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An Open-Loop Positioning Method for Reduction of Influence of Nonlinearities in Piezoelectric Actuator*

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Abstract

A unique driving method of piezoelectric actuator to reduce influences of hysteresis and creep is represented in the paper. It is for point-to-point (PTP) open-loop positioning. In the method, when an object is stepwise positioned using the piezoelectric actuator, the input voltage to the actuator is raised up to maximum value and pulled down to 0V sinusoidally in order to initialize the actuator condition, and then it is returned to a constant starting point at the beginning of every step. Finally it is raised up to appropriate step height with some overshoot. Both influences of hysteresis and creep characteristics are reduced drastically using the method. Stepwise positioning of 2μm step height with 0.2μm accuracy is realized using the basic method. For nano-meter order positioning accuracy, creep behavior of the actuator is serious problem. It is found that multi-cycle large sinusoidal drive which is called initializing drive can reduce creep motion significantly. Eventually, less than 5nm accuracy for 20nm stepwise PTP positioning is realized.

Key words: Piezoelectric Actuator, Open-Loop Drive, Precise Positioning, Voltage Drive, Creep, Hysteresis

1. Introduction

Stack type piezoelectric actuators are utilized in precise positioning systems because they can easily generate precise motion and large force. However they have non-linear characteristics such as hysteresis and creep for input voltage. Therefore feedback control is usually applied for precise positioning by means of measuring object position directly, but full-closed loop feedback control cannot be adopted in every application. So the author aims at open-loop precise positioning with piezoelectric actuators.

When the piezoelectric actuators are driven using electric charge amplifiers, the nonlinearities are fairly reduced(1),(2). However development of high performance voltage amplifier can be easier than high performance charge amplifiers from speed and energy consumption points of view. A driving method of piezoelectric actuator for voltage amplifier is required. There are some studies about open-loop voltage driving method to reduce hysteresis and creep characteristics of piezoelectric actuators. Changhai and Lining determined the open-loop driving voltage by referring PID control signal(3). The nonlinearities are strongly reduced in a condition by their method, but they don't take initial condition of piezoelectric actuator into account. Initial conditions of the actuator influence on positioning accuracy under open-loop drive. Shinoda et al. found that creep behavior of a piezoelectric actuator can be strongly eliminated under open-loop drive by means of turning

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back the driving voltage from moving point on hysteresis loop curve to some voltage-displacement driving curve, which they call "non-creep line"(4). The discovery of the curve is significant but both of the "non-creep line" and hysteresis loop should change by conditions of piezoelectric actuator. They also don't take the influence of initial condition of the actuator into account.

In the previous papers(5), (6), fundamental concept and characteristics of the open-loop point-to-point (PTP) driving method of piezoelectric actuator are described, and about 0.25μm accuracy and repeatability for 5μm stepwise positioning over 30μm motion range are achieved. The open loop driving method can reduce both influences of hysteresis and creep drastically for micro-meter order accuracy.

In the present paper, positioning performance for micro-meter order accuracy is investigated at first. Then it is investigated that a driving method for PTP positioning of nano-meter order accuracy for several tens or hundreds of nano-meter motion range. One of the most serious problems to achieve nano-meter order accuracy is creep behavior of the actuator. The behavior depends on status of the actuator at the beginning of drive, i.e. drive history before the drive. Creep behavior during short time range can be eliminated by sinusoidal step-up motion with appropriate overshoot. For long time range motion, variation of actuator condition at the beginning of the drive causes difference of creep motion. In order to make the actuator condition same, the author has proposed to apply one cycle large amplitude sinusoidal input to the actuator just before each positioning motion(6). The procedure is called an initializing drive or initializing motion in the study. For nano-meter order positioning accuracy, one cycle initializing motion is not enough. One cycle initializing motion almost eliminates creep behavior but nano-meter order gradual motion still remains. In order to control creep motion more precisely, the actuator needs to be made the same status before applying a sequence of positioning drive input. It must be sufficiently initialized by applying multi-cycle initializing drive. In the paper, influence of multi-cycle initializing drive is also investigated.

