

Open-loop control of creep and vibration in dielectric elastomer actuators with phenomenological models

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Abstract—Dielectric elastomer actuators (DEAs) have shown great potentials for biomimetic soft robots. The inherent viscoelastic nonlinearities (such as creep and hysteresis) and the vibration dynamics of the DEAs may limit their motion accuracy in practical applications. However, few control efforts are made to handle these problems. In this paper, we propose a feedforward control approach for creep and vibration compensation of a dielectric elastomer actuator. To this end, a relative creep model of the DEA is first established, and a creep compensator based on the relative creep model is designed to eliminate the creep. Then, a vibration compensator based on zero vibration input-shaping (ZVIS) technique is developed to suppress the vibrational dynamics of the creep compensated DEA. The experimental results with the proposed control approach demonstrate that the creep of the DEA is reduced from 20% into less than 7%, and the overshoot initially about 38.72% is almost completely removed.

Index Terms—Dielectric elastomer actuator, creep modeling, creep compensation, vibration compensation

I. INTRODUCTION

RECENTLY, investigating the soft actuator technology for emerging soft robots has attracted significant attentions in the field of robotics. Comparing with traditional actuators (such as electric motors, piezoelectric actuators, hydraulic motors), dielectric elastomers actuators (DEAs) are a kind of promising soft actuators that have advantages of light-weight, high efficiency, large strain, high energy density, fast response, and low cost [1]–[4].

During the past decade, many efforts have been made in the literature to design different configurations of DEAs, for instance circular DEAs [5], folded DEAs [6]–[8], rolled DEAs [9]–[11], rotatable DEAs [12] and so on. And there are also some soft manipulator [13]–[15] robots and smart sensors [16] made of DEAs. However, the inherent strong nonlinearity of the DEAs, such as the viscoelasticity, greatly degrades the performance of the DEAs. Creep is a kind of nonlinearity caused by such viscoelasticity, which exhibits drift phenomenon of the output displacement of the DEAs when subjected to a voltage. The creep becomes noticeable over extended periods of time after the transient response due to the system dynamics. As an illustration, Fig. 1 shows the

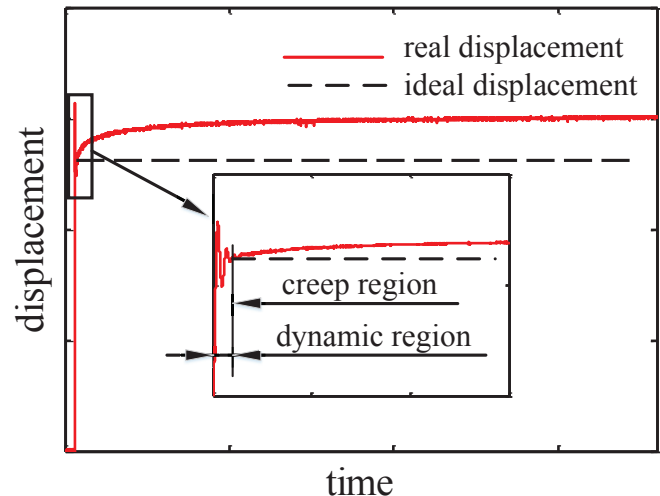


Fig. 1. a common step response of a circular DEA.

response of a DEA when a step input voltage is applied. It can be seen the displacement of the DEA reaches a final value after a transient part in the dynamic region. Then, a slow drift, generally called the creep, appears although the constant voltage is kept. Therefore, both the creep and badly damped vibration degrade the motion performance of the DEAs. It is worth of mentioning that the settling time of the transient part is lower than 1s, but that of the creep persists more than tens of minutes.

To explain this viscoelastic creep, the researchers have developed several models. By using Christensen's theory of viscoelasticity [17], Yang established a non-linear creep model [18] for dielectric elastomer membranes. However, this model is usually suitable to stretch ratio between 1.6 and 3 which may limit its application. Based on experimental observations, Plante found key performance mechanisms of the viscoelasticity, and developed an analytical method [19] to describe the creep using a modified Bergström-Boyce model. Although the model achieves good agreement with experimental data, electromechanical coupling is ignored in the model development. As an alternative, Hong developed a more general model [20] according to the principles of non-equilibrium thermodynamics, fully considering electromechanical coupling and large deformation of dielectric elastomer. Wissler [21] has modelled the viscoelastic creep by a Prony series with 4 different time constants. Extended works can also be found in [22]–[25].

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In general, these models take the continuum mechanics and material nonlinearity into consideration, which belongs to the physical-based models. However, they are usually complex and are difficult to transform them into compensating the creep of the DEAs. In fact, it is important as well to mitigating the creep of the DEAs for practical applications. As an alternative, several feedback control approaches without physical-based models have been developed to well control DEAs with the self-sensing capability, may referring to Gisby *et al.* [26], Rizzello *et al.* [27] and Rosset *et al.* [28].

In this paper, we propose a new creep model for both creep description and compensation. Different from the physical-based model, this new modeling method only relies on the input-output experimental data of the DEAs, which is completely phenomenological. The developed model can produce similar behaviors but without necessarily providing physical insight into the modeling problem. Then, the real-time experimental results are presented to demonstrate the effectiveness of the proposed method. With the creep model, a controller is developed for inverse compensation in the open loop. For verification, a circular DEA is designed and fabricated for proof-of-concept testing. The experimental evidence shows that the creep is reduced from 20% into less than 7%. Finally, for further improving the compensation performance, we develop a damping controller with the zero vibration input-shaping (ZVIS) technique to attenuate the vibration of the creep compensated system. The experimental results show that with the ZVIS based controller, the overshoot initially about 38.72% is almost completely removed.

