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ABSTRACT
The energy conversion process of dielectric elastomers is an electromechanical coupling behavior, and the constitutive model of the material is the basis for studying electromechanical coupling characteristics. In order to explore the constitutive model of dielectric elastomers, based on the theory of continuum mechanics, combined with the superelastic constitutive model, a mechanical constitutive model was described, and the basic equations of the constitutive model were obtained. At the same time, combined with uniaxial, biaxial, and pure shear stretching, the three tensile methods, the relationship between the tensile rate and the force of the dielectric elastomer under three kinds of stretching modes was obtained. The experimental data were fitted by the COMSOL software, and the fitting curves of the relationship between stress and elongation of four superelastic models were obtained. Comparative analysis of the experimental data and fitted curve showed that the Neo-Hookean model had the worst fitting effect. The Yeoh model and the Ogden model had better shear fitting. The Mooney-Rivlin model fitted well in the three stretching modes. The conclusions of this study provided the basis for the study of the electromechanical coupling characteristics of dielectric elastomers.

I. INTRODUCTION
Dielectric elastomers (DE) are a member of electroactive polymers (EAPs), including polyacrylate, silicone rubber, silicone resin, and natural rubber. It is a new type of functional material capable of not only being used as a bionic drive to convert electrical energy into mechanical energy but also to be reversely applied to the field of power generation, converting mechanical energy into electrical energy.1–4 DEs have the characteristics of large strain, fast response, low price, light weight, and high flexibility.5–8 Compared with other materials, DEs have a higher energy conversion efficiency and specific energy density. For example, the specific energy density of polyacrylate is up to 3.4 J/g, and the energy conversion efficiency can reach 60%–80%; the specific energy density of silicone resin is 0.75 J/g, and the energy conversion efficiency can reach up to 90%.9,10 DEs are very suitable for applications that require a high modulus and fast response, such as human bio-energy, bionic robots, artificial joints, and artificial hearts.11 It is also applicable to wind energy and ocean energy that require a greater efficiency and in large deformation sites, such as wind energy generators and wave energy generators.12,13

A dielectric elastomer actuator (DEA) is a DE with upper and lower coated electrodes. After the electrodes are charged, the charges between the upper and lower surfaces of the flexible electrodes attract each other to generate Maxwell’s force, thereby compressing the DE film and realizing the conversion of electric energy to mechanical energy.14,15 A dielectric elastomer generator (DEG) is a kind of a “sandwich” three-layer variable capacitor, coated with flexible electrodes on the upper and lower layers, with the DE as the carrier and extracted by electrode wires. Its generation principle is similar to that of a variable capacitor.16 The conditions that restrict the conversion efficiency of the converter include brittleness and electrode deformation not meeting the requirements. Therefore, it is important to thoroughly study the mechanical properties of DEs. Because DEs and their composites have large deformation and geometric nonlinearity in mechanics and most of them work in the...
environment of multiple physical coupling fields, it is of great value to study the mechanical problems of DE materials. At the same time, the study of the constitutive model parameters of DE materials is the basis of the study of mechanical problems.

Continuum mechanics is the mechanics for dealing with the macroscopic properties of a continuum. It focuses on the axiom system with commonality, the conservation law, and the objectivity requirements for establishing constitutive relations. It is a powerful tool to study the law of soft material motion. DEs are a superelastic material with large nonlinear deformation characteristics. The general models that describe their superelastic constitutive relations are the Neo-Hookean model, the Yeoh model, the Ogden model, and the Mooney-Rivlin model. The general deformation mode of the film-type dielectric elastomer, shown in Fig. 1, includes (a) uniaxial stretching, (b) biaxial stretching, and (c) pure shear stretching.

