Large-Strain, High-Stress Tubular Dielectric Elastomer Actuator with High Pre-stretch and Oil Encapsulation

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ABSTRACT

Rolled dielectric elastomer actuators (DEA), which are prepared by rolling up a flat dielectric elastomer , are subjected to non-homogenous deformation and thus does not perform as well as the flat ones. Typically, the rolled ones reported actuation of not more than 37.3% axial strain; whereas the flat one undergoing pure-shear deformation reported much greater actuation . This study shows that oil encapsulation helps the rolled DEA suppress pre-mature breakdown. Under isotonic test, oil-encapsulated tubular DEAs sustain very high electric field of up to 712.0 MV/m, which is 50% higher than that of the dry DEAs. Hence, it can produce up to 50% axial strain while deforming the passive oil capsules. In addition, it produces an isometric stress up to nearly 0.6 MPa, 114% higher than that of the dry one.

Keywords: Dielectric elastomer actuator, non-homogenous deformation, oil encapsulation, electric breakdown

1. INTRODUCTION

Recently, rolled dielectric elastomer actuators (DEA) have been developed to drive bio-inspired robots [1-8]. They are prepared by first pre-stretching and subsequent rolling up of a dielectric elastomer membrane into multiple wounds [1-11]. Hoop reinforcement, such as that for spring roll (see Figure 1a), causes contact stress to the rolled membrane [6,8]. However, a non-reinforced roll of elastomeric membrane forms necking upon relaxation from hoop pre-stress (see Figure 1b-c). As a result of necking, the rolled membrane thickens and is subjected to a lower electric field under the same voltage as compared to the flat membrane of the same pre-stretched thickness [11-12]. Not to surprise, the rolled DEAs generally produces less axial actuation as compared to the flat pure-shear DEAs. For example, multiple-wound rolled DEAs demonstrated axial actuation of not more than 32% strain [1-6]; a single-wound roll [9-11] produced axial actuation of up to 37.3% strain [5-6, 9, 11]. In contrary, a flat DEA that undergo pure-shear deformation produced greater actuation, well beyond 100% axial strain [13].

As a result of non-homogenous deformation, rolled dielectric elastomer actuators generally exhibit lower electrical breakdown strength as compared to the flat ones. For example, a DEA with hoop reinforcement, like the spring roll, exhibits breakdown strength of up to 109MV/m while producing 26% axial strain [1-3]. A tubular DEA without reinforcement sustained merely 40.9 MV/m though it can produce a large deformation as much as 35.8% [11]. The low electrical breakdown strength severely limits the maximum Maxwell stress generation [12, 14]. Hence, the rolled DEAs can hardly produce enough force to do work against external load like human muscles do. To improve its electric strength, one may consider the use of dielectric oil encapsulation [15-17], which was applied to flat DEAs to achieve muscle-like high stress. Previously, oil encapsulation was shown to help to suppress electrical breakdown by preventing partial discharge [17], extinguishing electric arcing [15-17], and stopping thermal runaway. It is anticipated that the oil encapsulation could be effective as well to rolled DEAs, despite non-homogenous deformation.

A single-wound roll, which is also known as a tubular DEA [9-11], is free from interfacial radial stresses that were prevalent to a multiple-wound roll [5-6, 9, 11]. A short tube is found to produce more axial strain than a longer tube because it is subjected to stronger hoop constraint and less necking [11-12]. On the other hand, a long tube can be designed to perform as well as a short tube by means of hoop clamping using nylon fibers (0.2mm diameter) [11] or helical spring [1-6]. In theory, the tubular DEA with large hoop pre-stretch could achieve a much larger axial actuation strain [12, 14]. However, in practice, they succumb to pre-mature electrical breakdown [11-12]. This study will experimentally investigate the non-homogenous deformation and electrical breakdown of tubular DEAs under pre-stretch. Subsequently, this study proposes the use of oil encapsulation over the compliant electrodes to suppress possible electrical breakdown and consequently improve actuation of the tubular DEAs.