2. Experimental setup

The schematic of experimental system is shown in Fig.1. The figure shows the flow of signals. Input wave form signal is made in the computer. It is amplified by a power amplifier and is inputted into a piezoelectric actuator. Actuator displacement is measured by a non-contact capacitance type displacement sensor. Both of the input voltage and sensor signal are transmitted to a digital recorder. Characteristics of the stacked type piezoelectric actuator used in the experiments are represented in Table 1.

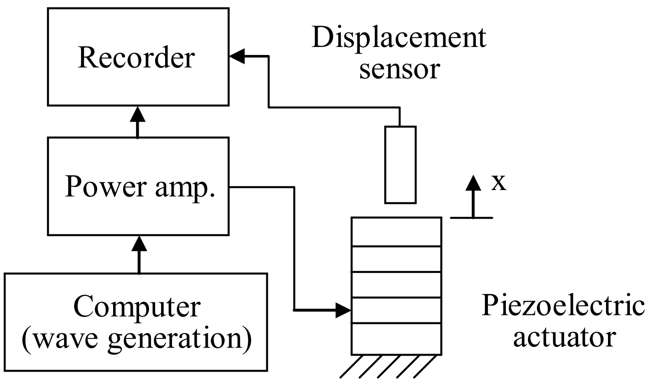

Fig. 1 Experimental system

Table 1. Characteristics of actuator

Material	PZT
Dimensions mm×mm×mm	5×5×20
Maximum input voltage V	150
Generative force N	850
Generative displacement μm	17.4
Capacitance μF	1.4
Resonance frequency kHz	69
Young's modulus N/m^2	4.4×10^{10}

3. Fundamental Characteristics of Piezoelectric Actuator

3.1 Hysteresis Characteristics

Figure 2 shows hysteresis loops for 10Hz sinusoidal drive of different amplitude. Generally, displacement of piezoelectric actuator becomes up when amplitude of the sinusoidal driving voltage becomes large, and thus the displacements value at 0V changes by the amplitude. However, in Fig.2, the hysteresis loops are drawn so as to agree their displacement at 0V with 0μm. The figure shows that all of the curves of voltage increasing side of the hysteresis loop are on the same curve. It means that open-loop positioning without influence of hysteresis can be realized if the actuator is set on the same initial displacement every time before positioning and if the positioning is executed only by increasing the input voltage.

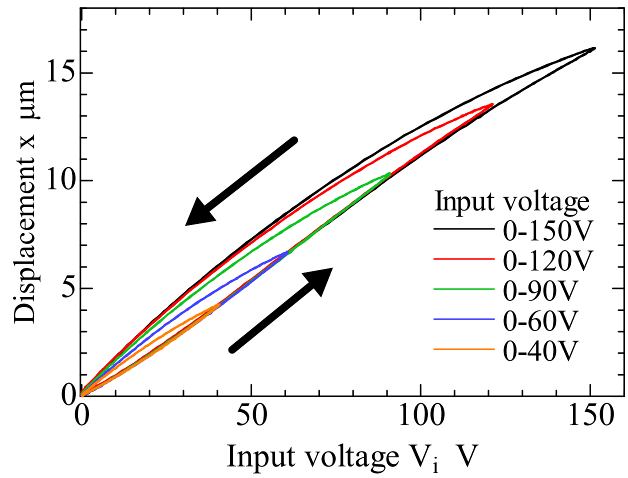

Fig. 2 Hysteresis loops for sinusoidal drive of different amplitude

The relation between input voltage and displacement of the voltage increasing side in Fig.2 can be represented with a polynomial approximation, Eq.(1). Input voltage according to required displacement can be determined with the approximated equation. Both input voltage step heights for 2μm and 20nm stepwise positioning is determined using this equation.

$$\begin{aligned} V_i = & -4.753\times10^2(x_r+x_0)^{1/6} + 2.483\times10^3(x_r+x_0)^{2/6} - 5.079\times10^3(x_r+x_0)^{3/6} \\ & + 5.080\times10^3(x_r+x_0)^{4/6} - 2.480\times10^3(x_r+x_0)^{5/6} + 4.813\times10^2(x_r+x_0) \end{aligned} \quad (1)$$

where x_r is desired displacement, x_0 is displacement for initial standard voltage input, and V_i is input voltage for x_r. The definition of initial standard voltage and step height voltage are described in section 4. In this case, initial standard voltage is set at 21.8V, and then the value of x_0 is 2.11μm.

