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Control frequency and voltage for large displacement inchworm using piezoelectric actuator

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Abstract

This paper describes the control frequency and voltage for a large displacement inchworm that uses a piezoelectric actuator. The project aims to achieve a long-travel precision stage without the use of a guide mechanism. However, the limited control frequencies of electromagnets and a piezoelectric actuator due to transient phenomena cause the inchworm to consume a lot of time when traveling long distances. The piezoelectric actuator is typically operated using unipolar voltage control. However, semibipolar drive, which involves bipolar voltage control below a coercive electric field, extends the displacement of the piezoelectric actuator compared to unipolar voltage control.When the coercive electric field is exceeded with bipolar voltage control, the resulting strain-electric field loop is called bipolar drive, which has a butterfly-shaped loop. The experiment yielded the following results: at low frequency control, the amount of displacement per cycle with bipolar control is higher than that with unipolar control due to contraction and extension displacement. At high frequency, the displacement of the inchworm using bipolar control that exceeds the coercive electric field is the largest. The displacement of the inchworm is maximized when a bipolar voltage is used.

Inchworm, piezoelectric actuator, strain-electric field characteristic, butterfly loop, coercive electric field

1. Introduction

Miniaturization and improvement of various products are progressing. Small components used in these products are highly integrated. Developing small scale production systems has big advantages. We have developed inchworm actuators towards the application of positioning devices or motion devices[1]. Using inchworm principle, the inchworm has unlimited working areas. A lot of inchworms are summarized in review paper[2]. The motion of the inchworm relies on the small displacement of the piezoelectric actuators (piezos). Therefore, the inchworm cannot drive fast and large areas.

In this paper, we propose a control of a 1 degree-of-freedom (DOF) inchworm driven by strain characteristics of the piezo for obtaining large displacement per cycle. This paper deals with the relationship between various applied voltage waveforms, including the strain characteristics, and the amount of the displacement of the piezo focused on frequency, followed by the amount of the inchworm displacement using each control signal. Considering the strain characteristics can improve the displacement and velocity of the inchworm that uses the piezo.

2. Inchworm

Figure 1 shows a 1-DOF inchworm and control principle. The inchworm moves in micron or submicron scale. The inchworm consists of two electromagnets for clamping and one stacked type piezo for moving. The piezo (NEC-tokin, AE0505D16DF) exdtends 17.4 μm by the applied voltage of 150 V_{DC}. The inchworm repeats the excitation of the electromagnets and the deformation of the piezo. First, electromagnet A which is a back leg of inchworm holds it in position. Secondly, piezo extends to move the inchworm forward. Thirdly, electromagnet B which is a front leg of inchworm holds it in position at the destination where it moves. Lastly, the electromagnets A moves by shrinking the piezo. The inchworm moves 17.4 μm in one cycle, which equals the deformation of the piezo.

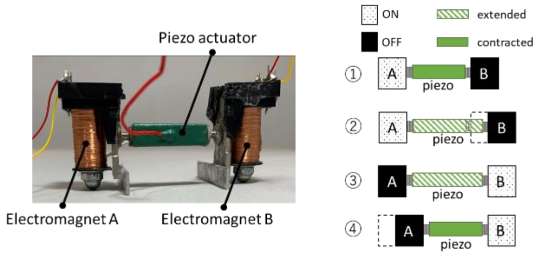

Figure 1. One-DOF inchworm and control principle.

3.Characteristics of piezoelectric actuator

3.1. Displacement

The displacement of the piezo used in the inchworm with different control voltage is measured by a laser displacement meter (Keyence, LK-H050). The voltage $v(t)$ applied to the piezo is

$$v(t) = V_a \sin 2\pi f t + V_o, \quad (1)$$

where f, V_a, and V_o denote the frequency, amplitude and offset voltage of the signal, respectively. The parameters are listed in table 1 and the frequency f equals 1 Hz. The minimum and maximum voltages are summarized the control signals.

Table 1. Parameters used for piezoelectric actuator.

Case	V_a /V	V_o /V	Min /V	Max /V	Remark
1	75	75	0	150	unipolar, DC
2	100	50	-50	150	semibipolar, AC
3	150	0	-150	150	bipolar,AC, butterfly

Figure 2 shows the displacement curve of the piezo. The shape of the displacement curve for bipolar and semibipolar is determined by the polarity of the piezo when the coercive electric field is reached. The displacement curve shows a significant change in polarization at the reversal points. After reversing the polarity, the contraction of the piezo turns into extension again. A control voltage that does not exceed the coercive electric field results in a semibipolar signal or a unipolar signal, whereas a control voltage that exceeds the coercive electric field results in a bipolar signal.

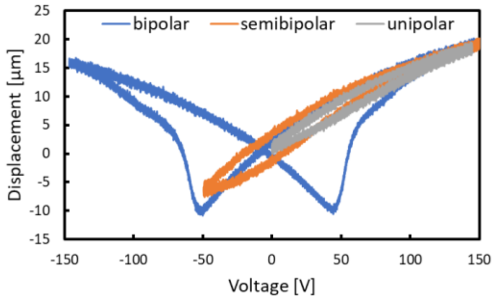

Figure 2. Displacement as a function of input voltage.