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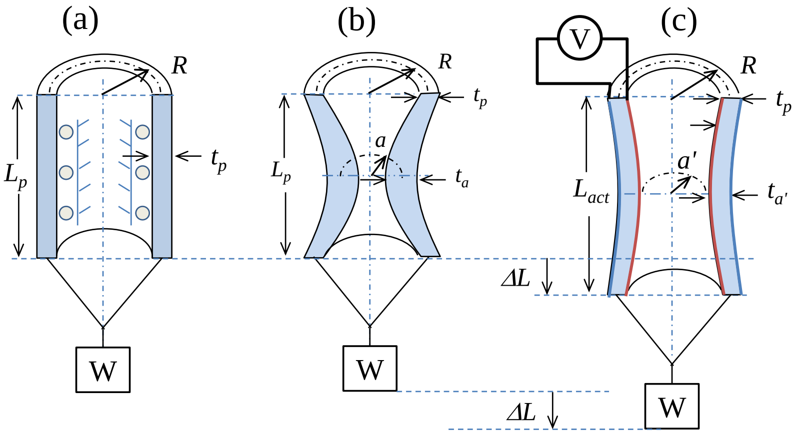


Figure 1. Shape change of the tubular DEA at different states: (a) the initial pre-stretched state without the hoop-stress relaxation; (b) the idle state with the hoop-stress relaxation; (c) the activated state during isotonic test.

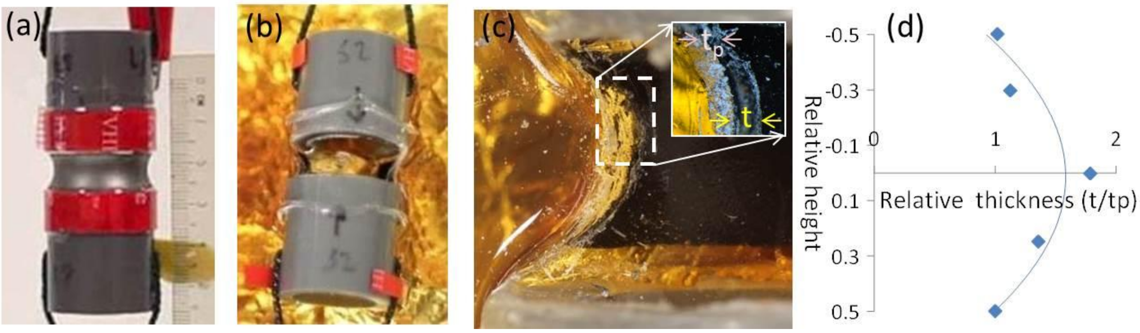


Figure 2. Section of a tubular DEA under pre-stretch for 5 times by 2 times in the hoop and axial directions respectively: at different states: (a) a tubular DEA; (b) epoxy casting over a half of the DEA; (c) the section of the halved DEA and cavity between epoxy after removal of VHB membrane (which was mold for epoxy casting); (d) membrane thickness distribution

2. NECKING PROBLEM OF PRE-STRECHED TUBULAR DEAS

A pre-stretched tubular DEA (see Figures 1 and 2) usually forms necking upon relaxation from hoop pre-stress. Its longitudinal profile and radius can be readily measured. However, its membrane thickness is difficult to be measured because the dielectric elastomer is soft and sticky. Lack of thickness measurement makes estimation of electric field difficult even though the driving voltage is known. An attempt to section a cryogenically frozen sample of flat DEA, however, was unsuccessful and cannot reveal the thickness of pre-stretched elastomer membrane. The unsuccessful sectioning happens because the frozen VHB samples quickly rises in temperature and regains adhesiveness and viscoelasticity upon contact friction with rotating blade.

