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Giant continuously-tunable actuation of a dielectric elastomer ring actuator

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ABSTRACT

Electric stimulus triggers mechanical deformation in an electroactive polymer actuator, much like the human muscle. Here, we demonstrate a dielectric elastomer actuator in a ring configuration, exhibiting electrically-induced linear strains in excess of 200%. We use theory to inspire the possibility of giant voltage-induced actuation, and create an experimental prototype of a ring dielectric elastomer actuator with continuously-tunable actuation of up to 200% strain. We further demonstrate giant actuation of a free-standing module of ring actuator, pre-tensioned using buckled carbon fibre strips, exhibiting electrically-induced mechanical linear strains in excess of 100% that is continuously-tunable with voltage. Unlike areal strains, displacements from electrically-induced linear strains may be fully utilized to do work, thereby allowing ring actuators to be integrated as actuator modules in robotic systems.

1. Introduction

A dielectric elastomer (DE) consists of a stretchable polymer membrane sandwiched between compliant electrodes. When a potential difference (ϕ) is applied on the electrodes, the resulting electric field polarizes the dielectric (polymer) and induces Maxwell stress, thereby thinning the membrane and expanding its area (Fig. 1). This phenomenon may take place in the absence of mechanical forces P_1, P_2.

Dielectric elastomer actuators (DEAs) are capable of generating high actuation strain and energy density comparable to biological muscles [1]. Hence, they are also termed “artificial muscles” [1]. Along with other attributes such as light weight, silent operation, fast response and low cost, DEAs have become a topic of great interest in the field of soft robotics [2–6], and have been studied for use as adaptive optics [7,8], refreshable Braille displays [9–11], and Sepia displays [12].

Under a moderately high electric field, DEAs undergo electromechanical instability (EMI). EMI is the positive feedback between a thinning dielectric and an increasing electric field, initiating a runaway electric field within the dielectric, leading to electrical breakdown. In the absence of pre-stretch, EMI limits voltage-induced actuation of DEAs to linear strains of between 30% and 50% [13]. In order to enhance actuation strain, one may choose to either harness EMI or eliminate it. EMI may be harnessed by carefully controlling the mechanical loading and voltage, so that the DEA will settle at an alternative stable state after experiencing EMI [14,15]. A large areal strain of 1600% has been attained using this approach, but here the DEA only operates in two bi-stable states of small and large strains. EMI may be suppressed or eliminated by pre-stretch, allowing linear or areal strains to exceed that of an unstretched DEA [16–19]. Pelrine et al. first

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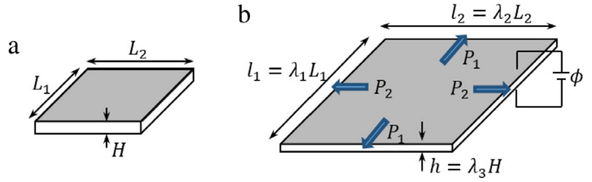

Fig. 1. Schematic of flat DE in (a) reference state and (b) stretched and charged state.

demonstrated a 158% voltage-induced area expansion of a circular acrylic elastomer membrane radially pre-stretched and attached to a rigid frame [16]. In the same study, they also demonstrated a 215% linear strain for an unequally pre-stretched membrane. This lays the basis for an unequally (orthotropically) pre-stretched DEA to achieve very high linear strains. An areal strain of 488%, which corresponds to a linear strain of 142%, was later shown using equal-biaxial dead load [18]. Following Pelrine et al.'s demonstration [16], theory was used to predict the possibility of linear strains in excess of 1000% for an orthotropically pre-stretched DEA [20, yet to be published].

Giant actuation with a record high linear strain of 500% has been demonstrated for a flat laterally-clamped DEA [21, yet to be published]. Such an actuation was made possible when the DE is pre-stretched orthotropically in one direction, while allowing deformation in the other two unconstrained Cartesian directions. Such a configuration is commonly known as "pure shear" (Fig. 2). Unlike the case with only two bistable states, here the actuation may be continuously tunable with a voltage. A flat DEA is however less durable and difficult to be incorporated into actuator systems. Rolling up the DEA into a ring configuration helps to mitigate these issues and is therefore the key focus of this paper. In the section that follows, we shall establish equilibrium equations for a generically-deformed dielectric elastomer (Fig. 1), followed by analyses for the orthotropically pre-stretched, clamped configuration and ring configuration.

