# Solution for suppressing viscoelastic creep in cylindrical dielectric elastomer actuator

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## ABSTRACT

*The cylindrical dielectric elastomer actuator (CDEA) is known as a self-prestretching structure of dielectric elastomer actuators (DEAs). However, their inherent viscoelastic nonlinearity leads to nonlinear viscoelastic creep and hysteresis, which makes the modeling and control of CDEAs challenging and can affect their motion accuracy in practical applications. In this paper, the generalized KV-GM rheological model is employed to characterize the actuator's viscoelastic creep behavior, and an adjusted voltage signal is derived from maintaining a constant output stretch by making the input voltage time-dependent. Experimental results with the preprogrammed voltage demonstrate that the creep rate of the CDEA decreases from 27% to less than 9%. The proposed solution effectively minimizes energy dissipation caused by nonlinear viscoelastic properties, playing a significant role in promoting the practical application of CDEA.*

**Keywords:** Cylindrical dielectric elastomer actuator; Viscoelastic creep; Creep compensation.

## 1. INTRODUCTION

CDEA is shown as a smart actuator, whose working principle is based on the electromechanical coupling characteristics of dielectric elastic materials (DEs). As shown in figure 1, the dielectric elastomer membrane forms a sandwich structure consisting of a layer of dielectric elastomer between two compliant electrodes. When a high voltage is applied in the direction of the membrane thickness, the two electrodes gain charge +Q and -Q attract each other, forming an electrostatic force, which makes the DEs membrane shrink in thickness and expand in the area. Compared to other smart materials, DEs exhibit energy density (3.4 J/g), high efficiency (up to 90%), high strain rate (up to 380%), low cost, low modulus, and excellent environmental compliance [1-3]. Therefore, many DEA configurations have been investigated with multiple structures to generate different actuation, which allows them to mimic natural muscle and has promising potential for the field of soft robots [4-7].

Based on the electromechanical coupling deformation of the DEs, CDEA can be known as an effective type of DEAs that has a relatively large axial output force and output displacement. Different from other DEAs, CDEA is a self-stretching actuator whose structure includes a DE membrane roll on the circumferential direction of the pre-compressed spring, forming the compact structure actuator. By using different flexible electrode coating methods on the dielectric elastic membrane, CDEA can achieve two actuation modes, including axial elongation and bending deformation, it realizes the artificial muscle function of the actuator. Adopting the characteristics of different actuation modes, CDEA is widely used in robotic fields for the development of an arm-wrestling robot [8], walking robots [9], serpentine robots [10], and flying robots [11]. These achievements of CDEA have potential applications in the military field for unmanned robots and unmanned aerial vehicles (UAVs), especially in environments requiring high flexibility. Nevertheless, suppressing the inherent viscoelastic characteristics of CDEA and improving the kinematic accuracy of the actuator is still a challenge.

In the previous literature, some previous studies have made efforts to reduce the nonlinear viscoelastic creep characteristics of DEAs to limit the energy dissipation caused by the viscoelastic properties of dielectric elastomer materials. Zou et al [12] proposed a phenomenal model to suppress the creep properties of DEA, and (ZVIS) technique was developed to suppress the vibrational dynamics of the creep compensated DEA. The results show that the creep of DEA can be reduced to 7% and overshoot is almost completely removed. As a further development, Zou and his research group [13] propose a control method that comprehensively addresses the effects of energy consumption resulting from the viscoelasticity of the actuator. Adopting a conventional feedback controller [14] eliminated DEA creep by using PID controller, this method presents several challenges in establishing a high-accuracy creep characterization model and finding a set of optimal controller parameters to improve the effectiveness of the controller. In order to study the prediction accuracy of the constitutive model, recent studies have shown that rheological models with multiple relaxation times can increase the predictive ability of the model [15, 16], especially for the complex response of DEAs under high voltage excitation, this could be a development direction of the physics-based control methods.

