The dissipative dynamic performances of dielectric elastomer actuator with viscoelastic effects

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Abstract

With large deformability and high energy density, Dielectric elastomers (DEs) deserve interest in soft robotics. Many challenges remain in the real-world applications, for the dynamic performance of dielectric elastomer actuator and their energy efficiency are affected by the dissipation mechanisms in the actuators. Concerning the viscoelasticity of DEs, we present a modeling approach to describe the dissipation mechanism to predict how the dissipative process affects the dynamic behavior. The validity and generalization of the model have been extensively verified under various excitation voltages (different peak voltages, frequencies, pre-stretching, and signal waveforms). For harmonic voltages at different frequencies (0.05, 0.1, 0.2, 0.5, 1 Hz), the root mean square error is less than 5.99%. The phase difference was adopted to quantify the viscoelastic hysteresis dissipative behavior of DEs. The results show that the viscoelastic hysteresis is sensitive to frequency and waveform. In addition, we found that the viscoelastic hysteresis of the DEs under harmonic excitation can be improved by inserting a small amount of saw-tooth excitation loads. This finding is particularly useful for the actuation of soft actuators and soft robots, which use alternating loads as the dominant excitation signal. For future applications, this model presents a method to describe the dissipative behaviors in dynamic actuation quantitatively and paves the way to high-performance actuation control and manipulations for soft robots.

1. Introduction

Electro-active polymers are hyper-elastic polymers capable of inducing deformation in response to electrical stimuli. They have the potential to mimic muscle-like behavior enabling the development of lightweight, energy-efficient and silent actuators, motors and sensors [1]. Among different types of electro-active polymers, Dielectric elastomers (DEs) are more promising in the emerging scientific field of soft robotics. The significant advantages lie in low weight, large strain rate (up to 380%), high energy density (3.4 J g$^{-1}$), fast response and excellent environmental compliance [2–4]. Therefore, DEs are extensively used in the field of soft robotics to develop climbing robots [5], swimming fish robots [6–8] and flying insect robots [9, 10], and have been widely used in many other fields for the development of soft sensors, artificial muscles, energy generators and optical devices.

1.1. Background

A dielectric elastomer actuator (DEA) consists of a pre-stretched DE film sandwiched between two compliant electrodes. Under the electric stimuli, the electrostatic attraction between the two oppositely charged electrodes and the polarization-induced intrinsic deformation of the material will induce membrane thickness shrinkage and area enlargement [11]. DEs are not a perfect dielectric, which suffers from dissipative processes like viscoelasticity, current leakage, and dielectric relaxation [12–14]. Furthermore, the experiments have shown that...
Dielectric elastomers can deform in dimension and actuator consists of a thin dielectric elastomer membrane sandwiched between two compliant electrodes on both sides. The electrode has negligible mechanical stiffness, which can synchronously follow the large strain of measurements. The electrode has negligible mechanical stiffness, which can synchronously follow the large strain of viscoelasticity can adversely affect the performance of DEA and limit its application. Therefore, developing a reliable model to describe the dissipative dynamic performance of DEA is significant and necessary.