Alternately, we propose here an epoxy-casting method, which make use of the elastomeric membrane as the mold. A tubular DEA with necking (as shown in Figure 2a-b) is dipped in a bath of liquid EpoFix resin until the tube was half immersed. Room-temperature curing of the epoxy yields a solid epoxy with dielectric elastomer membrane embedded as shown in Figure 2b-c. Subsequently, the soft adhesive dielectric elastomer embedded is removed using sharp tip tweezers, leaving a cavity in the solid epoxy (see Figure 2c). As a passive replicate of the tubular membrane, the cavity gap provides a measure for the membrane thickness. Accuracy of this thickness measurement depends on levelness and capillary effect of the liquid epoxy. Figure 2d showed that the membrane thickness distribution of the relaxed dielectric elastomer (resulting from necking) is non-uniform along the tube length. The elastomer clamped on the rigid PVC tube has the same membrane thickness as the pre-stretched value; whereas, the elastomer membrane at the middle of the necking tube thickens to be 1.78 times of the clamped membrane thickness.

This hoop-stress relaxation causes necking to the tubular DEA. The middle hoop membrane, which is free to deflect, reduces in diameter and thickens; whereas, the end-hoop membrane is clamped by rigid rings and remains a constant pre-stretch and thickness. Activation of such relaxed tubular DEA yields longitudinally non-uniform electric field and non-uniform axial strain. The thickened parts of the middle tubular membrane, which are subjected to a lower field, contribute to lesser axial strain. However, the thinner parts of the end tubular membrane, which contribute to a larger strain, are subjected to electrical field and stress concentration and thus more prone to breakdown (see Figure 3a). If the electrical breakdown can be suppressed, waistline of the activated tubular DEA could be straightened again to be cylindrical.

Usually, the more hoop pre-stretch the more the tubular DEA necks. Yet, a hoop pre-stretch (λ_ϕ) greater than the axial one (λ_z) is found to help the tubular DEA achieve high actuation strain and dielectric strength. For example, the tubular DEA with λ_ϕ=3 and λ_z=2 pre-stretches achieved near twice the breakdown strength of the one with λ_ϕ=2 and λ_z=3 pre-stretches. Breakdown of this low pre-stretched tubular DEAs are attributed to electromechanical instability manifested as wrinkling of the nearly broken-down DEA with λ_ϕ=2 and λ_z=3 pre-stretches. A higher hoop pre-stretch can suppress such wrinkling. To achieve even higher breakdown strength, higher pre-stretches and thicker membrane of elastomer may help.

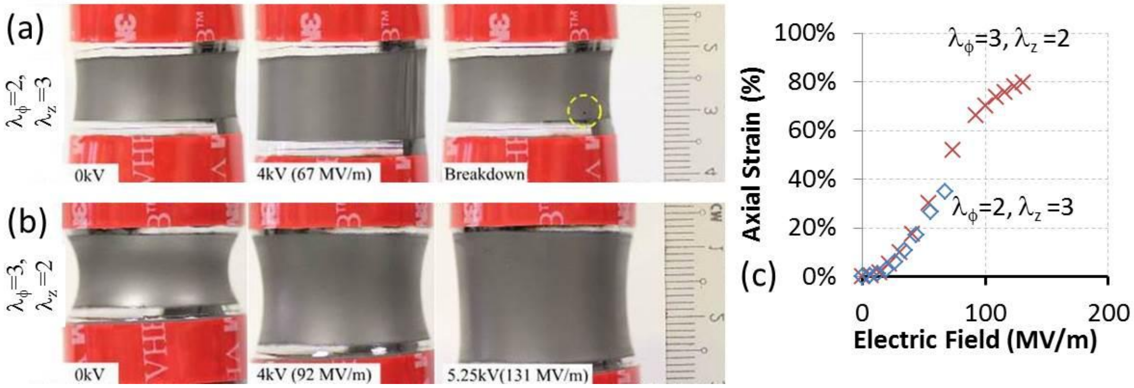


Figure 3. Effect of hoop pre-stretch on performance of tubular DEAs (VHB4905): (a) a tubular DEA with λ_ϕ=3 and λ_z=2 pre-stretches; (b) a tubular DEA with λ_ϕ=2 and λ_z=3 pre-stretches; (c) actuation strain as a function of the electric field for the two tubular DEAs.

