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Control waveform and frequency of an inchworm-type actuator using piezoelectric element

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Abstract

A control waveform and frequency of an inchworm-type actuator utilizing piezoelectric elements (piezos) are described. Linear and rotational displacements are generated by the rapid deformation of three piezos connected in an equilateral triangle on a horizontal plane. The inchworm-type actuator takes advantage of friction and inertial forces. The rapid deformation of two piezos produces a minute displacement based on the law of inertia. The piezos are driven by rectangular waveforms, with either two piezos extending and contracting simultaneously or one piezo extending while the other contracting. The repeated minute displacements achieve both linear and rotational displacement. The deformation of the piezo and the frequency of deformation vary the velocity of the inchworm. The velocity is proportional to the drive frequency, and a small voltage applied to the piezo reduces the displacement. These results contribute to the improvement of the inchworm-type actuator.

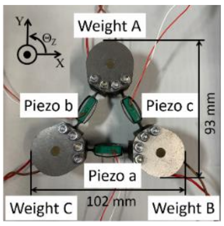
Inchworm, piezoelectric actuator, friction, inertia drive

1. Introduction

The goal of this project is to realize a long-travel stage without guide mechanisms. Conventional positioning components usually require guide mechanisms and typically have one degree-of-freedom (DOF). We have developed multi-DOF inchworm-type actuators (inchworms) using piezoelectric actuators (piezos) and electromagnets [1]. The inchworms are implemented in a compact manufacturing system that saves energy and materials. In contrast, rapid deformations of piezos are used in precise positioning [2]. The rapid deformation of the piezos can achieve step movements of several nanometers. In this paper, the inchworm's piezos are controlled by rectangle waveforms. Although nanopositioning stages are realized by sinusoidal waveform inputs and control circuit [3], the rectangular waveform is easily prepared by a microprocessor.

2. Inchworm

Figure 1(a) shows a photograph of an inchworm. An equilateral triangle is formed by three multi-layered piezos (AE0505D18F, TOKIN) inserted into holders. Three weights are attached to the apexes of the triangle, with each weight having a mass of 0.12 kg. Figure 1(b) illustrates the fundamental displacements of Weight A. When two piezos rapidly extend, Weight A moves perpendicular to Piezo a. When one piezo extends and the other contracts, Weight A moves parallel to Piezo a.

(a) 

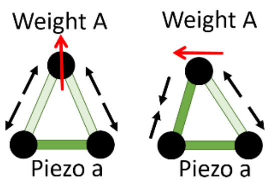
(b) 

Figure 1. (a) Photograph and (b) illustration of inchworm-type actuator.

The motion principle of linear displacement is shown in Figure 2(a). Weight A moves according to the rapid extension of Piezo b and Piezo c, while the equivalent mass of Weight b and Weight c inside the broken rectangle is approximately twice of that of Weight A. The moving direction of Weight A is perpendicular to Piezo a. Subsequently, in sequence A(ii), Piezo c contracts and Piezo a extends simultaneously, causing Weight B to move in parallel with Piezo b. Next, Piezo b and Piezo a contract, resulting in Weight C moving perpendicular to Piezo c. This sequence tilts the angle of the inchworm. To counteract this, sequence B, where the contraction of the piezo is reversed, is introduced. Piezo b contracts first while Piezo a extends, and then Piezo c contracts wile Piezo a contracts. By repeating the two sequences of three intervals, the inchworm moves in Y-direction.

Figure 2(b) shows the motion principle of rotational displacement in counterclockwise (CCW) direction. One piezo extends and the other piezo contracts simultaneously. During the contraction of Piezo c and extension of Piezo a, Weight B moves parallel to Piezo b. As Piezo a contracts and Piezo b extends, Weight C moves parallel to Piezo c. Finally, when Piezo b contracts and Piezo c extends, Weight A moves in parallel with Piezo a. By repeating these three intervals, the inchworm moves in the CCW direction.

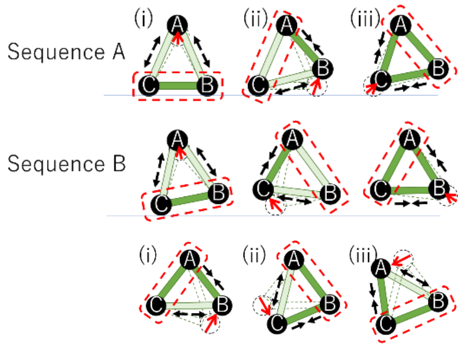


Figure 2. Motion principle of inchworm for (a) linear displacement in Y-direction, and (b) rotational displacement in CCW direction.

Figure 3(a) shows the waveforms for linear motion. In Squence A(ii), Piezo c contracts and Pieozo a extends. Then in A(iii), Piezo a and Piezo b contract. In Sequence B(ii), Piezo b contracts first, and then Piezo c contracts in B(iii). Repeating these two sequences makes the inchworm actuator move in the linear displacement. Figure 3(b) shows the waveforms for rotational displacement. One piezo contracts and other pipezo extends, simultaneously. The control waveforms of the rotational displacement consist of three intervals.

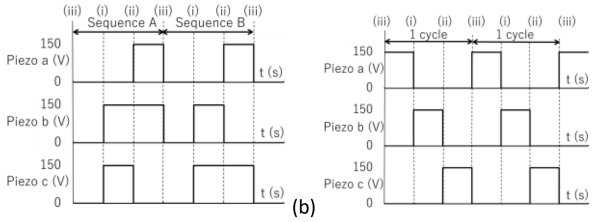


Figure 3. Control waveforms for (a) linear displacement in Y-direction, and (b) rotational displacemt in CCW direction.