1.2. Related work
Since large strains in DEs were reported by Pelrine [15], many researchers have built theoretical models to predict the electromechanical responses of DEs. Early models treated the material as linear elastic, and their predictions are far from accurate [16]. Later models achieved a better agreement with experimental measurements [17, 18], but their physical origins are unclear. With the development of coupled nonlinear field theories, the mechanisms of dissipative factors such as viscoelasticity, dielectric relaxation and conductive relaxation are predicted. Wissler [19] first proposed a Prony series model based on the quasi-linear viscoelasticity assumption to characterize the time-dependent responses of DEs. But it is difficult to describe the complex electromechanical responses of DE materials, especially at large strains. Afterward, Hong [20] used a rheological model with two parallel units, the standard linear solid model, to describe DEs. Since this model is relatively reliable and simple, it has been adopted in a great deal of work on viscoelastic DEs modeling [13, 14, 21] and viscoelastic drift. Subsequently, more complex models were proposed to improve the model accuracy. Zhang [22] proposed a general constitutive model based on a combined Kelvin-Voigt-Maxwell model, which can describe the entire process of DEs. Gu [26] established a multi-relaxation time rheological model to accurately predict the electromechanical response of DEs. In a recently released study, Nguyen [23] used nonequilibrium thermodynamics to construct a model of DEs focusing on two dissipative processes-viscoelasticity and current leakage. Khan [22] proposed a generalized Maxwell (GM) model for DEs, and the modeling results were in good agreement with the experimental data. Zhang [23] established a viscoelastic model of DEs and proposed two correction strategies to eliminate viscoelastic drift. Subsequently, more complex models were proposed to improve the model’s prediction accuracy. Zhang [25] proposed a viscoelastic model based on the quasi-linear viscoelasticity assumption to characterize the time-dependent responses of DEs. But it is difficult to describe the complex electromechanical responses of DE materials, especially at large strains. Afterward, Hong [20] used a rheological model with two parallel units, the standard linear solid model, to describe DEs. Since this model is relatively reliable and simple, it has been adopted in a great deal of work on viscoelastic DEs modeling [13, 14, 21]. Foo [13] used nonequilibrium thermodynamics to construct a model of DEs focusing on two dissipative processes-viscoelasticity and current leakage. Khan [22] proposed a generalized Maxwell (GM) model for DEs, and the modeling results were in good agreement with the experimental data. Zhang [23] established a theoretical model to describe the dissipative performance of DEs by considering leakage current and viscoelasticity, and reported a detailed simulation analysis of the dissipation behavior of DEs under different waveforms. Liu [24] established a viscoelastic model of DEs and proposed two correction strategies to eliminate viscoelastic drift. Subsequently, more complex models were proposed to improve the model’s prediction accuracy. Zhang [25] proposed a general constitutive model based on a combined Kelvin-Voigt-Maxwell model, which can describe the entire process of DEs. Gu [26] established a multi-relaxation time rheological model to accurately predict the electromechanical responses of DEs. In a recently released study, Nguyen [23] combined the Kelvin-Voigt model and the generalized Maxwell model to derive the KV-GM model, which absorbed the advantages of both models. Compared with the experimental validation with limited waveforms and frequencies, the maximum prediction error is 3.762%. However, the commonly physics-based models are generally complicated, containing more than three parameters. To reduce material parameters possible, a rheological model based on the second thermodynamic continuum mechanic method has been proposed by Behera [28]. Xiao [29] used a differential evolution algorithm to simplify the model parameters. A phenomenological modeling model was proposed by Zou [30], which utilizes the modified rate-dependent Prandtl-Ishlinskii model to characterize the asymmetric viscoelastic hysteresis behavior of DEs. The phenomenological model only needs experimental data and fewer parameters than previous physics-based modeling approaches.

1.3. Study contribution
In the present article, we developed a theoretical model to describe the dissipative mechanism of DEs by considering viscoelasticity. The main contributions of our work are summarized as follows.

1. A viscoelastic model was proposed to describe the dissipation mechanism of DEs. Compared with experimental measurements, the validity and generalization of the model were extensively verified. The model can accurately describe the responses of DEs under various electrical loads (different peak voltages, frequencies, pre-stretching, and signal waveforms).

2. The effects of frequency and waveform on the viscoelastic hysteresis dissipation behavior of DEs were quantitatively investigated by the phase difference. In addition, an effective method was proposed to reduce the viscoelastic hysteresis of DEs under harmonic excitation.

The rest of this article is structured as follows. The theory of viscoelasticity and modeling approach is introduced in section 2. Section 3 describes the preparation for the experiment. In section 4, the viscoelastic behaviors of DEA are discussed under various pre-stretches and exciting voltages through experiments and simulations. Finally, some conclusions are summarized in section 5.

