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A novel electro-active bushing based on dielectric elastomer and circular double-V auxetic structure

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ABSTRACT
A novel electro-active bushing (EAB) design is proposed based on the unique physical properties of dielectric elastomers. A dielectric elastomer is applied as the tendon layer to a circular two-dimensional double-V auxetic structure. When load and voltage excitation vary, mechanical performance and dimensions of dielectric elastomers change, which empowers EAB to realize an electrostrictive phenomenon and real-time variable stiffness under different voltages. An EAB structure can endure mechanical loads along all directions in a cross-sectional plane, which is more practical than our previous design which can only bear loads along one direction. A theoretical electromechanical model of an EAB unit cell was proposed based on the physics theory of dielectric elastomers. The influences of unit cell parameters on electromechanical responses were researched. Moreover, an EAB prototype was fabricated via the 3D printing method. The experiments using EAB prototype applied 3M VHB 4910 and 3M VHB 9473 acrylic membranes prestretched by 200% and 300%, respectively, were conducted. The results indicated that the electrostrictive displacement increases as the load increases, and the stiffness decreases with the rise in voltage. Greater stiffness is obtained by higher original thickness and prestretch rates, but the electrostrictive displacement and stiffness variation under high excitation was dramatically affected.

I. INTRODUCTION
A dielectric elastomer with compliant electrodes is a focused category of the electro-active polymer (EAP). Its structure is similar to a sandwich panel where the core material is a dielectric elastomer membrane. Compliant electrodes were coated on both sides of the dielectric elastomer membrane. The shape and dimensions of a dielectric elastomer vary greatly and respond fast to a certain electric excitation and vice versa. It can achieve interconversion between electric energy and mechanical energy. The states of voltage, charge, load, and displacement of a dielectric elastomer are all coupled. A change in any of these states will cause a change in the states of the other parameters. In view of this issue, Suo established an electromechanical coupling model of dielectric elastomers based on thermodynamic free energy theory, which avoids complex coupling between mechanics and electrostatics. Instability is one primary issue of dielectric elastomers. Zhao and Suo overcame the electromechanical instability of dielectric elastomers by applying proper dielectric elastomer materials. Moreover, a moderate prestretch is an important method to improve its electromechanical performance. Electro-active displacement and force, energy density, and transition efficiency can all be enhanced. However, the thickness of a dielectric elastomer membrane varies much less than its length and width. Many studies used support components to change the stretching deformation of dielectric elastomers into a translation motion in order to achieve large actuation displacement, including cone-type and rolled-type dielectric elastomer actuators.

Wang et al. applied dielectric elastomers to a double-V auxetic (DVA) structure. It revealed that the combination of the DVA structure and dielectric elastomer can result in real-time variable stiffness and large electro-active displacement. The electromechanical property of one unit cell can be superimposed to achieve greater
performance. Auxetic is also known as negative Poisson’s ratio (NPR). Poisson’s ratio is a material inherent property that indicates the relation between longitudinal and lateral deformation behavior of a material or even a structure in a more generalized perspective. When the materials or structures have negative Poisson’s ratio, it will exhibit some attractive behavior, including material concentration, stiffness hardening, and even vibration insulation and energy absorption when applying certain materials, which are ideal for some specific conditions. There are several categories of auxetic structures: re-entrant hexagonal, double-V, chiral, rotating unit, hollow sphere, porous, and origami. Generally, a dielectric elastomer can only be applied on re-entrant types of auxetic structures, especially the DVA type, because in the entranent types of auxetic structures, there are cell walls that only bear tension stress. These cell walls can be replaced by dielectric elastomer membranes. Additionally, the DVA structure had the highest effective Young’s modulus and modest absolute value of effective Poisson’s ratio among all types and was most appropriate to be applied as load bearing components, especially bushing. Applying a dielectric elastomer in a DVA structure is a promising idea to achieve real-time variable mechanics, energy harvesting, sensing, and other fascinating behaviors of auxetic structures. However, the previously proposed structure can only deform along one direction.

II. MATERIALS

Bushing is a flexible component in mechanical systems and connects parts with compliance. It should endure mechanical loads along all directions in the cross-sectional plane. It can isolate high frequency shock, absorb vibration energy, reduce noise, and reduce mechanical wear. Its stiffness influences the abovementioned performances of a mechanical system. The mechanical performances of conventional bushings, especially stiffness, are basically fixed. They cannot change instantaneously with respect to diverse conditions. In this paper, the conceptual design of a circular auxetic structure was first proposed by wrapping a two-dimensional DVA structure and connecting it end-to-end, as shown in Fig. 1(a). When applying hyperelastic materials as its tendon parts, the circular auxetic structure can be used as bushing components to isolate vibration between components. However, when its base materials and structural parameters were determined, its mechanical performance was fixed.

