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A self-sensing dielectric elastomer actuator

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Abstract

A novel self-sensing method based on the dielectric elastomer (DE) actuator/sensor, was successfully developed and evaluated in order to extract accurate displacement information during the actuation process without using any additional sensing device. The proposed self-sensing method is based on a capacitance characteristic of a DE actuator. The DE actuator with a serial external resistor can serve as an electrical high-pass filter. The voltage gained using the high-pass filter, which is virtually built by the DE, varies due to the change of overall capacitance when the DE actuator is expanded electro-mechanically. To realize actuating and sensing simultaneously with a DE actuator, we used a modulation technique to mix signals, which have a low frequency signal for actuating and a high frequency with small amplitude for sensing. Several experiments were performed to verify the usability of the proposed self-sensing method. The results showed a fine resolution and an excellent correlation with the displacements measured by a laser displacement sensor.

Keywords: Self-sensing; Dielectric elastomer

1. Introduction

Many kinds of actuators – such as electrical motors, pneumatic or hydraulic cylinders, and magnetic solenoids – have been widely used for engineering disciplines. The necessary displacement information of the actuators for close-loop control requires various sensors, such as an encoder or tachometer, or a linear variable differential transformer depending on specific applications. In practice, an actuator needs an independent sensing device to create a feedback control system; however, that is a challenging task when considering micro-to-meso scale actuation systems and/or multi-number of actuators, which are commonly used in robotic application fields. For example, when a robot researcher attempts to mimic lower animals in nature such as inchworm, earthworm, centipede, and etc. [1–6], a high degree of freedom must be realized with micro-to-meso scale actuators. This requirement is unavoidable and lead to a bulky system due to the required interface-sensor for each actuator. In this work, we introduce a novel concept of self-sensing method based on an electro active polymer (EAP) actuator, more specifically a dielectric elastomer (DE) actuator. The self-sensing actuator can be functional without using additional interface-sensors.

EAP actuators have been studied as a potential candidate for artificial muscles because their mechanical properties of actuation are close to natural muscle [7]. In addition, EAP can be used for sensor applications. For examples, an ionic polymer metal composite and a polyvinylidene difluoride make mechanical motions such as bending and expanding when an electrical field is applied [8,9]. On the contrary, when those materials are mechanically deformed, a proportional electrical voltage is generated [10,11]. A DE has been studied as a sensor and an actuator, as well. Sommer-Larsen et al. have studied the capacitive sensing response of the dielectric elastomer [12]. Goulbourne et al. researched the dynamic-stretch response of a DE membrane and simulated a corresponding capacitance response when voltage was applied to DE sandwiched between compliant electrodes [13].

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A limited numbers of researchers have studied actuators that can function as an actuator and a sensor, simultaneously. EAMEX company, in Japan, has announced that they have developed a conducting polymer actuator, which is able to measure external contact forces [14]. Punning et al. published a paper about a self-sensing actuator based on IPMC [15]. The team presented a possibility to measure the displacement of an IPMC by monitoring the resistance variation of external electrodes on the IPMC. O'Brien et al. introduced a self-sensing DE actuator [16] and measured the variable conductivity of coated compliant electrodes when the DE actuator was expanded by the actuation voltage. The article reported that the presented method showed a low bandwidth, less than 0.2 Hz, and had a large error of more than 5%. Goulbourne et al. presented a self-sensing Mckibben actuator using a DE sensor [17]. In this approach, however, the DE worked only as a capacitive sensor and was used to measure the overall displacement of Mckibben pneumatic actuator.

We propose a novel approach: measure an electrical characteristic, for example capacitance, that varies due to the mechanical deformation of DE material, itself, under an applied actuation voltage. The proposed method does not require an additional sensing device or electrodes on the actuator. It also showed repeatable results in experiments that were conducted to observe the actuator's response. The basic concept and working principle of this method are introduced in Section 2 and are followed by a description of a proposed self-sensing method and an overview of a DE actuator. Section 3 has the experimental results that prove the feasibility of the introduced method. Detailed experimental results, with measurements, and discussions are presented in Section 4. Conclusions from our experiments are in the last section.