The main characteristics of this paper lie in the facts that:

- i) Compared to the commonly used physical-based models, a new phenomenological model is proposed in this work for the creep description of the DEAs, where only the input-out experimental data are sufficient without taking the physical behaviors into account;
- ii) A real-time open-loop controller is developed for both creep and vibration compensation of the DEAs, which is the first study in the field of controlling DEAs, to the best knowledge of the authors.

The reminder of this paper is organized as follows. Section II introduces the system description. In section III, the creep model and creep compensator are presented. Then, the damping controller with the ZVIS technique is developed in section IV. Finally, conclusion and discussion are drawn in section V.

II. SYSTEM DESCRIPTION

A. A circular DEA

In this work, a circular DEA is designed and fabricated for proof-of-concept testing. Fig. 2 shows the structure of the circular DEA. A VHB membrane (3M VHB 4905 acrylic, in gray) is equiaxially stretched to 9 times in area and fixed on an outer rigid PMMA frame (in green). Then, the membrane is coated on both sides with compliant carbon grease (in black). A 67g mass (in yellow), consisting of a circular plate (17g) and a weight (50g), is adhered to the center of membrane as an end-effector of the DEA. Fig. 3 (a) shows the schematic illustration of the DEA movement when driven by a step

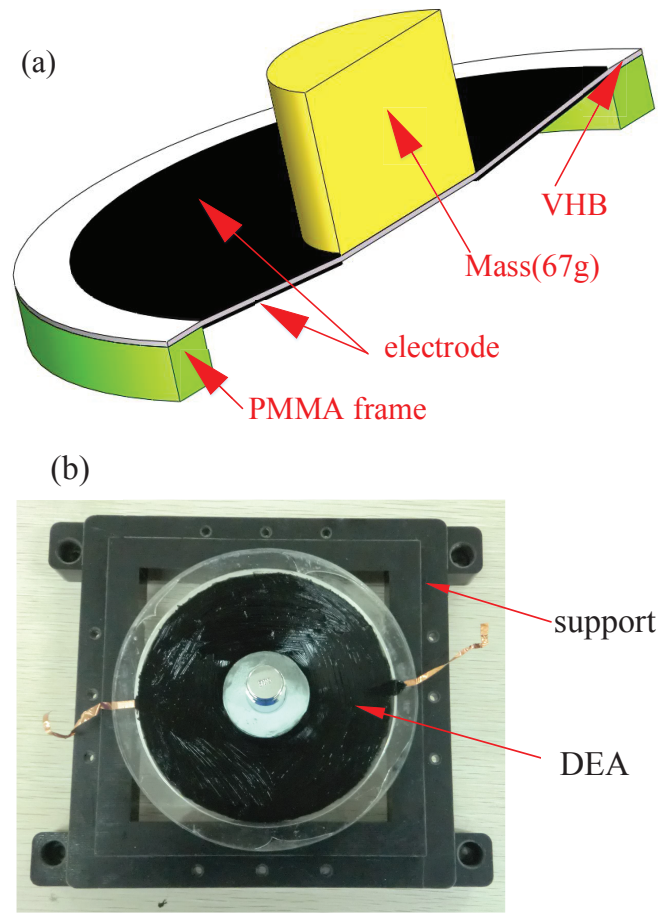


Fig. 2. Description of the designed circular DEA: (a) CAD model of the circular DEA; (b) a picture of it.

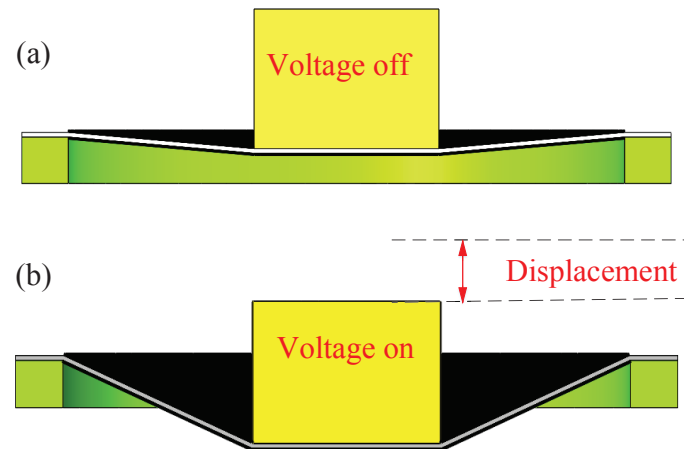


Fig. 3. Illustration of movement of the circular DEA: (a) without an applied voltage; (b) with an applied voltage

voltage. Fig. 3 (b) shows a picture of the fabricated DEA. The active region is circular with an inner diameter of 20mm and an outer diameter of 60mm.