A dielectric elastomer membrane was applied as the tendon part to the circular auxetic structure in this paper, as shown in Fig. 1(b). It is called electro-active bushing (EAB). In EAB, the outer and inner stuffers were designed to be solid to ensure high stiffness. The dielectric elastomer membrane was initially uniaxial prestretched and then installed between the inner stuffer and outer stuffer. Great energy absorption capability can already be achieved when applying a dielectric elastomer. The EAB structure can endure mechanical loads along all directions in the cross-sectional plane. It is more practical than the previous design which can only bear loads along one direction and is not applicable in certain applications. The shade sector area represents one EAB unit cell. There are 10 EAB unit cells in the entire EAB structure, as shown in the figure. The number of unit cells can be varied in order to satisfy different design requirements. The inner diameter of the inner stuffer is 26 mm, while the outer diameter of the outer stuffer is 132 mm. The width of the EAB prototype is 36 mm. The tendon part in one EAB unit cell is V-shape, similar to the cross-section of a cone-type dielectric elastomer actuator. The stuffer part hardly deforms and functions as the support structure of the dielectric elastomer tendon. Therefore, EAB will not show auxetic behavior. However, the support structures change the stretching deformation of the dielectric elastomer membrane into a translational motion. Similar to the cone-type dielectric elastomer actuator, EAB can also realize actuating, sensing, and energy harvesting. The electromechanical performance of EAB, primarily the electrostrictive displacement and real-time variable stiffness, will be researched both theoretically and experimentally in this paper. The energy harvesting and sensing performances of EAB will not be discussed.

In order to research the experimental electromechanical performances of the entire EAB structure, an EAB prototype was manufactured, as shown in Fig. 1(c). The structural parameters of the prototype are the same as the one shown in Fig. 1(b). The outer and inner stuffers were manufactured using photosensitive resin via stereo lithography appearance (SLA) 3D printing technology. The photosensitive resin has a high dielectric strength and is able to insulate high voltage that a dielectric elastomer requires. Two stands were added at the bottom of the outer stuffer to support the entire EAB prototype in the experiment. Furthermore, the outer stuffer was divided into two parts, which are designed for the assembling of the tendon membrane. Eight holes were slotted from the outer stuffer to reduce weight and costs, but holes were not slotted at the left.
and right sides of the outer stuffer considering convenient installation. Two types of acrylic membranes were applied as the dielectric elastomer in this study, which are a 1 mm thick 50 mm wide 3M VHB 4910 acrylic membrane and a 0.25 mm thick 100 mm wide 3M VHB 9473 acrylic membrane. Actually, they are both adhesive tapes and originally manufactured for adhesive purpose. However, they exhibit excellent dielectric performance and had been widely used as electro-active polymers. The acrylic membrane was firstly uniaxial pre-stretched and coated with carbon grease on both sides. Carbon grease is made up of carbon powder, silicone oil, and n-heptane in the proportion of 1 g:12 ml:25 ml. It has high conductivity and can be uniformly and firmly attached to the surface of the acrylic membrane. Then, the acrylic membrane was wrapped around the inner stuffer and was placed on the corresponding position connected with the lower half part of the outer stuffer. Finally, the upper half part of the outer stuffer was installed on the top of the lower half part of the outer stuffer and was also connected with the tendon membrane. Two parts of the outer stuffers were connected using a bolt-slot mechanism and then were glued together. After that, the inner stuffer can move vertically under different loads and voltages.

III. THEORETICAL METHOD

Both sides of the dielectric elastomer membrane are coated with soft and thin compliant electrodes, as shown in Fig. 2. The original dimensions of the dielectric elastomer are length $L_1$, width $L_2$, and thickness $L_3$. After applying a voltage $\Phi$ on the dielectric elastomer, charges $\pm Q$ will be accumulated on the two compliant electrodes. The positive and negative charges produce an electrostatic Coulomb force along the thickness direction. Then, the dielectric elastomer is compressed along the thickness direction, which reduces the thickness and expands the area.

