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Memory characteristics of hysteresis and creep in multi-layer piezoelectric actuators: An experimental analysis

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ABSTRACT

In this paper we provide an experimental characterization of creep and hysteresis in a multi-layer piezoelectric actuator (PEA), taking into account their relationships in terms of memory structure. We fit the well-known log-t model to the response of the PEA when driven by piecewise-constant signals, and find that both the instantaneous and the delayed response of the PEA display hysteretic dependence on the voltage level. We investigate experimentally the dependence of the creep coefficient on the input history, by driving the PEA along first-order reversal curves and congruent minor loops, and find that it displays peculiar features like strict congruence of the minor loops and discontinuities. We finally explain the observed experimental behaviors in terms of a slow relaxation of the staircase interface line in the Preisach plane.

1. Introduction

Piezoelectric actuators (PEAs) [1,2] are widely employed in micro- and nano-positioning applications, because of their high operating bandwidths, their capability of generating relatively high forces in compact designs, and their high resolution. However, PEAs often exhibit strongly nonlinear dynamical effects, like hysteresis and creep [1,3], that can deteriorate significantly the positioning accuracy of the actuators. Hysteresis manifests itself as a dependence of the actuator strain at a given time t_0 not only on the value of the applied voltage at time t_0, but also on the extremum values of the voltage input for all times $t < t_0$ [3–6], while creep consists of a slow elongation or contraction of the actuator due to thermal effects even in the presence of a constant driving signal [7,8]. In order to employ PEAs in real positioning systems, it is necessary to reduce and/or compensate these undesired effects; a popular and efficient way of doing this is by means of feedforward compensation schemes [1]. These methods do not require the sensing of the actuator displacement, but need accurate, and preferably simple, models of the actuator nonlinear dynamics; these models have to be invertible, so that suitable compensators, to be connected in a feedforward way to the actuator, can theoretically remove, and practically reduce to a given tolerance, the undesired nonlinear effects.

There is an extensive literature on the mathematical modeling of rate-independent hysteresis, and on the relative inverse models for compensation purposes [5,6,9–11]. A well-established framework for modeling quite general rate-independent hysteretic systems is provided by the so-called *Preisach-like* models [5,6]. These models represent the hysteretic nonlinearity by a superposition of simple bi-stable units, whose specific mathematical form can vary from model to model. The single units display a *local* memory property, whereas a linear superposition of them can be proven to have *non-local* memory characteristics, a typical property of most of the experimentally observed hysteretic systems [5].

There is much less agreement and mathematical formalism on modeling and compensation of creep. Several phenomenological models of different complexities have been proposed, from linear ones, based on a superposition of elementary Kelvin–Voigt units [12], to ad hoc models that represent the creep drift by a logarithmic time-dependence [8]. Other papers [13–15] have proposed models of the creep dynamics based on rate-dependent generalizations of elementary hysteresis operators.

In Ref. [7], the authors made an experimental analysis of the creep and hysteresis behavior of a piezoelectric actuator. In each constant part (corresponding to a value V of the applied voltage) of a staircase signal, like the one shown in Fig. 1 (upper panel), they fitted the deformation x of the PEA to the following logarithmic

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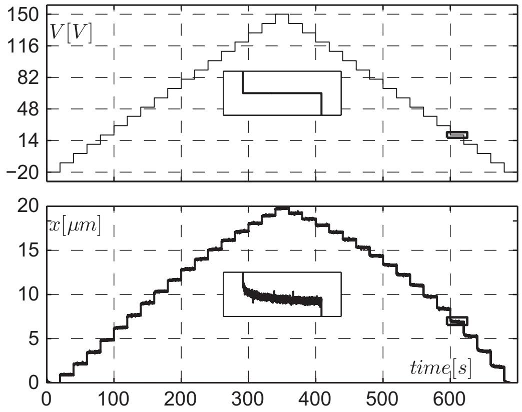

Fig. 1. Upper panel: applied piecewise-constant voltage for the identification of the coefficients in Eq. (1). Lower panel: response of the PEA to the applied input. The insets are enlargements of the boxed details.

time dependence [16,17]:

$$x(V,t) = a(V) + b(V)\log(t/\tau) \tag{1}$$

and found that both the *instantaneous response* coefficient $a(V)$ and the *creep* coefficient $b(V)$ have a hysteretic dependence on the applied voltage V. In Eq. (1), τ represents the starting time of the drift due to the creep effect, and is typically on the order of 10–100 ms.