B. Experimental setup

For modeling, controller design and experimental verification, an experimental platform with the DEA is built, which

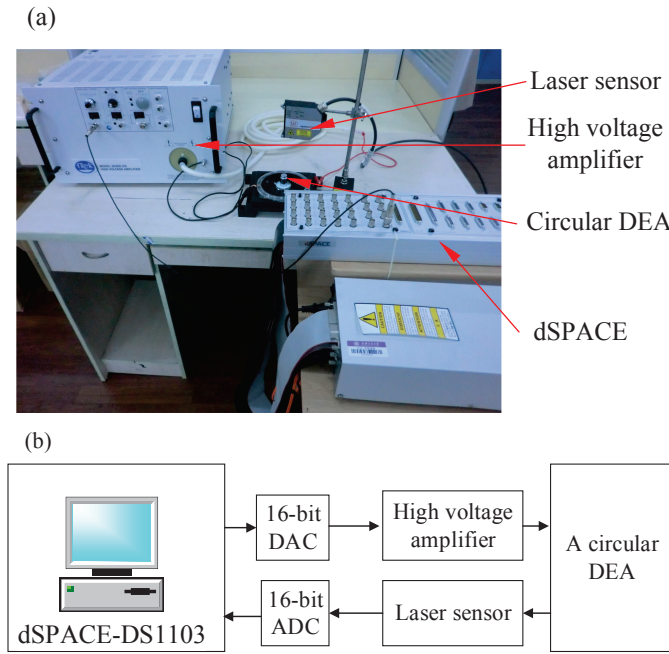


Fig. 4. The whole experimental setup: (a) experimental platform; (b) block diagram.

is shown in Fig. 4. A high voltage amplifier (TREK 20/20C-HS) with a fixed gain of 2000 is used to provide excitation voltage for the DEA. The output displacement of the DEA is measured by a laser sensor (Micro-Epsilon ILD2300-100, range of 100mm with an analogue output of 10V). A dSPACE-DS1103 board equipped with 16-bit analogue-to-digital converters (ADCs) is utilized to generate the control voltage for the high voltage amplifier and capture the actual displacement of the DEA from the laser sensor. In this work, the sampling time is set to be 1ms. As an illustration, Fig. 4 also shows the block diagram of the whole experimental platform.

C. Experimental phenomena

With the experimental setup, the dynamic performances of the circular DEA are tested. Fig. 5 shows the step responses of the circular DEA when it is excited by four step input voltages (1.5kV, 2kV, 2.5kV and 3kV). The solid curves represent the experimental displacement while the dotted curves denote the ideal displacement. As described in Section I, the step response can be separated into dynamical region and creep region. Based on experimental observation, the vibration is dominated and the creep can be ignored during dynamic region which lasts about one second after applying the voltage. Then, the creep is in charge of the response, where the displacement drifts slowly as shown in the partial enlarged curve in Fig. 5. Therefore, the ideal displacement (D_{ideal}) can be determined depending on the separated time t of the two regions. In this work, $t=7s$ is selected because the step voltage is applied when $t=6s$. Of course, it should be noted that the exact time of ideal displacement depends on the responses of different actuators. The differences between step response curves and the idea displacements are absolute creep displacements as

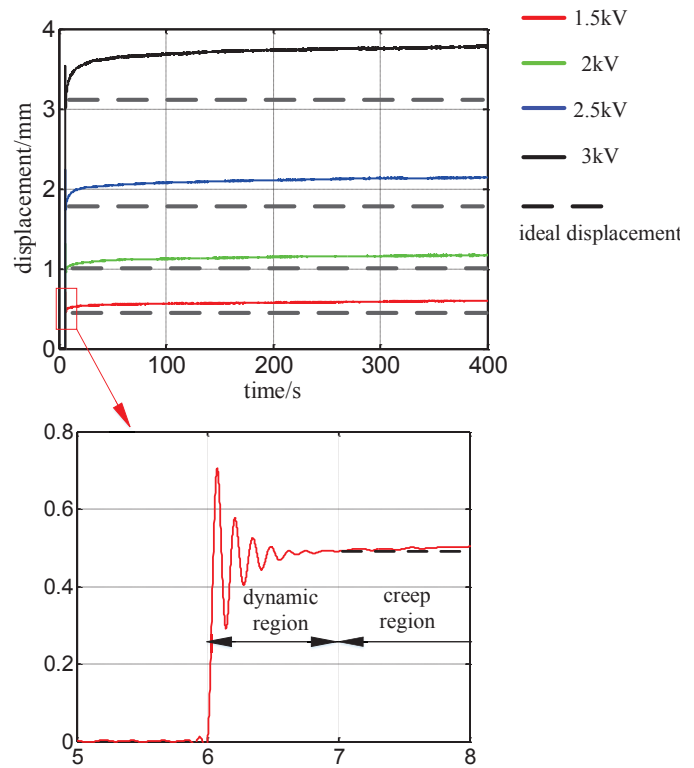


Fig. 5. Step responses of the circular DEA under different input voltages.

shown in Fig. 6, which demonstrates that the absolute creep displacement significantly depends on input voltage.

Furthermore, we can see from Fig. 5 that there are unwanted vibrations during the dynamic region of the DEA responses. In the following development, we will present a feedforward control technique for compensation of both the creep and vibration. We firstly establish a model to describe the creep. Then, the creep is remedied by a compensator with the developed model. Finally, to eliminate unwanted vibration, a ZVIS technique is developed for the creep compensated DEA.

Remark: We should mention that according to experimental results, the breakdown voltage of the fabricated DEA is about 4.5 kV. In this work, pull-in instability, loss of tension, and electrical breakdown are not analyzed. Therefore, for simplicity, the input voltage of the DEA is limited to 3kV in the present study. In addition, the lowest input voltage is 1.5 kV considering the resolution of the laser sensor.