3. OIL-ENCAPSULATED TUBULAR DEAS

This study proposes the use of oil encapsulation over the compliant electrodes to suppress possible electrical breakdown and consequently improve actuation of tubular DEAs, which are subjected to large pre-stretch and necking. As shown in Figure 4, there are two passive oil capsules, on the inner and on the outer sides of the DEA tube. These oil capsules add passive weight, occupy more volume, and stiffen the tubular DEA. In addition, they alter the pre-stress required to maintain the same pre-stretch of active tube. By adjusting the volume of oil in the capsule, it is possible to slightly straighten the waistline of the active tube and make its deformation more homogeneous.

Under isotonic test as shown in Figure 1 and 2, the oil-encapsulated tubular DEA is activated to produce elongation while it is axially pre-loaded by deadweight. While the core of tubular DEA elongates under Maxwell stress, the passive capsule membranes conforms to the electrically induced elongation. The elongation is a sum of electrically induced axial strains in the core DEA, which varies longitudinally. The induced actuation strain is defined as

$$s_z = \frac{L_{act}}{L_p} - 1 \qquad (1)$$

where L_{act} is the activated length and L_p is the idle pre-stretched length.

When activated towards the full potential, the waistline of an activated tube could be straightened again. As the activated tube become cylindrical. Hence, the membrane thickness change can be estimated from the length change, just like it was for the spring roll [1-6], following:

$$\bar{t}^{c}_{act} = \left(\frac{L_p}{L_{act}}\right) t_p \tag{2}$$

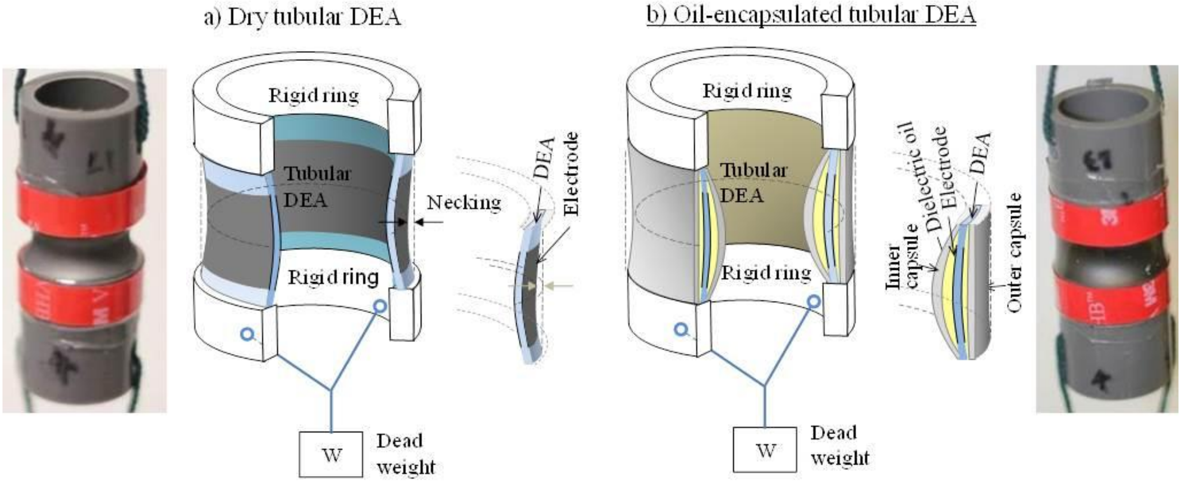


Figure 4. Design of tubular DEAs: (a) a photograph and a schematic drawing with sectional view of a dry tubular DEA; (b) a photograph and a schematic drawing with sectional view of an oil-encapsulated tubular DEA

