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Self-sensing control of piezoelectric positioning stage by detecting permittivity

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ABSTRACT

Piezoelectric displacement contains hysteresis and creep properties. Therefore, a displacement sensor is indispensable in precise positioning devices; however, the additional space and cost are problems. On the other hand, self-sensing methods that utilize the piezoelectric actuator itself as the displacement sensor have been proposed. With these self-sensing methods, precise positioning becomes possible without an additional displacement sensor. We developed a self-sensing method utilizing the non-hysteresis relationship between the permittivity change and the piezoelectric displacement. Furthermore, a differential current measurement method using two piezoelectric elements with a bimorph actuator could improve the positioning accuracy. In this study, we examine the control of a positioning stage using two multilayered piezoelectric actuators by applying the differential current measurement method for self-sensing control. The results indicate that the differential current measurement method is effective for precise positioning control. The positioning errors due to hysteresis decreased from 0.8 μm to 0.1 μm for a 10 μm displacement range. In addition, permittivity feedback control could compensate for the creep property.

1. Introduction

Piezoelectric materials have the advantages of accuracy and rapid response. Therefore, they are used in high-precision devices as actuators. For example, a piezoscanner of AFM or a deformable mirror for a telescope adopts piezoelectric actuators [1,2]. However, piezoelectric displacement contains hysteresis and creep properties, and these properties have been studied from various viewpoints [3–5]. To eliminate the hysteresis property of a piezoelectric actuator for precise positioning control, a displacement sensor, such as a capacitive sensor or a laser interferometer, is indispensable. However, for a low-cost and simple system, self-sensing methods that utilize the piezoelectric actuator itself as a displacement sensor are required [6–9]. For example, a self-sensing method based on the non-hysteresis relationship between the piezoelectric displacement and the electric charge was proposed [6,7]. However, this method is not stable in the quasi-static state, because the electric charge is difficult to hold and the offset charge signal accumulates, due to the integration of the current signal.

On the other hand, we have reported the non-hysteresis relationship between the piezoelectric displacement and the permittivity of piezoelectric actuators. This relationship was utilized for the self-sensing method for detecting the piezoelectric displacement from the permittivity change. By applying this method, the piezoelectric displacement of the bimorph actuator was controlled within a 0.4 μm error for an 80 μm displacement range [10–12].

In this study, we examine our self-sensing method for the positioning stage using multilayered actuators, which are mainly utilized in precise positioning devices. In addition, the differential current measurement method, which was quite useful in our previous study using the bimorph mechanism [12], is applied to the positioning stage for the improvement of the permittivity detection accuracy.

2. Experimental setup

2.1. Permittivity detection

Self-sensing control by detecting permittivity is based on the non-hysteresis relationship between the piezoelectric displacement and the permittivity change. This is related to the fact that the permittivity follows a similar butterfly curve to that of the piezoelectric displacement versus input voltage, as shown in Fig. 1. It

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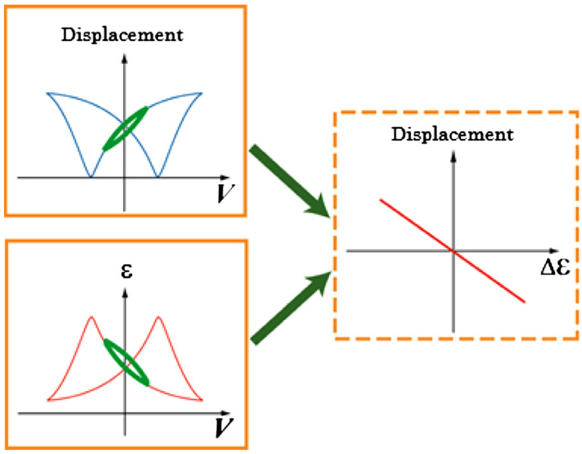

Fig. 1. Relationship between applied voltage, displacement, and permittivity.

is considered that domain structure modification strongly affects both the piezoelectric displacement and the permittivity [13]. Therefore, the domain structure information can be obtained from the permittivity change detection, and this information includes the piezoelectric displacement [12].