2. Theoretical model of viscoelastic DE membrane
Dielectric elastomers can deform in dimension and/or shape by the external electrical stimulus. The DE actuator consists of a thin dielectric elastomer membrane sandwiched between two compliant electrodes on both sides. The electrode has negligible mechanical stiffness, which can synchronously follow the large strain of...
the elastomer membrane, but without generating opposing stress or losing conductivity. As shown in figure 1, the membrane has three states: (1) the reference state, (2) the pre-stretch state and (3) the excited state. Subjecting to no force load and voltage, the reference state has initial geometry dimensions, where \( H, L_1 \) and \( L_2 \) are the initial thickness, length and width, respectively. When loads \( P_1 \) and \( P_2 \) are applied on the plane, the membrane is pre-stretched. The pre-stretch ratio is determined as \( \lambda_{\text{pre}} = \frac{L_{\text{pre}}}{L} \). The pre-stretched length and width are \( L_{\text{pre}} = L_1 \lambda_{\text{pre}} \) and \( L_{\text{pre}} = L_2 \lambda_{\text{pre}} \). Therefore, in the pre-stretch state, the two in-plane pre-stresses of the membrane are:

\[
\begin{align*}
\sigma_{1p} &= \frac{P_1}{L_{\text{pre}}} H_{\text{pre}} = \frac{P_1}{L_{\text{pre}}} \lambda_{\text{pre}} L_1 H \\
\sigma_{2p} &= \frac{P_2}{L_{\text{pre}}} H_{\text{pre}} = \frac{P_2}{L_{\text{pre}}} \lambda_{\text{pre}} L_2 H
\end{align*}
\] (2-1)

(2-2)

When an electric field is applied across the electrodes, the charges \( +Q \) and \( -Q \) are collected on the two electrodes. The attraction of charges on the electrodes converts electrical energy to mechanical energy and provides the actuation mechanism. The active region of the DE membrane deforms uniformly to a configuration of thickness \( h = \frac{H}{\lambda_1 \lambda_2} \) and two-dimensional lengths \( l_1 = L_1 \lambda_1 \), \( l_2 = L_2 \lambda_2 \). The two in-plane stresses of DEs are:

\[
\begin{align*}
\sigma_1 &= \frac{P_1}{l_1 h} = \frac{P_1}{l_1} \lambda_1 L_1 H \\
\sigma_2 &= \frac{P_2}{l_2 h} = \frac{P_2}{l_2} \lambda_2 L_2 H
\end{align*}
\] (2-3)

(2-4)

The viscoelastic behavior of the DE is modeled with a mass-damping-spring system, known as the nonlinear rheological model. Figure 2 illustrates a rheological model with two parallel units. A spring \( \alpha \) is paralleled with another spring \( \beta \) with a dashpot \( \eta \). \( m_\alpha \) and \( m_\beta \) are the shear modulus of the spring \( \alpha \) and spring \( \beta \), \( J_{\text{lim,}\alpha} \) and \( J_{\text{lim,}\beta} \) are the material constant of DEs and are related to the limited stretches of the two springs. The net deformations in both directions are described by the two in-plane stretches, \( \lambda_1 \) and \( \lambda_2 \). For the spring \( \beta \), the inelastic stretches are \( \lambda_1 \) and \( \lambda_2 \), and the equivalent damping in the dashpot are \( \xi_1 \) and \( \xi_2 \), respectively. So we obtain \( \lambda_1 = \lambda_1' \xi_1 \), \( \lambda_2 = \lambda_2' \xi_2 \).

To describe the relationship between the actuation strain and the stress of a DE membrane, the Gent model is employed, and the potential of the conservative forces in the system can be described as:

\[
W = -\frac{m_\alpha J_{\text{lim,}\alpha}}{2} \log \left( 1 - \frac{\lambda_1^2 + \lambda_2^2 - \lambda_1^2 \lambda_2^2}{J_{\text{lim,}\alpha}} \right) - \frac{m_\beta J_{\text{lim,}\beta}}{2} \log \left( 1 - \frac{\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^2 \lambda_2^2 - 3}{J_{\text{lim,}\beta}} \right)
\] (2-5)
Considering the viscoelasticity, the governing equation based on non-equilibrium thermodynamic theory is [31]:

$$\begin{align*}
\sigma_1 + \varepsilon E^2 &= \frac{m_\alpha (\lambda_1^2 - \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2} \lambda_2^{-2})/\lim_{\alpha}^2} + \\
&\quad \frac{m_\beta (\lambda_1^2 \xi_1^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \\
\sigma_2 + \varepsilon E^2 &= \frac{m_\alpha (\lambda_2^2 - \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2} \lambda_2^{-2})/\lim_{\alpha}^2} + \\
&\quad \frac{m_\beta (\lambda_2^2 \xi_2^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \\
\end{align*}$$