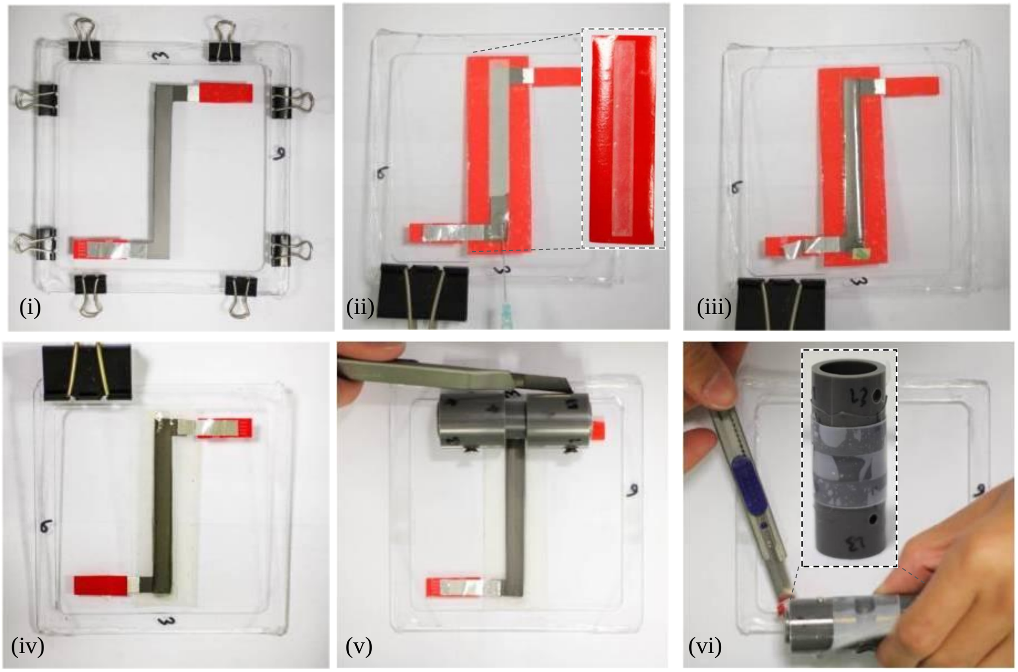


Figure 5. Major preparation steps for an oil-encapsulated DEA sample: (i) a flat DEA with graphite-powder electrodes; (ii) Lay up of a talcum-coated cover layer over the DEA layer to form a non-adhesive cavity for oil injection; (iii) completion of an oil capsule after oil injection by a syringe; (iv) lay-up with a Teflon layer to protect the oil capsule; (v) rolling up of the two-sided oil-encapsulated flat DEA; (vi) Completion of a single-wound rolled DEA, as known as a tubular DEA, with the Teflon protective layer on.

Fabrication of an oil-encapsulated tubular DEA involves three major steps: 1) preparation of a flat DEA of pre-stretched membrane; 2) oil encapsulation over the flat DEA; 3) rolling up of the oil-encapsulated DEA and clamping the ends of a roll to two rigid rings. The fabrication steps are basically the same for preparing a dry rolled DEA [4,5,11], except the additional steps to prepare the oil encapsulation. The major steps of the sample preparation are shown in the photographs of Figure 5.

The build of this oil capsule is similar to that for a tunable liquid lens [18-20], but it serves to enhance breakdown strength of DEAs. Firstly, to make a capsule membrane, a passive adhesive layer is to be covered over the DEA substrate. This cover layer can be a thinner VHB tape, non-stretched or stretched. Before bonding onto the DEA substrate, a patch of the adhesive cover layer is made non-adhesive by coating with talcum powder. Afterwards, the talcum-coated cover layer is laid on top of the flat DEA substrate. While its border is bonded to the substrate, the non-adhesive interface between the cover layer and the DEA substrate forms a cavity for catching liquid. Subsequently, oil is injected from a needle of a syringe into the cavity. While doing injection, the air bubbles in the capsule are removed by drawing another syringe. Afterwards, the needle puncture is sealed by another adhesive patch. A Teflon layer is laid to protect the first oil capsule before the second oil capsule is made on the other side. Completion of these processes yields a flat DEA with oil encapsulation on both sides. With the temporary backing by the Teflon transfer layer, the oil-encapsulated DEA membrane, even at high pre-stretch, can be rolled neatly over two rigid rings

