Improvement of Self-sensing Piezoelectric Actuator Control Using Permittivity Change Detection*

Yusuke ISHIKIRIYAMA** and Takeshi MORITA**
**Graduate School of Frontier Sciences, The University of Tokyo,
5-1-5 Kashiwanoha, Kashiwa 277-8563 JAPAN
E-mail: ishikiriyama@ems.k.u-tokyo.ac.jp

Abstract

We present a self-sensing control method of piezoelectric actuators that compensate the hysteresis characteristics by using the linear relationship between the permittivity change and the piezoelectric displacement. In this article, improvement of this method is described. Increasing the frequency of the voltage for a permittivity detecting, the sensitivity of the permittivity detection was improved and the accuracy of the displacement sensing could be enhanced. In addition, by applying this self-sensing method, we tried to overcome the creep phenomenon that is a peculiar problem of piezoelectric actuators.

Key words: Piezoelectric Actuator, Self-sensing, Hysteresis, Permittivity

1. Introduction

Piezoelectric actuators are widely used in various fields, such as precise positioning, micro mechatronics and active vibration control. On the other hand, these actuators have some severe drawbacks; hysteresis, nonlinearity and creep appear in this displacement when a high electrical field is applied for the large displacement. Therefore, a feedback control with a displacement sensor is indispensable for the precise positioning using the piezoelectric actuator. However, installing such a sensor causes the obstruction for device miniaturization, simple configuration, and low cost, etc. So, it is desirable to be controlled without these sensors. Some researchers have proposed the self-sensing methods [Ref. 1-3] (The sensing principle is based on the linear relationship between the induced charge and the piezoelectric displacement). These techniques can reduce hysteresis effectively, but these require the use of a specially designed charge drive amplifier or very high voltage input. Our research focuses on the precise positioning system utilizing the linear relationship between the permittivity change and the piezoelectric displacement as a self-sensing operation. Moreover, in applying this method, we tried to overcome the creep phenomenon that is a particular problem of piezoelectric actuators.

2. Purpose

2.1 Proposed Control Method

Both the piezoelectric displacement and the permittivity change show a similar butterfly curve against applied electrical field including the polarization reversal, as shown in Figure 1. Focusing attention on this similarity, the linear relationship between the permittivity change and the piezoelectric displacement was clarified in our previous research [Ref.4].
utilizing this relationship, the self-sensing control of the piezoelectric actuator becomes possible. In order to detect the permittivity change depending on the driving voltage in real-time, a permittivity detection voltage is added to piezoelectric driving voltage, as shown in Figure 2. The amplitude and the frequency of the detection voltage are fixed; therefore the permittivity can directly be calculated from the current amplitude induced by the permittivity detection voltage. So as not to influence the piezoelectric displacement, the permittivity detection voltage must have small amplitude (1.0 V_{pp}) and high frequency. [Ref.4]
The current amplitude flowing to the piezoelectric actuator is measured with a current probe. By using a lock-in amplifier (NF Co.:5610B), the change of the current amplitude, that is, the permittivity change is detected. At the same time, the piezoelectric displacement by driving voltage is measured with a laser positioning sensor as a reference signal.

2.2 The Problem and the Purpose

In our previous research [Ref.4], the principle of this system was confirmed; however the signal-to-noise ratio of the measurement result about this linear relationship was not enough. The noisy current signal resulted in insufficient displacement control. So, in this research, we report on the improvement of the accuracy of the self-sensing positioning detection by refinement of the permittivity detection sensitivity.

3. Experiments

3.1 Improving of the Detection Sensitivity

As the current amplitude is proportional to the frequency of the permittivity detection voltage, this frequency was increased from 100 kHz to 500 kHz to improve the sensitivity. In the previous study, the maximum usable frequency of a present lock-in amplifier (NF Co.:5610B) was up to 200 kHz. In this study, by using a frequency converter (NF Co.: Lock-in amplifier frequency extender), the detecting with 500 kHz became possible. The frequency of the detection voltage was set to 500kHz, because the best result was obtained by increasing the frequency empirically. The amplitude of the detection voltage remained fixed to 1.0 \(V_{pp}\) of sine wave to be small against the actuators driving voltage. At the same time, the current probe was changed to the higher resolution type (Tektronix: TCPA300) than that of before (YOKOGAWA: 700937).

In the experiment, a unimorph PZT actuator (Nihon Ceratec Co.: LPD3713) was used. This actuator was 0.6mm in thickness, 37mm in length (28mm PZT) and 13.4mm in width. The PZT ceramics (0.2mm layer) is bonding to a 0.2mm stainless steel. The unimorph actuator is polarized from driving electrode toward the stainless steel. One end of the unimorph actuator was clamped with the aluminum based. And the operation voltage was supplied from a function generator (NF Co.: WF1974) through an amplifier (NF Co.: 4010). A triangular driving voltage with a frequency of 1.0Hz and amplitude of 40\(V_{pp}\) was applied to this actuator. The tip displacement was measured by a laser displacement sensor (Canon: DS-80). Figure 3 shows the relationship between the piezoelectric displacement and the permittivity when the frequency of detection voltage was 100 kHz and 500 kHz.

