TEXTILE-AMPLIFIED DIELECTRIC ELASTOMER ACTUATORS FOR SOFT ROBOTICS

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ABSTRACT

In recent years the field of soft robotics has gained a lot of interest both in academia and industry. One material class used frequently in soft robotics are dielectric elastomer actuators (DEA) consisting of a thin elastomer layer between two compliant electrodes. Their low mechanical strength and durability result in the necessity to add support structures. A textile based reinforcement of these actuators is advantageous, due to its highly anisotropic mechanical properties, which enhance the actuation and provide stability. In this paper a Carbon Fiber (CF) based reinforcement structure combined with DEAs is presented and discussed with respect to its actuation properties.

Key Words: CARBON FIBER-REINFORCED ELASTOMER, SMART MATERIALS, SOFT ROBOTICS, DIELECTRIC ELASTOMERS

1. INTRODUCTION

In recent years the field of soft robotics has gained a lot of interest both in academia and industry [1, 2]. In contrast to rigid robots, which are potentially very powerful and precise but lack the versatility of natural organisms, soft robots are composed of relatively soft materials like gels or elastomers. Their facile adaptability and compliance offer the potential to extend the use of robotics to fields like healthcare and advance the emerging domain of cooperative human-machine interaction [3]. One material class used frequently in soft robotics as actuators are dielectric elastomers consisting of a thin elastomer layer between two compliant electrodes. Under an applied electric potential, the resulting Maxwell stress leads to a reduction in thickness and expansion in both planar axes (figure 1) which can lead to strain levels as high as 300 % for acrylic elastomers [4].

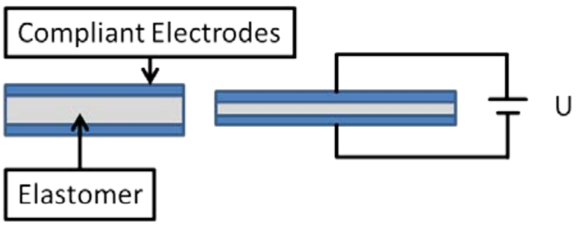


Figure 1. Mechanism of a dielectric elastomer actuator

Consequentially, the mechanical pressure in thickness direction *z* is

$$\sigma_Z = -\varepsilon_0\varepsilon_r E^2 = -\varepsilon_0\varepsilon_r\left(\frac{U}{t}\right)^2$$

with ε_0 as the permittivity of free space, ε_r the relative permittivity of the elastomer and *E* as an applied electric field which is equivalent to the applied voltage *U* over the elastomer's thickness *t*. When *Y* is the Young's modulus of the elastomer, the resulting strain in thickness direction δ_X corresponds to

$$\delta_Z = \frac{\sigma_Z}{Y}$$

The combination of actuators and textile materials has been proposed frequently, for example by Rossi et al., but research has mostly been focused on smart textiles in wearable applications [5, 6]. Similar to their biological models, many fish- or arthropod-based robots use endo- or exoskeletons to provide stability and enable the efficient transfer of forces from and to the robot [7, 8]. Secondly, the dielectric elastomer actuator has to be pre-strained in order to achieve usable strain response and increased breakdown strength when activated [9, 10]. To retain the necessary degree of pre-strain, supplementing support structures are added. In most endoskeletal, i.e. fish-like, demonstrators additional elastomeric or thermoplastic polymers are used for this purpose because these reinforcement structures are easy to manufacture and integrate. On the downside, due to their low and isotropic mechanical properties the structures either do not provide enough stability, which leads to unprecise and inefficient motions or are very voluminous [8, 11, 12].
The use of further elastomer for stabilization leads to quasi incompressible material being located distant to the neutral axis, consequently reducing the potential strain enormously.
Specifically adapted fiber-based reinforcements are not only able to provide stability where required but can also be used to amplify the strain response of electromechanical transducers based on dielectric elastomer actuators by restricting the expansion to quasi uniaxial strain.
The advantage of such a setup becomes obvious when comparing the usually used biaxial elongation to the restricted uniaxial elongation considering the same strain δ_X. As elastomers are quasi incompressible the strains are related as follows for biaxial strain ($\delta_X = \delta_Y$)

