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Closed loop control of force operation in a novel self-sensing dielectric elastomer actuator

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ABSTRACT

Closed loop feedback is essential in achieving the precise control of dielectric elastomer actuators (DEAs) due to their inherent nonlinear viscoelasticity. A novel self-sensing mechanism that uses capacitive sensing to detect the actuation of force in a dielectric elastomer sensing actuator (DESA) is proposed in this paper. In contrast to a conventional self-sensing DEA, it consists of an electro-active region (AR) for the actuation together with an independent electro-sensing region (SR). By doing so, the self-sensing mechanism does not exhibit long-term drift in the correlation between the structural deformation and the capacitive change, which is commonly found in conventional self-sensing DEAs. The results show that the proportional-integral (PI) controlled DESA performs effectively under uniaxial actuation. The DESA can suppress the relaxation of the viscoelastic DE and thus enable a constant force output. It also shows that the sensing capacity of the DESA can be enhanced further with appropriate electrode arrangement and motion-constraining. Furthermore, the results show that the DESA senses the off-plane expansion distinctly compared with the in-plane deformation, which helps to detect any wrinkling of the structure.

1. Introduction

As a next generation soft actuation technology, dielectric elastomer actuation is of particular interest because of its similar capability to human muscle [1–8]. It consists of a dielectric elastomer (DE) film that is sandwiched between compliant electrodes. When a high voltage is applied across the electrodes, the structure responds in planar expansion with contraction in thickness. The outstanding material properties in the electro-mechanical coupling make the DE ideal for displacement/strain sensing [9,10], energy harvesting [11–13], as well as actuation [14–17]. A dielectric elastomer actuator (DEA) has demonstrable muscle-like capability in bio-inspired robots [18–21], tuneable optics [22–26], flexible robotic legs [27], and lighter-than-air vehicles [28]. However, the advancement in other applications is hindered by the viscoelasticity of the DE. For a typical elastomer such as VHB 4910 from 3 M, the time-dependent stress-strain relationship causes long-term relaxation upon loading and sluggish responses, which limit high-frequency actuation. The force and displacement control of the DEA require feedback to achieve the required performance.

Closed loop operation has been applied to adjust actuation force and strain [29–32]. These works show that with external sensors, motion control can be achieved with proportional-integral-derivative (PID) controllers. The DEA-based tuneable grating is a typical example [25]. A compliant grating is placed on the DEA so that it deforms with the DE as the voltage is applied. It uses the first-order diffraction angle of the grating that is measured by a photo-diode to drive the DEA to the desired deformation. However, the main drawbacks are the complexity and high cost of the system. Furthermore, it contradicts the intention in utilizing a low-cost polymeric actuation approach.

Another alternative is to use a DEA as a motion sensor, to form a self-sensing DEA. Past work has focused on use a single electro-active region (AR) to perform both the actuation and the sensing. Resistive sensing is commonly avoided as the conductivity of the electrode depends on many factors, including the electrode material, the electrode configuration and the deformation of the DE [33]. Capacitive sensing is better because the capacitance depends only on the geometry of the capacitor and the electrode coverage [34,35]. The capacitance is measured typically by using a high frequency AC signal that is superimposed on the actuation voltage [10,36–39]. Other approaches use pulse width modulation to measure the capacitive discharge rate [40], and step voltage application to measure charge [41]. However, these publications show also that large deformations of the DE and coupled high electric fields during the operation cause complex changes in the electrode resistance and dielectric resistance, which leads to the unexpected capacitive response in the actuation [42–45].

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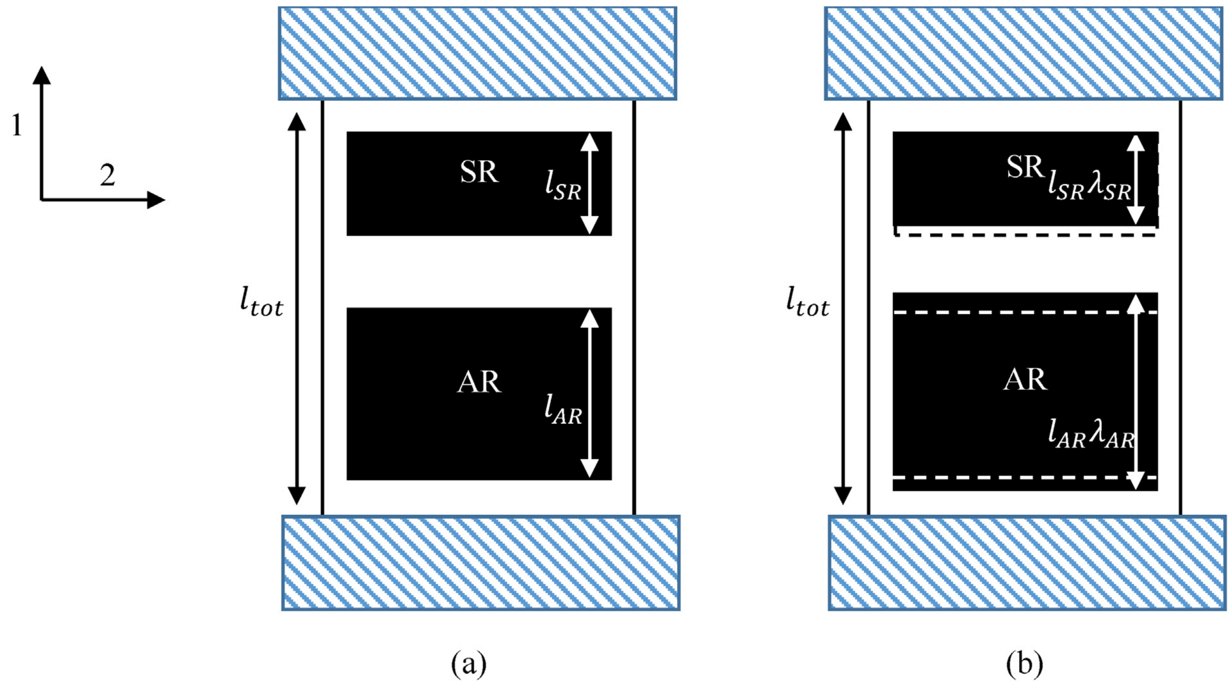