III. CREEP MODELING AND COMPENSATION

In this section, a new model is developed to describe the creep. Then, a compensator with the developed model is designed to remedy the creep.

A. Creep modeling

The absolute creep displacement relies on input voltage, it is not convenient to establish absolute creep model directly. In order to deeply understand the relationship between the creep displacement and input voltage, an index of relative creep displacement $C_D(t)$ and a proportionality coefficient K are defined as:

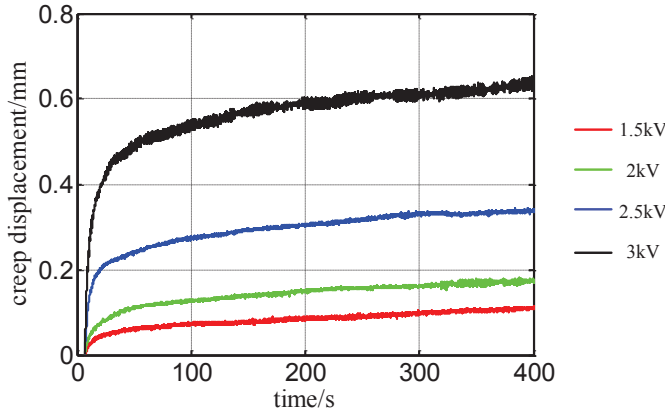


Fig. 6. Absolute creep displacements of the circular DEA.

$$C_D(t) = \frac{D(t) - D_{ideal}(t)}{D_{ideal}(t)} = \frac{D_{creep}(t)}{D_{ideal}(t)} \quad (1)$$

$$K = \frac{D_{ideal}(t)}{V(t)} \quad (2)$$

where $D(t)$ and $D_{ideal}(t)$ represent the actual displacements (solid line in Fig. 5) and ideal displacements (dotted line in Fig. 5), respectively; $D_{creep}(t)$ (Fig. 6) denotes the absolute creep displacements after the dynamic region, which starts from $t = 7s$. For illustration, the relative creep displacements are shown in Fig. 7. It can be seen that all the relative creep displacements with different step voltages reach 20% with absolute error 3% when $t=400s$. Therefore, we can draw a conclusion that within a certain voltage range, the relative creep displacements mainly depend on the DEA itself, rather than on the amplitude of the input voltages. Based on this conclusion, only one relative creep model is needed. However, we still need worried about the effect of the K . Fig. 8 shows the fitted relationship between input voltage and the K , it demonstrates that the K significantly relies on the input voltage, so we have to take the K into account when we compensate for the creep, but can ignore the K while establishing the relative creep model.

Remark: We should mention that, in this work, $t = 7s$ is chosen as a reference to split the two regions based on the experimental results of the costumed-built DEA. Of course, the exact time of dividing those two regions depends on the responses of different actuators. It should be noted that this treatment is not specific. Without losing generality, it can also be applied for other smart material based actuators for the creep modeling, may referring to [29]–[31].

Based on the definition of the relative creep (1), a creep model relating the output displacement and the step voltage can be given by:

$$\frac{D(t)}{V(t)} = K \cdot [1 + C_D(t)] \quad (3)$$

where $V(t)$ represents step voltage. We should mention that the transient part of the DEA response is not considered in the creep model, which will be taken into account in the following

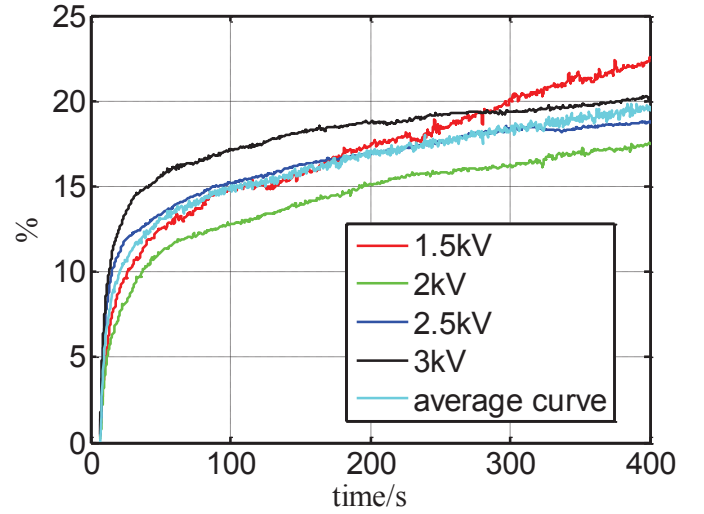


Fig. 7. Relative creep displacements of the circular DEA.