At present, researchers usually use a constitutive model obtained by uniaxial fitting to characterize the constitutive material of uniaxial, biaxial, and pure shear. However, in practical applications, the deformation of DEs is the composite state of uniaxial, biaxial and pure shear. Figure 2 shows the schematic diagram of the DEG electromechanical coupling simulation. The determination of the constitutive model is the basis of electromechanical coupling simulation. The purpose of this paper is to obtain a constitutive model suitable for the three stretching modes and the corresponding material parameters. In order to get more accurate DE material constitutive model parameters, this study is based on the theory of continuum mechanics, combined with four superelastic constitutive models, and the mechanical properties of the strains were analyzed under three kinds of stretching. The large deformation strain, superelastic strain energy function, and superelastic constitutive equation of DEs were obtained. At the same time, three kinds of stretching experiments were carried out, and the experimental data were fitted by the COMSOL software. The composite fitting curve and experimental data were compared to obtain the most suitable superelastic model and material constitutive parameters. It provided a reference and basis for the study of the electromechanical coupling characteristics of dielectric elastomer drivers or generators.

II. DIELECTRIC ELASTOMER CONSTITUTIVE MODEL

A. Material configuration and coordinate system description

In a particular geometric space, it is assumed that the spatial area occupied by the DE material at the initial moment was A, called the initial configuration, and the $t_0$ time was set to the initial state of the DE stretch contraction. It is assumed that the spatial area occupied by the DE material at any time (any time during the stretching process) was B, which is called the current configuration, as shown in Fig. 3.

To describe the strain of the large deformation of a DE material, its specific location in the geometric space region must be determined. Let $X[X_1, X_2, \ldots, X_i]$ be the set of points in the initial configuration A. According to Lagrange's law, the position $X[X_1, X_2, \ldots, X_i]$ of the point set in the initial configuration A is represented by the coordinate vector $X[x_1, x_2, \ldots, x_i]$ in the Lagrange coordinate system. Similarly, let $x[X_1, X_2, \ldots, X_i]$ be the set of points in the current configuration B. According to Lagrange's law, the position...
\[ x = X + u - b. \] (1)

**B. Strain description of the large deformation of the material**

The mapping between vector \( X \) and vector \( x \) can be expressed as
\[ x = f(X, t). \] (2)

The deformation gradient tensor \( F \) from the initial configuration \( A \) to the current configuration \( B \) can be shown as
\[ F = \frac{\partial x}{\partial X}. \] (3)

Let the tiny shape of the initial configuration \( A \) be \( dX \), and the minute shape of the current configuration \( B \) be \( dx \); then,
\[ dx = FdX. \] (4)

Let \( ds^2 \) be the square of the length of the tiny deformation \( dX \) of the current configuration \( B \); then,
\[ ds^2 = dX \cdot dX = dX \cdot F^T \cdot F \cdot dx, \] (5)

where \( C = F^T \cdot F \) represents the right Cauchy Green tensor, and \( B = F^T \cdot F \) is defined as the left Cauchy Green tensor. Let \( dS^2 \) be the square of the length of the tiny deformation \( dX \) of the initial configuration \( A \); then,
\[ dS^2 = dX \cdot dx = dx \cdot B^{-1} \cdot dx. \] (6)

The primary elongation is defined as
\[ \lambda = \frac{ds}{dS} = \frac{|dx|}{|dX|}. \] (7)

The strain tensor can also be used to describe the deformation of the initial configuration \( A \) to the current configuration \( B \), and the strain tensor takes a value of zero when there is no deformation
\[ E = \frac{1}{2} (C - I), \] (8)

where \( I \) is a second-order unit tensor.
\[ \epsilon = \frac{1}{2} (I - B^{-1}). \] (9)

and
\[ E = F^T \cdot \epsilon \cdot F, \] (10)

where \( F = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} \). Since the DE film has an incompressible property, \( \lambda_1\lambda_2\lambda_3 = 1 \), and \( \det(F) = 1 \).

For the left and right Cauchy Green tensors, the primary elongation \( \lambda_i = (i = 1, 2, 3) \) can be used to represent the three invariants in the second order unit tensor \( I \).
\[ \begin{cases} I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2, \\ I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2, \\ I_3 = \lambda_1^2\lambda_2^2\lambda_3^2. \end{cases} \] (11)

**C. Superelastic strain energy function description**

DEs are a superelastic material, where the energy in the material depends only on the initial state and final state of the deformation; DEs are independent of the deformation (load) path, so the strain energy function is an effective way of stress-strain constitutive relations to describe the superelastic material.

