New open-loop actuating method of piezoelectric actuators for removing hysteresis and creep

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Many researchers have studied the actuation of piezoelectric actuators using a model of the hysteresis of piezoelectric transducer (PZT). However, these hysteresis modeling methods to remove the nonlinearity in PZT did not include the consideration of PZT’s creep effect which is a very important factor in many open-loop application of piezoelectric actuator. In order to compensate for the creep effect of PZT as well as the hysteresis of displacement, the notion of “voltage creep” is proposed in this article. And, with the notion, a new actuation method of piezoelectric actuators for removing the hysteresis and creep will be proposed and the actuation result will be presented. © 2000 American Institute of Physics.

I. INTRODUCTION

To compensate for the hysteresis and creep on the actuation of piezoelectric actuators, many methods have been proposed. Okazaki and Mizutani used a feedback of the displacement of the PZT.1,2 Kaizuka used an insertion of an additional capacitance in series.3 Newcomb applied the charge control by driving a current source.4 And Katsushi used a feedback of induced charge on the ends of a PZT.5 These methods not only need additional equipments but also do not guarantee the effective compensation of PZT hysteresis except for the case of using the displacement feedback sensor. Even the case of the feedback sensing methods may not be easy to implement in some application for their high price of displacement sensors and the limit of space to attach the displacement sensor. Therefore, many researchers have studied the PZT actuation methods using a model of the hysteresis of PZT and compensate it by the model. For instance, Landau and Lifshitz proposed polynomial relation to match its graphical representation.6 Jung and Kim presented a feed-forward control method with three different deterministic models to reduce the hysteresis effect in PZT actuators.7 Goldfarb and Celanovic incorporated a generalized Maxwell resistive capacitor as a lumped parameter causal representation of hysteresis.8 Richter used a nonformal analogy between nonlinear viscoelasticity and the observed hysteresis behavior.9 Ge and Jouanah used the Preisach Model to represent the hysteresis in PZT actuator.10 However, these hysteresis modeling methods to remove the nonlinearity in PZT did not include the consideration of PZT’s creep effect which is a very important factor in many open-loop application of PZT actuator. Especially in many scanning surface measurement fields, for instance, phase shift interferometer (PSI) confocal microscopy and scanning probe microscopy (SPM) which includes atomic force microscopy (AFM), scanning tunnelling microscope (STM), near-field scanning optical microscopy (NSOM), etc. In these measurement applications, measuring sample must not only be positioned precisely, but also keep its position without any movement while the measuring operation is going on. In order to compensate for the creep effect of PZT as well as the hysteresis, the notion of “voltage creep” is proposed in this article. Using the notion, new actuation method for PZT actuator without the hysteresis and creep will be proposed.

II. CREEP EFFECT IN PZT

Figure 1 shows a step response of a general stack-type PZT actuator. As shown in the figure, there are the displacement differences for the same input voltage. This difference is a hysteresis effect in PZT. In addition to hysteresis, we can see the creep effect in each step. Generally, it has been known that the creep response has a logarithmic shape over time. This can be represented by the following equation:11

\[ L(t) = L_0 \left( 1 + \gamma \log_{10} \left( \frac{t}{0.1} \right) \right), \]

(1)

where \( L(t) \) is a PZT actuator’s displacement for any fixed input voltage, \( L_0 \) is a nominal constant displacement value which is the displacement of 0.1 s after applying the input voltage. \( \gamma \) is a creep factor which determines the rate of the logarithm. Rates of creep \( \gamma \) are different each other according to an input voltages. Moreover, even if the final applied voltages are the same, the value of the parameter \( \gamma \) is still different from the others according to the past applied voltages. It is surprisingly like the phenomenon known as the hysteresis. And these phenomenon is related to “voltage creep” that will be described in the next section.

III. DEFINITION OF VOLTAGE CREEP

In the previous chapter, it was shown that the constant input voltage lead to the displacement creep in the PZT. Based on this fact and the correlation between the electrical energy and mechanical energy in PZT, we can hypothesize that the constant displacement could lead to the creep of the input voltage—in other words—if we apply the input voltage changing logarithmically with a appropriate creep factor,
PZT displacement could be constant without the creep effect. To test the validity of the hypothesis, such an experimental setup shown in Fig. 2 was made. The experimental setup consists of a stack type PZT, guide, displacement sensor, and feedback circuit. Gap sensor is adopted for sensing the displacement of PZT, which has 5 nm resolution and 25 μm stroke. The dynamic characteristic of the feedback system is not our concern and the only thing we expect just to have no steady-state error for a reference input. Therefore, it could be a reasonable choice to apply an analog PI controller for the control system. The experiment is performed as follows. While the displacement of the PZT is controlled without the hysteresis and creep using the gap sensor and analog PI controller, the input voltage entered into the PZT through the amp is monitored. If we analyze this monitored input voltage, we can use this to actuate the PZT without hysteresis and creep effect in an open-loop manner. For this purpose, 1 μm step command input is applied to the feedback system. Figure 3 shows the PZT response for the input step. It shows 4 nm resolution for this system. Since this system is controlled by the PI controller, it is natural that it had no steady state error and almost all of the creep is absent except for a small initial overshoot that exists for less than 0.1 s. At the same time we monitor the voltage applied to PZT actuator, which is shown in Fig. 4. In Fig. 4(a), “d” is the voltage input difference for the same PZT displacements caused by the inherent hysteresis effect in PZT. Figure 4(b) is the input voltage response for 3 μm command. It shows the creep-like effect clearly and this creep effect has a different rate for each input step (see Fig. 5). To represent the difference of drift rates of voltages, displacement at 0.05 s after applying command inputs for each response curves are shifted to zero. I will define this creep effect of input voltage as “voltage creep.”