Suppose the dimensions of the dielectric elastomer become $l_1$, $l_2$, and $l_3$. The stretches of the dielectric elastomer are defined by $\lambda_1 = l_1/L_1$, $\lambda_2 = l_2/L_2$, and $\lambda_3 = l_3/L_3$. True stresses are $\sigma_1$, $\sigma_2$, and $\sigma_3$. The true electric field is $E = \Phi/l_1$. An acrylic membrane was applied as the dielectric elastomer in this study, which can be considered as an incompressible material. Then, the relation between the stretches is $\lambda_1 \lambda_2 \lambda_3 = 1$. An isothermal process is assumed, and the influence of temperature is ignored. With reference to Suo’s theory, the following equilibrium equations are considered:

$$
\begin{align*}
\sigma_1 - \sigma_3 &= \lambda_1 \frac{\partial W_s(\lambda_1, \lambda_2)}{\partial \lambda_1} - \varepsilon E^2, \\
\sigma_2 - \sigma_3 &= \lambda_2 \frac{\partial W_s(\lambda_1, \lambda_2)}{\partial \lambda_2} - \varepsilon E^2,
\end{align*}
$$

(1)

where $W_s(\lambda_1, \lambda_2)$ is the strain energy function of the hyperelastic material with respect to $\lambda_1$ and $\lambda_2$, and $\varepsilon$ is the dielectric constant of the dielectric elastomer. Equation (1) can be used for the prediction of the electromechanical state of the dielectric elastomer membrane if the permittivity $\varepsilon$ and strain energy function $W_s(\lambda_1, \lambda_2)$ were confirmed.

When assembling the dielectric elastomer membrane into EAB, its mechanical state will be more complex. In this paper, an EAB unit cell will be studied theoretically. The entire EAB will be researched by experiments. The cross-sectional view of a half EAB unit cell is shown in Fig. 3. A stuffer can be made of any material, and its deformation should be taken into consideration. However, this problem may become much more complicated. Consequently, stuffer parts were considered as rigid bodies since they were much stiffer than the dielectric elastomer membrane. The unstretched tendon represents the dielectric elastomer membrane in a half unit cell before being assembled into the EAB. Suppose the length of the unstretched tendon is $L_1$, its width and thickness are $L_2$ and $L_3$, respectively. The prestretched tendon represents the dielectric elastomer membrane when it was prestretched and just connected with the outer stuffer. Its length was elongated to $l_1$, while its stretch was defined by $\lambda_0 = l_1/L_1$. When a force $P$ or voltage $\Phi$ is applied on the tendon, it will be further stretched and move downwards. The length, width, and thickness of the stretched tendon become $l_1$, $l_2$, and $l_3$, respectively. The stretch of the stretched tendon will be $\lambda_1 = l_1/L_1$. The internal force inside the tendon is $P_1$. Then, $P_1 = P/2 \cos \theta$, where $\theta$ is the angle between the stretched tendon and the vertical axis. Since $\sin \theta = l_0/l_1 = \lambda_0/\lambda_1$, it is known that $\cos \theta = \sqrt{1 - \lambda_0^2/\lambda_1^2}$. The vertical displacement of the tendon is defined by $u$, which is also equal to the displacement of the inner stuffer.

The dielectric elastomer membrane is assumed to be pure uniaxial stretched. Therefore, the stretches and stresses along the lateral directions are $\lambda_2 = \lambda_3 = \lambda_1^{-1/2}$ and $\sigma_2 = \sigma_3 = 0$. Then, the first relation of Eq. (1) becomes

$$
\sigma_1 = \lambda_1 \frac{\partial W_s(\lambda_1)}{\partial \lambda_1} - \varepsilon E^2,
$$

(2)

where $W_s(\lambda_1)$ is the strain energy function with respect to $\lambda_1$. At present, several empirical strain energy functions of hyperelastic materials has been proposed and verified by experiments. The
Ogden strain energy function was applied in this paper due to its high reliability for constitutive modeling of dielectric elastomers. Its strain energy function is as follows:

$$W_s(\lambda_1) = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left( \lambda_1^{\alpha_i} + 2\lambda_1^{-\frac{\alpha_i}{2}} - 3 \right). \quad (3)$$

where $\mu_i$ and $\alpha_i$ are the Ogden model parameters which were obtained from Ref. 17. As per Eq. (2), $\sigma_1 = P_1/l_1$ and $E = \Phi/l_3 = \Phi \lambda_1^{1/2}/L_3$. Substituting all these relations and Eq. (3) into Eq. (2),

$$\frac{P_1^2}{2L_2L_3 \sqrt{\lambda_1^2 - \lambda_0^2}} - \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i} \left( \lambda_1^{\alpha_i} - \lambda_1^{-\frac{\alpha_i}{2}} \right) + \epsilon \Phi^2 \lambda_1 = 0. \quad (4)$$