3.2 Creep Characteristics

Figures 3 and 4 show examples of displacement creep behaviors for different stepwise input waves, i.e. normal step drive (Fig.3) and step drive with overshoot (Fig.4). In Fig.3, when normal stepwise drive is applied to the actuator, actuator displacement changes gradually after the input voltage keeps constant. On the other hand, in Fig.4, when stepwise drive with some overshoot is applied to the actuator, displacement keeps constant after the input voltage becomes constant. Creep behavior cannot be almost observed. From these results, influence of creep can be reduced by drive with overshoot. Of course, there is appropriate overshoot value for step height. Too large and too small overshoot values cannot eliminate the influence of creep characteristics. The author investigated the relation between overshoot value and creep behavior experimentally.

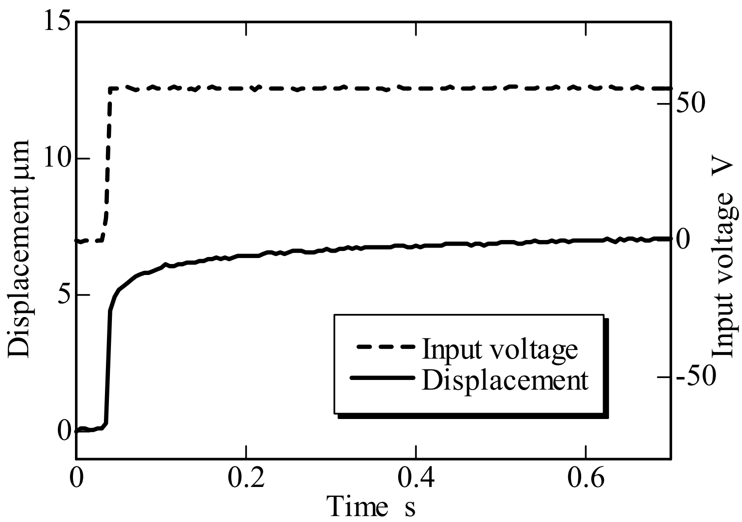

Fig. 3 Displacement behavior for normal step drive

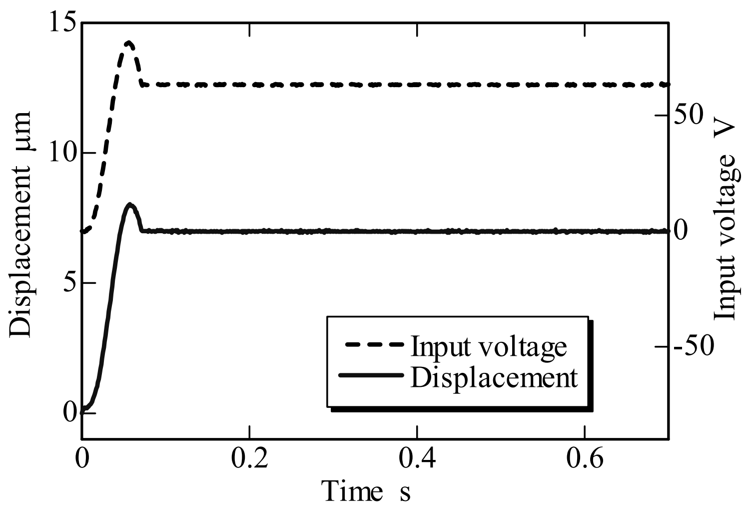

Fig. 4 Displacement behavior for step drive with overshoot

4. Outline of the Driving Method for Micro-meter Order Positioning

According to the results of Fig.2, influence of hysteresis characteristics can be reduced by elongating the actuator from a contracted position to desired positions. Also from the results of Fig.3 and 4, creep characteristics can be eliminated by stepwise driving with overshoot. The authors proposed the following open-loop point-to-point positioning driving method.

