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

Jiang Zou, Guo-Ying Gu, Member, and Li-Min Zhu Member

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, great 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 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 Christensens 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].
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 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
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 \( D_{\text{ideal}}(t) \) 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 ideal displacements are absolute creep displacements as 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:
where \( D(t) \) and \( D_{\text{ideal}}(t) \) represent the actual displacements (solid line in Fig. 5) and ideal displacements (dotted line in Fig. 5), respectively; \( D_{\text{creep}}(t) \) (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 relative creep displacement shown in Fig. 7, the sampling time is 0.001 in this work, other parameters use the default settings; 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 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 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:
relative creep response with creep compensator

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

relative creep displacements 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:

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

(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 cannot 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 between the creep model and creep voltage can be given by

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

(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; $\mu$ and $\nu$ 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:

$$C_D(t) \cdot \frac{1}{\lambda} = \left[ \frac{D(t)}{D_{\text{ideal}}(t)} - 1 \right] \cdot \frac{1}{\lambda}$$

$$= \left[ 1 - \frac{V_h(t)}{V(t)} \right] \cdot \frac{1}{\tau}$$

$$= C_V(t) \cdot \frac{1}{\tau}$$

(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, $\tau$ and $\lambda$ 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 $\frac{1}{\tau} \cdot C_D(s)$. Based on (6), a creep compensator can be designed as:

$$\frac{V_h(t)}{V(t)} = 1 - C_V(s)$$

$$= 1 - \frac{\tau}{\lambda} \cdot C_D(s)$$

$$= 1 - \eta \cdot C_D(s)$$

(7)

where $\eta$ equals to $\frac{1}{\tau}$. Fig. 10 shows the control block of the system with the creep compensator. In this work, the $\eta$ 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. 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:

\[
\frac{D(s)}{V_h(s)} = \frac{P}{s^2 + \frac{2\xi}{\omega_n}s + 1}
\]  

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

\[
T = \frac{2\pi}{\omega_n\sqrt{1 - \xi^2}}
\]  

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

$$A_i : \begin{cases}
A_1 = \frac{a_1}{(1+\beta)^{m-1}} \\
A_2 = \frac{a_2}{(1+\beta)^{m-1}} \\
\vdots \\vdots \\vdots \\
A_m = \frac{a_m}{(1+\beta)^{m-1}} \\
t_1 = 0 \\
t_2 = T_d \\
\vdots \\
t_m = (m-1)T_d
\end{cases} \quad (10)$$

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

### 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 $\omega_n$ is $33.15rad/s$ and the damping ratio $\xi$ 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 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
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.

REFERENCES

Jiang Zou received the B.E. degree (with honors) in mechanical engineering from University of Science and Technology Beijing, Beijing, China, in 2014, and he is currently working toward the Ph.D. degree in Shanghai Jiao Tong University. His research interests include design and control of dielectric elastomer actuators based soft robots.

Guo-Ying Gu (S’10-M’13) received the B.E. degree (with honors) in electronic science and technology and Ph.D. degree (with honors) in mechatronic engineering from Shanghai Jiao Tong University, Shanghai, China, in 2006 and 2012, respectively. From October 2010 to March 2011 and from November 2011 to March 2012, he was a Visiting Researcher with Concordia University, Montreal, QC, Canada. Since October 2012, he has been with Shanghai Jiao Tong University, Shanghai, China, where he is currently a Lecturer with the Faculty of the School of Mechanical Engineering. Supported by the Alexander von Humboldt Foundation, he was with the University of Oldenburg, Oldenburg, Germany, from August 2013 to July 2014. He has authored and coauthored more than 30 peer reviewed papers, including 20 SCI-indexed journal papers. He has served as the guest editor of the special issue on Micro/Nano Mechatronics and Automation in International Journal of Advanced Robotic Systems. His research interests include robotics and equipment automation, design and high-bandwidth control of nanopositioning stages, modeling and control of systems involving with hysteresis.

Dr. Gu was the recipient of the Best Conference Paper Award of the 2011 IEEE International Conference on Information and Automation, Scholarship Award for Excellent Doctoral Student granted by Ministry of Education of China in 2011, Hiwin Excellent Mechanical Doctoral Dissertation Award of China in 2013, and Alexander von Humboldt Fellowship in 2013. He has served for several conferences as an international program committee member.

Li-Min Zhu (M’12) received the B.E. degree (with honors) and the Ph.D. degree in mechanical engineering from Southeast University in 1994 and 1999, respectively. From Nov. 1999 to Jan. 2002, he worked as a postdoctoral fellow in Huazhong University of Science and Technology. Since March 2002, he has been with Shanghai Jiao Tong University. He is currently the Cheung Kong Chair Professor, Head of the Department of Mechanical engineering and Automation, and Vice Director of the State Key Laboratory of Mechanical System and Vibration. His research interests include: (1) Modeling and control of smart materials-based actuators, (2) Control, sensing and instrumentation for micro/nano manufacturing, (3) Motion control and trajectory generation for CNC machine tools, (4) Mechanics and dynamics of machining operation for process optimization, monitoring and control, and (5) Coordinate measurement and computational metrology.

Prof. Zhu was the recipient of the National Science Fund for Distinguished Young Scholars in 2013 and selected into the National High-level Personnel of Special Support Program in 2016. He has published one monograph and more than 200 peer reviewed papers, including 122 on international journals. He is now an Associate Editor for the IEEE Transactions on Automation Science and Engineering and Editorial Board Members of the Proceedings of the Institution of Mechanical Engineer (IMechE), Part B: Journal of Engineering Manufacture and the International Journal of Intelligent Robotics and Applications.