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Temporal evolution and instability in a viscoelastic dielectric elastomer

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ABSTRACT

Dielectric elastomer transducers are being developed for applications in stretchable electronics, tunable optics, biomedical devices, and soft machines. These transducers exhibit highly nonlinear electromechanical behavior: a dielectric membrane under voltage can form wrinkles, undergo snap-through instability, and suffer electrical breakdown. We investigate temporal evolution and instability by conducting a large set of experiments under various prestretches and loading rates, and by developing a model that allows viscoelastic instability. We use the model to classify types of instability, and map the experimental observations according to prestretches and loading rates. The model describes the entire set of experimental observations. A new type of instability is discovered, which we call wrinkle-to-wrinkle transition. A flat membrane at a critical voltage forms wrinkles and then, at a second critical voltage, snaps into another state of winkles of a shorter wavelength. This study demonstrates that viscoelasticity is essential to the understanding of temporal evolution and instability of dielectric elastomers.

1. Introduction

The ability to control motion by means of electricity has been sought ever since the scientific dispute on the origin of electricity and muscular contraction in a dissected frog (Galvani, 1791; Volta, 1918). The dispute is often recognized as an opening for the physical understanding of modern electricity and the development of the modern battery by Volta (1800). Many devices and systems capable of voltage-induced motion have been developed since then. However, only few display the unique inherent properties of soft viscoelastic response and large deformation found in biological systems.

First reported in 1880 by Röntgen (1880), the dielectric elastomer actuator is one particular type of actuator, which relies on the electric field to induce large deformation (Pelrine et al., 2000). A dielectric elastomer actuator consists of an elastomeric membrane sandwiched between two compliant electrodes (Fig. 1). When the electrodes are subject to a voltage, electrical charges of the opposite polarities accumulate on the two electrodes, causing the dielectric membrane to reduce thickness and increase area. This electromechanical transduction has many desirable attributes, including large voltage-

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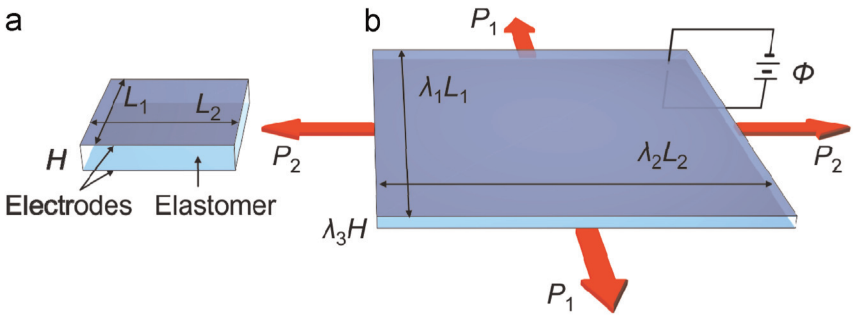

Fig. 1. A membrane of a dielectric elastomer, sandwiched between two compliant electrodes, is at (a) the reference state and (b) a current state.

induced deformation, high energy density, fast response, quiet operation, light weight, and low cost (Pelrine et al., 2000; Ashley, 2003; Carpi et al., 2010). Dielectric elastomers are being employed for interesting applications, including stretchable electronics (Keplinger et al., 2013), tuning stages for soft diffractive grating (Aschwanden and Stemmer, 2006; Kollosche et al., 2011a), tunable organic lasers (Döring et al., 2011), energy harvesters (Koh et al., 2011; Ahnert et al., 2011; McKay et al., 2011; Kornbluh et al., 2011), soft motors (Anderson et al., 2011; O'Brien et al., 2012), soft computers (O'Brien and Anderson, 2013), structural health monitoring for buildings (Laflamme et al., 2010, Kollosche et al., 2011b). In spite of these promising applications of soft transducers, the interplay of mechanics, electrostatics and designs in dielectric elastomers remains challenging.