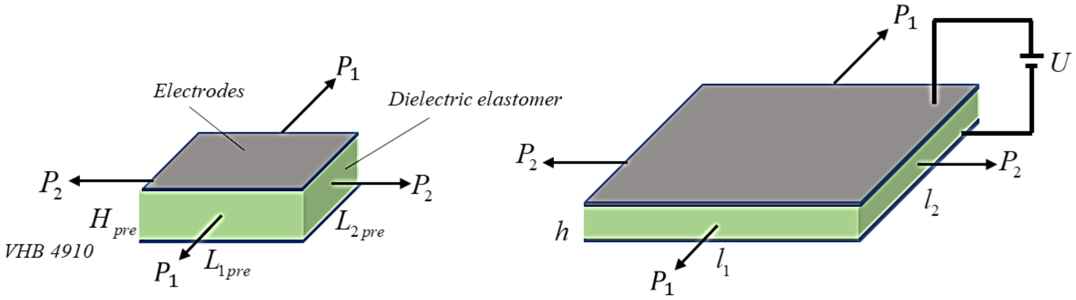
As a contribution, our research proposed a method to suppress viscoelastic creep by considering the physical properties of the actuator, which have not been adequately captured in the phenomenological models of previous studies. The implementation of high-precision physical models in the control process is expected to enhance the effectiveness of the feedforward control method proposed in previous studies.

The remainder of this paper is arranged as follows. In section II, we introduce the working principle of CDEA. The creep compensation is presented in section III. Subsequently, the viscoelastic creep suppression result and discussion are proposed in section IV using the feed-forward control method. Finally, section V concludes this paper.

## 2. WORKING PRINCIPLE OF THE CDEA

Dielectric elastomers represent a prominent class of smart soft materials capable of undergoing substantial deformation when subjected to electric fields. As illustrated in figure 1, the application of a voltage across the material's thickness induces charges of +Q and -Q on the two electrodes, generating an attractive electrostatic force. This force reduces the thickness and expands the surface area of the dielectric elastomer film due to Maxwell stress. For the fabrication of our actuator, 3M VHB 4910, with a thickness of 1 mm, was selected as the dielectric elastomer material.

Inheriting the properties of electroactive polymers, the CDEA functions as a self-stretching actuator with significant potential for future applications. It is constructed by winding a pre-stretched dielectric elastomer membrane multiple times around a pre-compressed spring. The actuation mechanism is based on the interaction between the compressive force in the dielectric elastomer (DE) membrane and the restoring force of the spring. A detailed description of the fabrication process, working principle and actuation process can be found in our previous research [17].



**Pre-stretch state** **Actuation state**

***Figure 1.*** *Actuation process of the DEs membrane.*

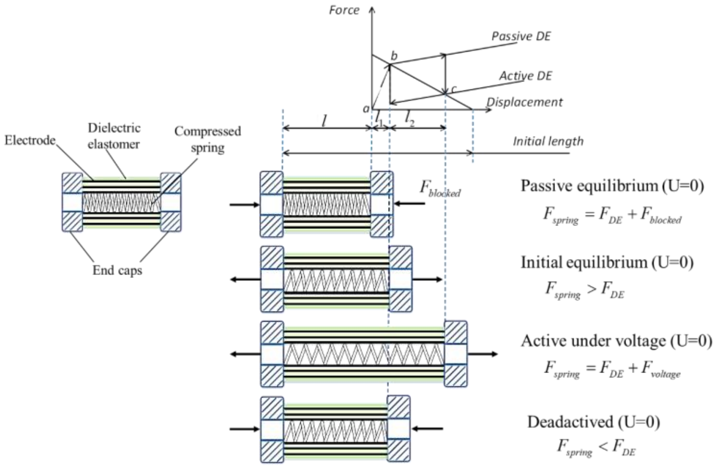


***Figure 2.*** *Working principle schematic diagram of the CDEA.*

## 3. VISCOELASTIC CREEP COMPENSATION MODELING

In this section, a high-precision rheological model is utilized to describe the viscoelastic creep characteristics of CDEA. Subsequently, based on the previously developed model, a compensator is designed to offset the energy dissipated by the nonlinear viscoelastic creep features.

### 3.1. Viscoelastic creep model

To understand the viscoelasticity behavior of CDEA, in previous work, our research group has proposed a generalized rheological model [18] as shown in figure 3.

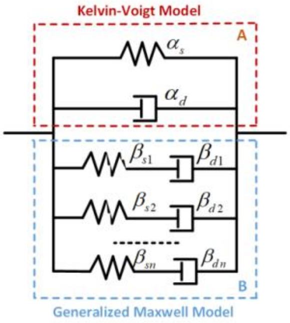


***Figure 3.*** *The Kelvin-Voigt-Generalized Maxwell (KV-GM) model.*

By adopting a generalized KV-GM rheological model with multiple relaxation times to characterize the nonlinear viscoelastic behavior of the actuator, and utilizing the principles of virtual work and nonequilibrium thermodynamics, a constitutive model for the CDEA was established, as detailed in [17]. The results show that the proposed generalized rheological model can accurately describe the nonlinear viscoelastic time-dependent behavior of the cylindrical dielectric elastomer actuator, and the maximum prediction error reached 1.97% in the relaxation stage response.