Common superelastic constitutive models are Neo-Hookean, Mooney-Rivlin, Ogden, and Yeoh models. These superelastic constitutive models are defined by the strain energy density \( W_S \), which is a function \( W_S = W(I_1, I_2, I_3) \) of the left Cauchy strain tensor invariant \( I_1, I_2, I_3 \).

The Neo-Hookean model is an upgraded version of Hooke's Law that describes the mechanical nonlinearity of materials and is used to describe the mechanical behavior of superelastic materials. The Neo-Hookean model is the simplest model of several superelastic models and is only related to the first left Cauchy strain tensor invariant \( I_1 \). For the DE, which is an incompressible material, the strain energy density function is
\[ W_S = C_1(I_1 - 3), \] (12)

where \( C_1 \) is the material parameter, and \( I_1 \) is the first left Cauchy strain tensor invariant.

The Mooney-Rivlin model is a superelastic material jointly proposed by Melvin Mooney and Ronald Rivlin.\(^ {22} \) The model can accurately describe the state of superelastic material under large deformation, and its structure is relatively simple; there only two material parameters in the model. The Mooney-Rivlin model is related to both the first and second left Cauchy strain tensor invariants \( I_1 \) and \( I_2 \). The strain energy density function is
\[ W_S = C_1(I_1 - 3) + C_2(I_2 - 3), \] (13)

where \( C_1 \) and \( C_2 \) are the material parameters, \( I_1 \) is the first left Cauchy strain tensor invariant, and \( I_2 \) is the second left Cauchy strain tensor invariant.

The Yeoh model is only related to the first left Cauchy strain tensor invariant \( I_1 \); it weakly describes biaxial stress strain, and its strain energy density function is
\[ W_S = C_1(I_1 - 3) + C_2(I_1 - 3)^2 + C_3(I_1 - 3)^3, \] (14)
where $C_1$, $C_2$, and $C_3$ are the material parameters.

The Ogden model is a superelastic model proposed by Ogden in 1972. Its expression of strain energy density function is more complicated. Although it can be used for materials with strain levels up to 700% and it can describe the characteristics of materials under large strain, the calculation is complicated. Its strain energy density function is

$$W_S = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i} \left( \lambda_i^{n_i} + \lambda_i^{m_i} + \lambda_i^{\alpha_i} - 3 \right), \quad (15)$$

where $\mu_i$ and $\alpha_i$ are the material parameters, and $\lambda_i$ is the main elongation rate.

D. Superelastic constitutive basic equation

According to the theory of elastic mechanics, for superelastic materials, the Cauchy principal stress $\delta_i$ is given by the strain energy to the elongation rate $\lambda_i$, as follows:

$$\delta_i = \lambda_i \frac{\partial W_S}{\partial \lambda_i} - p(i = 1,2,3), \quad (16)$$

where $p$ is the hydrostatic pressure and is given by the kinetic boundary conditions.

According to kinetic boundaries of uniaxial stretching, biaxial stretching, and pure shear stretching,

\[
\begin{align*}
\text{uniaxial}: \delta_1 &= \delta, \delta_2 = \delta_3 = 0, \lambda_1 = \lambda, \lambda_2 = \lambda_3 = \lambda^{-1/2}, \\
\text{pure shear}: \delta_1 &= \delta, \delta_2 = 0, \delta_3 = 0, \lambda_1 = \lambda, \lambda_2 = 1, \lambda_3 = \lambda^{-1}, \\
\text{biaxial}: \delta_1 = \delta_2 = \delta, \delta_3 = 0, \lambda_1 = \lambda_2 = \lambda, \lambda_3 = \lambda^{-2}.
\end{align*}
\]

(17)

The relevant principal stress can be derived. Now, based on the pure shear tensile mode and the Yeoh superelastic constitutive model, the relevant derivation is made.