Several phenomenological models have been proposed to capture the aforementioned hysteretic dependencies of both the creep and the instantaneous response of piezoelectric actuators. However, to the best of the authors' knowledge, it has never been explicitly shown experimentally whether the two observed hysteretic relationships are truly independent nonlinear phenomena or share a common memory structure. In this paper, we provide experimental evidence that the observed hysteretic loops in the instantaneous and creep response coefficients share a common memory structure. We show that the hysteresis loop of the creep coefficient $b(V)$ displays discontinuities and strict congruence of the minor loops, features that cannot be explained by a standard Preisach model, but that can be understood, at least qualitatively, by a noise-driven Preisach model [5, Chapter 4]. According to this model, we interpret the observed creep hysteresis behavior as a slow relaxation of the staircase interface line in the Preisach plane that describes the underlying rate-independent memory.

2. Experimental setup

In order to fully characterize the PEA displacement dependence on different driving input voltage profiles, an experimental setup (shown in Fig. 2) has been assembled. The considered multi-layer PEA is a commercial sample, of size $5 \times 5 \times 20\ \text{mm}^3$. Its nominal displacement is 20 μm for an input voltage in the range $[-20, 150]$ V. For the displacement measurements, a contact-less capacitive sensor with a measuring range of 1 mm has been used. The multi-layer PEA has been driven with a linear amplifier with a voltage gain of 20 V/V. Finally, a National Instruments real-time controller *NI PXIe*-8133 has been used for data generation and acquisition purposes.

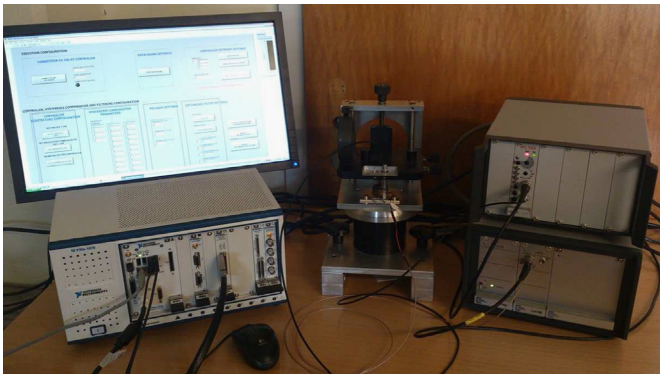

Fig. 2. Experimental setup for creep characterization.

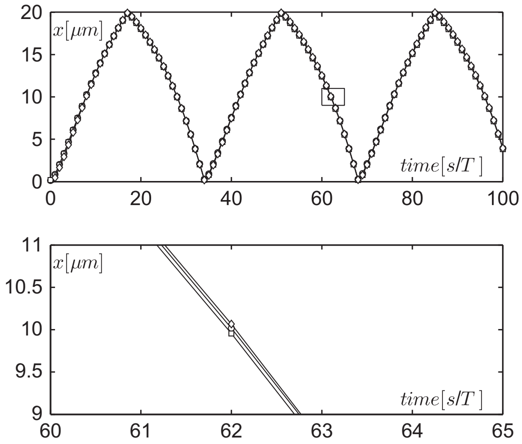

Fig. 3. Upper panel: PEA response to a piecewise-constant voltage signal with steps of different durations. Time is normalized to the duration T of the steps for the creep measurements. Circles: $T=5$ s, squares: $T=10$ s, diamonds: $T=20$ s. Lower panel: enlargement of the boxed region in the upper panel.

3. Experimental results and discussion

The input to the actuator is a piecewise-constant signal, like the one shown in Fig. 1 (upper panel). The displacement of the actuator in response to the driving signal is shown in Fig. 1 (lower panel). In each constant step of the piecewise-constant driving signal, we fitted the response of the actuator to Eq. (1), using standard linear regression methods, hence extracting the parameters a and b as functions of the applied voltage level V [7]. We verified that the results of the fitting are quite independent of the particular value of τ chosen, in a range between 5 and 200 ms. The results presented here have been obtained with $\tau = 100$ ms. The coefficient a shows a hysteretic dependence on the voltage V similar to the one observed under continuous driving. Fig. 3, shows a comparison between the extracted a coefficients using different durations of the steps; the extracted coefficients show a negligible dependence on the step duration, also for more complex piecewise-constant driving signals.

Fig. 4 shows the coefficients $a(V)$ and $b(V)$, which, as already pointed out in Ref. [8], display a hysteretic dependence on the input voltage. However, the a-loop varies continuously with the voltage, whereas the b-loop shows discontinuities coinciding with the turning points of the driving signal. Indeed, the sign of the creep coefficient is equal to the sign of the time derivative of the driving signal, and hence there is a jump each time the driving signal changes the direction.

Fig. 5 sketches a possible phenomenological interpretation of our experimental results. We consider the creep dynamics as a slow relaxation of the staircase line on a Preisach plane [5,6]. It can be shown [5] that such a relaxation effect can result from a noise-driven Preisach model, in which the noise represents the thermal fluctuations, and that the time dependence of the relaxation dynamics is logarithmic, with a multiplicative coefficient that can depend on the DC component of the driving voltage signal,