(2-6)

(2-7)

Where $\varepsilon$ is the dielectric permittivity of the DEs and $\varepsilon E^2$ is the Maxwell stress. Many researchers have proposed that DEs is not an ideal elastomer and that the dielectric constant is dependent on many parameters such as temperature and the deformation process of the film. So the dielectric constant equation of DEs is [32]:

$$\varepsilon(\lambda_1, \lambda_2, T) = (\varepsilon_{\infty} + A/T) \left[ 1 + a(\lambda_1 + \lambda_2 - 2) \right] + b(\lambda_1 + \lambda_2 - 2)^2 + c(\lambda_1 + \lambda_2 - 2)^3$$

(2-8)

Where $\varepsilon_{\infty} = 2.1$ is the dielectric permittivity in high frequency, $A = 740$(for carbon grease-MG Chemical), $a = -0.1658$, $b = 0.04086$, $c = -0.003027$ are the coefficients of DEs, the temperature is kept $T = 300$ K during the experiment. From equations (2-1)–(2-8), the constitutive relation of the viscoelastic DE membrane is:

$$\begin{align*}
\sigma_{p\alpha}/\lambda_p + \varepsilon \lambda_1^2 U^2/H^2 &= \frac{m_\alpha (\lambda_1^2 - \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2} \lambda_2^{-2})/\lim_{\alpha}^2} + \\
&\quad \frac{m_\beta (\lambda_1^2 \xi_1^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \\
\sigma_{p\beta}/\lambda_p + \varepsilon \lambda_2^2 U^2/H^2 &= \frac{m_\alpha (\lambda_2^2 - \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 + \lambda_2^2 + \lambda_1^{-2} \lambda_2^{-2})/\lim_{\alpha}^2} + \\
&\quad \frac{m_\beta (\lambda_2^2 \xi_2^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \\
\end{align*}$$

(2-9)

(2-10)

The strain rates in the dashpot are $\xi_1^{-1} \, d\xi_1/dt$ and $\xi_2^{-1} \, d\xi_2/dt$, respectively. Then we get the stress and the rate of the deformation in the dashpot are:

$$\begin{align*}
\xi_1^{-1} \, d\xi_1/dt &= \frac{1}{3\eta} \left[ \frac{m_\beta (\lambda_1^2 \xi_1^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} - \right. \\
&\left. \quad \frac{m_\beta (\lambda_2^2 \xi_2^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \right] \\
\xi_2^{-1} \, d\xi_2/dt &= \frac{1}{3\eta} \left[ \frac{m_\beta (\lambda_1^2 \xi_1^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} - \\
&\left. \quad \frac{m_\beta (\lambda_2^2 \xi_2^2 - \xi_1^2 \lambda_1^{-2} \lambda_2^{-2})}{1 - (\lambda_1^2 \xi_1^2 + \lambda_2^2 \xi_2^2 + \xi_1^2 \xi_2^2 \lambda_1^{-2} \lambda_2^{-2})/\lim_{\beta}^2} \right] \\
\end{align*}$$

(2-11)

(2-12)