2. Basic concept and working principle of the proposed self-sensing dielectric elastomer actuator

The operating principle of a dielectric elastomer actuator is shown in Fig. 1. A dielectric elastomer film is sandwiched between compliant electrodes. When a voltage is applied across the compliant electrodes, the film's thickness compresses and the area of the actuator expands. The field-induced deformation occurs in an electrostatic model, and the effective pressure to generate the deformation of the film can be measured. Since the electrostatic force, called Maxwell stress, causes contractions in the field direction, the compression pressure σ_z can be derived as follows:

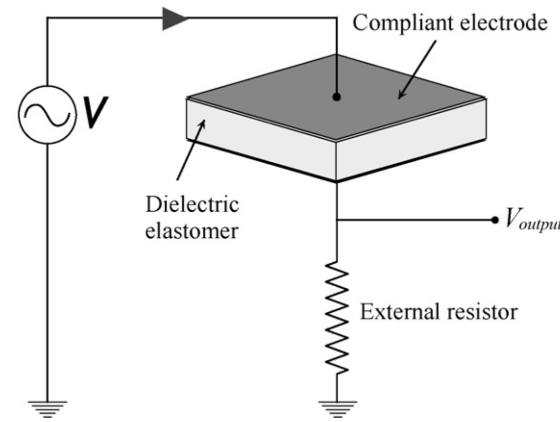

Fig. 2. Block diagram of an installed external resistor.

$$\sigma_z = -\varepsilon_o \varepsilon_r \left(\frac{V}{t}\right)^2 = -\varepsilon_o \varepsilon_r E^2 \tag{1}$$

where E is the imposed electrical field, t is the final thickness, V is the applied voltage, and ε_o and ε_r are the permittivity of the free space and the relative permittivity of the polymer, respectively. The details of the equation can be found in elsewhere [18,19].

In general, a DE actuator can be modeled as a simple capacitance, electrically. The capacitance is defined in the following equation:

$$C = \varepsilon_o \varepsilon_r \frac{A}{t} \tag{2}$$

where A and t are the area and the thickness of capacitor, respectively. As shown in Eq. (2), the capacitance is directly related to the electrode area, A, and inversely related to the separation, t. When the DE actuator is expanded by applying the actuation voltage, the capacitance of the actuator can be increased due to the increased area and the decreased thickness. To measure the variation of the capacitance, a resistor was installed between the DE actuator and the common ground to measure the current, as illustrated in Fig. 2.

The block diagram in Fig. 2 can be modeled as two different electrical circuits.

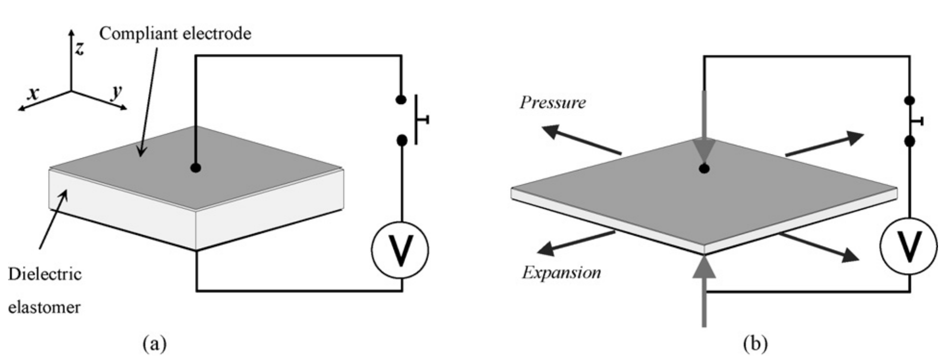

Fig. 1. Basic operating principle of a dielectric elastomer; (a) off state (normal) and (b) when voltage is applied on the both electrodes, the dielectric elastomer is compressed in the electric field's direction and expands perpendicular to the direction of the applied electric field (actuation).