$$\ddot{\lambda} = F(U,\mu_{\alpha},\eta_{\alpha},\mu_{\beta i},\eta_{\beta i},\lambda,\dot{\lambda},\xi_i) \tag{1}$$

$$\dot{\xi} = F(\lambda,\xi_i) \tag{2}$$

Where, $\lambda$ is the total stretch of the CDEA, and $\xi_i$ is the stretch of the dashpot in the corresponding Maxwell unit $\eta_{\alpha}$ and $\eta_{\beta i}$ are the viscous damping coefficient of the dashpot, $\mu_{\alpha}$ and $\mu_{\beta i}$ are the shear moduli of the spring in the part A and B of the KVGM model, respectively.

### 3.2. Inverse creep compensation

A physical model is employed to compensate for viscoelastic creep. Given the time-dependent nature of the viscoelastic creep behavior in CDEA, the adoption of the KV-GM model, as established in our previous work [17]. To compensate for the viscoelastic creep, the KV-GM model parameters are identified through the experimental data and Monte Carlo statistical simulation method. Then, the feedforward controller is established to keep the output stretch kept constant. As an illustration, figure 4 shows the principle of the inverse creep compensation method.

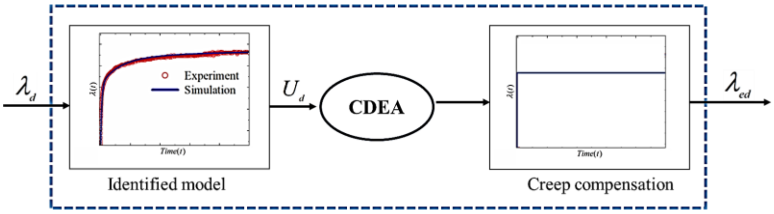


***Figure 4.*** *The principle of the inverse creep compensation method.*

Firstly, through the parameter identification method proposed above, we can obtain a set of optimal parameters $\left[\mu_{\alpha-m},\eta_{\alpha-m},\mu_{\beta i-m},\eta_{\beta i-m}\right]$. The desired stretch, denoted as $\lambda=\lambda_d$, is determined by identifying the intersection between the initial stage and the creep stage, and then substituted into equation (2). It is observed that the deformation rates of the various Maxwell elements change in response to the desired stretch. Finally, in order to develop the feedforward controller in practice, compromising voltage signals can be obtained by building an inverse viscoelastic creep model, as shown in equation (3).

$$U_d = f(\lambda_d, \xi_{id}) \tag{3}$$

### 3.3. Experimental setup

Based on the inverse creep compensation method, the control voltage signal is derived, and a feedforward control experiment is conducted. Figure 5 presents a block diagram of our experimental setup with a CDEA. As shown in Platform, a dSPACE_DS1103 control board with 16-bit digital-to-analog converters (DAC) for generating an analog control voltage, which is transferred to the high voltage amplifier (10/40A, Trek, Inc. Waterloo, Wisconsin, USA) to generate the high voltage signal, and loaded directly into CDEA. A laser sensor (LK_G4000A, Keyence, Osaka, Japan) measured the real-time axial output displacement of the CDEA. The laser sensor was connected to a set of 16-bit analog-to-digital converters (ADCs). The displacement measured by the laser displacement sensor is converted into a voltage signal (0 to 1 V), which is stored and displayed through the Control Desk interface. The signal is extracted from the Output Monitor outlet of the voltage amplifier to monitor the exciting voltage signal and collected by another analog-to-digital converter. Our experiments were all performed at room temperature, so the influence of temperature variation on the experimental results could be ignored.