When a piezo is used as an actuator, a positive unipolar voltage is typically applied to extend of the piezo. However, bipolar voltage is more effective for extending the displacement. In case 1, using unipolar voltage, the displacement is about 18 μm. In case 2, using semibipolar voltage, the total displacement is about 26 μm which is larger than the displacement in case 1. In case 3, using bipolar voltage, the total displacement is about 30 μm. Additionally, the piezo deforms twice in one control cycle of the input voltage. As shown in Figure 2, the coercive electric field are about ±50 V. Therefore, we propose controlling the inchworm using bipolar voltage, where the piezo extends and contracts twice in one control cycle.

3.2. Frequency characterisdics

The following three signals are applied to the piezo: (1) two-level unipolar voltages of 0 V and 150 V, (2) two-level semibipolar voltages of -37 V and 150 V, and (3) four-level bipolar voltages of 150 V, -37 V, -150 V, 37 V, 150 V. The displacement obtained at the step from -37 V to -150 V is named negative step, and that from 37 V to 150 V is named positive step.

Figure 3 shows the one step displacement obtained by three control signals. The displacements remain constant in the low-frequency range. The displacement obtained by the positive step of 4-level voltage is the largest, and that by the 2-level unipolar voltage is the smallest. The displacements above a certain critical frequency decrease. The displacement starts decreasing at 420 Hz with the negative step of 4-level voltage and at 660 Hz with the 2-level semibipolar voltage. Since the 4-level voltage causes the piezo to extend twice a cycle, the frequency of 420 Hz is equivalent to 840 Hz. Therefore, the bipolar control is effective. In semibipolar control, the contraction of the piezo extends the displacement. At about 500 Hz, no significant decrease was observed in the positive step of the bipolar control.

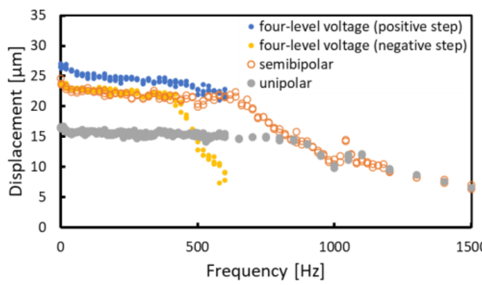

Figure 3. One step displacement of piezoelectric actuator.

4. Control voltage and displacement at low frequency

The inchworm is operated through three control methods, as shown in Figure 4. The electromagnets are synchronized with the deformation of the piezo. The difference between the control signals is the voltage applied to the piezo. The inchworm's piezo is driven by a 4-level voltage, a 2-level semibipolar voltage, and a 2-level unipolar voltage. The frequency of the piezo voltage is set to 1 Hz. By using the 4-level voltage, electromagnet B moves twice in one control cycle, while it moves only once in one control cycle by the 2-level unipolar voltage and 2-level semibipolar voltages.

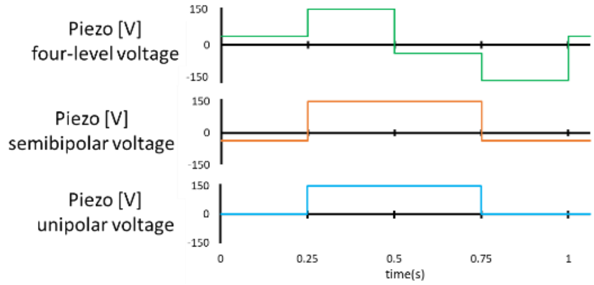

Figure 4. Control signals for inchworm.

Figure 5 shows the displacement of the inchworm at 1 Hz. The displacements for 10 s were 390.0 μm, 190.0 μm, and 146.0 μm with the 4-level bipolar voltage, 2-level semibipolar voltage, and 2-level unipolar voltage, respectively. The 4-level voltage control improves the displacement of the inchworm, with the displacement per cycle obtained by the 4-level bipolar voltage being over two times larger than those obtained with the other control signals.

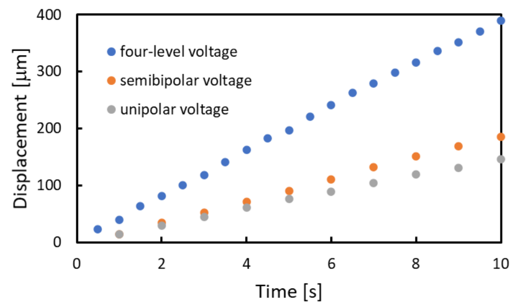

Figure 5. Inchworm displacement at 1 Hz.

5. Conclusions

This paper discussed the control frequency and voltage for an inchworm using a piezo. The displacement and velocity were improved by taking the strain characteristics of the piezo into account. The results showd that a 4-level bipolar voltage determined by the coercive electric field was effective for the inchworm across a wide frequency range. At low frequencies, the displacement obtained by the 4-level bipolar voltage was the largest, while that obtained by the 2-level unipolar voltage was the smallest. The 4-level bipolar control of the piezo was found to be optimal for improving the displacement of the inchworm.

Acknowledgement

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