2. Analysis of an orthotropically pre-stretched dielectric elastomer

Subjected to forces P_1, P_2 and a voltage ϕ, a DE membrane changes its dimensions from L_1, L_2 and H in its reference state, to l_1, l_2 and h in its stretched and charged state. As shown in Fig. 1, we quantify deformation by stretches: λ_1, λ_2 and λ_3. In our analyses, we assume that the elastomer is incompressible, giving: $\lambda_1\lambda_2\lambda_3 = 1$.

We further assume that the DE deforms under an isothermal condition. The Helmholtz free energy (Π) of the thermodynamic system therefore comprises the dielectric elastomer, the mechanical force and the electrical voltage in the actuated state, given as:

$$\Pi = L_1L_2HW(\lambda_1, \lambda_2, D) - P_1l_1 - P_2l_2 - \phi Q \tag{1}$$

$(P_1l_1 + P_2l_2)$ gives the mechanical work done by the elastomer, ϕQ is the electrical work done by the electric field, and the magnitude of the charge is $Q = Dl_1l_2$ with D being the electric displacement. $W(\lambda_1, \lambda_2, D)$ is the free energy density of the DE, which is the arithmetic sum of the free energy due to mechanical stretching $W_s(\lambda_1, \lambda_2)$, and the free energy due to dielectric polarization $W_p(D)$. We use the Gent hyperelastic material model to represent $W_s(\lambda_1, \lambda_2)$ [22]. An elastomer comprises of a three-dimensional network of long and highly coiled polymer chains, which are very flexible when being stretched initially but stiffens steeply when approaching the fully-stretched state [23]. The Gent model takes into account this strain-hardening behaviour as the DE approaches its stretch limit. The second term $W_p(D)$ represents the dielectric energy. Here it is assumed that the DE is a linear, ideal elastomer which polarizes almost as freely as polymer melt [23] and hence, $W_p(D) = D^2/2\varepsilon$. In this case, the electric displacement D is related to the true electric field E as: $D = \varepsilon E$. Here, we assume that the dielectric permittivity ε is independent of the state of deformation. The Gent model is given in Eq. (2), where J_{lim} is a constant related to the stretch limit and μ is the small strain shear modulus. We assume $J_{lim} = 120$, a typical value measured for acrylic-based elastomers [24].

$$W_s(\lambda_1, \lambda_2) = -\frac{\mu}{2}J_{lim}\ln\left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2}\lambda_2^{-2} - 3}{J_{lim}}\right). \tag{2}$$

We consider a DEA with orthotropic pre-stretch—stretch applied in the lateral direction and then clamped to preserve it, as shown in Fig. 2. This results in a membrane that is stretch-stiffened in one direction, while remaining compliant in the other. Previous studies have shown that DEAs utilizing such a mode of pre-stretch is able to achieve electrically-induced strains of more than 100% [21,25]. Since orthotropic pre-stretch allows the membrane to be stretch-stiffened in one direction, while allowing free actuation in the direction perpendicular to the pre-stretch, it may potentially be harnessed to do significant mechanical work induced by electrical actuation. While previous studies have demonstrated large electrically-induced strains, they have not explored if such strains induced may be further enhanced. We shall, in this paragraph, analyse this configuration to inspire the possibility of very large electrical actuation, beyond what was demonstrated previously.

In an orthotropically pre-stretched membrane, the DEA is pre-stretched in the lateral direction before it is clamped (Fig. 2(a)). In our analysis, for simplicity, we idealize that the lateral pre-stretch is preserved for the entire height of the elastomer. In reality, one may expect some relaxation of pre-stretch away from the clamps, but we shall reserve this analysis to a later section. The lateral pre-stretch is denoted by λ_{2p}. Before application of voltage, the DEA may also be pre-stretched in the longitudinal direction, for example, in the form of a fixed mechanical load P (Fig. 2(a)). We denote the stretch due to P, in the absence of voltage, as λ_{1p} (Fig. 2(a)). Under an electric field, the DEA actuates in the longitudinal λ_1 direction (Fig. 2(b)). From (1), we write the Helmholtz free energy of an orthotropically pre-stretched DEA as follows:

$$\Pi = L_1L_2HW\left(\lambda_1, \lambda_{2p}, D\right) - PL_1\lambda_1 - P_2L_2\lambda_{2p} - \phi DL_1L_2\lambda_1\lambda_{2p}. \tag{3}$$