$$(1+\delta_X)(1+\delta_Y)(1+\delta_Z) = (1+\delta_X)^2(1+\delta_Z) = 1$$

which can be modified and then approximated for $\delta_Z \approx 1$ to

$$\delta_X = \frac{1}{\sqrt{1+\delta_Z}} - 1 \approx -\frac{1}{2}\delta_Z.$$

In comparison, when restricting the strain to uniaxial strain in direction x ($\delta_Y=0$), it follows

$$\delta_X = \frac{1}{1+\delta_Z} - 1 \approx -\delta_Z$$

which is twice that of the usually used operation mode.

2. MATERIALS AND METHODS

The electroactive fiber-reinforced elastomeric beam actuator presented in this paper is composed of coated unidirectional carbon fibers, an elastomer matrix material and the dielectric elastomer actuators (figure 2).
The carbon fiber tape is made from SGL's Sigrafil C T50-4.4/255-E100 fiber (SGL TECHNOLOGIES GMBH, Germany) and has a grammage of 200 g/m². To ensure good adhesion of the matrix material to the fibers and maximum infiltration they are first coated with a low-viscosity styrene-butadiene rubber-based coating optimized for carbon fibers (Lefasol VL 90/1, Lefatex Chemie GmbH, Germany). The coating is applied using the

Basecoater BC 32 (Coatema GmbH, Germany) in a Kiss-Coater setup in order to prevent dryspots and gaps and is crosslinked at 160 °C (figure 2).

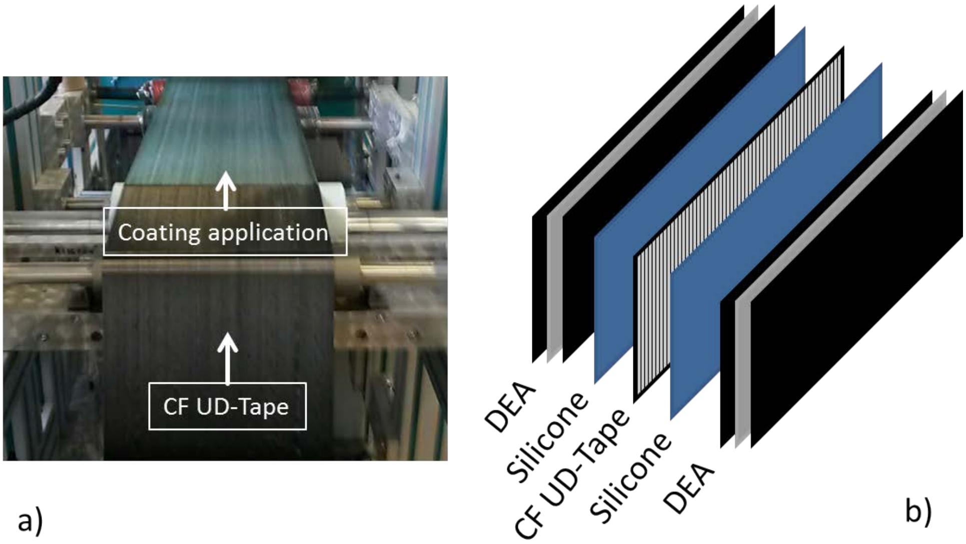


Figure 2. a) Coating of unidirectional carbon fiber tapes, b) Structure of the textile reinforced DEA

