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New electromechanical instability modes in dielectric elastomer balloons

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ABSTRACT

Under the actions of internal pressure and electric voltage, a dielectric elastomeric membrane mounted on an air chamber can deform to a balloon shape. Due to the nonlinear deformation, snap-through instability can happen in the balloon, which has been harnessed to achieve giant voltage-triggered deformation. In addition to the snap-through instability, with an applied voltage, a new electromechanical instability mode with a localized bulging-out in the balloon has been recently observed in experiments. However, the reported phenomenon has not been well explained. In this article, through numerical computation, we obtain the relation between the volume of the balloon and its internal pressure, when the balloon is subjected to different voltages. We find out that when the applied voltage is small, the pressure vs. volume diagram of a balloon can be represented by an N-like curve, which is similar to the conventional hyperelastic balloon only subjected internal pressure; when the voltage is larger than a critical value, new instability modes in the balloon emerge, which have a localized bulging-out, similarly to the shape observed in the experiments. We further show that the critical voltage for the new instability mode of the DE balloon is closely associated with the prestretches applied to the membrane and the hyperelastic model for the elastomer.

1. Introduction

Dielectric elastomer (DE) has been regarded as a promising soft active material due to many of their unique properties such as large voltage-induced deformation, low noise during operation, low cost and fast response (Carpi et al., 2011a). In a recent decade, DE has been intensively explored in various applications, including artificial muscle (Kornbluh, 2004; Kwak et al., 2005; Palli and Berselli, 2013; Pelrine et al., 2002), haptic devices (Carpi et al., 2011b; Henann et al., 2013), micro-pumps (Bowers et al., 2011; Goulbourne et al., 2003; Goulbourne et al., 2004; Pope et al., 2004) and adaptive lens (Hwang et al., 2013; Lau et al., 2014; Liang et al., 2014; Son et al., 2012). DE adopted in the aforementioned applications is normally a sandwich structure with a soft elastomeric layer covered by two compliant electrodes on the top and bottom surfaces (Suo, 2010). The elastomer can dramatically reduce its thickness and expand in area when external electric voltage is applied across the thickness direction.

Nonlinear field theory for elastic dielectric accounting for the coupling between mechanics and electricity was originally proposed by Toupin (1956). Relevant studies of elastic dielectric were further developed by Landau (1960), Eringen (1963) and Tiersten (1971). The theory has been re-examined in recent years due to the rapidly growing applications of DE. Constitutive models of DE accounting for large deformation have been developed to explain diverse experimental observations and also provide guidelines for designing new DE devices (Dorfmann and Ogden, 2005; McMeeking and Landis, 2005; Suo et al., 2008).

Among all the DE devices, balloon is one of the most frequently adopted geometries. DE balloons have been successfully developed as spherical-shape actuators and tactile devices (Goulbourne et al., 2003, 2004; Wang et al., 2012). Recently, more applications of DE balloons have been explored due to their unique responses to different electromechanical loadings. Nonlinear vibration with tunable frequency has been demonstrated in spherical DE balloons subjected to a constant pressure and an AC voltage (Zhu et al., 2010). Rudykh and Bhattacharya (2012) predicted snap-through actuation in a thick-walled DE balloon. Liang and Cai (2015) has recently identified inhomogeneous shape bifurcation modes in a spherical DE balloon subjected to internal pressure and a constant electric voltage. Recently, Li et al. (2013) has observed voltage induced snap-through instability in DE balloons. In their experiment, an acrylic elastomer membrane (3MVHB4910), covered by carbon grease over the top and bottom surfaces as soft electrodes, is mounted on an air chamber. The membrane deforms to a balloon shape after air is pumped into the chamber through a valve.

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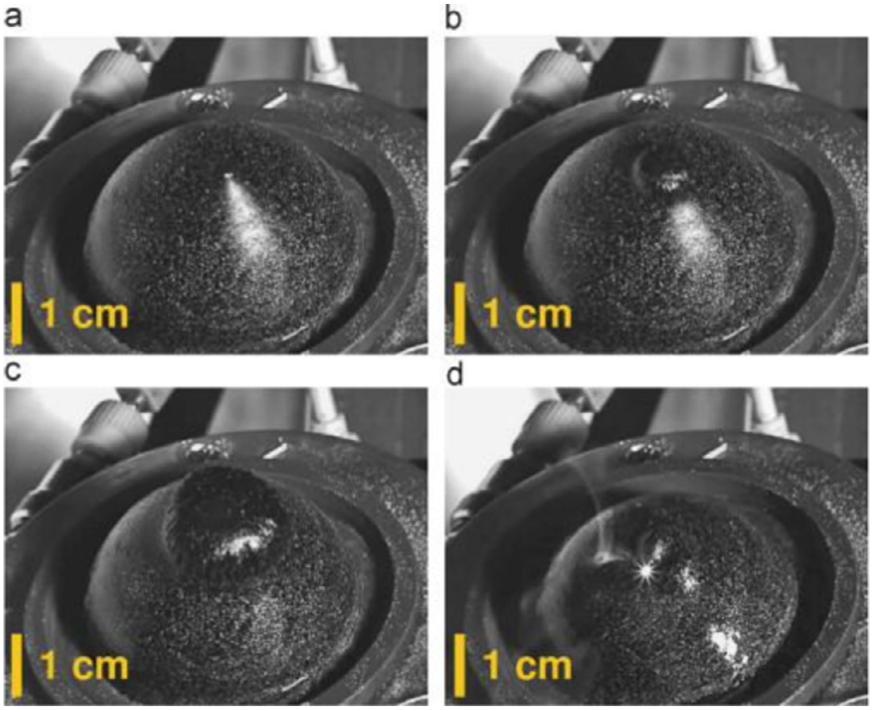