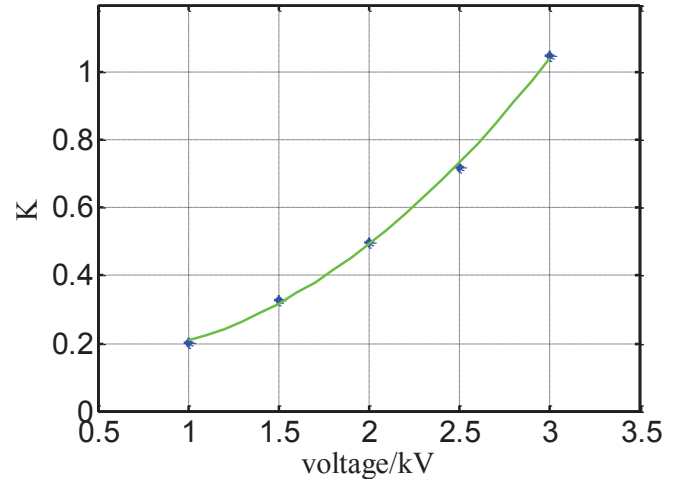


Fig. 8. The relationship between the input voltage and the proportionality coefficient K .

development. In order to obtain $C_D(t)$, we can describe it in the s-domain and use the system identification method with the experimental data. The identification steps can be performed as follows:

- i) Using the four relative creep displacement curves to calculate the average relative creep displacement;
- ii) Choosing a continuous-time transfer function as our estimation model of (1) and the first estimation of the transfer function contains one zero and two poles;
- iii) Using Matlab identification toolbox to determine the model parameters, the input is unit step, and the output is the average creep displacement shown in Fig. 7, the sampling time is 0.001 in this work, other parameters use the default settings;
- iv) Comparing the step response of the model with experimental results, if they are not fit well, increasing the model order and repeating the identification process. It should be noted that we adopt two methods to evaluate the identified models: comparing the goodness of fit to experimental data and comparing the unit-step response curve with the average

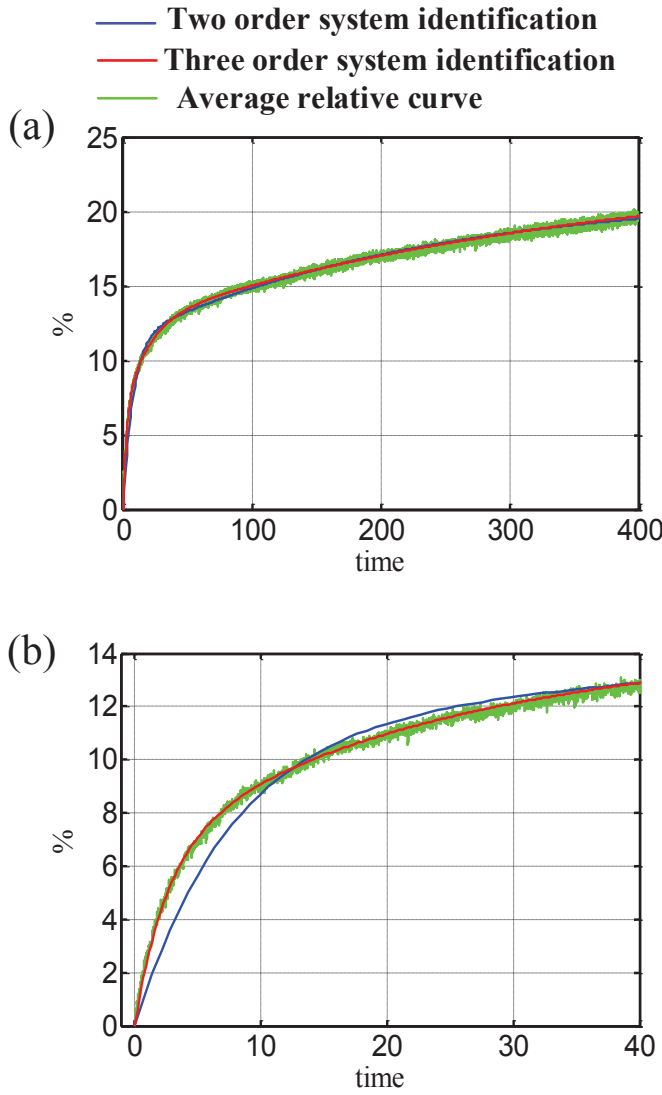


Fig. 9. Comparison between experimental results and identified models: (a) in the whole time period; (b) partial enlarged curves of the (a).

relative creep displacement curve.

Fig. 9 shows the comparison between experimental results and identified models. It demonstrates that the advantages of the three-order function for the creep description. So we choose the three-order function as the relative creep model. In this work, the identified model is expressed as:

$$C_D(s) = \frac{0.0281s^2 + 0.0028s + 0.000014}{s^3 + 0.45s^2 + 0.023s + 0.000059} \quad (4)$$

B. Creep compensation

The voltage-independent relative creep model for the circular DEA is established, but it should be noted that the $C_D(t)$ only depends on time, and has no relationship with the step voltage $V(t)$. So, we can not get the acquired voltage to compensate creep by inverting the relative creep model. Inspired by the work in [29]–[31], the concept of a creep voltage is utilized to remove the creep. The relationship

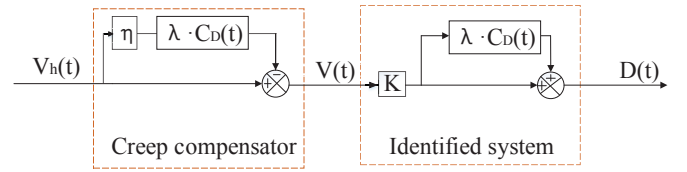


Fig. 10. Bloc-diagram displaying the creep compensator.