In Eq. (4), only $\lambda_1$ is a variable. Thus, it can be calculated by solving the equation. Also, all the mechanical and electric states of the EAB unit cell can be confirmed. The vertical displacement of the tendon $u$ can be obtained through the following equation:

$$u = \frac{l_0}{\tan \theta} = L_1 \sqrt{\lambda_1^2 - \lambda_0^2}. \quad (5)$$

Three specific parametric studies were designed and performed by examining the effects of varying the (i) prestretch rates, (ii) thickness of the membrane, and (iii) width of the EAB unit cell on the electromechanical performance of the EAB unit cell. First, 4 cases with 150%, 200%, 250%, and 300% prestretch rates were researched. Although the dielectric elastomer can be stretched to a fairly high strain, it is still required to limit the maximum strain of the dielectric elastomer membrane. If the prestretch rate is too high, it may lead to a low critical breakdown voltage. Other parameters were the same as in the case in the experiment, which will be discussed later. The displacements under different loads were obtained by an established model and were shown in Fig. 4(a). It indicates that electrostriction displacement is ignorable under no external load in all cases. The electrostrictive displacement increases as the prestretch rate reduces.
Although the initial displacement was enlarged. The stiffness curves under different voltages have been illustrated in Fig. 4(b). It implies that 5 kV voltage excitation had a slight influence on the stiffness of the EAB unit cell with a 300% prestretched tendon. As prestretch rate decreased, the stiffness variation between 0 kV and 5 kV voltages increased. The region between the two curves of the same prestretch rate indicated the achievable mechanical states of the EAB unit cell in one case, which can be realized through the tuning of voltage. On the other hand, the stiffness of the EAB unit cell was gradually weakened with the reduction of the prestretch rate. Since the acrylic membrane was a highly nonlinear hyperelastic material, the effective Young’s modulus at a large nominal strain was much greater than the one at a small nominal strain.

Second, the results of 0.25 mm, 0.5 mm, 0.75 mm, and 1 mm thicknesses of the acrylic membrane have been illustrated in Figs. 4(c) and 4(d). The effect of increasing thickness is fairly similar to that of the rising prestretch rate, except for the fact that the stiffness variation of the thicker dielectric elastomer is much less apparent. Thus, increasing the thickness of a dielectric elastomer is not a recommended method to improve load bearing capacity since the electroresponse will be largely influenced. It is possible to apply a multi-layer tendon configuration to enhance the stiffness while keeping a considerable electroresponse.

Finally, the results of 18 mm, 36 mm, 54 mm, and 72 mm widths of the EAB unit cell have been illustrated in Figs. 4(e) and 4(f). The electrostrictive displacement in all cases is close. Also, the width hardly influences the level of stiffness variation despite the stiffness being dramatically enhanced with a larger width. Therefore, it is feasible to improve the load bearing capacity by increasing the width without sacrificing the degree of electroresponse.

**IV. EXPERIMENTAL RESULTS**

The theoretical model only refers to one EAB unit cell. Therefore, its electroresponse was relatively small. Since each EAB unit cell deforms diversely, the electromechanical performance of the entire EAB structure is much more complex and was studied in an experimental way. Two surfaces of the tendon membrane in the EAB prototype were connected to the positive and negative poles of the power supply using wires and an aluminum foil tape. Voltage and load are external input conditions. Voltage was applied by the DW-P103-1ACD8 power supply produced by Tianjin Dongwen High Voltage Inc. Voltage inputs were taken from 0 kV to 3 kV. The loads were applied by putting M1 class standard weights into the center of the inner stuffer. The mass loads weigh 50 g, 100 g, 200 g, and 250 g. In each test scheme, the load was kept unchanged, while the voltage increased from 0 kV to 3 kV with an interval of 0.5 kV. Under each voltage, all data were recorded after the EAB prototype reached the equilibrium state. The displacement of EAB was recorded by a Panasonic HG-C1050 laser displacement sensor with a precision of 30 μm.

In the first comparison group, VHB 4910 and VHB 9473 acrylic membranes were both 200% prestretched. The displacement results of EAB applied VHB 4910 are listed in Table I. It indicates that the displacement change from 0 kV to 3 kV under no extra load or a 50 g mass load was ignorable. As the load increased, the electrostrictive displacement at 3 kV voltage gradually improved. The displacement change from 0 kV to 3 kV was 0.08 mm under a 100 g mass load, while the displacement change was 0.23 mm under a 250 g mass load.

