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Thermoelectromechanical stability of dielectric elastomers undergoing temperature variation

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ABSTRACT

In this paper, the influence of both temperature and deformation on dielectric constant is considered during the establishment of free energy function of dielectric elastomers. A constitutive model of the thermodynamic systems undergoing adiabatic process is derived to study its thermoelectromechanical stability. The relations between different work conjugated parameters of dielectric elastomer are theoretically described, including the relations between nominal electric field and nominal electric displacement, entropy and temperature. Under different temperatures and electric fields, the allowable energy range of dielectric elastomer is calculated. Furthermore, the electric-induced variation of dielectric elastomer's temperature and entropy is also studied under various principal planar stretch ratios. These simulation results should offer assistances in guiding the design and fabrication of excellent actuators featuring dielectric elastomers.

1. Introduction

Large deformation will be generated when an electric field is applied on a thin dielectric elastomer film (Pelrine et al., 2000; Brochu and Pei, 2010; O'Halloran et al., 2008; Zhang et al., 2010). Due to its excellent properties, such as high elastic energy density, fast response, low cost, light weight, high efficiency, and easy to be processed, dielectric elastomers show great application potential in the area of smart bionics, medical devices, aeronautics and astronautics. Various devices based on dielectric elastomers such as actuators, sensors, tactile display and energy harvesters etc. have also been designed (Gallone et al., 2004, 2010; Carpi et al., 2008, 2010a; Keplinger et al., 2010; Kollosche and Kofod, 2010; Plante and Dubowsky, 2006; Adrian Koh et al., 2011; Liu et al., 2010b). The principal failure modes of the dielectric elastomers include electric breakdown, material rupture, loss of tension, electromechanical instability (Adrian Koh et al., 2011), would definitely hinder their wide applications. Hence, a well established theoretical model on the failure mechanism of dielectric elastomers is important. Recently, the nonlinear mechanical performance (Suo et al., 2008; Liu et al., 2009b,c), electromechanical stability (Liu et al., 2009d,e; Zhao et al., 2007, 2008b; Zhou et al., 2008; Liu et al., 2008, 2010a,b,c; Kong et al., 2011; Li et al., 2012), dynamical performance (Zhao et al., 2011; Zhu et al., 2010b) and failure of application devices (Adrian Koh et al., 2011; Moscardo et al., 2008; Liu et al., 2014) of dielectric elastomers are hotspots in all theoretical researches on electroactive materials.

Zhao and Suo have proposed an analytical method based on thermodynamics and continuum mechanics to predict the electromechanical stability of dielectric elastomers (Zhao and Suo, 2007). Based on the method, the electromechanical instability of Mooney–Rivlin type dielectric elastomers and the allowable area of the energy harvester were studied (Liu et al., 2009a, 2010a). The stable area of dielectric elastomers was investigated by research groups of

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Díaz-Calleja and Suo respectively (Díaz-Calleja et al., 2008; Adrian Koh et al., 2009). The bifurcation and chaos performance of dielectric elastomer's thermodynamic system was also studied by Zhu et al. (2010a). The electromechanical stability of dielectric elastomer undergoing homogeneous and inhomogeneous large deformation was investigated by Zhao and Suo (2008a) and He et al. (2009). Suo et al. studied electromechanical stability of dielectric elastomers of interpenetrating networks (Suo and Zhu, 2009). Zhao and Suo proposed the theory of dielectric elastomers capable of giant deformation for actuation (Zhao and Suo, 2010). Besides, the constitutive relation and electromechanical instability of different dielectric elastomer actuators, such as planar, rolled, tubular and hemispheric actuators, were also studied by Zhao and Suo (2007), Moscardo et al. (2008), Zhu et al. (2010c). However, the influence of temperature to dielectric elastomers has not been considered in the above mentioned theoretical analyses. Recent experiments indicate that the temperature plays a considerable role in the dielectric property of dielectric elastomers (Jean-Mistral et al., 2010). In Suo's research group, a model was proposed to show that the snap-through instability is markedly affected by both the extension limit of polymer chains and the polarization saturation of dipoles. The model is essentially useful for the future research of high-performance dielectric elastomer transducers (Li et al., 2011a; Liu et al., 2012a,b). In addition, some potential applications of stretchable dielectric elastomers are predicted by Carpi et al. (2010b). In Zhuo's research group, Li proposed a model to study the polarization mode, and characterize the behavior when the dipolar alignment is constrained by deformation. The conditional polarization would modify the final state as well as the path to instability during actuation due to the mechanism of induced electrostriction, indicating a new route to optimize the performance of elastic dielectrics (Li et al., 2011b).

Suo reviews the theory of dielectric elastomers developed within continuum mechanics and thermodynamics. The theory couples large deformation and electric potential, and describes nonlinear and nonequilibrium behavior. It also enables the finite element method to simulate transducers of realistic configurations, and suggests alternative routes to achieve giant voltage-induced deformation (Suo, 2010).

In this paper, a constitutive model of the thermodynamic systems under adiabatic process is deduced in order to study the thermoelectromechanical stability of dielectric elastomers. The allowable energy range of dielectric elastomer's thermodynamic system is predicted and the electric-induced changes of dielectric elastomer's temperature and entropy are also evaluated.

2. Fundamental theory

After being uniformly coated with compliant electrodes on the both surfaces and applied a voltage across, a thin dielectric elastomer film will endure shrinkage in thickness and expansion in area. As a result of increased temperature, the material's modulus will decrease and then generate faster deformation during its thickness reduction and area expanding. The decreased thickness of dielectric elastomer film results in a higher electric filed in the material. Under the coupling effect of thermal, electric and mechanical fields, such positive feedback continues. When the induced electric filed surpass the critical filed, the dielectric elastomer film will breakdown, resulting in the thermo-electromechanical instability.

As we know, a dielectric elastomer is actually a network of polymer chains. Each polymer chain consists of many monomers. The polymer chains are crosslinked by covalent bonds. The covalent bonds give solid-like behavior to the rubber. If these crosslinks are removed, the rubber becomes a polymer melt of liquid form. In fact, a dielectric elastomer is very similar to liquid at the level of monomers, where the scales are not large enough yet to include any crosslink. Like liquids, the polymers are densely packed and it is difficult to change the rubber's volume. Also like liquids, the polymers can move relative to one another, which contributes to dielectric elastomers' strong abilities in shape alternation (Liu et al., 2011a). For this

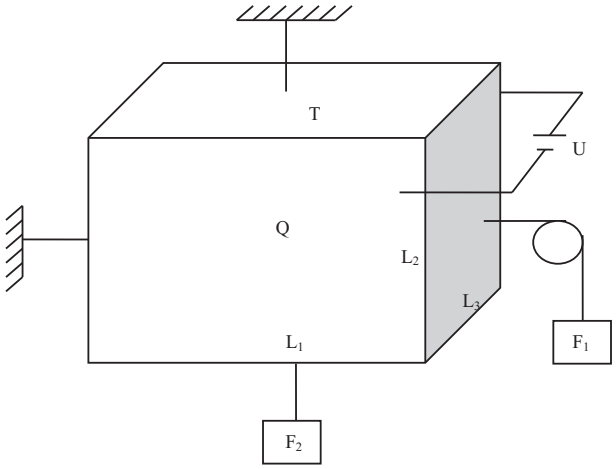

Fig. 1. Thermoelectromechanical coupling system of dielectric elastomer.