The resulting material has a total thickness of 3.5 mm and exhibits highly anisotropic bending characteristics. Furthermore, despite the non-conductive coating, it is still electrically conductive. In a next step, the textile layer is inserted into a 3D-printed mold to center the textile layer and recast with Ecoflex 00-30 (Smooth On Inc, USA) with Part A and Part B mixed at a weight ratio of 1:1 and cured at 22 °C for 24 hours.
The dielectric elastomer actuator is produced using an Elastosil membrane of 100 µm which is pre stretched to 45 %. In a next step the pre-stretched membrane is then fixated by an acrylic frame. To apply compliant electrodes an aerosol spray gun is used to coat the elastomer with a thin film of carbon black and Ecoflex solved in heptane. A rectangular pattern is achieved by using a vinyl mask to shield the remaining membrane.
The same solution is used to connect the inner electrodes of the DEA to the textile layer which leads to good accessibility for bonding. To connect the electrodes to the voltage source aluminum tape is glued to the edges of the electrodes and the textile layer which are then connected to the voltage source.
In order to supply the necessary high voltage for the actuation the open-source Multi Channel High Voltage Power Supply by petapicovoltron is used which enables to actuate at up to four different voltages, frequencies or phases simultaneously [13].
The deformation is tracked using a camera as well as the image acquisition and computer vision toolbox of Matlab by identifying characteristic points on the end of the specimen as illustrated in figure 3.

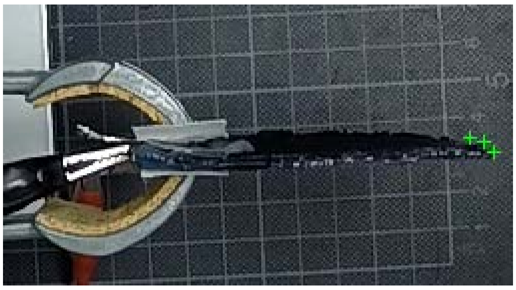
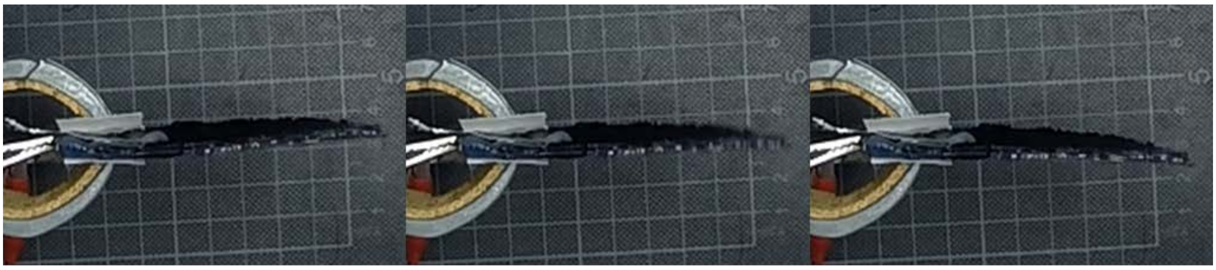


Figure 3. Tracking the displacements during actuation

3. RESULTS

The produced specimen is actuated with voltages between 1 kV and 4 kV and frequencies from 2 Hz to 10 Hz. At voltages of 3.5 kV or more disruptive charges are audible and visible close to the connectors. This is caused by carbon black solution which was pushed under the mask by the airflow. Therefore, frequency variations were conducted using a supply voltage of only 3 kV.
As expected the stiff carbon fibers inhibit a biaxial expansion of the specimen resulting in actuation only perpendicular to the fiber orientation, which leads to a bending motion towards the actuated membrane (figure 4).



Not actuated In Motion Maximum Deformation

Figure 4. Fiber reinforced actuator when activated with 3kV

The achievable deformations for different actuation voltages are shown in figure 5. The non-linear relation is caused by the Maxwell pressure, resulting in a stress being quadratically influenced by the applied voltage. If the fiber reinforcement did not prevent the elongation in both directions, the displacement from the neutral axis would only grow linearly with increasing voltage.

