A Precise Motion Measurement of a Miniature Robot Driven by the Deformation of Piezoelectric Actuators

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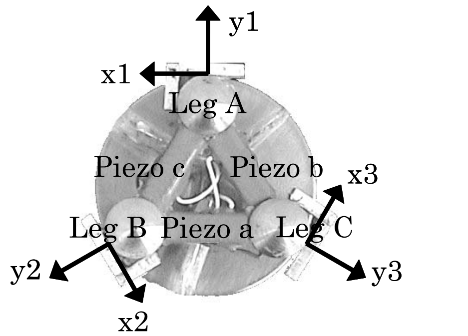
Abstract

We measure the motion of a miniature robot and the trajectories of three legs. The robot consists of three stacked-type piezoelectric actuators connected in an equilateral triangle. The three legs, which support the main body of the robot, are fixed at every vertex of the triangle. The input waveforms applied to the piezos are rectangle and sinusoidal waveforms. We discuss the motion of the miniature robot and the trajectories of the legs under the conditions that the miniature robot can rotate or not.

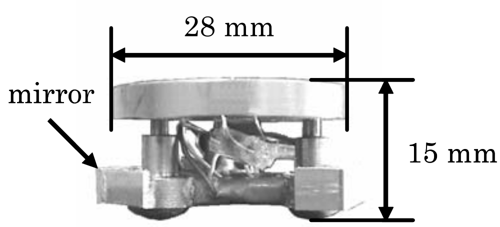
1 Introduction

The motion of a miniature robot driven by the deformation of piezoelectric actuators (piezos) is described. The size of the robot is approximately one cubic inch. The miniature robot is designed for a precise motion stage, which consists of three stacked-type piezos connecting in an equilateral triangle. Three legs, which support the main body of the robot, are fixed at every vertex of the triangle. The deformation of the piezos thrusts the legs of the miniature robot. By repeating the deformations of the piezos, the miniature robot realizes the linear and rotational displacement in a plane surface [1]. However, the miniature robot sometimes did not follow the control waveforms. By using control waveforms of the counter clockwise (CCW) direction, the miniature robot rotated in the clockwise (CW) direction, and by using control waveforms of the CW direction, the miniature robot rotated in the CCW direction.

In our previous work, the motions of three legs of the miniature robot were measured. When the miniature robot was operated by rectangle waveforms, the legs moves incrementally. In this paper, first, the motion of the miniature robot is measured by changing the input waveforms and frequencies. The input waveforms applied to the piezos are rectangle and sinusoidal waveforms. The direction of the rotational displacement is described. Next, the motion of the legs is measured. We discuss the motion of the miniature robot and the trajectories of the legs under the conditions that the miniature robot can rotate or not.



(a)



(b)

Fig. 1 The miniature robot's photograph. (a) Bottom view of a miniature robot. (b) Side view of a miniature robot.

2 Miniature Robot

Fig. 1(a) shows the bottom view of the miniature robot and Fig. 1(b) shows the side view of the miniature robot. The miniature robot is 28 mm in diameter, 15 mm in height, and weights 27 g. In Fig. 1(a), we represent the piezos as Piezo a, b, c and represent three legs as Leg A, B, C. The miniature robot consists of three stacked-type piezos connecting in an equilateral triangle. The size of the piezos is 2*3*10 mm (NEC TOKIN AE0203D08). When a voltage is applied to

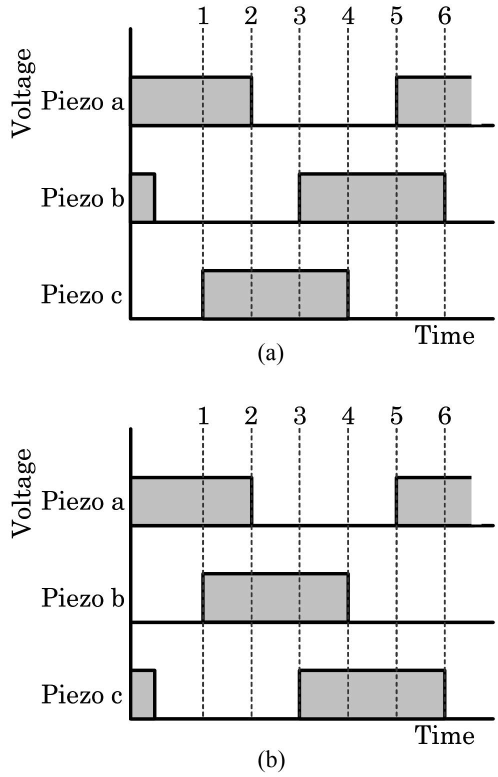


Fig. 2 The control waveforms which rotate the miniature robot. (a) In the CCW direction. (b) In the CW direction.

the piezos, it deforms 0.06 μm/V. Three legs, which support the body of the miniature robot, are fixed at every vertex of the triangle. Three legs has mirrors for a measurement. A thin wire supplies power to the piezos. We define x1, y1, x2, y2, x3, y3 as the local coordinate of the legs. The miniature robot has a circular plate on the piezos. The circular plate will carry optical components and work tools.