between the creep model and creep voltage can be given by

$$\left[\frac{L(t)}{L_0(t)} - 1 \right] \cdot \frac{1}{\mu} = \left[1 - \frac{V_p(t)}{V_0(t)} \right] \cdot \frac{1}{\nu} \quad (5)$$

where $L(t)$ represents the step response of the actuators; L_0 represents the ideal displacement; $V_p(t)$ is the creep voltage which is defined in [30] and $V_0(t)$ is the step voltage; μ and ν are displacement creep factor and voltage creep factor, respectively. It demonstrates that the relative creep voltage $[1 - V_p(t)/V_0(t)]$ owns similar creep feature with the relative creep displacement $[1 - L(t)/L_0(t)]$, and the main difference is the creep factor. With the identified relative creep model, the relationship between the creep voltage and the creep displacement of the circular DEA satisfies:

$$\begin{aligned} C_D(t) \cdot \frac{1}{\lambda} &= \left[\frac{D(t)}{D_{ideal}(t)} - 1 \right] \cdot \frac{1}{\lambda} \\ &= \left[1 - \frac{V_h(t)}{V(t)} \right] \cdot \frac{1}{\tau} \\ &= C_V(t) \cdot \frac{1}{\tau} \end{aligned} \quad (6)$$

where $V_h(t)$ is the creep voltage and defined as a time-varying voltage which can compensate the creep of the DEAs and keep the displacement of the DEAs stable, $C_V(t)$ is the relative creep voltage, τ and λ are two constant ratios which represent the difference between the relative creep displacement and the relative creep voltage. So, we can get a conclusion that the $C_V(s)$ equals to $\frac{\tau}{\lambda} \cdot C_D(s)$. Based on (6), a creep compensator can be designed as:

$$\begin{aligned} \frac{V_h(t)}{V(t)} &= 1 - C_V(s) \\ &= 1 - \frac{\tau}{\lambda} \cdot C_D(s) \\ &= 1 - \eta \cdot C_D(s) \end{aligned} \quad (7)$$

where η equals to $\frac{\tau}{\lambda}$. Fig. 10 shows the control block of the system with the creep compensator. In this work, the η is identified as 0.2. For the verification, Fig. 11 shows the step responses of the system with the creep compensator under four different exciting voltages (1.5kV, 2kV, 2.5kV and 3kV). Fig. 12 also shows the relative creep displacements of the compensated system. It can be seen that, with the compensator, the creep is limited to less than 7%, which is reduced by 65% compared with the uncompensated DEA as shown in Fig. 7.

IV. VIBRATION COMPENSATION

With the creep compensator, the creep of the circular DEA has been successfully removed. However, it can be seen from

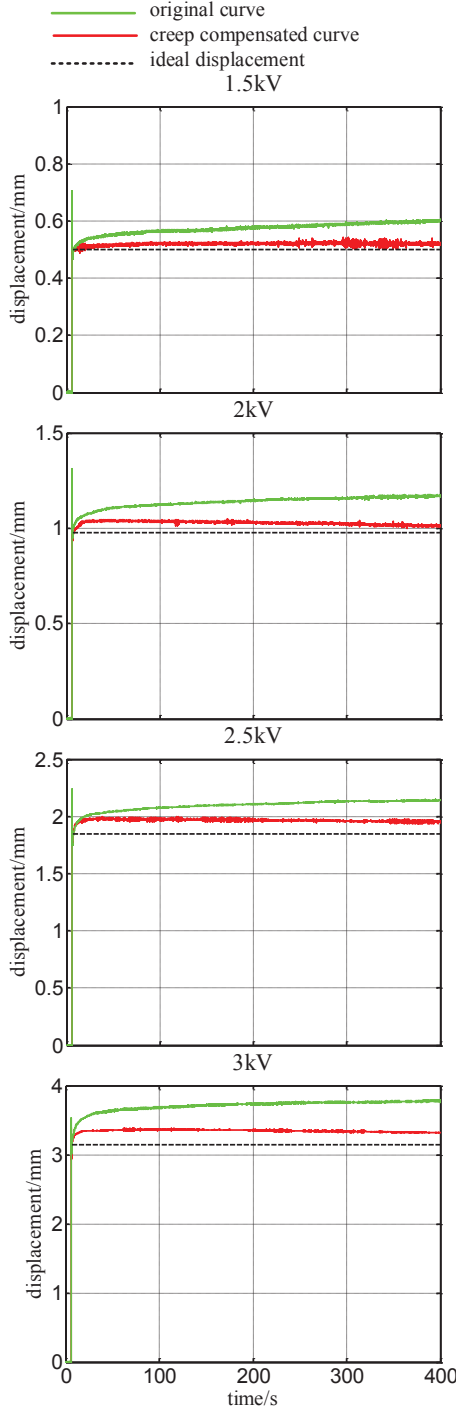


Fig. 11. Step responses of the circular DEA with the creep compensator under different input voltages.

Fig. 13 (partial enlarged curve to Fig. 11), that the overshoot of each step response reaches about 38.72%, 30.91%, 20.83% and 8.53%, respectively. In this section, we will propose the ZVIS technique to suppress the vibration and overshoot of the creep-compensated DEA.