When DEs are subjected to an equal biaxial pre-stretch force and the membrane is assumed to have uniform deformation in two in-plane directions. Let $P_1 = P_2 = P$, $\lambda_{p\alpha} = \lambda_{p\beta} = \lambda_{1/2\alpha} = \lambda_{1/2\beta}$, $\sigma_{p1} = \sigma_{p2} = \sigma_p$, $\lambda_1 = \lambda_2 = \lambda$, $\xi_1 = \xi_2 = \xi$, the equations (9)–(12) can be abbreviated as the symmetry of the problem to:

$$\begin{align*}
\sigma_p/\lambda_p + \varepsilon \lambda U^2/H^2 &= \frac{m_\alpha (\lambda^2 - \lambda^{-4})}{1 - (2\lambda^2 + \lambda^{-4})/\lim_{\alpha}^2} + \\
&\quad \frac{m_\beta (\lambda^2 \xi^2 - \lambda^{-4} \xi^2)}{1 - (2\lambda^2 \xi^2 + \lambda^{-4} \xi^2)/\lim_{\beta}^2} \\
\end{align*}$$

(2-13)
3. Experiment preparation

3.1. Membrane actuator fabrication

In this paper, we discuss a square actuator consisting of a thin square membrane sandwiched between two compliant electrodes. The material is acrylic elastomer VHB 4910 (3M Company, Minnesota, USA) with a thickness of 1 mm. It has the highest performance in terms of strain (380% relative area strain) and actuation pressure (up to 2 MPa) among the testing results of several different DE materials. Pre-stretching has been validated to improve mechanical efficiency, eliminate electromechanical instability, and increase actuation strain. After pre-stretching, we keep for one hour to stabilize, and then mounted the sample on a rigid square acrylic frame with a width of 100 mm to maintain the pre-stretched load statically. Carbon conductive grease (MG Chemical 846–80G) is used as compliant electrode, the principal components of electrode are Polydimethylsiloxane and Carbon Black. The electrode is brushed on both sides of the membrane uniformly by placing a pierced square mask with an area of 30 mm × 30 mm in the center of the film. We use two soft conducting wires to connect the electrodes to an external high voltage amplifier.

3.2. Experiment setup

To capture the viscoelasticity characteristics of DEA and verify the effectiveness of the constitutive model, we build a measuring system as shown in figure 3. The measuring system is composed of a signal generator (AFG3022C, Tektronix, Oregon, USA), a high voltage amplifier (Trek 20/20C-HS, Trek, New York, USA), two laser displacement sensors (LK-G4000A, Kenyence, Osaka, Japan) and a data acquisition module (PXIe-6361, National Instruments, Texas, USA). The high voltage amplifier with a fixed gain of 2000 can proportionally amplify the analog control voltage generated by the signal generator and applies it to DEA. It is well known that DEA may lose tension or instability under high voltage, so the highest control voltage is limited to 4 kV. The two laser displacement sensors are used to measure the displacement in two in-plane directions of the actuator, and the displacement data is converted into voltage (1 mm V⁻¹). The measurement principle of such sensor is triangulation, with a measuring range of 400 ± 100 mm, and a resolution of 2 μm. Each sensor can only get the displacement of one point, so we choose the midpoints of the two adjacent sides as the measured points. The data acquisition module with a 16-bit analog-to-digital converter can collect the actuator control voltage and displacement response through the LabVIEW program, and the sampling time is 1 ms.

4. Results and discussions

For the model verification, we compared numerical calculations and experimental measurements with various excitation conditions and studied the dynamic performances of dielectric elastomers with viscoelasticity concerns. Once the pre-stretching and the applied voltage are determined in the simulation, we can calculate our
model’s time-dependent deformations and all the physical parameters of our model are listed in table 1. Initially, we have \( \lambda_1 = \lambda_{1p} \) and \( \lambda_2 = \lambda_{2p} \). As time goes by, they will slowly creep to approaching \( \lambda \) and release the elastic stress furtherly. The ODE45 is used for numerical simulations, and the input parameters are listed below:

| Table 1. Parameters in simulation. |
|-----------------------------------|
| \( m_{\alpha} \) | 20000 Pa |
| \( m_{\beta} \) | 50000 Pa |
| \( h_{\text{lim,1}} \) | 115 |
| \( h_{\text{lim,2}} \) | 70 |
| \( t_v \) | 50 s |
| \( H \) | 1 mm |