3 Principle

The miniature robot moves by the deformation of the piezos, and the deformation pushes or pulls the legs which supports the miniature robot. The miniature robot does not have clamp mechanism such as an electromagnet. Therefore, the counterforce occurs, and the legs moves as the piezos deform.

Control waveforms are shown in Fig. 2. The waveforms in the CCW direction (Fig. 2(a)) and those in the CW direction (Fig. 2(b)) are different in phases. Fig. 3 shows a model as the robot rotates in the CCW direction. A period of the rotational displacement consists of six steps. In Fig. 3, Piezo c, Piezo b and Piezo a extend at point 1, 3, and 5, and Piezo a, Piezo c and Piezo b contract at point 2, 4, and 6. The principle of the rotational displacement is as follows. At point 1 in Fig. 3, Leg A moves by the expansion of Piezo c. At point 2 , Leg C moves by the contract of Piezo a. From point 3 to point 6 is the similar principle. By repeating these six steps, the miniature robot rotates in the CCW direction.

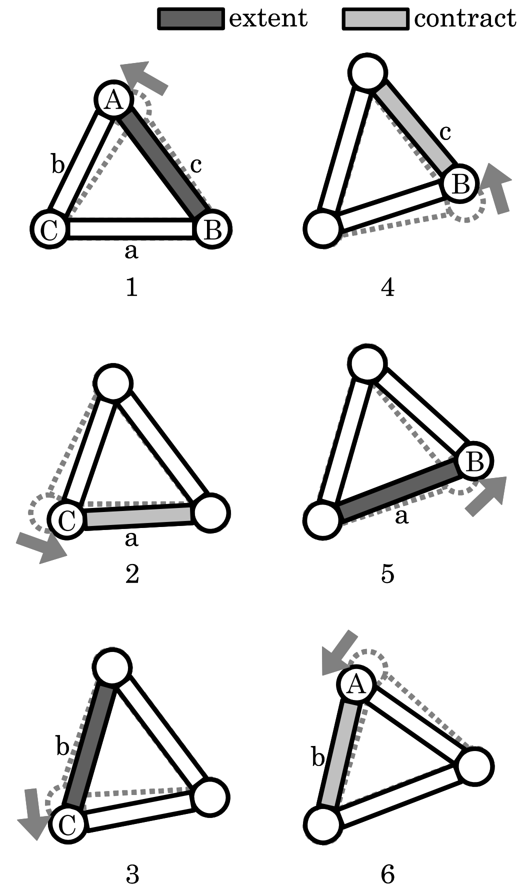


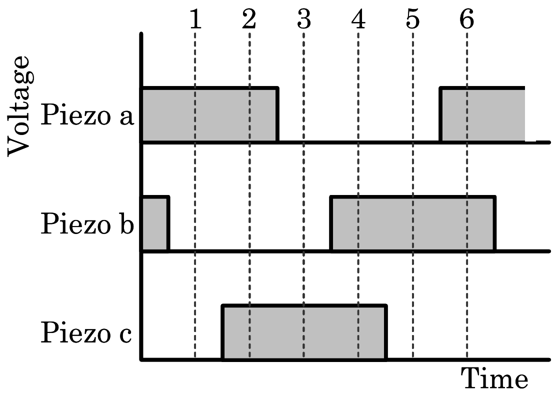
Fig. 3 The motion mechanism in the CCW direction.

The CW directional rotation is realized by replacing the signal to Piezo b with that to Piezo c (Fig. 2(b)).

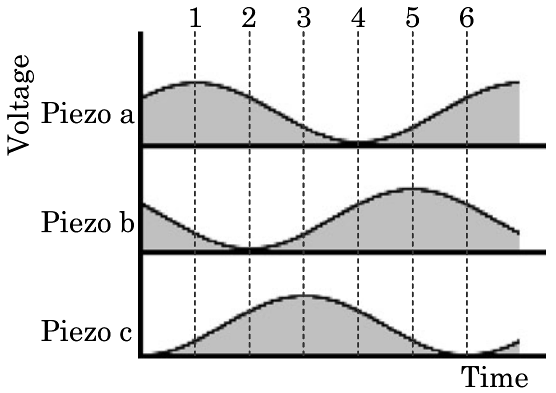
4 Experiments

The miniature robot is moved by the deformation of the piezos. Fig. 4 shows control waveforms which have the miniature robot rotate in the CCW direction. In our experiment, the signal in the CCW direction is used. The control waveforms are rectangle and sinusoidal waveforms. The sinusoidal waveform is the fundmental component of the rectangle waveform. The vertical axis denotes voltage and horizontal axis denotes time. The minimum voltage of the control waveforms is 0 V, and the voltage dose not take a negative value. The control waveforms in Fig. 4(a) are three-phase rectangle waveform. The control waveforms in Fig. 4(b) are three-phase sinusoidal waveform. The amplitude of the voltage is 100 V and input frequencies are from 100 Hz to 1000 Hz.