Let $\delta_3 = 0$ be substituted into formula (16); the formula of $p$ is

$$p = \lambda_3 \frac{\partial W_S}{\partial \lambda_3}, \quad (18)$$

Substituting formula (14) into formula (18), the formula of $p$ is

$$p = \lambda_3 \frac{\partial W_1}{\partial \lambda_3} \left[ C_{10} + 2C_{20} (I_1 - 3) + 3C_{30} (I_1 - 3)^2 \right]. \quad (19)$$

Substituting formula (14) and (17) into formula (16), the formula of $\delta_1$ is

$$\delta_1 = \left( \lambda_1 \frac{\partial W_1}{\partial \lambda_1} - \lambda_3 \frac{\partial W_1}{\partial \lambda_3} \right) \left[ C_{10} + 2C_{20} (I_1 - 3) + 3C_{30} (I_1 - 3)^2 \right]. \quad (20)$$

From formula (17), the following formula can be derived:

$$\lambda_1 \frac{\partial W_1}{\partial \lambda_1} - \lambda_3 \frac{\partial W_1}{\partial \lambda_3} = 2\lambda_3^2. \quad (21)$$

Substituting formula (21) into formula (20), the formula of $\delta_1$ is

$$\delta_1 = 2(\lambda_1^{-2} - \lambda_3^{-2}) \left[ C_{10} + 2C_{20} (I_1 - 3) + 3C_{30} (I_1 - 3)^2 \right]. \quad (22)$$

Since the DE material is incompressible, the main tensile rate of the DE film in the pure shear stretching mode has the following relationship:

$$\lambda_1 = \lambda, \lambda_2 = 1, \lambda_3 = \lambda^{-1}. \quad (23)$$

According to formulas (17) and (21), the 1-direction principal stress based on the Yeoh model in the pure shear mode is

$$\delta_1 = 2(\lambda^2 - \lambda^{-2}) \left[ C_{10} + 2C_{20} (\lambda^2 + \lambda^{-2} - 2) + 3C_{30} (\lambda^2 + \lambda^{-2} - 2)^2 \right]. \quad (24)$$

Let us define $T$ as the nominal stress. In the pure shear mode, there is a relationship between nominal stress and true stress: $\delta_1 = \lambda T_1$; thus, the formula of $T_1$ is

$$T_1 = 2(\lambda - \lambda^{-3}) \left[ C_{10} + 2C_{20} (\lambda^2 + \lambda^{-2} - 2) + 3C_{30} (\lambda^2 + \lambda^{-2} - 2)^2 \right]. \quad (25)$$

According to the abovementioned derivation process, the relationship between the nominal stress and the elongation rate of the Neo-Hookean, Yeoh, Ogden and Mooney-Rivlin superelastic models under three stretching modes can be derived as follows:

For the Neo-Hookean model,

\[
\begin{align*}
\text{Uniaxial}: T_1 &= 2C_{10} (\lambda - \lambda^{-2}), \\
\text{Pure shear}: T_1 &= 2C_{20} (\lambda - \lambda^{-3}), \\
\text{Biaxial}: T_1 &= 2C_{30} (\lambda - \lambda^{-5})
\end{align*}
\]

(26)

for the Yeoh model,

\[
\begin{align*}
\text{Uniaxial}: T_1 &= \frac{\mu}{\alpha} \left( \lambda^{-\frac{\alpha}{2}} - \lambda^{-\frac{\alpha}{2} - 1} \right), \\
\text{Pure shear}: T_1 &= \frac{\mu}{\alpha} \left( \lambda^{-\frac{\alpha}{2}} - \lambda^{-\frac{\alpha}{2} - 1} \right), \\
\text{Biaxial}: T_1 &= \frac{\mu}{\alpha} \left( \lambda^{-\frac{\alpha}{2}} - \lambda^{-\frac{\alpha}{2} - 1} \right); \\
\end{align*}
\]

(27)

for the Ogden model,
and for the Mooney-Rivlin model,

\[
\begin{align*}
\text{Uniaxial: } & T_1 = 2 \left[ C_{10} (\lambda - \lambda^{-2}) + C_{01} (1 - \lambda^{-1}) \right], \\
\text{Pure shear: } & T_1 = 2 (C_{10} + C_{01}) (\lambda - \lambda^{-3}), \\
\text{Biaxial: } & T_1 = 2 \left[ C_{10} (\lambda - \lambda^{-1}) + C_{01} (\lambda^{3} - \lambda^{-3}) \right].
\end{align*}
\] (29)

where \( C_{10}, C_{20}, C_{30}, C_{01}, \mu, \) and \( \alpha \) are material parameters, and \( \lambda \) is the main tensile rate. According to the relationship between the derived nominal stress and elongation rate, it is used as the mathematical theoretical model of the following composite fitting simulation.