Fig. 1. Geometric correlation of the DESA: (a) the undeformed state and (b) the actuated state.

This paper presents the concept of a dielectric elastomer sensing actuator (DESA), a self-sensing DE actuator that utilizes separate electrode regions for sensing and actuating. By doing so, it demonstrates that the capacitive sensing mechanism in the DESA performs effectively and does not suffer from the previously mentioned deficiencies. Moreover, the performance of the structure with alternative electrode arrangements and motion constraining are also assessed. Finally, the challenges in implementing the DESA structure, the effects of electrode coverage and off-plane actuation on sensing resolution of the DESA are studied.

2. Theory

2.1. Capacitive sensing in the DESA

In the structure of a DESA, the high voltage application across the AR deforms the entire elastomer. The electro-sensing region (SR) detects such deformation, and its capacitance changes correspondingly. For an understanding of the self-sensing mechanism, the correlation of $\lambda_{AR} = f(C)$ is derived, where C is the capacitance in the SR and λ_{AR} is the voltage induced mechanical deformation in the AR. Fig. 1 shows the geometric correlation of the DESA with and without the voltage application. The DESA is pre-strained and constrained in direction 1, serving as a linear actuator. It is assumed that the SR only detects the deformation of the AR in direction 1 (e.g. the sensing is independent of the lateral expansion of the AR and the resulting inhomogeneous thickness due to the actuation). This assumption was validated from the experimental results (Section 4.1, Fig. 5b) when a 15 mm gap was set between the electrode regions. Moreover, the overall length of the film in direction 1 is assumed to be constant as in the experiment the DESA was fixed on the top and clamped to a load cell on the bottom that was much stiffer than the DESA. When the voltage is applied, assuming the AR expands uniformly in the strain of λ_{AR} (Fig. 1b), the corresponding strain in the SR, λ_{SR} is given by

$$\lambda_{SR} = \frac{l_{tot} - l_{AR}\lambda_{AR}}{l_{tot} - l_{AR}} \tag{1}$$

where l_{tot} is the total length of the film, l_{AR} is the length of the AR and λ_{AR} is the voltage-induced strain in l_{AR}. Taking the incompressibility of the elastomer, the volume associated with the SR implies that

$$\lambda_{SR}\lambda_h\lambda_w = 1 \tag{2}$$

where λ_w and λ_h are the resulting strains of the SR in direction 2 and the direction of thickness, respectively. Assuming that the elastomer is isochoric, the uniaxial loading condition gives

$$\lambda_w = \lambda_h = 1/\sqrt{\lambda_{SR}} \tag{3}$$

The capacitance of the SR in the undeformed state is therefore given by

$$C_0 = \frac{\varepsilon_0\varepsilon_r w l_{SR}}{h} \tag{4}$$

where ε_0 is the permittivity of free space, ε_r is the relative permittivity of the elastomer and w, h are the width and the thickness of the SR, respectively. Substituting Eqs. (3) into (4) gives the resultant capacitance in the actuated state C_a as

$$C_a = C_0\lambda_{SR} \tag{5}$$

Substituting Eqs. (1) into (5) gives the strain in capacitance λ_{cap} that can be defined as

$$\lambda_{cap} = \frac{C_a}{C_0} = \frac{l_{tot} - l_{AR}\lambda_{AR}}{l_{tot} - l_{AR}} \tag{6}$$

Equation (6) shows that by applying voltage across the AR, the increase in the mechanical strain λ_{AR} causes a decrease in the capacitive strain λ_{cap} (i.e. decrease in measured capacitance). This equation also shows the linear relationship between the capacitive strain in the SR and mechanical strain in the AR, which is ideal for implementing linear controllers.

In order to understand fully the proposed sensing mechanism, one extreme case to consider would be that with the SR placed adjacent to the AR, in which the deformation of the SR is also affected by the lateral expansion of the AR. It is assumed that in direction 1