Electromechanical behavior of fiber-reinforced dielectric elastomer membrane

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Based on its large deformation, light weight, and high energy density, dielectric elastomer (DE) has been used as driven muscle in many areas. We design the fiber-reinforced DE membrane by adding fibers in the membrane. The deformation and driven force direction of the membrane can be tuned by changing the fiber arrangements. The actuation in the perpendicular direction of the DE membrane with long fibers first increases and then decreases by the increasing of the fiber spacing in the perpendicular direction. The horizontal actuation of the membrane decreases by decreasing the spacing of short fibers. In the membrane-inflating structure, the radially arranged fibers will break the axisymmetric behavior of the structure. The top area of the inflated balloon without fiber will buckle up when the voltage reaches a certain level. Finite element simulations based on nonlinear field theory are conducted to investigate the effects of fiber arrangement and verify the experimental results. This work can guide the design of fiber-reinforced DE.

Keywords: Dielectric elastomer; fiber reinforced; electromechanical

1. Introduction

As an electro-active polymer (EAP), dielectric elastomer (DE) possesses the attributes of large deformation, light weight, and noise-free operation [1–10]. The electromechanical coupling behavior of DEs has been studied extensively in numerous applications, including actuators [11–15], soft robotics [16–22], artificial muscles [23–25], and energy harvesters [26,27]. Recently, the electromechanical behaviors of DE have been widely investigated. Specially, based on the giant voltage–induced actuation of the DE, various methods have been used to enhance the electromechanical performances of the DEs such as synthesizing composite DE material [24], harnessing the electromechanical instabilities of DE [4], and improving the properties of electrodes [23]. Those approaches mainly focus on tuning the stiffness of the DE membrane or the effective stiffness of the DE structure to improve electromechanical properties of the DE under the voltage loads [28,29]. A simple way to make DE composite material is to embed fibers into the DE membrane [13]. This approach can restrain the actuation of the DE structure in some directions, and then enhance the actuation in other directions. We can design the arrangement of fibers to tune the actuation of DE structure in specific directions. This paper presents a fiber-reinforced DE structure to improve the driven forces and the...
actuation in specific directions. We investigate the effects of fiber arrangements on the performance of DE structure. FEM analysis have been conducted to verify the experimental results and to illustrate the stress and strain distribution of the fiber-reinforced DE membrane under electromechanical loads [30]. The paper is organized as follows. In Section 2, we present the fabricating procedures and the experimental results of DE in-plane actuator. Section 3 shows the procedures and the experimental results of DE membrane inflating structure. Section 4 presents the working principle and FEM simulation results of the DE structure. Finally, conclusions are given in Section 5.

2. Fiber-reinforced dielectric elastomer in-plane actuator

In-plane actuator with DE membranes and rigid frames is a typical DE structure [31–33]. In this structure, the DE membranes are pre-stretched and then fixed by the rigid frames. We investigate the electromechanical behaviors of DE membrane with two types of arrangement of fibers, which are parallel arranged long fibers and parallel arranged short fibers.

In our experiment, we use 3 M-VHB 4910 as the DE and nylon fishing lines (~0.3 mm in diameter) as the fibers. In order to improve the strength of bonding between fibers and DE membranes, we sandwich the fibers between two layers of DE membranes. We use laser cutter to cut ABS plastic plates as the rigid frame. The length of the outer side of the frame is 80 mm, the length of the inner side of the frame is 60 mm, the width of the frame is 10 mm, and the thickness of the frame is 1 mm; the frame will be used to fix the pre-stretched membrane [11]. Second, we use the same way to cut A4 paper into exactly same shape with the ABS plastic plates frame, this paper frame will be used to ensure the membrane cannot detach from the plastic frame. Then we manufacture the fiber-reinforced DE membranes. As shown in Figure 1, we use 3 M-VHB 4910 as the DE, which has been bi-axially pre-stretched three times.

![Figure 1](image_url)

Figure 1. Manufacturing procedures of the fiber-reinforced DE membrane structure. (a) The reference state of DE membrane; (b) pre-stretched DE membrane; (c) enhancement of the membrane by aligned fibers; (d) electrode coating.
times by the biaxial stretching machine before attaching on the ABS plastic frame [10]. After pre-stretch, we fix the elastomer on plastic frame and then attach the paper frame on the other side of the membrane, make the membrane sandwiched by the plastic frame and the paper frame. Compliant electrodes (MG Chemical 846–80 G carbon grease) are coated on both sides of the DE membrane. Figure 2 shows (a) the DE membrane actuator in the pre-stretched state and (b) the actuated state by voltage.

