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Dielectric elastomer based prototype fiber actuators

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Abstract

Dielectric elastomer based prototype fiber actuators have been developed and evaluated. The work is motivated by the tremendous potential offered by the current multicomponent fiber forming technologies as a means to fabricate fiber actuators. To explore the potential, prototype fiber actuators have been fabricated using commercially available dielectric elastomer tubes and by applying appropriate compliant electrodes to inner cavity and outer walls of these tubes. The force and displacement generated by such actuators have been studied as a function of applied electric field under different prestrained conditions. In order to introduce anisotropy in the fiber behavior, two types of prestrains (uniaxial and uniform) were applied. Actuation strains of 7 and 18% were recorded for silicone tubes in the axial and radial directions, respectively. Polyurethane tubes produced significantly higher blocking force compared to silicone tubes. The results demonstrate significant influence of applied prestrain on actuation strains and blocking force measured under isometric condition.

Keywords: Electroactive polymer actuator; Dielectric elastomer; Fiber actuator; Artificial muscle

1. Introduction

In recent years, a class of electroactive polymers (EAP) has drawn particular interest because of their high actuation strain and energy density. These are so called dielectric elastomers, and their deformation is due to the electrostatic attraction between conductive layers applied to opposite surfaces of the elastomer film, see Fig. 1. The electrostatic pressure (p) between two electrodes upon application of a potential difference, is related to the applied electric field (E), the dielectric constant of the EAP (ε), and permittivity of free space (ε_0) [1]:

$$p = \varepsilon\varepsilon_0 E^2 \tag{1}$$

The performance of some of the dielectric elastomers closely match that of biological muscles in terms of strains, energy densities, pressure and speed [2] and can potentially be used to develop actuators with muscle-like capabilities. Over the years, several different configurations of planar and cylindrical actuators have been proposed [2–12]. Most of these actuators are unique and have potential applications in diverse fields. However, their dimensional characteristics, scalability, and adaptability to useful systems limit their application and use.

As one possible way to overcome these limitation, we have proposed the use of multicomponent dielectric elastomer fibers that can be scaled to small sizes. It is important to note that using today's multi-component fiber manufacturing technologies it is possible to combine various polymeric materials in fiber forms of many geometric dispositions and shapes, see Fig. 2. These technologies can be potentially adapted to manufacture dielectric elastomer fibers actuators in a single step. In addition, these fiber actuators can be used as building blocks of hierarchical structures that have the potential to give biological muscle like performance. These fiber actuators can also be incorporated in conventional textiles to produce active, smart structures.

1.1. Prototypes design

As the first steps in exploring the possibilities of these multicomponent fiber structures, for ease of testing and to gather appropriate experimental data we choose to study a coaxial fiber design, but scaled up in cross sectional dimension by approximately 1 order of magnitude, by using commercially available thin walled tubes. The design of the fiber actuators

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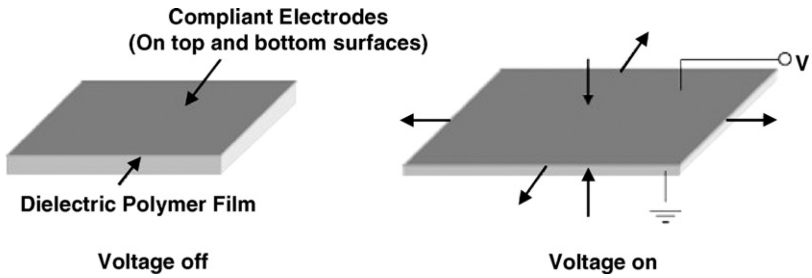

Fig. 1. Principle of operation of a dielectric elastomer actuator.

