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The characteristics of an inchworm stage using piezoelectric actuators and electromagnets

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Abstract
The drive signal of an inchworm stage using piezoelectric actuators (piezos) and electromagnets is experimentally discussed in this paper. The inchworm stage repeats a minute displacement many times and realizes long-range positioning. With the help of three piezos and three electromagnets, the inchworm stage can realize linear and rotary motion. The electromagnet is a clamp unit which holds the stage position, and the piezo is a thrust unit which moves the stage. A non-excited electromagnet moves by the deformation of piezos. The motion of the inchworm is measured as a function of the drive frequency. The maximum velocity of the inchworm stage is experimentally obtained. As a result, the larger the control frequency is, the smaller the displacement in control cycle is. The experimental results indicate the maximum velocity of the inchworm stage.

Keywords: electromagnet, piezoelectric actuator, inchworm stage, velocity, frequency

1. Introduction

We previously developed long travel range stages using piezoelectric actuators (piezos) [1, 2]. The goal of the project is to realize a precision and large travel xyθ stage without guide mechanisms, although conventional multi degree-of-freedom (DOF) stages consist of one-dimensional linear and rotary stages. Commercially available piezo stages can realize picometer positioning. However, travels for the piezo stages range from nanometers to micrometers. The developed stage utilized the principle of an inchworm, and can realize unlimited travel. Since three stacked-type piezos are connected in a triangle form, the stage realizes 3-DOF motion on a surface.

Three electromagnets generates electromagnetic force when a voltage is applied to a coil. The electromagnets connect and disconnect the stage and a floor. The disconnected electromagnet moves sequentially by the deformation of the piezos. When the stage travels long distance, the maximum speed is one of the most important specifications. The maximum speed, however, were not discussed [1, 2].

In this paper, the drive frequency of the stage is clarified by experiments. The displacement and control signals in one control cycle are measured as a function of the drive frequency. We show that the time constant of the electromagnet determines the maximum drive frequency.

2. Three-DOF Inchworm stage and experiment

Figure 1 shows the 3-DOF stage we developed. Stacked-type piezos a, b, c (NEC-tokin, AD0505D16) and electromagnets A, B, C (4000 turns, 800 mH and 300 Ω) are used. The commercially available piezo (20 mm long) deforms 17.4 μm when 150 V_{DC} is applied. The electromagnetic force is about 5 N when 10 V_{DC} is applied. Three metal parts bond the piezos in 60 degrees. The size of the stage depends on the dimensions of the piezos and electromagnets. Three electromagnets can connect and disconnect the stage and an operation surface.

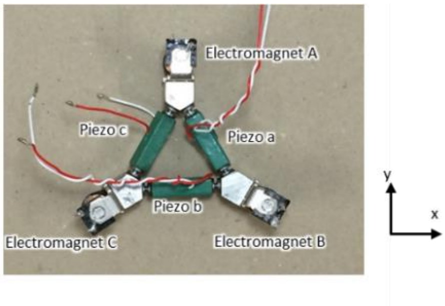

Figure 1. Three-DOF inchworm stage.

The control signals used in y-displacement and x-displacement are shown in figure 2. The electromagnets and piezos are controlled synchronously. Non-excited electromagnet moves by the deformation of the piezos. The voltage applied to the piezos are calculated by the inverse kinematics. The control signals used in rotary motion are similar with figure 2. By changing the control frequency, the control signals and the displacement of the stage are measured, simultaneously.

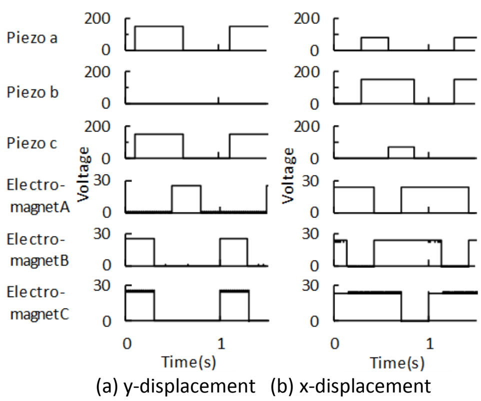

Figure 2. Control signals.

3. Experimental results

3.1. Control signal

Figure 3 shows waveforms used in x-displacement. The deformation of a piezo c, the voltage applied to the piezo c, the voltage applied to an electromagnet A, and the current flowing in an electromagnet A are indicated. They are based on the waveforms shown in figure 2(b). In figure 3 (a), at 1 Hz, the signals correspond with those shown in figure 2(b). However, in figure 3 (b), at 50 Hz, the deformation of piezo and the voltage applied to the piezo are distorted due to an amplifier (200 mA max), since the piezo is a capacitive load. The current in the electromagnet shows transient period. When the piezo extends at 12 ms, the current in the electromagnet is decreasing and the electromagnetic force remains. This phenomenon causes the non-excited electromagnet to stay still. The time constant of the electromagnet, about 3 ms, never changed, although we increased the drive frequency. The time constant and control frequency, therefore, affect the performance of the stage.