4.1. Responses of static voltages

We study the step responses of DE membrane actuators under static voltages. In figure 4, the numerical calculations by our model (solid line) and the model with no viscoelasticity (dash line) are compared. Our model
shows a better agreement with experimental measurements than the non-viscoelastic model in the dynamic process, and both models can converge over time. In the experimental measurements, the response can be divided into two parts: the quick response process and the creeping process. The actuator needs time (hundreds of seconds) to deform slowly before the steady-state, while the non-viscoelastic model cannot predict such a creeping process. This indicates that viscoelasticity does dominate the dynamic responses but barely affects the steady deformations. Figure 4(a) shows the time-dependent responses with different pre-stretches \( l = 2, P_l = 3, P = 4 \) and under the same step stimulus \( U = 3000 \text{ V} \). The DE actuator needs time to deform when the exciting voltage suddenly increases. It can be observed that by increasing the pre-stretch, the actuation strain of DEA increases. This is due to the thickness of the membrane decreasing, which causes the Maxwell stress to increase. Figure 4(b) shows the response of the same pre-stretches \( l = 3 \) under different voltages. Where higher voltage induces greater strain and higher steady deformation. The increasing peak voltage can generate a large electric field in the thickness direction of the membrane, leading to a larger Maxwell stress. According to the above discussion, we can see the validity of the rheological model and the dissipative characteristics expected to predict the dynamic response of DEs.

### 4.2. Responses of ramp voltages

Various ramp voltages are applied to study the effect of voltage ramp rate on the viscoelasticity. The ramp voltage is:

\[
U = \begin{cases} 
K_t \cdot t & 0 \leq t \leq \frac{3000}{K} \\
3000 + \frac{3000}{K} & \frac{3000}{K} < t \leq 400
\end{cases}
\] (4-1)

We also can divide the voltage \( U \) into two parts: part A and part B. In part A, the voltage increases linearly with a rate of \( K_t \) enters part B after reaching 3000 V and then remains constant. Point P connects the two parts. Figures 5(a)–(c) illustrate the simulations and experimental results of the dynamic response of the DEA at three ramp rates \( K = 10, 15 \) and 30 V s\(^{-1}\) (\( \lambda_p = 3 \)). We can notice that the strain rapidly climbs by increasing voltage in part A kept for a while after P by inertia. The simulation results of the three loading approaches are summarized in figure 5(d). The actuation strain is sensitive to the ramp rate. The deformation at the inflection point tends to be close when the rising time is long enough (\( K = 10, 15 \)), while the actuator cannot deform...
adequately by a sharply increasing ramp rate \((K = 30)\). This phenomenon is also attributed to viscoelasticity: with the voltage ramp rate increasing, the stress in the membrane has less time to relax. After the inflection point, viscoelasticity is the only fact that the membrane continues to deform. As time goes by, the steady-state deformations are similar to the step response.

### 4.3. Responses of harmonic voltages

Figure 6(a) shows the dynamic response of DEA when subjected to a harmonic voltage with a frequency of 1 Hz. Figure 6(b) shows the real-time strain as a function of voltage, and it can be observed that the loops are asymmetric. The strains for the first three and last two cycles are plotted in figures 6(c)–(d), respectively. We can observe that:

(a) The strain drifts with time, larger after each cycle, and slowly reaches the equilibrium stage. This phenomenon is viscoelastic creep. The viscoelastic creep is significantly observed in the first three cycles and decreases over time, becoming ignorable in the last two cycles.
The responses of loading and unloading are asymmetric, exhibiting a strong viscoelastic hysteresis. Therefore, when excited by oscillatory voltage, the DEA’s viscoelastic creep and viscoelastic hysteresis are coupled. The area enclosed by the strain indicates the energy dissipation during the dynamic response.

The peak of the strain is observed during the unloading process and lags of the peak of voltage. The phase difference between voltage and response is used to account for these phenomena quantitatively. It can be seen that the response of DEA exhibits strong nonlinear coupling of viscoelastic creep and viscoelastic hysteresis. To express the creep and hysteresis more clearly, we conducted experiments and simulations under different frequencies of harmonic voltage in the following. Figures 7(a)–(e) show the steady-state responses with the frequencies of 0.05, 0.1, 0.2, 0.5 and 1 Hz. The corresponding viscoelastic hysteresis loops are shown in figure 7(f). The amplitude, phase difference and time-averaged strain are compared in table 2.