4. EFFECT OF OIL ENCAPSULATION

To show the effect of oil immersion, the oil encapsulated tubular DEAs are compared with those dry one without oil encapsulation. These tubular DEAs are made from 42 μm thick dielectric elastomer membrane, which was obtained by bi-axially pre-stretching a 1mm thick VHB 4910 tape for 6 times along the hoop direction and 4 times along the axial direction and brushed with graphite-powder compliant electrodes. Both sides of the DEA are sealed by oil capsules, which has dielectric oil (Dow Corning Fluid 200 50cSt) enclosed by a 90μm thick cover membrane of lightly pre-stretched VHB93015LE and the DEA membrane. Large hoop pre-stretch of the membrane is clamped by the rigid rings of PVC, while the axial pre-stretch is kept by deadweight in the isotonic test. With extra capsule, the oil-encapsulated DEA is axially stiffer than the one without encapsulation and thus requires a higher axial pre-load to maintain the same axial pre-stretch. The oil-encapsulated DEA weighs 2.81 gram with 0.7 ml silicone oil in each capsule; whereas, the dry DEA weighs less at 1.3 gram.

During the isotonic test, the tubular DEAs are subjected to a voltage ramp up at a step of 1kV until the electrical breakdown. During the activation, the high voltage supply (Spellman HV supply) is set with a current limit of 120μA. Each voltage step is held for one minute during which a snapshot of the activated tubular DEAs is taken. Meanwhile, time-varying axial displacements of the activated DEAs are measured continuously by a laser displacement sensor (Keyence LC-2440). Figures 6 and 7 shows electrically induced elongation of the tubular DEAs under isotonic test. This axial actuation increases with increasing electric field. Below 150MV/m electric field, the actuation shows a quadratic rise with respect to the applied electric field. At higher electric fields, the actuation however increases at decreasing rate due to strain stiffening. High hoop pre-stretch and the use of thin graphite-powder compliant electrodes help the present tubular DEAs produce much larger actuation strain. Even the dry tubular DEAs achieve very high axial actuation of up to 80.2% strain at the breakdown field of 475.9 MV/m. Meanwhile, the oil-encapsulated tubular DEA produces an axial strain of up to 55.4% at 712.0MV/m. The lower axial strain achievable by the oil-encapsulated one is attributed to stiffening effect by the inner and outer oil capsules of 90 μm thick membranes.

In addition, it is found that oil encapsulation helps tubular DEAs self-clear and stop pre-mature breakdowns. Figure 8 shows the voltage ramp while leakage current across tubular DEA during isotonic test. In the event of electrical breakdown, voltage falls and current surges were observed across the DEAs. Without oil encapsulation, a sample of dry DEA is completely damaged by current spikes at 13-14kV and eventually burnt with a big puncture. On the other hand, a sample of the oil-encapsulated DEA has current spikes at 16kV subdued and stopped so that the terminal breakdown is delayed to happen at a higher voltage at 19kV. Details of electrical breakdown can be referred in our latest paper [21].