Figure 5 shows the waveform of input voltage to the actuator for stepwise PTP positioning by the proposed open-loop drive. The voltage changes as follows.: First of all, in order to reduce the influence of difference of initial condition of actuator, the input voltage raises up to high value which is called initializing voltage(shown in Fig.5 as [a]). This motion is called initializing motion in the study. Next, the input voltage is brought down to 0V and returned to some voltage which is called initial standard voltage [b], at the beginning of every step. Then it is raised up to step height [c] with some overshoot [d]. This unique driving motion is executed in order to eliminate both hysteresis and creep behaviors of the piezoelectric actuator. When the actuator moves to next position, the voltage is brought up to the next initializing voltage again and changed at the similar way as the previous step.

For the actuator whose characteristics are shown in Table 1, the initializing voltage[a] and initial standard voltage[b] are set at 150V and 21.8V respectively in this case. The value of initial standard voltage is determined so as not to appear creep behavior in displacement when the input voltage is kept constant after initializing drive. Input voltage for each step, i.e. summation value of step height [c] and initial standard voltage [b], is determined with Eq. (1). The overshoot value is determined observing creep behavior of actuator and set at 28.9% of step height voltage for more than 1μm stepwise positioning. For sub-micron stepwise positioning, constant percentage is not enough to eliminate the creep behavior. Thus appropriate overshoot value for each step height is determined individually for 20nm stepwise positioning in this paper. To find how to optimize the overshoot is an assignment of next step of the research.

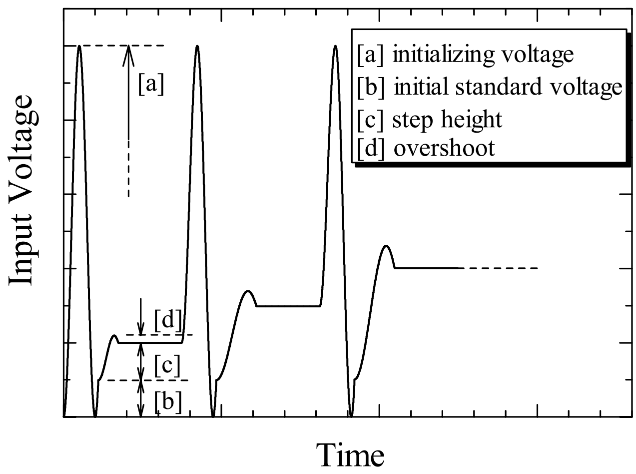

Fig. 5 Schematic of input voltage for stepwise positioning

5. Results by the Method for Micro-meter Order Positioning

This method has several driving parameters, i.e. initializing voltage, initial standard voltage, overshoot value and so on. According to some experimental results, appropriate values of each of the parameters are determined. Figure 6 shows the input voltage of stepwise positioning drive. Figure 7 shows the positioning result for the input voltage. The first and last steps from about 0 to 2s and from about 16 to 18s are the step for initial standard voltage, and between the steps, about 2μm stepwise positioning is realized by the driving method. The influences of hysteresis and creep are reduced. The actuator is driven at a constant step height by open-loop drive. The accuracy of about 0.2μm is achieved for 2μm stepwise positioning by the driving method. The spiky behaviors observed just before every step position in Fig.6 and 7 are due to the initializing motion. As mentioned before, initializing voltage driven by 10Hz sinusoidal wave with large amplitude voltage, 150V, is applied before every stepwise motion. The reason why the actuator displacement does not come down to 0μm at the 0V in initializing motion is due to dynamic characteristics of the piezoelectric actuator. Since the input voltage changes sinusoidally at 10Hz in initializing drive, the actuator naturally moves with some delay and unfollowing motion.