The hysteresis loops are asymmetric, and the width of the loops is rate-dependent. As the frequency of voltages increases, the width of hysteresis loops increases. This illustrates that viscoelastic hysteresis is sensitive to rate and becomes more severe at high frequencies. The areas of the loops are related to energy dissipation.
loop areas with different frequencies (0.05–1 Hz) in the steady oscillations (the response becomes repeatable, \( t = 360–400 \) s) are compared. It is found that a higher frequency results in a larger area, which means more energy dissipation during loading-unloading cycles and the energy conversion efficiency is reduced. The dissipation is also validated by phase difference in the dynamic response. As the exciting frequency increases, it is hard to respond quickly, and the phase difference increases.

Our model concerning viscoelasticity can explain the phenomenon above. As the frequency rises, a rate-dependent dashpot, the stress has less time to relax. Thus, more stress is left in the dashpot, balancing the electrostatic stress. As a result, the amplitude response is reduced and reduces energy efficiency. To further evaluate the performance of our model, the root mean square error \( e_{\text{rms}} \) is defined as follows:

\[
e_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\lambda_e(i) - \lambda_i(i))} \text{max}(\lambda_e) - \text{min}(\lambda_e)
\]  

(4-2)

\( \lambda_e \) and \( \lambda_i \) are experimental data and prediction results, respectively, and \( N \) is the number of measurements. The root mean square error of harmonic voltage excitation modeling at different frequencies is shown in table 3. The results show that the root mean square error of the modeling for any frequency is less than 5.99%.

4.4. Responses of different waveforms

For multiple actuations in real applications, DEA may be stimulated by various excitations. Figures 8.4. Responses of different waveforms show that the root mean square error of the modeling for any frequency is less than 5.99%. Although the model prediction may have large errors locally, the prediction accuracy of vibration amplitude and the phase difference is high. Continuing the effective predictive ability of the model, and experimental results, we have quantitatively investigated the effects of frequency and waveform on the viscoelastic hysteresis dissipation behavior of DEs by the phase difference. The results show that the viscoelastic hysteresis is sensitive to frequency and increases with frequency. Meanwhile, we further found that the viscoelastic hysteresis of the DEs under harmonic excitation can be improved by inserting a small amount of saw-tooth excitation loads. It is particularly useful for the actuation of soft actuators and soft robots, which uses alternating loads as the dominant excitation signal. For future applications, the results presented herein can provide a method to describe the viscoelasticity in dynamic actuation quantitatively and paves the way to high-performance actuation and manipulations for soft robots.

5. Conclusion

In the present article, a theoretical model was proposed to describe the dissipation mechanism of DEs by considering viscoelasticity. The proposed model was extensively verified under various electrical loads (different peak voltages, frequencies, pre-stretching, and signal waveforms). Compared with the experimental measurements, the root mean square error of harmonic voltage excitation modeling at different frequencies (0.05, 0.1, 0.2, 0.5, 1 Hz) is less than 5.99%. Although the model prediction may have large errors locally, the prediction accuracy of vibration amplitude and the phase difference is high. Continuing the effective predictive ability of the model, and experimental results, we have quantitatively investigated the effects of frequency and waveform on the viscoelastic hysteresis dissipation behavior of DEs by the phase difference. The results show that the viscoelastic hysteresis is sensitive to frequency and increases with frequency. Meanwhile, we further found that the viscoelastic hysteresis of the DEs under harmonic excitation can be improved by inserting a small amount of saw-tooth excitation loads. It is particularly useful for the actuation of soft actuators and soft robots, which uses alternating loads as the dominant excitation signal. For future applications, the results presented herein can provide a method to describe the viscoelasticity in dynamic actuation quantitatively and paves the way to high-performance actuation and manipulations for soft robots.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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