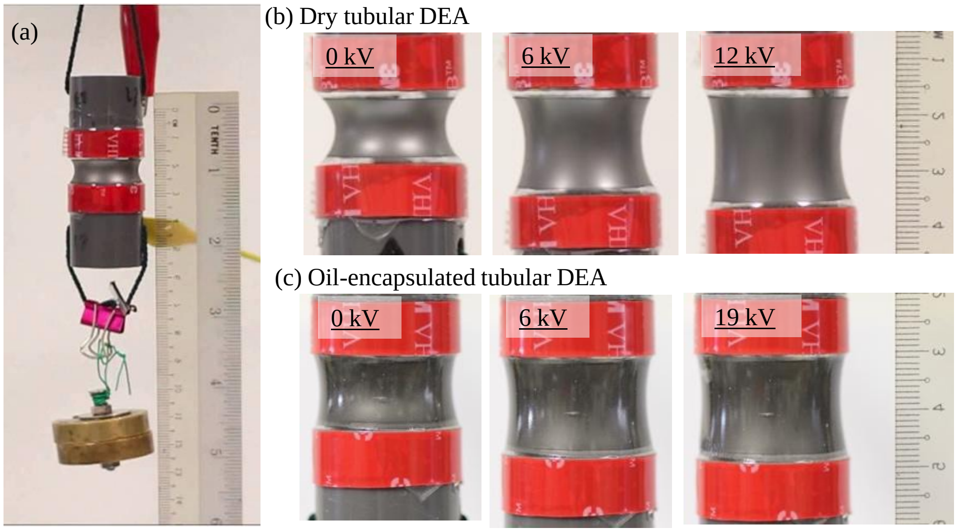


Figure 6. Photographs of tubular DEAs under isotonic test: (a) An actuator sample hanged with a deadweight under the isotonic test; (b) shape change and elongation of a sample of the dry tubular DEAs; (c) shape change and elongation of a sample of the oil-encapsulated tubular DEAs. These tubular DEAs are subjected to pre-stretches of λ_ϕ=6 and λ_z=4.

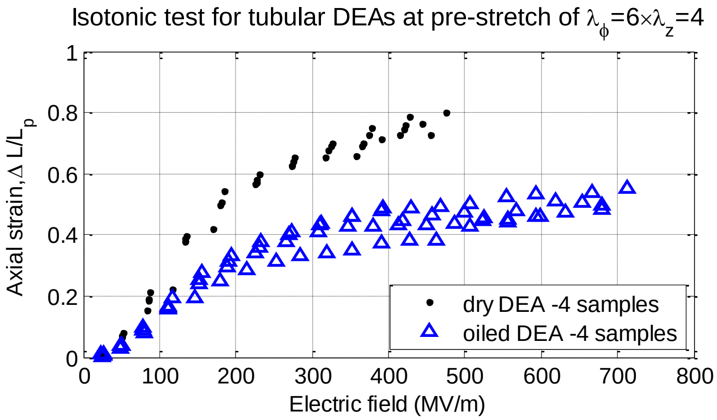


Figure 7. The induced axial strain as a function of the average electric field, which is estimated from the cylindrical model, for the tubular DEAs, which were pre-stretched at λ_ϕ=6 and λ_z=4 in the hoop and axial directions respectively during the isotonic tests.

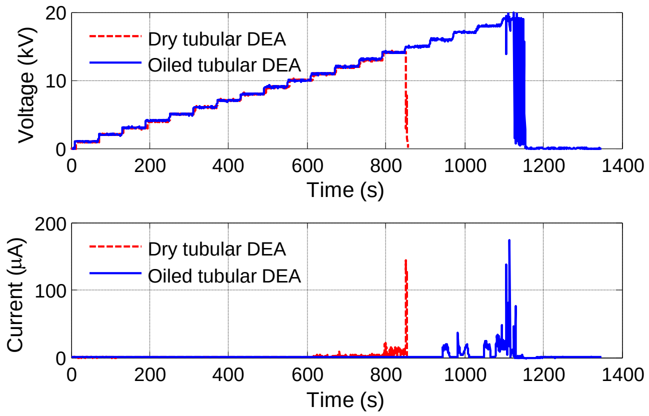
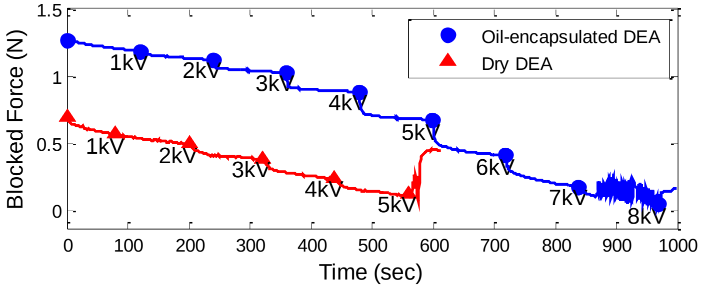


Figure 8. Monitor of (a) step-wise voltage ramp, (b) leakage current for tubular DEAs, which were pre-stretched at λ_ϕ=6 and λ_z=4 in the hoop and axial directions respectively, with or without oil encapsulation.