III. TENSILE EXPERIMENT AND THE DATA FITTING PROCESS

A. Tensile experiment

The selection of superelastic material models relies on mechanical experiments, and the complete expression of superelastic material models theoretically requires six pure strain state mechanical experiments, such as uniaxial stretching, uniaxial compression, biaxial stretching, biaxial compression, plane stretching, and plane compression, as shown in Fig. 4. In general, the more the types of tests, the more accurate the material model and the more wider the applicability will be.

Since the film type DE material cannot be uniaxially compressed or biaxially compressed, the three basic mechanical tests for the DE film material include uniaxial stretching, biaxial stretching, and pure shear stretching, as shown in Fig. 5; the film material is fixed at one end, and the other end is subjected to a unidirectional outward vertical tensile force, causing the film to be uniaxially stretched; the sides inwardly contract because of unapplied force. Pure shear stretching is based on uniaxial stretching with roller support constraints applied on both sides (restricting the
displacement in the Y-axis direction without retraction on both sides). In the biaxial stretching method, one end is fixed, and the other three sides are applied with equal loads.\textsuperscript{13,14}

The uniaxial stretching method is simple and easy to implement, but the implementation of the pure shearing and biaxial stretching methods is difficult. The conventional pure and biaxial stretching experimental apparatus are shown in Figs. 6 and 7, respectively. Among them, when the pure shear tensile test method is used, the length of the clamping side of the sample is required to be more than 10 times the length of the side without force. As shown in Fig. 6, the two sides of the unstressed force still have a contraction behavior, and the stretching method is demanding on the sample; the film is less deformed in the main stretching direction, and is not suitable for a place requiring large deformation. The biaxial stretching method mainly has two modes, as shown in Fig. 7. The main disadvantage, as shown in Fig. 7(a), is that the tensile change is uneven, and the peripheral edges are easily damaged. Also, the disadvantage, as shown in Fig. 7(b), is that the contact surface of the small clip and the film is small, and the point is fixed; hence, it is easy to cause damage to the film, and the film clamping is cumbersome.

This study designed a scissor-fork type pure shear stretching device and a biaxial stretching device in the form of a scissor fork. The former overcame the demanding requirements such as the fixed sample ratio, and the latter was simple to assemble. The film was uniformly deformed and was not easily damaged.

The pure shear stretching device used in the experiment is shown in Fig. 8. In the form of a scissors fork, the critical dimensional conditions required for pure shear stretching could be effectively avoided. The sample size was 120 × 80 mm, thickness was 0.5 mm, and tensile rate was $\dot{\lambda} = 0.05 \text{ s}^{-1}$. In order to eliminate the error, the tensile force data of one film were subtracted from the tensile data of the two films to obtain the desired tensile value of the single layer film.

The biaxial stretching device is shown in Fig. 9 and was also in the form of a scissor fork so that the film deformation was more uniform. The test used was consistent with the pure shear tensile test. In order to eliminate the error, double-layer data were subtracted from the single-layer data to obtain an accurate pull value. The sample size was 90 × 90 mm, thickness was 0.5 mm, and tensile rate was $\dot{\lambda} = 0.05 \text{ s}^{-1}$.
The uniaxial tensile test device is shown in Fig. 10. A servo cylinder was used to drive the film to stretch and shrink, and the force sensor was used to measure the main tensile force. A high-speed paperless recorder was used to record the measured data while using the grating. The grating-ruler collected the stretching distance. In order to eliminate the viscoelastic effect of the film, the tensile force data must be collected at a lower tensile rate, where $\dot{\lambda} = 0.05 \text{ s}^{-1}$ was used. In order to obtain large elongation, the sample size used was $40 \times 20 \text{ mm}$, and the thickness was $0.5 \text{ mm}$. In order to improve the precision and eliminate the error in the stretching process, several layers of the film were superimposed, and the data of the five layers of the film were subtracted from the data of the six layers of film, thereby obtaining the tensile value of the single layer film.