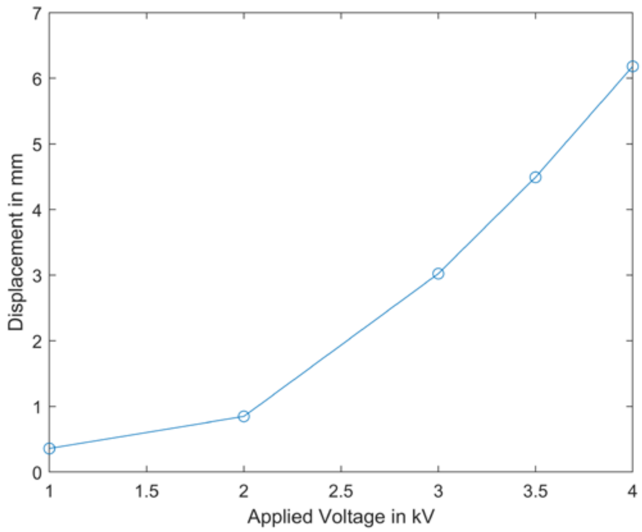


Figure 5. Displacement of the actuated bending beam for actuation voltages between 1 and 4 kV

To further increase the deformation potential, the textile reinforced DEA can be run close to its resonance frequency. As illustrated in figure 6, the deformation can be increased by 200 % if the specimen is actuated at its resonsance frequency of 7 Hz.

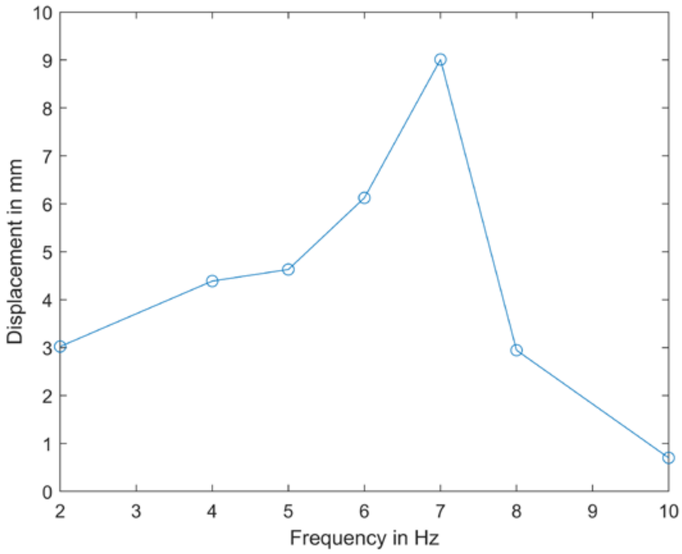


Figure 6. Displacement of the actuated bending beam for frequencies between 2 and 10 Hz

If the DEAs on both sides of the fiber-reinforced actuator are activated with 3 kV at the resonance frequency of 7 Hz then the maximum displacement is 21.1 mm which illustrates the potential of combining high-performance textile materials with dielectric elastomer actuators.

4. CONCLUSION AND OUTLOOK

In this work a novel carbon fiber reinforced DEA actuator is presented and its mechanical behavior experimentally evaluated. The active two way bending beam shows reproducible displacements of up to 20 mm which is 40 % of its length.
In order to further increase the adaptability and mechanical properties of interactive fiber reinforced elastomer composites the development of fiber-shaped DEAs, which can then be structurally integrated in the fiber system, is desirable. For other actuator types like shape memory alloy wires several integration methods have been developed and evaluated [14, 15].
Additionally, sensor fibers can be integrated, allowing an autonomous operation of the presented textile-amplified actuators in soft robots. Ideally these sensors are integrated by textile processes as well, consequently leading to an optimal signal response and a more precise knowledge of deformations [16], hence enabling structural health monitoring and self-sensing of the newly developed material.

5. ACKNOWLEDGEMENTS

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