In the isometric test, the axial blocked force of the tubular DEAs is measured by a 10N-capacity load cell of a tensile tester (INSTRON 5569). To simulate the condition at the maximum isotonic free stroke, the actuator samples under test are pre-stretched 65% axially relative to the initial pre-stretched length. As a result, the total axial pre-stretch ratio becomes 6.6 times for this isometrically tested sample, instead of the 4 times for the isotonically tested samples. Before electromechanical testing, the pre-stretched tubular DEAs are let fully relaxed in axial pre-stress. Subsequently, the actuator samples were subjected to a stepwise voltage ramp towards the maximum achievable voltages and its field-activated change in the blocked force was measured.

Figure 9 shows that electrical activation reduces the blocked forces for both types of DEAs. In response to stepwise voltage ramp, the axial blocked force decreases in steps. Each activation step is held for one minute and its response is an exponential decay due to the viscoelastic effect of the VHB material. The oil-encapsulated DEA sustains up to 8kV and produces a maximum blocked force change of 1.19 N. On the other hand, the dry DEA fails terminally at 5kV and produces a maximum blocked force change of 0.57N, which is lesser than the maximum change induced by the oil-encapsulated DEA. The breakdown voltages for the isometric test are found to be lower than those for the isotonic test because dielectric elastomer of fixed length are more prone to wrinkling and electrical breakdown, like flat DEAs do [16]. Figure 9b shows that the isometric stress change appears to increase with the electric fields in a quadratic trend. The oil-encapsulated isometric DEA sustains up to 307.5MV/m, which is 72.3% higher than 178.4 MV/m sustained by the dry DEA. As a result of improved breakdown strength, the oil-encapsulated DEA can induce an isometric stress change up to 0.58 MPa, which is 114.8% higher than the 0.27 MPA induced by the dry DEA.

(a) Axial Blocked Force



(b) Axial Stress Change

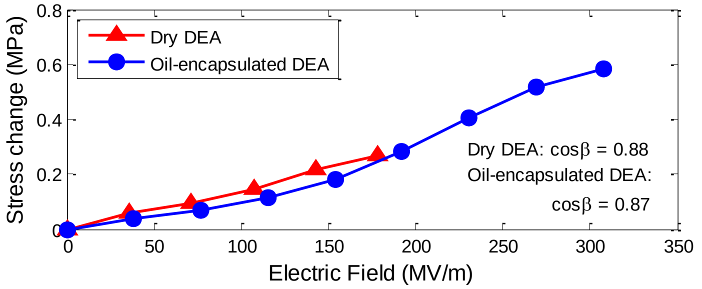


Figure 9. Isometric tests for the tubular DEAs with pre-stretches of at λ_ϕ=6 and λ_z=6.6: (a) time history of the measured axial blocked force during voltage ramp; (b) the induced axial stress change as a function of the average electric field.

5. CONCLUSIONS

In this paper, we have shown that the use of oil encapsulation and large pre-stretch help suppress pre-mature electrical breakdown. This study shows that oil encapsulation helps the same prepared tubular DEAs realize its fullest actuation potential, despite initially severe necking and non-uniform deformation of the tubular membrane due to large hoop pre-stretch. Under isotonic test, oil-encapsulated tubular DEAs sustained a very high electric field of up to 712.7 MV/m, which is 50.0% higher than that of the dry ones. They produced up to 55.4% axial strain despite being axially stiffening by the passive oil capsules. During the isometric test, the oil-encapsulated tubular DEA sustained up to 307.5MV/m, which is 72% higher than that of the dry one, and thus it produced a 114% higher stress change of up to nearly 0.6 MPa. In addition, it is noted that large pre-stretch helped even dry tubular DEAs sustain higher field of up to 476.0MV/m and thus produce also a very large axial strain of up to 80.2% as compared to the previous works.

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