The operation of dielectric elastomers is limited by electromechanical instability (EMI). Stark and Garton (1955) applied an electrical field to irradiated polyethylene under temperature variation, and found that EMI is responsible for electrical failure of this deformable polymer. EMI in dielectric elastomer is a positive feedback mechanism. When the voltage increases slightly, actuation causes thinning of the membrane, inducing even higher electric field. Due to the non-linear mechanical properties of elastomer, the positive feedback may cause the dielectric elastomer to thin down drastically, resulting in electrical failure (Zhao et al., 2007; Zhao and Suo, 2007; Kollosche and Kofod, 2010). EMI can be averted by affecting the non-linear properties of the elastomer, for instance by prestretching (Pelrine et al., 2000; Koh et al., 2011; Huang et al., 2012a), or by employing interpenetrating networks (Ha et al., 2006; Suo and Zhu, 2009). Alternatively, control of charge instead of voltage provides a robust method of averting EMI (Keplinger et al., 2010; Li et al., 2011), but this control is only effective if the dielectric is actuated without electrodes, or when the electrodes have small areas (Lu et al., 2014). In addition, there are conditions of particular boundary constraints under which EMI can be harnessed to achieve giant voltage-induced deformation (Zhao and Suo, 2010; Kollosche et al., 2012), including coupling to a pressurized container leading to planar actuation strain of more than 1600% through an aneurismic instability (Keplinger et al., 2012; Li et al., 2013). These previous papers disregarded the viscoelastic properties of the elastomer, and focused on their nonlinear stress–strain properties. However, we will later show that these effects must be included for a fuller understanding.

A membrane of a dielectric elastomer may form wrinkles as the applied voltage ramps up. During what we term flat-to-wrinkle (FW) transition, the homogeneous flat state of the dielectric elastomer becomes unstable, giving way to an inhomogeneous state in which the flat and wrinkled regions may coexist in the membrane (Plante and Dubowsky, 2006; Zhou et al., 2008; Huang and Suo, 2012; Zhu et al., 2012). Recently, we investigated two types of FW transition in a clamped membrane (Zhu et al., 2012). During type I FW transition, nucleation of wrinkles occurs in several small regions, followed by growth of each region until the whole membrane has undergone the transition. During type II FW transition, wrinkles form globally throughout the flat membrane, without the presence of a nucleation energy barrier. These two types of FW transition are analogous to the first and the second order phase transitions. While the type I FW transition is discontinuous and accompanied by a jump in the deformation, the type II FW transition is accompanied by a continuous change in the deformation. Keplinger et al. (2008) reported a slow viscoelastic drift in the FW transition. In that experiment, the dielectric elastomer was subject to stepwise voltages. It was found that at a certain voltage, wrinkled regions may grow, slowly driving the dielectric elastomer into failure.

Subject to electromechanical loads, a dielectric elastomer may exhibit time-dependent response. For example, a number of experiments with spectacular results were performed on a particular elastomeric material, known as VHB (Very High Bond, 3M). This elastomer has a relatively high dielectric constant, a very large elastic stretchability, and sufficient breakdown strength to enable voltage-induced strain above 100% (Pelrine et al., 2000; Ha et al., 2006; Keplinger et al., 2012; Kollosche et al., 2012). Importantly, VHB exhibits large viscoelastic effects, and experiments showed that the time for its viscoelastic relaxation is several hundred seconds (Wissler and Mazza, 2007; Carpi et al., 2008; Keplinger et al., 2008; Zhao et al., 2011). Viscoelasticity determines the temporal properties of polymers. The viscoelastic behavior of elastomers is derived from their network structure. Each polymer chain is connected to its neighbors by covalent crosslinks, allowing a chain to twist and coil, and neighboring chains to entangle. When the elastomer deforms, polymer chains will rearrange through localized slipping and sliding, leading to viscoelastic relaxation of mechanical stresses.

Plante and Dubowsky (2007) employed an electromechanical model with an exponentially decaying time response to analyze the strain rate effect on stress–strain curves. Wissler and Mazza (2007) attempted to describe time dependence