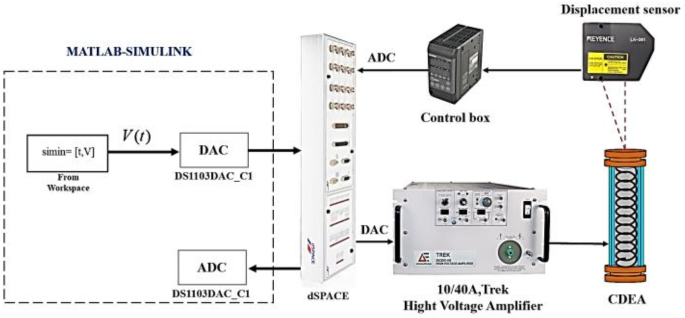


***Figure 5.*** *The experimental platform.*

## 4. RESULTS AND DISCUSSION

To verify the validity of the viscoelastic creep compensator proposed above, the response of the CDEA under $U = 6\ kV$ actuation voltage was selected as the compensation object. The expected stretch is assumed to be at the beginning of the creep phase $\lambda_d = 3.78$, as shown in figure 6(a). By bringing the desired response into the constitutive model, it can be obtained that the deformation rates $\xi_{id}$ of the dashpot in the Maxwell units change with the desired response, as illustrated in figure 6(b). By bringing the above results into equation (3), the time-dependent compensation control voltage can be obtained, as shown in figure 7(a).

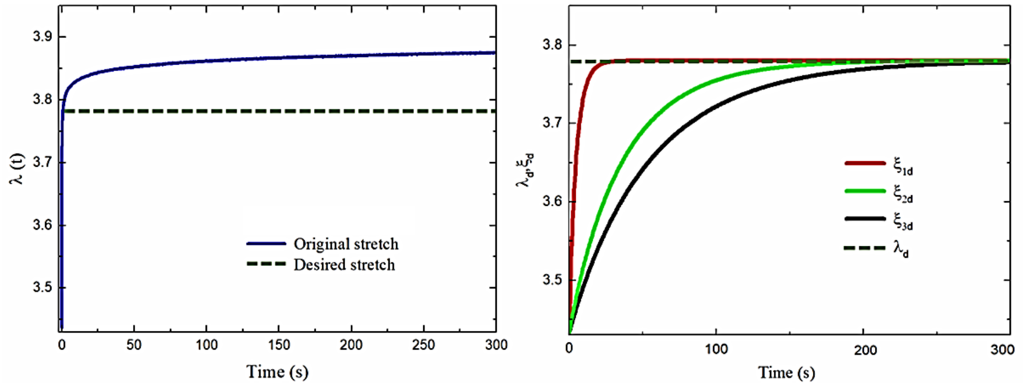
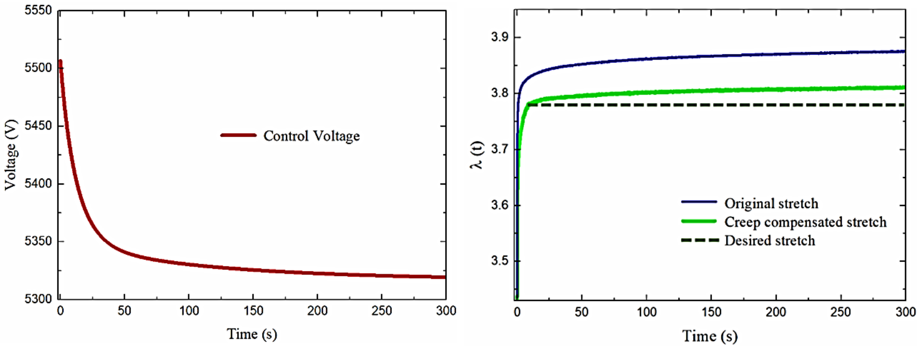


***Figure 6.*** *The response of the CDEA under $U = 6\ kV$ actuation voltage:*
*a) The original output and desired stretch; b) Dashpot stretch in the Maxwell unit.*



(a) (b)

***Figure 7.*** *The adjusted voltage signal and the corresponding response of the CDEA under this control voltage: (a) Adjusted voltage; (b) Control results.*

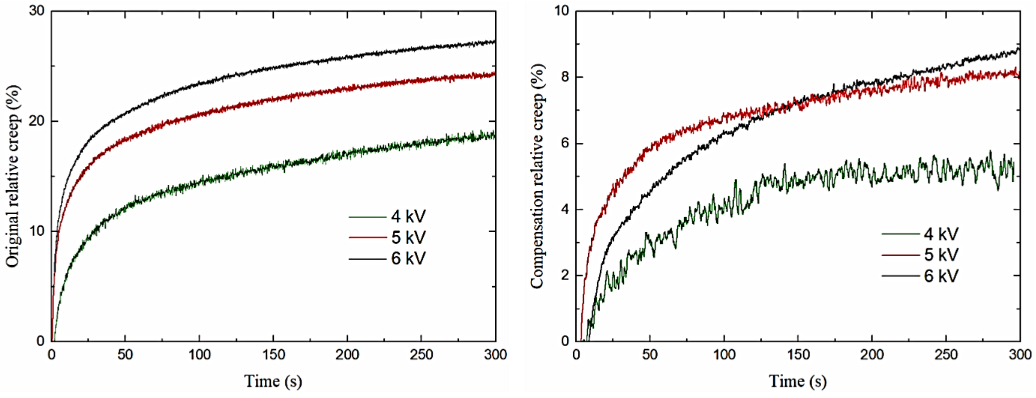
Based on the compensation control voltage signal, using the *Simin function* from the workspace of the MATLAB-SIMULINK software, put the voltage signal into the experimental configuration in section 3. Figure 7(b) shows the original response and compensation result of the CDEA under inverse creep compensation. Then, the same compensator modeling method is used for viscoelastic creep compensation of cylindrical actuator under different excitation voltages.