The rotational displacement of the miniature robot is measured by the liner displacement in x1, x2, x3 directions. The motion of the miniature robot, which moves on a glass, is measured by optical displacement sensors. We change the

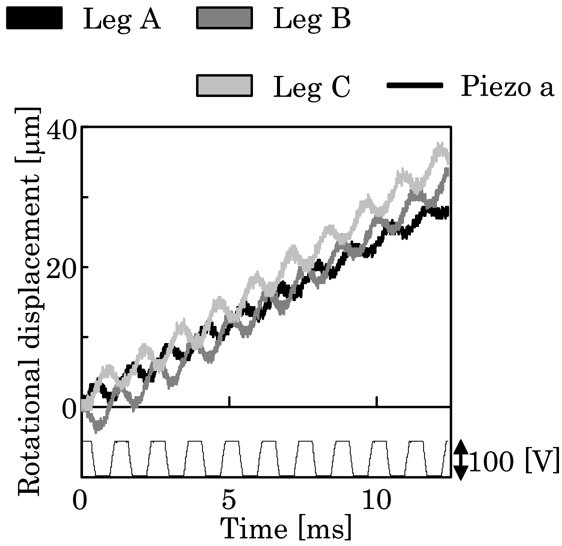


(a)

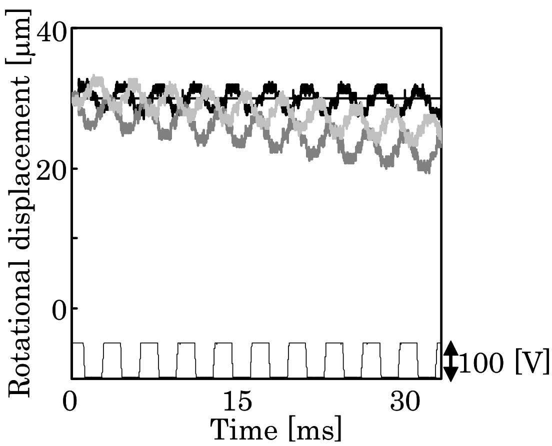


(b)

Fig. 4 The control waveforms which rotate the miniature robot in the CCW direction. (a) Rectangle waveform. (b) Sinusoidal waveform.



(a)



(b)

Fig. 5 The rotational displacement of the miniature robot. The control waveform is rectangle, and the direction is the CCW direction. The frequency is (a) 800 Hz and (b) 300 Hz.

input frequency and repeat the measurement. We investigate the relationship between the conditions that the miniature robot can rotate or not.

Then, we invert the miniature robot in order not to add a load to its three legs which are measured. The motions in the local axis of three legs are measured. The x-axis and y-axis are orthogonal axes. Measured results are processed by a personal computer.

Table 1 Experimental conditions. Waveform, frequency, and direction.

Figures	**Waveform**	**Freq.**	**Direction**
5(a), 7(a), 8(a)	rectangle	800 Hz	CCW
5(b), 8(b)	rectangle	300 Hz	CCW
6(a), 7(b), 9(a)	sinusoidal	800 Hz	CCW
6(b), 9(b)	sinusoidal	300 Hz	CCW