The displacement results of EAB applied VHB 9473 are listed in Table II. It implies that the displacement change from 0 kV to 3 kV with a 50 g mass load massively improved to 0.70 mm compared with EAB applied VHB 4910 under the same condition. When the load increased to 200 g, the electrostrictive displacement at 2.5 kV increased to 1.24 mm, but the acrylic membrane will break down under 2.9 kV. In comparison, the break down voltage of the VHB 4910 membrane under a 250 g mass load is nearly 6.1 kV, which is much higher than that of VHB 9473 even under a greater load. This result was attributed to the 0.25 mm initial thickness of the VHB 9473 membrane. It is much thinner than the 1 mm initial thickness of the VHB 4910 membrane. Since the acrylic membrane was not fairly uniform, the thickness was not exactly the same at every point. Down break usually appeared at the thinnest point of the membrane. Moreover, the thickness became much smaller after prestretching and loading, which makes the membrane much easier to be broken down by voltage. Considering the break down risk, the electrostrictive displacement of EAB applied VHB 9473 under a 250 g mass load was not tested.

As shown in Fig. 5(a), the displacement-voltage curves of EAB applied VHB 4910 and VHB 9473 under different loads were plotted according to the data in Tables I and II. The solid lines represent the displacements of EAB applied VHB 4910 under different loads, while the dashed lines illustrate the displacements of EAB applied VHB 9473. The following conclusions, which are the same, can be drawn: Both cases have ignorable displacement variation from 0 kV

| TABLE I. Displacement of EAB using 1 mm thick VHB 4910 with a prestretch rate of 200%. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Load (g) | 0 kV | 0.5 kV | 1 kV | 1.5 kV | 2 kV | 2.5 kV | 3 kV |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0.80 | 0.80 | 0.80 | 0.81 | 0.81 | 0.81 | 0.81 |
| 100 | 1.24 | 1.25 | 1.26 | 1.27 | 1.28 | 1.30 | 1.32 |
| 200 | 1.64 | 1.74 | 1.80 | 1.83 | 1.85 | 1.87 | 1.90 |
| 250 | 2.30 | 2.34 | 2.41 | 2.43 | 2.46 | 2.50 | 2.53 |
TABLE II. Displacement of EAB using 0.25 mm thick VHB 9473 with a prestretch rate of 200%.

| Load (g) | Voltage 0 kV | Voltage 0.5 kV | Voltage 1 kV | Voltage 1.5 kV | Voltage 2 kV | Voltage 2.5 kV | Voltage 3 kV |
|---------|--------------|----------------|--------------|----------------|--------------|--------------|--------------|
|         | 0            | 0              | 0            | 0              | 0            | 0            | 0            |
|         | 50           | 1.35           | 1.53         | 1.58           | 1.65         | 1.74         | 1.88         | 2.05         |
|         | 100          | 3.27           | 3.39         | 3.51           | 3.65         | 3.76         | 3.91         | 4.17         |
|         | 200          | 3.81           | 4.04         | 4.22           | 4.46         | 4.70         | 5.05         | Break down   |

to 3 kV under a low mass load. As the load increases, the electrostrictive displacement gradually improves as long as the voltage does not reach a critical value. The electrostrictive displacement with VHB 9473 was much greater than that with VHB 4910 despite the initial displacement being larger under the same load.

Extracting the data shown in Tables I and II on the load-displacement surface, the stiffness curves of EAB can be obtained as shown in Fig. 5(b). The solid lines represent the stiffness curves of EAB applied VHB 4910 under different voltages, while the dashed lines illustrate the stiffness curves of EAB applied VHB 9473. Figure 5(b) implies that the stiffness of EAB made of the same dielectric elastomer membrane decreased with the increase in voltage. EAB applied VHB 4910 was stiffer than EAB applied VHB 9473 due to its larger original thickness. However, all solid curves were fairly close to each other, especially at a small displacement. Also, there were apparent intervals between the dashed curves. Thus, VHB 4910 responded less than VHB 9473 under voltage excitation. The following factors should be responsible for the above fact: Larger thickness of the dielectric elastomer membrane led to higher stiffness of EAB, but the electrostatic force produced by the electric field was lowered and was much less than the internal elastic force of the dielectric elastomer under load. Therefore, voltage excitation had less influence on the stiffness of EAB with the thicker dielectric elastomer membrane. The results are in accordance with the theoretical analysis.