It can be seen from the graph that the viscoelastic creep control method proposed in this study has a certain compensation effect. To quantitatively analyze the effectiveness of the proposed compensator, we introduce the relative creep variable:

$$C_\lambda(t) = \frac{\lambda_e(t) - \lambda_d(t)}{\lambda_d(t)} \tag{4}$$

where $C_\lambda(t)$ is the relative creep, $\lambda_e(t)$ is compensation stretch, $\lambda_d(t)$ is the desired stretch.

Figure 8 shows the original relative creep curve and compensation relative curve of the cylindrical drive under different step voltages. The control results show that the relative creep rate of the drive decreases obviously after compensation, and the validity of the compensation modeling method is verified again.



(a) (b)

***Figure 8.*** *Relative creep curves of the CDEA under different step voltages: (a) Original relative creep; (b) Compensation relative creep.*

Table 1 shows the maximum relative creep rate of the cylindrical drive after the original response and compensation, and its relative creep rate can be reduced from 27% to less than 9%.

***Table 1.*** *Maximum relative creep of the CDEA under different voltage excitation.*

| Actuation voltage | Original relative creep (%) | Compensation relative creep (%) |
|---|---|---|
| 4 kV | 20.1 | 5.06 |
| 5 kV | 24.18 | 8.24 |
| 6 kV | 27.37 | 8.85 |

## 5. CONCLUSIONS

This work demonstrates that, based on the viscoelastic creep characterization capabilities of the KV-GM model, an inverse compensator can be developed to reduce the creep rate of the CDEA under step voltage excitation. Once the model parameters have been identified, an inverse creep model can be established, with the excitation voltage being a function of the output stretch. By setting the desired CDEA response to a constant value, the control compensation voltage can be obtained as a time-dependent signal. Experimental results indicate that the proposed feedforward controller effectively reduces the viscoelastic creep rate of the CDEA, specifically decreasing the relative creep rate of the cylindrical actuator from 27% to less than 9%. This result demonstrates that the physical constitutive model is effective for developing feedforward controllers to mitigate viscoelastic creep and supports the practical application of CDEA in high-precision systems and soft robotics.

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## TÓM TẮT

## Giải pháp giảm thiểu hiện tượng biến dạng kéo dài trên cơ cấu chấp hành điện môi đàn hồi hình trụ

*Cơ cấu chấp hành điện môi đàn hồi hình trụ (CDEA) được biết đến như một cấu trúc tự kéo dãn của các cơ cấu chấp hành điện môi đàn hồi (DEA). Tuy nhiên, tính phi tuyến đàn nhớt vốn có của cơ cấu chấp hành dẫn đến hiện tượng biến dạng kéo dài phi tuyến và trễ đàn hồi, gây ra những thách thức trong việc mô hình hóa và điều khiển CDEA. Trong bài báo này, một phương pháp bù ngược được đề xuất nhằm ức chế sự tiêu hao năng lượng phi tuyến do hiện tượng biến dạng kéo dài đàn nhớt trong CDEA gây ra. Dựa trên khả năng mô tả chính xác cao của mô hình toán-vật lý, một hệ thống điều khiển đã được áp dụng, và các kết quả thử nghiệm với tín hiệu điện áp được lập trình trước cho thấy rằng tốc độ biến dạng kéo dài của CDEA đã giảm từ 27% xuống dưới 9%. Giải pháp đưa ra có hiệu quả trong việc hạn chế sự tiêu hao năng lượng do các đặc tính đàn nhớt phi tuyến gây ra, điều này có ý nghĩa trong việc thúc đẩy quá trình ứng dụng thực tiễn của CDEA.*

**Từ khoá:** Cơ cấu chấp hành điện môi đàn hồi hình trụ; Biến dạng kéo dài đàn nhớt; Bù đắp biến dạng kéo dài.