As shown these graphs, the linearity in this relationship was confirmed and the noise level was successfully reduced.

Fig. 3  The relationship between the piezoelectric displacement and permittivity.  
(Comparision with 100 kHz and 500kHz in the detection voltage)
3.2 Self-sensing Control

After this improvement, the self-sensing control on the basis of the linear relationship between the permittivity change and the piezoelectric displacement was examined with integrating control using a digital signal processor (Mtt s-Box or dSPACE DS1104). From the permittivity change, the piezoelectric displacement was estimated. Figure 4 shows the block-diagram of the self-sensing system using the permittivity detection.

The detection voltage was sine wave of 500 kHz and 1.0 V_{p-p}. The results are shown in figure 5 when a triangular waveform with the frequency of 0.1Hz was settled as a driving voltage that target displacement was 100 µm. In order to confirm the controllability of the system, the piezoelectric displacement was measured with a laser displacement sensor.

Hysteresis was compensated by self-sensing control using permittivity change detection.

Fig. 4 The block diagram of the self-sensing system using the permittivity detection.

Fig. 5 Target displacement and actual displacement. (The target voltage was a triangular wave form)

Fig. 6 The relationship between the piezoelectric displacement and target displacement. Hysteresis was compensated by self-sensing control using permittivity change detection.
(Canon: DS-80). In the practical use, this sensor is not required. The figure 6 shows the relationship between the piezoelectric displacement and the target displacement. The accuracy of the displacement sensing was improved and the proposed system could compensate hysteresis characteristics in the piezoelectric displacement. The effectiveness of this self-sensing method was clarified.

3.3 Creep Compensation

In addition to the hysteresis and the nonlinear piezoelectric displacement, the creep phenomenon is also the particular problem. The phenomenon is that the piezoelectric induced strain has the time dependency even under constant electrical field. Figure 7 shows the piezoelectric displacement driven with 0.01 Hz square shaped voltage, which corresponds to 100 second constant voltage operation with open loop control. Also, figure 8 shows the close-up of the piezoelectric displacement in which the creep phenomenon is clearly indicated. In the same graph, the change of relative permittivity is also shown. This permittivity signal is only used to examine the relationship with the displacement change, and the self-sensing control was not carried out at this point. With 20 voltages, the unimorph actuator generates the displacement of 40 µm, and 50 second, from 2 to 3 µm creep displacement was observed. From figure 8, it is confirmed that the permittivity followed the change of the piezoelectric displacement when the plus voltage was applied. It looks these properties are proportional. On the other hand, with the opposite voltage, such proportional relationship was not indicated.

![Fig. 7 The piezoelectric displacement with open-loop control.](image)

![Fig. 8 The close-up of a creep phenomenon in the piezoelectric displacement and the permittivity change.](image)
Figure 9 and 10 show the results of the self-sensing operation to compensate the creep phenomenon. The target signal was selected to realize the displacement of 40 µm which was almost same to that of open-loop. The creep displacement became almost zero with the proposed method, when the applied voltage was plus. In the opposite direction, it was impossible to do so. These results agree with the above mentioned relationship between the creep displacement and the permittivity change as shown in figure 8. It is interesting research topic why only one direction creep could be compensated with the self-sensing control method. One clue is the polarization direction and the electrical field direction. In the experimental set-up, when the plus voltage is applied, the electrical field becomes parallel to the polarization direction. However, even in the case of the plus voltage is applied to the unimorph, the creep phenomenon could not compensated when the applied voltage became constant from much larger plus voltage. To clarify these complicated results is on-going work.

![Fig. 9](image1.png)  
**Fig. 9** Relationship between the target displacement and the measured one in the self-sensing control.

![Fig. 10](image2.png)  
**Fig. 10** The close-up of the piezoelectric displacement controlled with self-sensing. Left : The electrical field is parallel to the polarization. Right : The electrical field is anti-parallel to the polarization.
4. Conclusions

In the real-time permittivity detection method, the higher frequency of detection voltage was useful for the better sensitivity of the permittivity detection. As a result, the signal-to-noise ratio of the linear relationship between the piezoelectric displacement and the permittivity was improved. By utilizing this relationship, the hysteresis of a piezoelectric unimorph actuator was compensated and the control accuracy was enhanced. In addition, the possibility of the creep phenomenon compensation was confirmed by applying this method.

References