Fig. 2 shows an overview of the permittivity detection method. The driving voltage and the permittivity detection voltage were supplied from a function generator (NF, WF1974). These two signals were added and amplified by a high-speed amplifier (NF, 4025). The driving voltage brought about the piezoelectric displacement for positioning. The permittivity detection voltage was applied to the piezoelectric actuator for permittivity detection. It was a sinusoidal wave that should have a low amplitude and a high frequency in order not to influence the displacement. The high frequency causes the large current amplitude that improves the signal-to-noise (SN) ratio; however, the frequency must be far from the resonant frequency to avoid a current signal from the resonant effect. The current signal was picked up with a current probe (Tektronix, TCPA300) and a lock-in amplifier (NF, LI5640). By using the permittivity detection voltage as the lock-in amplifier reference, the current amplitude signal with the permittivity detection voltage can be measured. By calibrating in advance, the leakage current phase signal can be eliminated. The permittivity is proportional to the current amplitude because the dimensions of the piezoelectric actuator, such as the thickness and electrode size, can be considered to be constant. This method requires no positioning sensor. The actual displacement was measured by a laser interferometer (Canon, DS-80) which had a bandwidth of 5 kHz within a 10 μm displacement range. The actual peak-to-peak noise with our setup was 0.1 μm in this displacement measurement as shown later.

2.2. Differential current measurement method

The differential measurement method can improve the self-sensing positioning accuracy, as demonstrated in our previous study using a bimorph actuator [12]. The bimorph actuator is composed of two piezoelectric plates, which have a push-pull relationship. In other words, a decreasing or increasing permittivity change is opposite between them. Basically, the initial permittivity of the piezoelectric material is large compared with the permittivity change induced by the driving voltage. As a result, we have to use a wide range for the lock-in amplifier to detect a small current amplitude change. On the other hand, if the piezoelectric actuator contains a push-pull mechanism like the bimorph actuator, only the permittivity change can be obtained by the differential current method. With this method, the base current with the essential permittivity can be canceled, and a narrow lock-in amplifier range for the current amplitude change becomes possible for a better SN ratio.

2.3. Design of positioning stage

To utilize the differential measurement method, we designed a positioning stage using two multilayered actuators (NEC

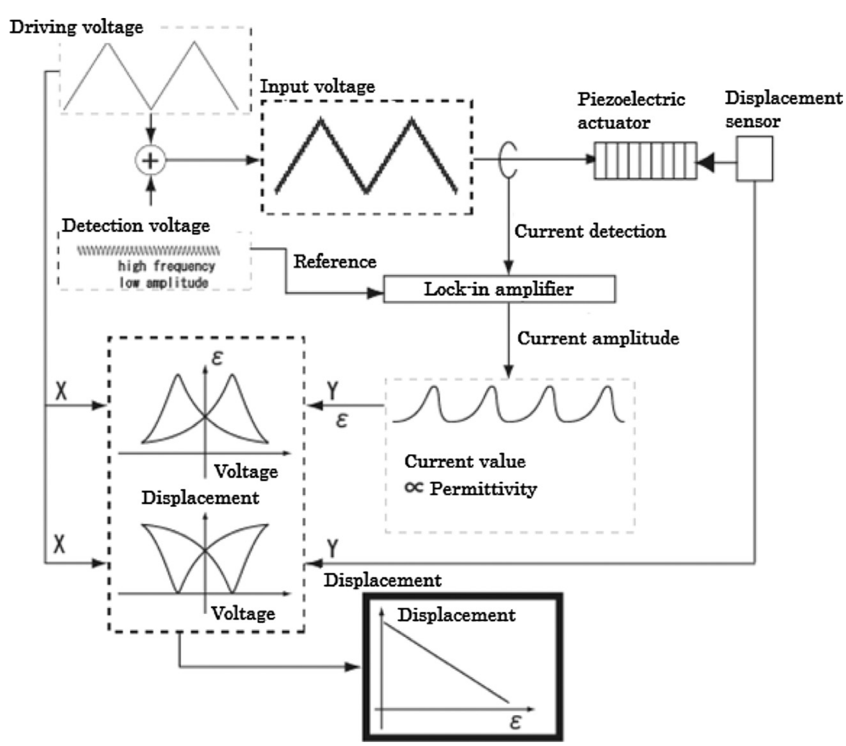

Fig. 2. Overview of permittivity detection.