A. The ZVIS technique

Firstly, the control principle of the ZVIS technique [32] is described. In general, with the ZVIS technique, the system

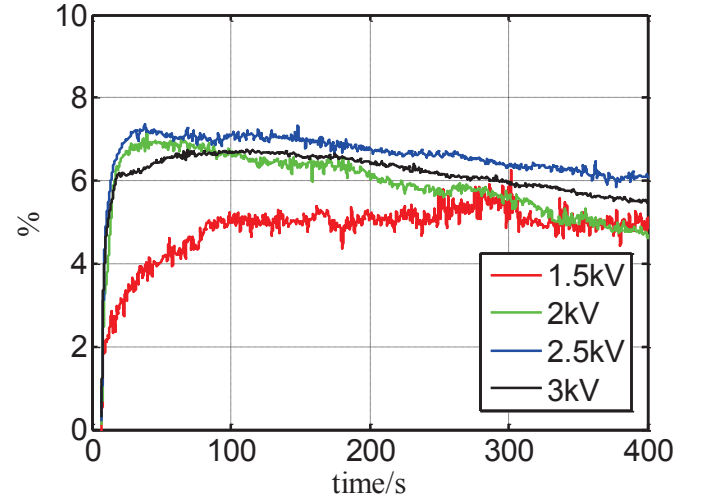


Fig. 12. The relative creep displacements of the circular DEA with the creep compensator under different input voltages.

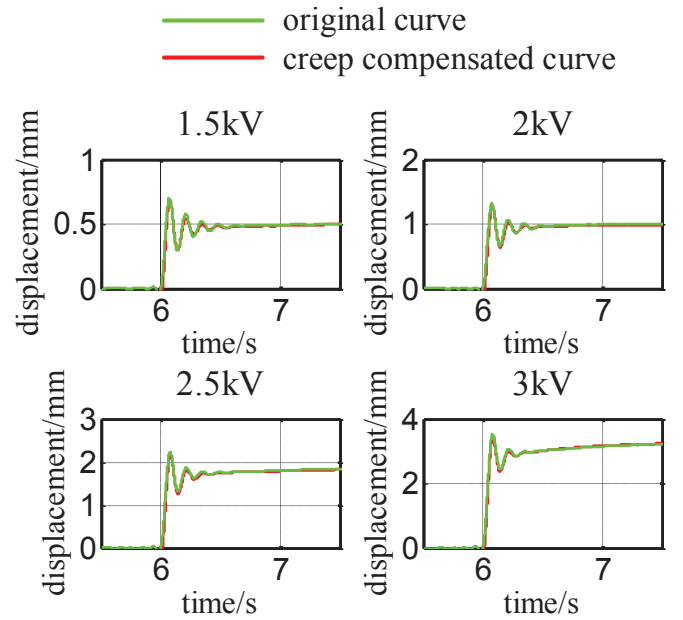


Fig. 13. Partial enlarged curve to Fig. 11.

model should be expressed as:

$$\frac{D(s)}{V_h(s)} = \frac{P}{\left(\frac{1}{\omega_n}\right)^2 s^2 + \frac{2\xi}{\omega_n} s + 1} \quad (8)$$

where $D(s)$ is the output displacement of system with the input voltage $V_h(s)$, $P > 0$ is a constant, ω_n is the nature frequency, and ξ is the damping ratio. From (8), the period of the vibration T can be calculated by:

$$T = \frac{2\pi}{\omega_n \sqrt{1 - \xi^2}} \quad (9)$$

From the system (8), a vibration generally appears when applying an impulse. In this work, a robust ZVIS technique [33], [34] is adopted to suppress such vibration. According to the robust ZVIS technique, a series of impulses with small

TABLE I
PARAMETERS OF THE VIBRATION COMPENSATOR.

parameter \ order number i	1	2	3
A_i	0.5845	0.3600	0.0554
t_i	0	0.1381	0.2763

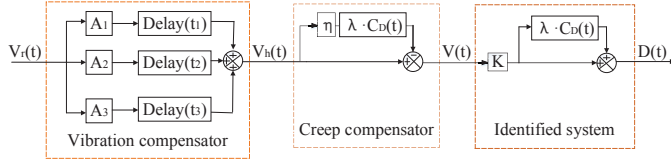


Fig. 14. Bloc-diagram displaying the vibration compensator.

amplitude are required. The amplitude of each impulse A_i and the delayed time t_i should satisfy:

$$A_i : \begin{cases} A_1 = \frac{a_1}{(1+\beta)^{m-1}} \\ A_2 = \frac{a_2}{(1+\beta)^{m-1}} \\ \vdots \\ A_m = \frac{a_m}{(1+\beta)^{m-1}} \end{cases} \quad (10)$$

$$t_i : \begin{cases} t_1 = 0 \\ t_2 = T_d \\ \vdots \\ t_m = (m-1)T_d \end{cases} \quad (11)$$

where $\beta = e^{-\left(\frac{\pi\xi}{\sqrt{1-\xi^2}}\right)}$, m is the number of used impulses, and $a_i = C_{m-1}^{i-1}\beta^{i-1}$, $i = 1, 2, 3, \dots, m$.

B. Vibration compensation

With the ZVIS technique, Fig. 14 illustrates the control block diagram for the creep-compensated system. Firstly, the dynamic model of the creep-compensated system is identified as:

$$\frac{D(s)}{V_h(s)} = \frac{192.01}{s^2 + 22.06s + 1098.61} \quad (12)$$

From (12), the nature frequency ω_n is 33.15rad/s and the damping ratio ξ is 0.333. Fig. 15 shows that the identified model agrees well with the experimental data.

In this work, we select the number of the impulses as three based on the priori experiment. Table I shows the parameters of the vibration compensator. Fig. 16 and Fig. 17 show the comparisons of step responses with and without the ZVIS based controller. It can be seen that both vibration and creep are well compensated.