2.1. Parallel arranged long fibers

As shown in Figure 1(d), the long fibers are continuously embedded in the DE membrane through the horizontal direction. The long fibers are parallel distributed with fixed spacing in the perpendicular direction. We use nylon fishing lines as the fibers with 80 mm in length and 0.3 mm in diameter. We attach several fibers on one side of the pre-stretched membrane and then put another pre-stretched membrane on the fiber and make the fiber sandwiched between two membranes, and then exclude the air between the two membranes. In order to investigate the effects of fiber spacing on the actuation performances of the membrane, we vary the fiber spacing in the perpendicular direction and the number of fibers in the DE actuator. As shown in Figure 3(a)–(c), the fiber spacing in the perpendicular direction are 2, 4, and 6 mm.

We coat square-shaped compliant electrodes (carbon grease MG Chemical 846–80 G) in the central area and on both sides of the DE membrane. The coated compliant electrodes are not beyond the area of fibers in both horizontal and perpendicular directions. The length of the square electrode is 25 mm. We wire the electrode out and connect it with high-voltage power supply (TREK-610E) to apply high voltage on the DE membrane. Figure 3 shows the behavior of DE membranes with different fiber spacing under the same high voltage load (0 V and 8 kV). The results show that once the high voltage is applied on the membrane, electrode-coated areas expand in plane. Because the membranes have been bi-axially pre-stretched three times, if there is no fiber to restrain the DE membrane, the electrode-coated area will expand in both horizontal and perpendicular directions. Figure 3(a)–(c) shows the horizontal actuation of the DE membrane is restrained by the long fibers, while the DE membranes expand along the perpendicular direction. Because the horizontal deformation of the membrane is restrained, the
perpendicular deformation increases. We further compare the behaviors of DE membrane with different fiber spacing. In Figure 3, we find when the fiber spacing increases, the perpendicular actuation will increase. The displacements of central point of the lateral fiber in Figure 3(a)–(c) are 2.3, 2.5, and 2.8 mm. The limit case of the fiber spacing is zero and infinite, which corresponds the DE membrane with fully occupied fibers and no fiber. From above we know that the long fiber will transfer part of the horizontal deformation into perpendicular deformation, but at the same time, since the perpendicular deformation will make fibers bending, will also block perpendicular deformation to a certain extent. That means there must be a most reasonable spacing that will induce the maximum perpendicular deformation. Parallel-arranged long fibers can help us eliminate deformation in one direction and increase the deformation in the other direction, and we can change the deformation value along the other direction through changing the fiber spacing.

2.2. Parallel-arranged short fibers

Short fiber can also be used to reinforce the DE membrane. The short fibers are not continuously embedded through the whole membrane. The short fibers are aligned in straight lines with gaps between each other in the horizontal direction. We use the spacing in the horizontal direction to define the short fiber arrangements (Figure 4). The manufacturing method of the parallel-arranged short fibers is the same as that of long fibers.

After we apply high voltage through the thickness direction of the DE membrane, we find that the short fiber will partly restrain the horizontal deformation, but not restrain the deformation along the perpendicular direction (Figure 4). Figure 4(a)–(c) also shows that when the fiber spacing in the horizontal direction decreases, the limitation to the
horizontal deformation increases. From these results, we find that parallel-arranged short fibers can help us change the deformation ratio along both the horizontal and perpendicular directions.

3. Fiber-reinforced dielectric elastomer membrane inflating structure

In this part, we experimentally investigate the electromechanical behavior of DE membrane inflating structure with radially arranged fibers. Figure 5 shows the fabricating procedure and the operation states of the DE membrane. The DE membrane is first pre-stretched and fixed by the rigid ring with the outer diameter of 80 mm and the inner diameter of 60 mm. We arrange eight fibers on the pre-stretched membrane along the radial direction. The fibers locate from the edge of the membrane and have the length of 26 mm. After we finish manufacturing the radially arranged fiber DE membrane, we fix it at one end of a cylindrical chamber of volume of 800 ml. After sealing the ring frame, DE membrane, and the chamber, we inflate air into the chamber using air pump through a one-way air valve. The membrane will be inflated to a spherical shape without applying voltage (Figure 5(d)). The amount of air in the chamber is fixed during the actuation of DE membrane by voltage loads. Figure 6 shows the experimental results of the DE membrane. Because the fiber is not connected at the center of the circular membrane, when the membrane expands to a semi-sphere [8], the part without fiber at the center of the membrane will have a larger deformation. The top area of the DE membrane buckles up (the buckled area is above the dashed line). Therefore, we observe that when we apply high voltage through the thickness direction of the DE membrane [23], the main deformation concentrates in the middle part of the membrane and produces great sonic characteristics.