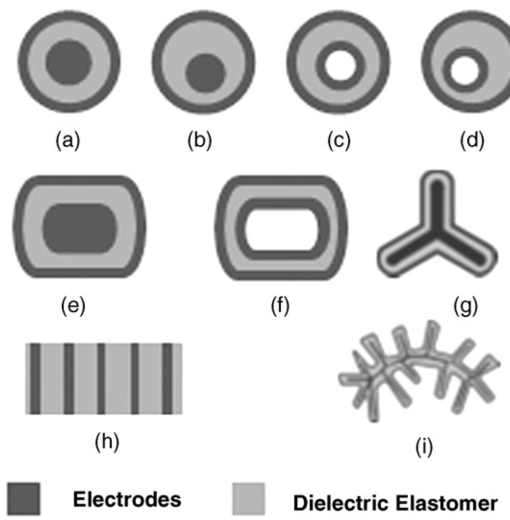

Fig. 2. Cross-sectional shapes of various multicomponent fibers as potential actuators. (a) Concentric: sheath/core; (b) eccentric: sheath/core; (c) hollow concentric: sheath/core; (d) hollow eccentric: sheath/core; (e) ribbon, (f) ribbon-hollow; (g) trilobal; (h) segmented ribbon; (i) multicellular-irregular.

investigated in this research is similar to cylindrical bicomponent polymeric fibers of core-sheath configuration with an additional layer, see Fig. 2a. The proposed fiber actuators consist of three parts: the conducting core, the dielectric actuating layer, and the conducting sheath or coating, see Fig. 3. The conducting components inside and outside of the fiber form the complaint electrodes required for actuation. Demonstrating actuation using the commercial thin walled fibers suggests that extrusion of multicomponet fiber actuators will be the next logical step. It should be pointed out that in extruded fiber technologies, the crossectional area can be controlled from the micron to millimeter scale, but it is anticipated that fibers with micron scale crossectional dimensions will be more useful since lower voltages can be used.

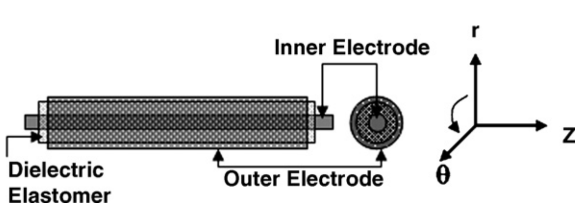

Fig. 3. Schematic of the fiber actuator showing placement of dielectric material and compliant electrodes.

1.2. Materials

Commercially available, thin walled (100–200 μm) elastomer tubes having inner and outer diameters around 500 and 900 μm, respectively were used in fabrication of the prototype fiber actuators. These tubes are same as hollow fibers but for their physical dimensions. Silicone[1] and polyurethane[2] dielectric elastomers were chosen for fabricating the prototype because they have good dielectric properties and can be potentially extruded in fiber form in the future. The dielectric constants of silicone and polyurethane are in the range of 2–4 [12] and 6–7 [13], respectively. Carbon black (CB) filled silicone [14,15] was used as the outer electrode as it forms a uniform, thin electrode on a surface and maintains its conductivity at high strains. In case of inner electrode, either a conductive silver-grease from Chemtronics® or an aqueous solution of calcium chloride was used. The solution of calcium chloride (74% by weight) had a conductivity of 11.5 Ω cm.

1.3. Large strain response of elastomers

The actuation response of elastomeric materials such as silicone and polyurethane is significantly influenced by their stress–strain behavior. During the initial evaluation of the elastomeric tubes repeated load cycling caused significant reduction in modulus along the axis of the tubes with the exception of polyurethane tube at high strains. This inelastic stress-softening phenomenon, often identified as preconditioning of specimens, is known as the Mullins effect [16]. In Mullins effect many elastomers exhibit a stress softening when subjected to cyclic loading and significant reduction in stress level at a given strain on unloading compared to the same on loading on the first and few successive cycles. This behavior demonstrates a departure from purely elastic materials. It has been shown that the material response becomes repeatable after the softening [17]. In order to stabilize their mechanical behavior, the elastomeric tubes were subjected to a series of loading–unloading cycles under constant load amplitude before being used in fabrication of the prototypes, see Fig. 4a and b. In case of silicone the modulus dropped significantly after the first cycle and after a number of cycles no hysteresis was observed. However, in case of polyurethane, sig-

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