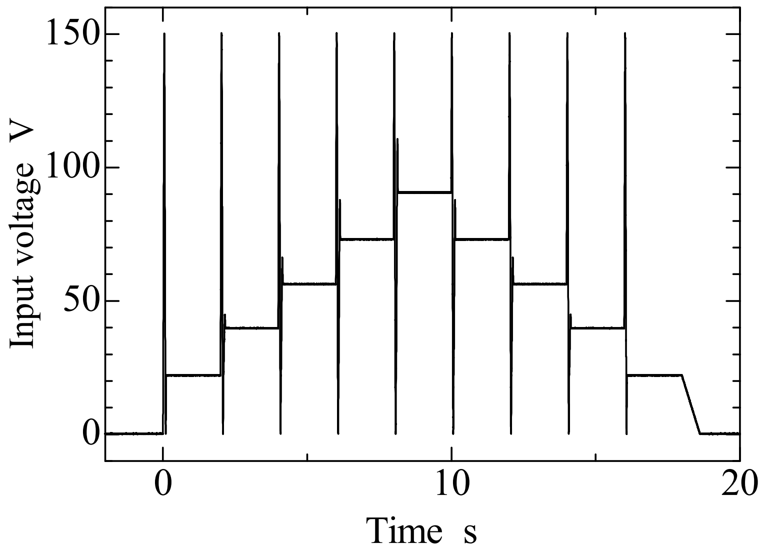

Fig. 6 Input voltage signal for about 2μm stepwise positioning

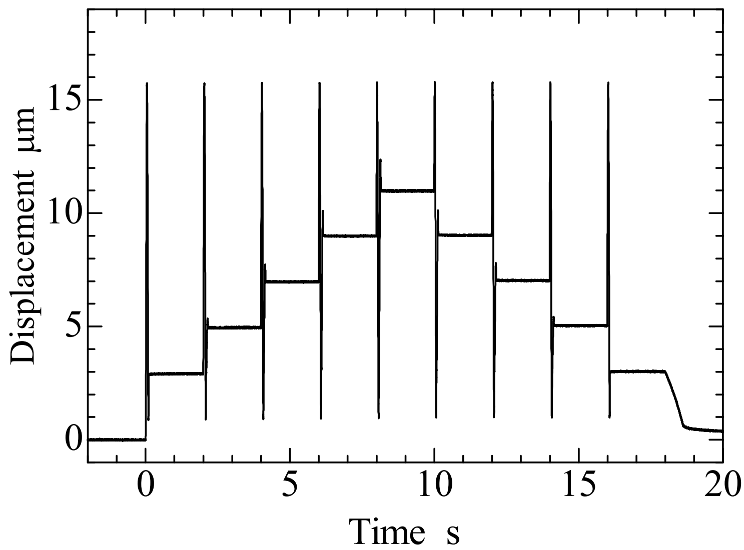

Fig. 7 Stepwise positioning result for about 2μm step height input by the driving method

When desired value of the step height is less than micro meter order, 0.2μm accuracy is not enough. The driving method cannot be utilized as it is. Figure 8 shows stepwise positioning results for about 20nm step height input by the same driving method as 2μm step height drive except for the overshoot value. The overshoot values for 20, 40, 60 and 80nm steps are set to 0.89, 1.02, 1.15, 1.28V respectively. They are determined experimentally observing the creep behavior at each step. Three results taken at different time are drawn in Fig.8. As the actuator displacement does not settle down in the sight of nano-meter order accuracy, the three results does not agree with each other. When the actuator is desired to position with nano-meter order accuracy, the actuator condition should be settled down so as enough to obtain the target accuracy.