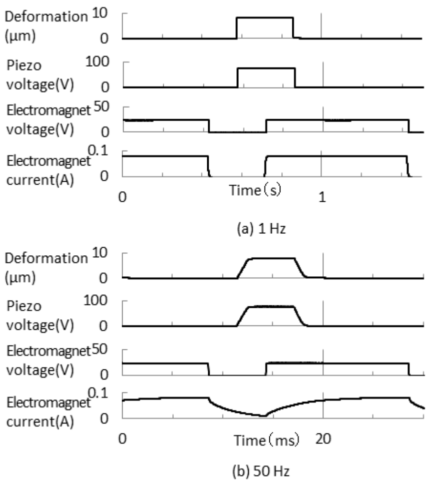

Figure 3. Piezo deformation and control signals.

3.2. Displacement of the stage

The position of the stage is defined by the positions of electromagnets. In the x- and y- displacement measurement, the positions of electromagnet A and B are measured. Figure 4 is obtained at 1 Hz. The major step displacements, about 18 µm in figure 4(a) and about 25 µm in figure 4(b), are obtained. Small steps, however, are observed. These small steps are caused by the impact force generated by the quick deformation of the piezos.

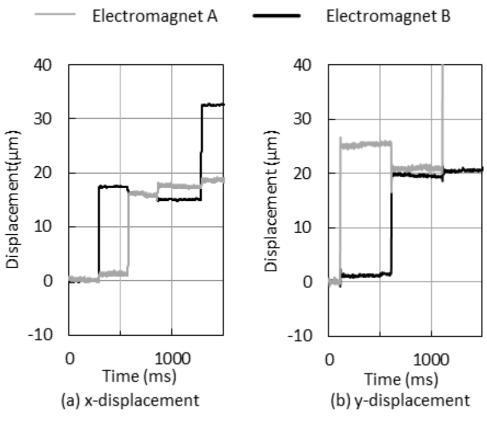

Figure 4. Displacement of the stage obtained at 1 Hz.

Figure 5 shows the results obtained at 50 Hz. The step displacements are expected both in x- and y- displacement. However, the positions shown in figure 5(a) fluctuate. The electromagnets A and B cannot keep their positions. In figure 5(b), electromagnet A returns at 12 ms, and the position of electromagnet B remains stable. The resistance-inductance transients in the electromagnet causes this phenomenon. The difference of the electromagnetic force between the excited electromagnet and the non-excited electromagnet is so small that the excited electromagnet cannot keep its position.

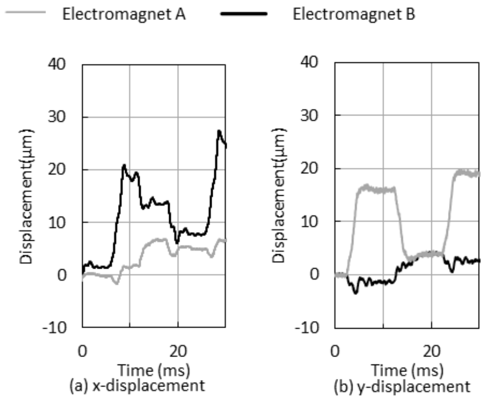

Figure 5. Displacement of the stage obtained at 50 Hz.

Figure 6 shows a displacement in one control cycle. When the control frequency is larger than 20 Hz, the displacement becomes smaller. Therefore, the velocity of the inchworm stage driven at 50 Hz is slower than the velocity at 10 Hz. The experimentally obtained fastest velocity of the inchworm was about 0.4 mm/s, which equals 20 µm step displacement multiplied by 20 Hz.

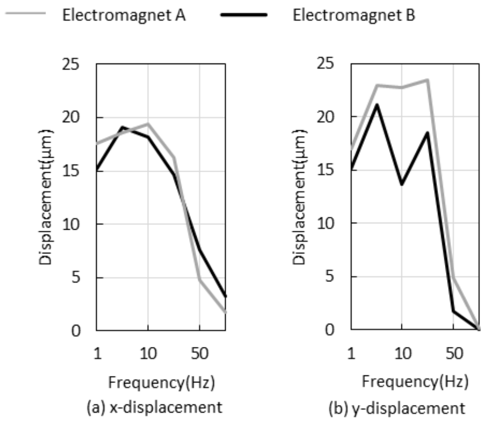

Figure 6. Displacement in one control cycle.

4. Summary

The control frequency of an inchworm stage was discussed. The displacement of the stage in one control cycle was measured. In our experimental conditions, the higher the control frequency was, the smaller the displacement was. The maximum frequency was 20 Hz, and the maximum velocity of the inchworm was about 0.4 mm/s. The transient period of the electromagnet interfered with the motion of the stage. The time constant of the electromagnet dominates the maximum drive frequency. This work was financially supported by the Japan Society for the Promotion of Science, “Grant-in-Aid for Scientific Research (C), No. 26420212.

References

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