**IV. EXPERIMENTAL PROCEDURE**

“Voltage creep” may be analyzed in the same manner with the displacement creep. Therefore, it can be modeled again by Eq. (1) as follows:

\[
V(t) = V_0 \left( 1 + \gamma_v \log_{10} \left( \frac{t}{0.1} \right) \right),
\]

where \(V(t)\) is a PZT input voltage for a fixed displacement, \(V_0\) is a nominal constant input voltage and \(\gamma_v\) is a voltage creep factor which determines the rate of logarithm. Figure 6 shows this logarithmic model fits well to the voltage creep. To investigate the voltage creep property, we applied a ladder-like command with 0.3 μm step and 6 μm height to the feedback system. Each step is 5 s. In each 5 s duration, the PZT actuator expands in proportion to the applied command step and the input voltage entered into the PZT directly is monitored. In each step, the response is stored with an interval of 0.2 s \(V_0\) and \(\gamma_v\) parameters can be estimated from the Eq. (2) with the least-square method.
V. RESULTS

$V_0$ and $\gamma_e$ in the input voltages with respect to the applied command displacements stated in previous chapter are shown in Fig. 7. As shown in the figure, $V_0$ and $\gamma_e$ show the

![Fig. 4. Monitored input voltage entered into the PZT for step command input. (a) Monitored input voltage: "$d$" is the voltage input difference for the same displacement output caused by the inherent hysteresis effect in PZT. (b) Response for 3 $\mu$m command. It shows the creeplike effect clearly.](image1)

![Fig. 5. Monitored input voltages for different step command input. To represent the difference of drift rates of voltages, displacement at 0.05 s after applying command inputs for each response curves are shifted to 0.](image2)

![Fig. 6. Fitted curve vs time response curve for the monitored voltage.](image3)

![Fig. 7. Hysteresis loops for $V_0$, $\gamma_e$, $V_0$, and $\gamma_e$ shows the hysteresis loop for the input displacements. It shows that $\gamma_e$ as well as $V_0$ for any displacement loops has a definite hysteresis loop pattern, not an unpredictable one.](image4)
hysteresis loop for the input displacements and it keeps its properties even when many loops had passed. We already know that the $V_0$ has a hysteresis loop pattern about any displacement loops. However, the important thing in this result is that $\gamma_v$ for any displacement loops has a definite hysteresis loop pattern, not an unpredictable one. This definiteness of these two parameters is an important key factor in the new actuation method of piezoelectric actuator being proposed in this paper. Using these two parameters, I propose the following actuation method. When we want a PZT actuator to be actuated to any displacement and keep its position constantly without any displacement sensor and control circuit, we can get it by applying the voltage over time following Eq. (2). And $V_0$, $\gamma_v$ in Eq. (2) can be acquired from the hysteresis loops like shown in Fig. 7. In order to prove this new open-loop actuation method, step motion experiment was performed as follows. Desired PZT displacement is a mountain-like pattern with an 1 $\mu$m step level. And $V_0$, $\gamma_v$ in Eq. (2) can be acquired from the hysteresis loops like shown in Fig. 7. In order to prove this new open-loop actuation method, step motion experiment was performed as follows. Desired PZT displacement is a mountain-like pattern with an 1 $\mu$m step-level like shown in Fig. 3(a). And each level should be kept in 5 s. In order to achieve this goal, at each level, $V_0$, $\gamma_v$ matched with the desired displacement was picked in the hysteresis loops acquired previously and the input voltage entered into the PZT was applied using the Eq. (2) with these two parameters. The experimental result is Fig. 8. As shown in figure, the error between the result and the command input is about 10 nm. This value is not inferior to the result from the closed loop control. This result can be possible because new actuation method includes the compensation of creep effect in PZT actuator. If we ignore the creep effect in PZT open-loop actuation like conventional hysteresis compensation method,\textsuperscript{7–10} in other words, use only the $V_0$ parameter as the input voltage for actuation and keep its value for 5 s, the
error could be larger than previous one by the creep effect. The result of such an actuation method is in Fig. 9, which shows the definitely increased error caused from the uncompensated creep effect. Figure 10 shows each step responses of Figs. 8 and 9. In this figure, displacements at 0.1 s after applying an input voltages for each response curves are all shifted to zero in order to represent the creep effect in step response. Figures 8–10 prove that the new actuation method has a good capability for removing the PZT creep effect as well as the hysteresis effect. However, there is one problem yet. Our experiments had command input series ascending from 0 to 5 μm followed by descending from 5 μm to 0. \( V_o \), \( \gamma_o \) parameters for this loop commands are drew out directly from the hysteresis loops in Fig. 7. However, determination of \( V_o \), \( \gamma_o \) parameters for an arbitrary (not the loop) command input series is another problem. Because, inherent PZT hysteresis characteristics prevents the direct drawing out the \( V_o \), \( \gamma_o \) for any desired displacement, that is, \( V_o \), \( \gamma_o \) for any desired displacement would be not unique, but changed with respect to the previous displacements—in general this previous displacement is called displacement history. However, once \( V_o \), \( \gamma_o \) are defined definitely in the form of the hysteresis loop like previously acquired in Fig. 7 at all, we can get accurate \( V_o \), \( \gamma_o \) for any desired displacement and for any displacement history by a number of methods.7–10 Using these parameters, we can get PZT responses without hysteresis and creep for any arbitrary input command series. This work is being proceeded.