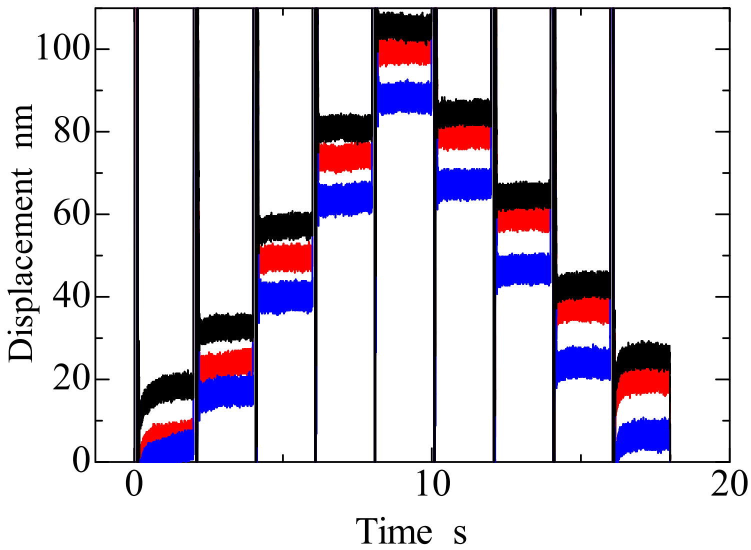

Fig. 8 Three time stepwise positioning results for 20nm step height input by the same driving method as 2μm step height drive

6. Influence of Initializing Motion

In order to make actuator status uniform, the driving voltage goes up to the maximum voltage and down to zero sinusoidally just before every stepwise motion. As mentioned before, this driving motion is called initializing motion in this study. According to some experiments, it is found that one cycle initializing motion is not enough for nano-meter order positioning. It is expected to keep displacement constant after the initialization, but small creep behavior remains for only one cycle initializing drive. However multi-cycle initializing drive settles actuator status down efficiently, the amount of creep motion decreases gradually for the increase of cycle of initializing drive.

Figure 9 shows actuator motion for sinusoidal input voltage of 75V amplitude and 75V offset driven at 10Hz frequency. The value of the voltage is allowable maximum voltage of the actuator. The figure shows a magnified view of lower part of about 17μm peak-to-peak amplitude sinusoidal motion of the actuator. Though input voltage goes up and down between 150V and 0V, the vibrating displacement goes up gradually. It means that the more initializing motion is applied, the more precisely actuator may settle down. How many cycles of initializing motion should be applied, depends on how much accuracy is required.

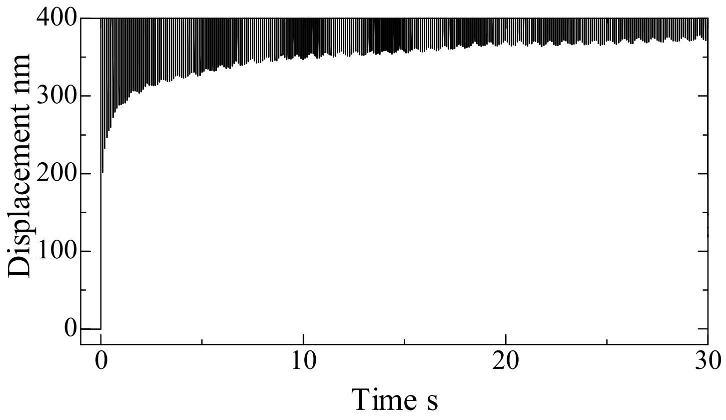

Fig. 9 Lower part of actuator displacement for multi-cycle initializing drive

As noise level of the displacement sensor used in the experiments is about 10nm, target accuracy is set to several nano-meter. Through some experimental examinations, 30-cycle initializing motion, i.e. 10Hz and 150Vp-p amplitude sinusoidal drive for 3 seconds, is adopted. Figure 10 shows stepwise positioning results by the proposed method after 30-cycle initializing motion. Figure 11 shows the input voltage for the positioning. Figure 11 shows full range of the input signal, but Fig.10 shows magnified view around positioning step area. After 30-cycle initializing motion, the input voltage is kept constant for about 2s, transferred to the first one-cycle initializing motion and reached to initial standard voltage. Then it continues to stepwise PTP positioning motion. Step height is set to 20nm. Three results are drawn also in Fig.10, but every result agrees to each other not like the result in Fig.8. 30-cycle initializing drive works successfully to eliminate variation of actuator status for the motion of at least 100nm position rage. Actuator status is settled down by the multi-cycle initializing motion before the PTP positioning drive. As mentioned before, input voltage for each step height is determined with the same equation as the one of 2μm stepwise positioning, i.e. Eq.(1). Therefore about 5nm or less positioning errors for 20nm step are observed in some steps, but it is noted that both of μm- and nm-order open-loop positioning can be executed using the same relation between desired position and step height of input voltage. Less than 5nm accuracy for 20nm stepwise PTP positioning is realized.

