voltage-induced deformation gives dielectric elastomers a competitive edge over other active materials. Reported voltage-induced strains have increased from a linear strain of 4% with polyurethane (Ma et al., 1994), to about 30% with

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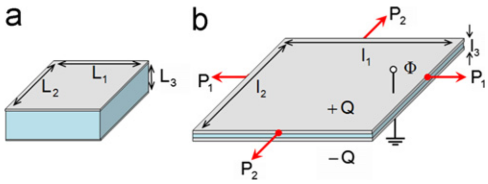

Fig. 1. A membrane of a dielectric elastomer is sandwiched between two compliant electrodes. (a) In the reference state, the membrane is subject to neither force nor voltage, and is undeformed. (b) In the activated state, the membrane is subjected to biaxial forces, and the two electrodes are subject to voltage.

silicone (Pelrine et al., 1998), and to over 100% with a prestretched acrylic elastomer (Pelrine et al., 2000). Reliably inducing large deformation by voltage, however, has remained a major challenge in practice. Deformable elastomers are susceptible to electromechanical instability (Stark and Garton, 1955). As the voltage is ramped up, the membrane thins down and the electric field amplifies, often leading to pull-in instability, followed by electric breakdown (Zhao and Suo, 2007; Norris, 2008). On the other hand, when charges are sprayed on a dielectric membrane with no electrodes, electromechanical instability is removed and extremely large deformation is achievable (Keplinger et al., 2010; Li et al., 2011). The lack of electrodes in this setup, however, limits its scope of application.

Electromechanical instability is affected by both material models and boundary conditions (e.g., Zhao et al., 2007; Diaz-Calleja et al., 2008; Leng et al., 2009; De Tommasi et al., 2010; Xu et al., 2010; Bertoldi and Gei, 2011; Rudykh, et al., 2012; Yong et al., 2012). Consequently, achievable voltage-induced deformation is not an intrinsic property of a material, but is a property of a structure that can be markedly affected by boundary conditions. For example, voltage-induced deformation is enhanced when a membrane is prestretched and constrained by a rigid ring (Pelrine et al., 2000; Wissler and Mazza, 2005a), and is further enhanced when the membrane is subject to equal-biaxial dead load (Koh et al., 2011b; Huang et al., 2012). By contrast, voltage-induced deformation is reduced when the membrane is subject to uniaxial dead load (Huang and Suo, 2012; Lu et al., 2012). Furthermore, Kollosche et al. (2012) show that a relatively simple setup—a membrane prestretched with two rigid clamps and a dead load—displays remarkably complex interplay of nonlinear processes, including local instability, wrinkling, and snap-through instability. The setup gives drastically different values of voltage-induced deformation, depending on the state of prestretches.

The complex nonlinear behavior suggests an important opportunity: electromechanical instability may be harnessed to achieve giant voltage-induced deformation (Mockensturm and Goulbourne, 2006; Goulbourne et al., 2007; Zhao and Suo, 2010). Rather than causing failure, the instability can be a feature. As an example, we have recently introduced the following principle of operation: 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 (Keplinger et al., 2012). We have demonstrated the principle of operation with a dielectric membrane mounted on a chamber (Fig. 2)—a setup commonly used to study electromechanical coupling of dielectric elastomers (e.g., Fox and Goulbourne, 2008; Rosset et al., 2009). When air is pumped into the chamber through a valve, the membrane is inflated into a balloon. The valve is subsequently closed to fix the amount of air enclosed by the chamber and balloon. When voltage is applied between the two carbon-grease electrodes, the balloon expands further. With an acrylic elastomer (3M™VHB™4910), we have demonstrated voltage-induced expansion of area by 1692%, well beyond the largest value of 380% reported before (Pelrine et al., 2000).

While our previous paper (Keplinger et al., 2012) has described the principle of operation and the experimental demonstration, the present paper reports theoretical analysis and further experimental observations. We use a computational model that combines the nonlinear electromechanical coupling of the material and the kinematics of large deformation of the membrane. In numerical simulation, care is taken to capture inhomogeneous and large deformation, as well as highly nonlinear behavior of the snap-through instability. We calculate bifurcation diagrams to map out multiple branches of solutions as the parameters of the setup vary. For example, we show that the behavior of the membrane is dramatically affected by varying the volume of the chamber. When the chamber is too small, the pressure drops steeply as the membrane is actuated by the voltage, and the achievable voltage-induced deformation is small. When the chamber is too large, the pressure is nearly constant as the membrane is actuated by the voltage, and the membrane snaps into an excessively large balloon, failed by electric breakdown before it reaches a stable state. When the chamber is of an intermediate size, the pressure drops somewhat as the membrane is actuated by the voltage, and the membrane snaps to a stable state of a large volume, averting electric breakdown. We compare these theoretical predictions with experimental observations. We further present experimental observations of voltage-induced local instability and clefts.

The VHB dielectric elastomer used in our experiments has been widely employed due to its large stretchability and high electric breakdown strength. The material, however, exhibits pronounced viscoelasticity (Lochmatter et al., 2007; Plante and Dubowsky, 2007). While a nonlinear viscoelastic model for dielectric elastomers has been proposed (Hong, 2011; Zhao et al., 2011; Foo et al., 2012), the model has not been reliably calibrated for the VHB. Here we will adopt a nonlinear elastic model. The object is to use numerical simulations to guide the experiment, rather than to achieve an exact match with the experiment. To reduce the effect of viscoelasticity in the experiment, we will use low voltage ramping rates. While such low ramping rates will not be interesting for the majority of projected applications, the combined model and experiment shed light on large voltage-induced deformation. It is also anticipated that less viscoelastic materials, such as natural rubber and PDMS, will be developed to function as dielectric elastomers.