Each of the above experiments was tested 5 times, and the averaged data were considered the final data.

### B. Data fitting process

In this study, the experimental data of uniaxial, pure shear, and biaxial states are considered by compound fitting so that the corresponding constitutive model can be selected and the material parameters can be better estimated. The compound fitting formula is

$$S_{\Sigma} = S_{us} + k_d S_{pss} + k_s S_{bs}, \quad (30)$$

where $S_{\Sigma}$ is the total stress, $S_{us}$, $S_{pss}$, and $S_{bs}$ each represent, respectively, uniaxial, pure shear, and biaxial stress, and $k_d$ and $k_s$ represent the weight coefficients. Since uniaxial, pure shear, and biaxial weights are the same, let $k_d$ and $k_s$ be equal to 1.
The stress in the stretched state is equal to the tensile force divided by the area of the force. In this study, under the pure shearing and biaxial stretching modes, the stretching ratio of the DE film was small, and the thickness variation of the film was not obvious; the thickness was regarded as a constant, so the force area for the pure shearing and biaxial stretching modes was $80 \times 0.5 \text{ mm}^2$ and $90 \times 0.5 \text{ mm}^2$, respectively. In the uniaxial stretching mode, the thickness of the film changes significantly. After the test, the thickness was rapidly mutated from the initial 0.5 mm–0.3 mm and slowly decreased in the subsequent stretching. Therefore, the force area of the film was $40 \times 0.5 \text{ mm}^2$ between the stretching ratios of 1 and 1.2, and the force area was about $40 \times 0.3 \text{ mm}^2$ at an elongation ratio of 1.2 or more.

COMSOL integrates many mature fitting curve methods. This study uses COMSOL to fit curves based on tensile test data and Eqs. (26)–(30), and the principle of fitting is the least squares method. Taking the Mooney-Rivlin model as an example, three variables were added to the global definition, and their expressions were as shown in formula (29). An optimization module (opt) was added to the component, three global least squares targets were added, the data source was a local table, and the tensile force and the converted stress of the uniaxial, pure shear, and biaxial tests were, respectively, applied to the component. The parameter name of the stretch rate was set to $\lambda$, and the stress weight ratio of the three stretch models was set to 1, according to formula (30). The research module was added, where the calculation method used the Levenberg-Marquardt algorithm; the optimization tolerance was 0.001, the research step was a steady state, the maximum model calculation number was 1000, the initial value and the scaling control variable were 1 Mpa, and the calculated objective function was selected as 3 variables and then calculated. After calculation, the derived value in the result module was added to the global calculation; this solution was selected in the data set, $C_{10}$ and $C_{01}$ were applied to the expression, the calculation was performed, and the specific values of $C_{10}$ and $C_{01}$ were directly obtained.

Each model obtained its material parameters, and then the material parameters were substituted into the superelastic model to obtain the relationship between the stress and tensile rate of the three tensile modes for different superelastic models. Finally, the experimental data and the fitting curve were compared and analyzed, the general constitutive model was selected, and the model parameters are determined.

The study process is shown in Fig. 11. The advantage of the present study was to comprehensively consider the three stretching methods to fit the curves.

IV. EXPERIMENTAL DATA AND FITTING RESULTS

The relationship between the force and the tensile rate of the uniaxial tensile mode obtained after data processing is shown in Fig. 12.
The relationship between the force and the tensile ratio of the pure shear and biaxial stretching modes obtained after data processing is shown in Fig. 13.