V. CONCLUSION AND DISCUSSION

This paper has developed an open-loop control system to compensate for the creep and vibration of the DEAs. First, four different step response curves of the circular DEAs are measured to analysis the creep phenomenon of them, it is found that within a certain voltage range, the relative creep displacement has no relationship with input voltage. Then, a new phenomenological creep model is developed for creep

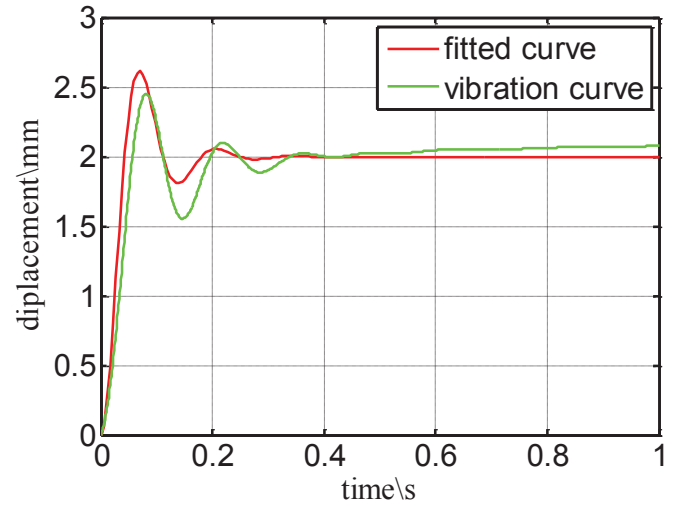


Fig. 15. Comparing the identified vibration model with experimental data.

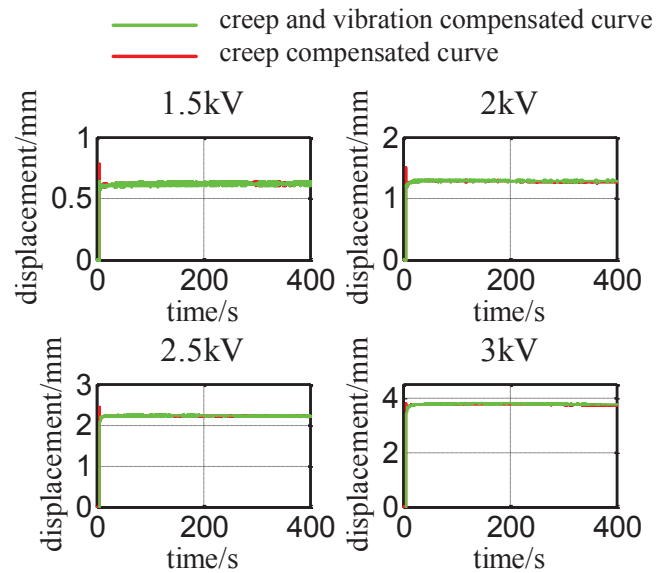


Fig. 16. Step responses of the circular DEA with both creep and vibration compensators under different input voltages.

description, and a creep compensator is established based on the inverse creep model. Last, for compensation of the overshoot, a ZVIS technique is utilized. The experimental results demonstrate that the creep and vibration of the circular DEA are well compensated. Compared to the reported methods for creep modeling and compensation, the advantages of the proposed method can be distinguished as follows.

- i) Compared to the physical-based creep models [19]–[25], a new phenomenological-based model is developed for describing the viscoelastic creep, without necessarily providing physical insight into the modeling problem. Therefore, the modeling method is relatively simple and convenient for developing an inverse compensator.
- ii) Compared to using the feedback controller [26]–[28] for creep compensation, an open-loop controller based on the developed creep model can be directly designed without

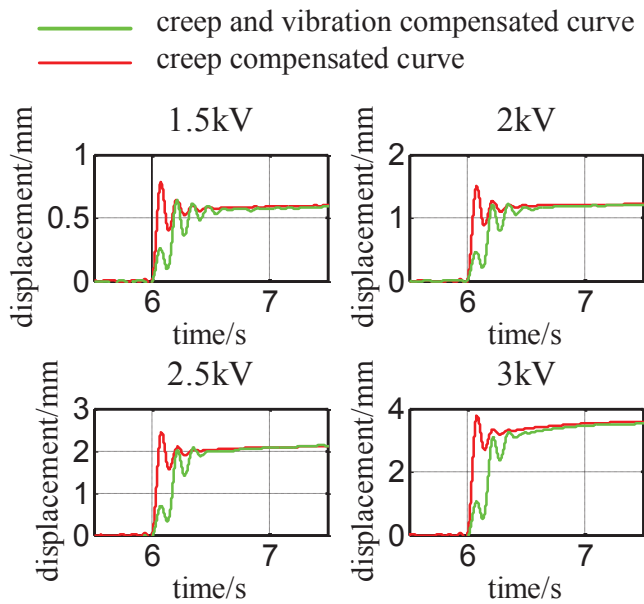


Fig. 17. Partial enlarged curve to Fig. 16.

necessarily using the sensors and considering the problem of controller stability.

In addition, we should mention that the effects of other factors (for example, temperature and material properties) are not taken into consideration. In the future, the proposed modeling and control approach may be considered to combine the feedback control techniques for further improving the tracking performance of the DEAs.

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