3. Experiment

Control signals are generated by a microprocessor, and applied to the piezos through an amplifier. The control waveform is on/off signal with 150 V. The control frequency is from 1 Hz to 100 Hz. Voltages of 100 V and 50 V are used to realize small displacements. The position of the inchworm in Y-direction is defined by the position of Weight A. The rotational displacement of the inchworm is defined by X-displacement of weight A divied by the radius of the inchworm, 88 mm. Displacement is measured with a laser displacement meter (Keyence, LK-G5000 series). The inchworm repeats a constant displacement, and therefore an open-loop control is used.

4. Results and discussion

Figure 4(a) shows the linear displacements at 1 Hz. One step displacement is approximately 15 μm which agrees with the rapid deformation of the piezos. However, a drawback of approximately 11 μm is observed, resulting in a total displacement is 4 μm. Figure 4(b) shows the displacement at 90 Hz. The displacement for two cycles is 14 μm. These results indicate the drawback caused by the inertia of the inchworm changes the displacement per cycle. Since the inset of Figure 4(b) does not display any rectangular waveforms, the maximum frequency based on this principle would be a few hundred Hz.

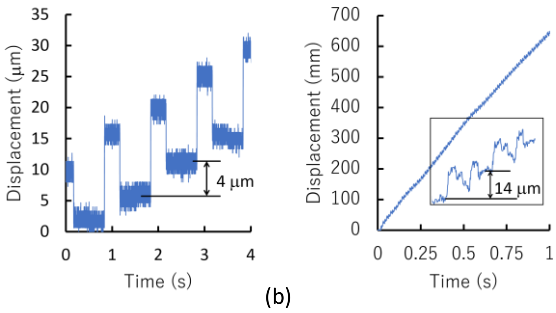


Figure 4. Linear displacement at (a) 1 Hz and (b) 90 Hz.

The displacement per cycle and the velocity are summarized in Figure 5. In principle, the displacement per cycle is constant. However, it slightly changes as the frequency varies. Under our experimental conditions, the vibration amplitude of the inchworm fluctuates, and this variation in vibration causes fluctuations in the one-cycle displacement. The velocity of the inchworm is mostly proportional to the drive frequency.

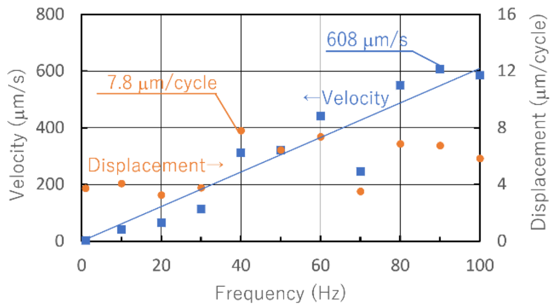


Figure 5. Displacement and velocity of inchworm.

The voltage of the rectangle waveform influences the step displacement. Figure 6 shows the results obtained by three different voltages; 150 V, 100 V, and 50 V. A lower voltage results in a reduced displacement.

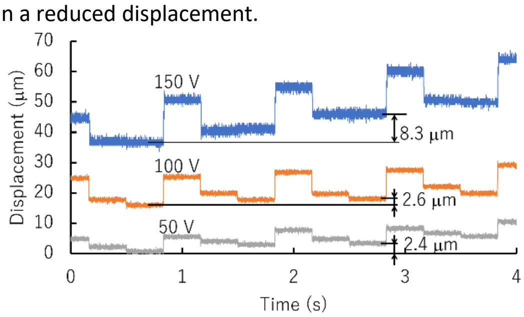


Figure 6. Displacement with 150 V, 100 V, and 50 V.

Figure 7 shows the rotational displacements at 1 Hz and 90 Hz. The rectangle waveforms applied to the piezos can achieve the rotational displacement of the inchworm actuator. Due to the law of inertia, a drawback occurs; however, the drawback is smaller than the displacement in the designed direction.

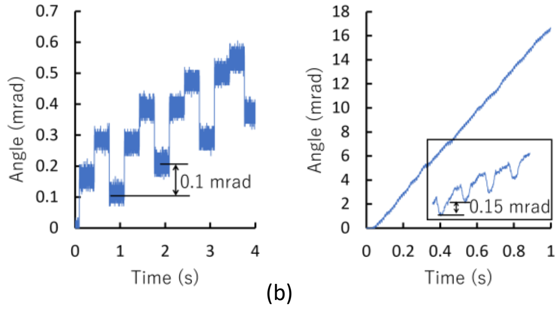


Figure 7. Rotational displacement at (a) 1 Hz and (b) 90 Hz.

5. Conclusion

This paper described the control waveforms of the inchworm. The rectangle waveforms were used to move the inchworm in the linear and rotational directions. The step displacement was mostly constant, and the velocity was proportional to the drive frequency. The use of a small voltage realized small displacements. The results are effective for driving the inchworm, as on/off control makes it easy to apply voltage to piezos. In future, weights which generate electromagnetic or electrostatic forces synchronizing with the piezo deformation are used to reduce the drawback motion

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References

[1] Kato H, Hayakawa K, Torii A, Ueda A 2000 *Electrical Engineering in Japan* **131(4)** 44-51, 2000

[2] Higuchi T, et al., IEEE Proceedings on Microelectromechanical Systems, 1990, pp. 222-226, doi: 10.1109/MEMSYS.1990.110280.

[3] Merry R.J.E, et al., IEEE/ASME Trans. Mechatronics **14(1)** 21-31,2008, doi: 10.1109/TMECH.2008.2006756.