By dividing the tensile forces shown in Figs. 12 and 13 by the force area, the relationship between the tensile rate and the stress in the three tensile modes is obtained. This was substituted into the COMSOL optimization module, and the fitting curve of the stress and tensile rate of the three tensile modes under the four superelastic models was obtained by compound fitting and then compared with the experimental data. The results obtained by COMSOL compound fitting are shown in Figs. 14–17, which were based on the fitting of stress-tensile ratios of Neo-Hookean, Yeoh, Ogden, and Mooney-Rivlin models, respectively.

As shown in Fig. 14, the upward trend of stress in the uniaxial tensile test under the Neo-Hookean model was the same as that of the composite fitting stress. However, the experimental stress curve had two inflection points, and the fitting curve had only one inflection point; the rate of change was different. When the tensile rate was less than 1.1, the experimental stress was consistent with the fitting stress, but when the elongation was greater than 1.1, the
former was larger than the latter. In the case of biaxial stretching, the experimental stresses were all above the fitted stress, and the fitting effect was the worst.

As shown in Fig. 15, the upward trend of stress in the uniaxial tensile test under the Yeoh model was the same as that of the composite fitting stress. Although the experimental stress curve and the fitting curve had two inflection points, the inflection point positions were different, and the rate of change was different. The experimental data of pure shear coincided with the fitted curve. In the case of biaxial stretching, when the elongation was less than 1.2, the experimental stress was consistent with the fitting stress. When the elongation was greater than 1.2, the experimental stress was above the fitting stress.

As shown in Fig. 16, the comparison between the experimental data and the composite fitting curve in the Ogden model was similar to that of the Yeoh model. The difference was that in the uniaxial stretching model, the composite fitting curve had only one inflection point.

As shown in Fig. 17, the experimental data and the compound fitting curve under the Mooney-Rivlin model were in good agreement.

According to the test data of this study, the uniaxial tensile yield point of the dielectric elastomer was that the tensile ratio was 6.85 and stress was 0.235 MPa. The biaxial tensile yield point was that the tensile ratio was 1.95 and stress was 0.118 MPa. The pure shear tensile yield point was that the tensile ratio was equal to 2.25 and the stress was 0.099 MPa.

In summary, comparing the fitting results with the experimental data, the results showed that the Neo-Hookean model had the worst fitting effect, and the uniaxial, biaxial, and pure shear fitting curves were very different from the experimental data. The Yeoh model and the Ogden model had a good pure shear fit, but the degree of the uniaxial fit and biaxial fit was poor. The fitting curve of the Mooney-Rivlin model in the three tensile modes was in good agreement with the experimental data. The Mooney-Rivlin model was selected as the most suitable constitutive model for dielectric elastomers. The material parameters of the composite fitting were $C_{10} = 15.031$ Pa and $C_{01} = 12.218$ Pa. This material parameter could be substituted into subsequent electromechanical coupling modeling, especially the mechanical simulation in finite element analysis, to improve the accuracy of the analysis and the reliability of the results.

V. CONCLUSIONS

The DE material is a superelastic material with large deformation and has nonlinear mechanical properties. Accurately describing the constitutive relationship of DE materials is the key to studying the electromechanical properties of DEA and DEG and is the basis for subsequent electromechanical modeling and related simulation. Previous studies have performed in-depth analysis and made a description of the selection of DE material constitutive models and often only use uniaxial data to obtain constitutive parameters; the constitutive relationship does not apply to the state of materials in other deformation modes.

Based on several types of superelastic constitutive models, this study analyzed the mechanical constitutiveness of DE materials. The uniaxial, pure shear, and biaxial tensile experiments were designed. The fitting curve was obtained by the COMSOL software through composite fitting. Compared with the experimental data, the appropriate constitutive model was selected, and its constitutive parameters were determined. The results showed that the Mooney-Rivlin model was suitable for three kinds of stretching methods, and it was the model with the widest application range and the highest degree of fitting among the four superelastic models, where the material parameters of the Mooney-Rivlin model were $C_{10} = 15.031$ Pa and $C_{01} = 12.218$ Pa. The Mooney-Rivlin constitutive model and material parameters can be universally applied to various deformations.
of DE materials, including uniaxial, biaxial, and pure shear stretching methods, which provided a reference for the study of subsequent electromechanical coupling characteristics and energy conversion processes.

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