Fig. 1. Experimental observation of localized bulge-out in an inflated DE membrane (Li et al., 2013). In the experiment, a soft DE membrane is mounted on a chamber and air is pumped into the chamber through a valve. The membrane deforms to a balloon shape (a) and the valve is then closed to fix the total amount of air inside the chamber and the balloon. A voltage is subsequently applied to the membrane to further deform the balloon (b-c). When the volume of chamber is small, the apex of the balloon bulges out significantly, which is greatly different from the shape expected from traditional balloon problem. The applied voltage ramps up until the membrane is failed by electrical breakdown (d).

By closing the valve, the amount of air enclosed by the chamber and balloon is fixed, and a voltage is subsequently applied between the electrodes to further deform the DE membrane. Similar to a hyperelastic balloon only subjected to an internal pressure (Alexander, 1971), snap-through instability in a DE balloon was observed due to the non-monotonic relationship between the internal pressure and the volume of the balloon. Additionally, in the experiment, an unusual deformation mode of a DE balloon has been observed (Li et al., 2013). When the volume of the chamber is small, a region on top of the balloon is observed to expand significantly more than its neighboring area (Fig. 1b and c). The area keeps bulging-out as the voltage increases until electrical breakdown happens in the membrane as shown in Fig. 1. Different from the conventional snap-through instability, the new instability mode is more localized around the apex of the balloon, with the rest of membrane almost unperturbed. Such a instability in a balloon has never been reported before in other loading conditions and was also left unexplained in the paper (Li et al., 2013).

In this article, we will study the new instability mode observed in a DE balloon described above. Our numerical calculations show that when the applied voltage is low, the relationship between the internal pressure and volume of a DE balloon is similar to that of a hyperelastic balloon only subjected to an internal pressure, only with quantitative differences; when the applied voltage is high, a new instability mode emerges in the DE balloon for a certain range of pressure. We believe that the new instability mode of the DE balloon is associated with the non-convexity of the free energy density function of DE.

The remainder of the article is organized as follows. Section 2 summarizes the field equations of a DE membrane mounted on a circular hole of an air chamber and subjected to internal pressure and electric voltage. Those equations are solved numerically in Section 3. New instability mode in the balloon with localized bulging-out is identified when the applied voltage is high. In Section 4, we demonstrate that localized bulging-out instability modes of the DE balloon can be affected by prestretches and material parameters in the hyperelasticity model. We propose that the new instability mode is associated with the non-convexity of the free energy density function of DE in Section 5. Section 6 summarizes our findings in the article.

2. Inhomogeneous deformation of a DE membrane mounted on an air chamber

To make this article be self-contained, in this section, we summarize the governing equations for a flat DE membrane with homogenous thickness H subjected to internal pressure p and electric voltage Φ as shown in Fig. 2. These equations are mathematically identical to the ones presented in the paper of Li et al. (2013), though the derivation is slightly different. In the problem, an undeformed DE membrane with radius R_0 is mounted over a circular ridge of a chamber, as shown in Fig. 2a. We assume the deformation of the actuated DE balloon is axisymmetric. A Cartesian coordinate system x–z is built upon the apex of the deformed membrane, which coincides with the material point of the center of the undeformed membrane (Fig. 2b). For a point in the undeformed flat membrane: $(X, 0)$, it deforms to (x, z) under electromechanical loading. Consider a material element of the membrane, between two particles X and $X+dX$. When the membrane is in the deformed state, the particle X takes the position of coordinates $x(X)$ and $z(X)$, while the particle $X+dX$ takes the position of coordinates $x(X+dX)$ and $z(X+dX)$. In the undeformed state, the material element is a straight segment, with length dX. In the deformed state, the material element becomes a curved segment, with length $\lambda_1 dX$, where λ_1 is the longitudinal stretch. In a curved state, let $\alpha(X)$ be the slope of a membrane at material particle X. Write

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