FIG. 5. (a) Displacement-voltage curves and (b) load-displacement curves of EAB applied VHB 4910 and VHB 9473 with a prestretch rate of 200% under different loads and voltages; and (c) displacement-voltage curves and (d) load-displacement curves of EAB applied VHB 9473 with a prestretch rate of 200% and 300% under different loads and voltages.
In the second comparison group, VHB 9473 was prestretched by 200% and 300%. The former case had already been conducted. In the 300% prestretched case, the maximum voltage and the maximum load are set at 2 kV and 200 g, respectively, to avoid electrical breakdown. The displacement results of this case are listed in Table III. It indicates that the displacement change from 0 kV to 2 kV with a 200 g mass load was 0.16 mm. It was much less than the 200% prestretched case, which is 0.89 mm. Since a greater prestretch rate resulted in higher stiffness at the initial range, the mechanical deformation of the greater prestretched acrylic membrane generated by electrostatic force will be less.

As shown in Fig. 5(c), the displacement-voltage curves of EAB applied VHB 9473 with different prestretch rates under different loads were plotted according to the data provided in Tables II and III. The dashed lines represent the displacements of EAB with a 200% prestretched membrane under different loads, while the solid lines illustrate the displacements of EAB with a 300% prestretched membrane. Dashed curves had larger slopes than solid curves, which indicates that the electromechanical response with the 200% prestretched acrylic membrane was greater than that with the 300% prestretched one, despite the displacement being larger under the same load. The influence of a decreasing prestretch rate is similar to that of decreasing thickness.

Extracting the data shown in Tables II and III on the load-displacement surface, the stiffness curves of EAB with different prestretch rates can be obtained as shown in Fig. 5(d). The dashed lines represent the stiffness curves of EAB with the 200% prestretched membrane under different voltages, while the solid lines illustrate the stiffness curves of EAB with the 300% prestretched membrane. Figure 5(d) implies that the stiffness of EAB with the same prestretch rate decreased with the increase in voltage. EAB with the 300% prestretched membrane was stiffer than that with the 200% prestretched membrane due to its larger prestretch rate. However, all solid curves were fairly close to each other, especially at a small displacement. However, there were apparent intervals between the dashed curves. Thus, EAB with the 300% prestretched membrane responded less than that with the 200% prestretched membrane under voltage excitation. The following factors should be responsible for the above fact: A larger prestretch rate of the dielectric elastomer membrane led to higher stiffness of the dielectric elastomer in EAB. The electrostrictive force produced by the electric field was also improved with a larger prestretch rate, but it was relatively too low to withstand the enhanced stiffness of the dielectric elastomer. Therefore, voltage excitation had less influence on the stiffness of EAB with a larger prestretched membrane. The effect of reducing the prestretch rate is fairly similar to that of decreasing thickness, which is also in accordance with the theoretical analysis.

V. CONCLUSIONS

This paper proposed a novel electro-active bushing design, which applied a dielectric elastomer membrane as the tendon part of a circular auxetic structure. The theoretical electromechanical model of the EAB unit cell was derived. An EAB prototype was manufactured. The electromechanical responses of the EAB prototype with two thicknesses and two prestretch rates of the dielectric elastomer were tested. The following conclusions can be drawn:

1. The test results agree well with the theoretical analysis results. The electrostrictive displacement of EAB under a fixed load increases as voltage increases, that is, a higher voltage leads to lower stiffness, which proved that real-time variable stiffness was achieved. VHB 4910 was much thicker than VHB 9473, and its stiffness was greater than VHB9473. However, the electrostrictive response of VHB 4910 was lower than VHB9473. Moreover, a greater prestretch rate resulted in greater stiffness of EAB, and the electrical response was also lowered.

2. The breakdown voltage is related to the thickness and prestretching rate of the membrane. A thinner membrane and larger prestretch rate led to a lower break down voltage. The load bearing capability of EAB is relatively small and requires further improvement to be actually applied in certain mechanical systems. Increasing the thickness of the dielectric elastomer is not a recommended method to improve load bearing capacity since the electroresponse will be largely influenced. It is possible to apply a multilayer tendon configuration to enhance the stiffness while keeping a considerable electroresponse. It is also feasible to improve the load bearing capacity by increasing the width or increasing the number of unit cells without affecting the electroresponse.

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