Figure 4. DE membrane in-plane actuator with short fiber in its pre-stretched state and actuated state under 8 kV. The fiber spacing in the perpendicular direction is 4 mm. The fiber spacing in the horizontal direction are (a) 8 mm, (b) 4 mm, and (c) 2 mm.
Figure 5. DE membrane inflating actuator with radially arranged fibers in various states: (a) the reference state of a DE membrane; (b) DE membrane is pre-stretched and fixed by a rigid frame; (c) fibers and carbon grease are integrated on the pre-stretched membrane. (d) the structure is inflated with only pressure but no voltage; (e) the structure is further actuated by voltage.

Figure 6. Experimental results of DE membrane inflating actuator: (a) the structure is inflated with only pressure but no voltage; (b) the structure is further actuated by 8 kV.
4. FEM simulation of DE in-plane actuator

Based on the experimental results in Section 2, we investigate the fiber-reinforced DE membrane with finite element simulations. The stress and strain distributions of parallel-arranged long fibers and parallel-arranged short fibers are illustrated by finite element simulations using ABAQUS 6.10. In the FEM simulation, the DE structure is consisted of two parts, the DE part and the fiber part. The actuation of the DE under the high voltage is simulated by using UMAT [28,33]. C3D8RH meshes are used in the simulation. The dimensionless shear modulus is 1, and the dimensionless permittivity is 0.3. The fiber part is set as linear elastic material, with the elastic modulus 15 times the shear modulus of the DE part [10]. The voltage loading is applied on the structure as temperature in the simulation. In order to compare the different structures, the pre-stretch of the DE part and the elastic modulus of the fiber part are the same, the load (equivalent to voltage in experiment) on the DE also equals. In the experiment, we sandwich the fiber between two pre-stretched membranes, but in the FEM simulation, we implant the fiber into the membrane. That means we first model the DE membrane as one structure, and then define part of its section as the fiber material. We change the number and the spacing of the fibers to show the comparison. The number of the fibers are 3, 5, and 7 with the corresponding spacing of 10, 6, and 4 mm. Figure 7 shows the comparison of long fiber–reinforced membrane of different numbers and spacing of

![Figure 7](image)

Figure 7. The displacement magnitude distribution of DE membrane in-plane actuator with long fibers. The fiber spacing in the perpendicular direction are (a) 4 mm, (b) 6 mm, and (c) 10 mm. (d) No fiber is used in the DE membrane.
fibers. The FEM results show the distribution of displacement on the DE membrane. We find if there is no fiber, the deformations of the membrane along horizontal direction and perpendicular direction are nearly the same (Figure 7(d)). In the DE membrane with long fibers, the deformation along horizontal direction is restrained. When we increase the number of fibers and decrease the spacing of fibers, the limitation to the horizontal deformation increases.

We also study the effects of driven force of the DE membrane with parallel long fibers. The distributions of Mises stress magnitudes are investigated to illustrate the driven force of the DE membrane. From Figure 8, we find if there is no fiber the stress of the membrane along horizontal direction and perpendicular direction are basically the same. But once we add long fibers into the membrane, the stress along horizontal direction is limited. From the analysis, we know that the displacement along horizontal direction is also limited. We can obtain the driven force by multiplying the stress and displacement. Therefore, we get the results that parallel long fibers can limit the driven force in one direction and only output force from the other direction.

Figure 9 shows the FEM simulation of DE membrane with parallel-arranged short fibers. We vary the fiber spacing in the horizontal direction to show the comparison. When the fiber spacing in the horizontal direction is small (Figure 9(a)), the limitation to horizontal

Figure 8. The Mises stress magnitude distribution of DE membrane in-plane actuator with long fibers. The fiber spacing in the perpendicular direction are (a) 4 mm, (b) 6 mm, and (c) 10 mm. (d) No fiber is used in the DE membrane.
deformation is almost the same with parallel-arranged long fibers. And when the fiber spacing in the horizontal direction increases, the limitation to the horizontal deformation decreases.

5. Conclusion

In this paper, we investigate the electromechanical behaviors of fiber-reinforced DE membrane structure. The actuation of the DE structures is investigated with both experiments and FEM simulations. Fiber arrangements largely affect the voltage-induced actuation of the DE membrane. The actuation in the perpendicular direction of the DE membrane with long fibers first increases and then decreases by increasing the fiber spacing in the perpendicular direction. The actuation in the perpendicular direction of the DE membrane with short fibers only depends on fiber spacing in the perpendicular direction, whereas the actuation in the horizontal direction depends on fiber spacing in the horizontal direction. In the membrane inflating structure, the radially arranged fibers will break the axisymmetric behavior of the structure. The top area of the inflated balloon without fiber will buckle up when the voltage reaches a certain level.
Disclosure statement
No potential conflict of interest was reported by the authors.

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