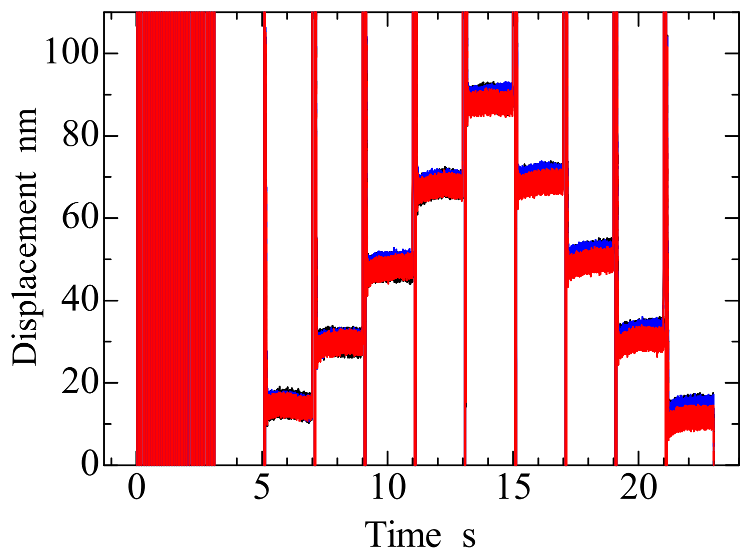

Fig. 10 Stepwise positioning for the proposed method with 30-cycle initializing motion

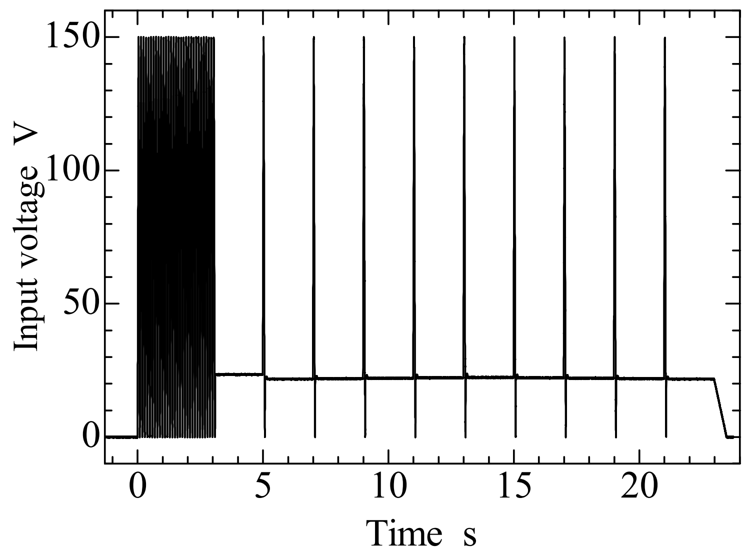

Fig. 11 Full view of the input voltage for about 20nm stepwise positioning with 30-cycle initializing motion

7. Conclusions

In this paper, fundamental nonlinear characteristics of piezoelectric actuator about hysteresis and creep were represented at first. Also possibility to reduce influence of the non-linearity was mentioned. The proposed unique open-loop driving method was described. The driving method was for PTP positioning of piezoelectric actuator. In the method, initializing motion was applied in order to make the status of actuator uniform before every stepwise motion. Then the actuator was contracted to a constant position and then elongated to desired position with some overshoot. Micro-meter order positioning accuracy can be obtained by the method. For nano-meter order accuracy, it was shown that actuator status needed to be settled down more precisely. 30-cycle initializing drive motion was applied in order to obtain several nano-meters order accuracy. By the modified driving method, nano-meter order stepwise positioning for several micro-meter motion range was realized by open-loop drive.

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