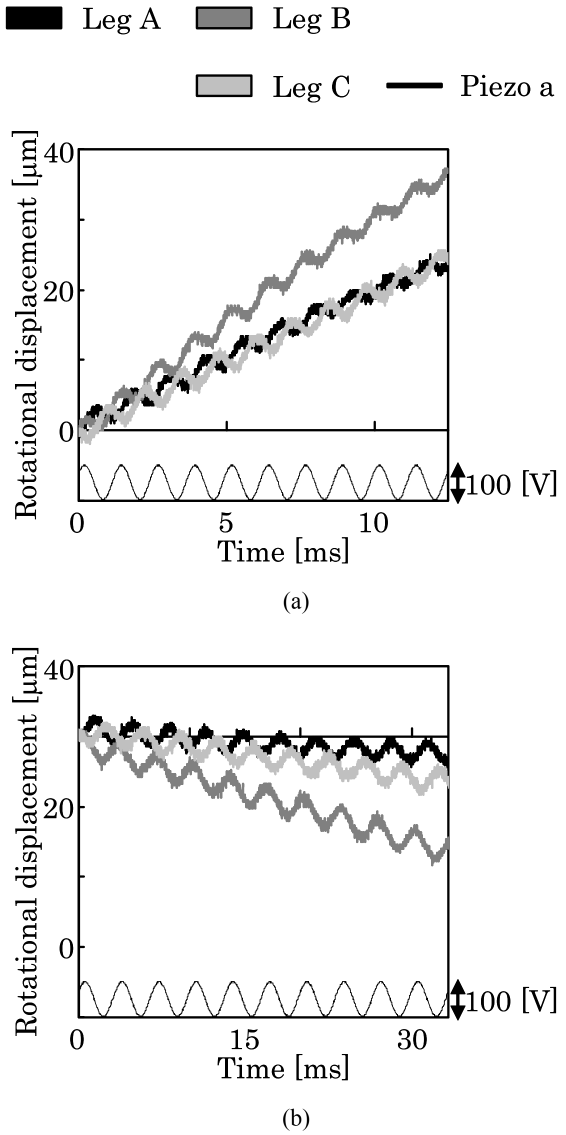


Fig. 6 The rotational displacement of the miniature robot. The control waveform is sinusoidal, and the direction is the CCW direction. The frequency is (a) 800 Hz and (b) 300 Hz.

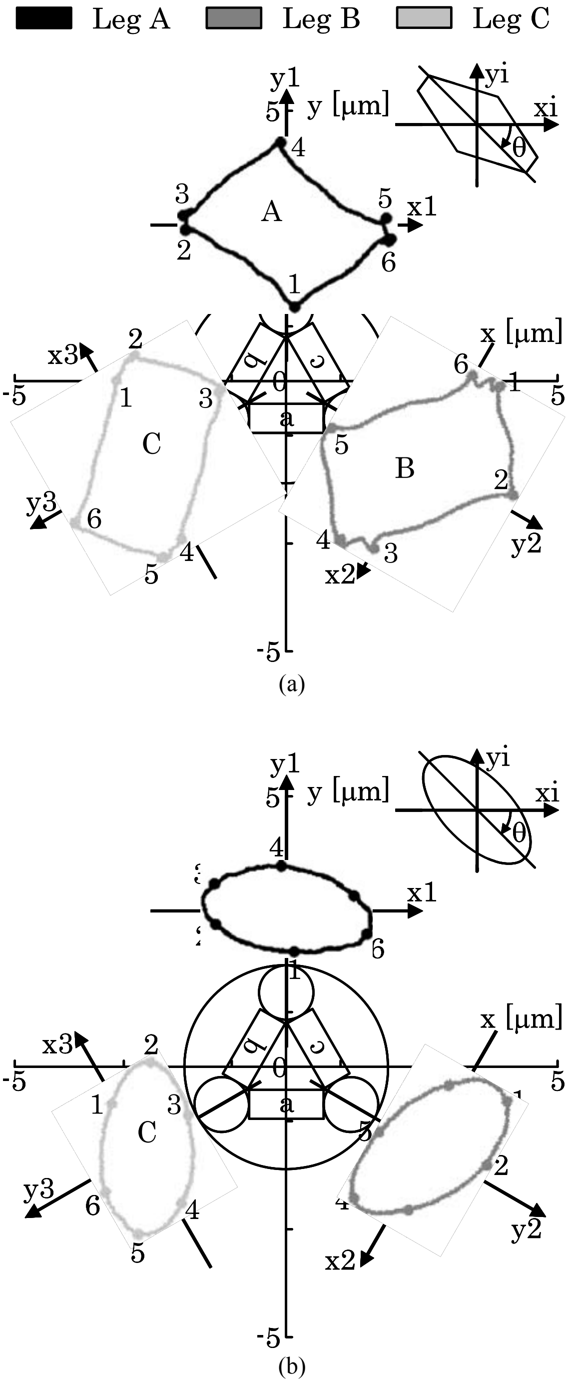


Fig. 7 Three legs' trajectories in the local xy plane and the long axis angle θ. The frequency is 800 Hz. The direction is the CCW direction. (a) The control waveform is rectangle. (b) The control waveform is sinusoidal.

5 Experimental Results

Table 1 summarized experiment conditions. We applied various input signals to the piezos. Fig. 5 and Fig. 6 show the rotational displacement of the miniature robot. Fig. 5(a) is obtained when the control waveform is rectangle, the frequency is 800 Hz, and the direction is the CCW direction. Fig. 5(b) is obtained when the control waveform is rectangle, the frequency is 300 Hz, and the direction is the CCW direction. Fig. 6(a) is obtained when the control waveform is sinusoidal, the frequency is 800 Hz, and the direction is the CCW direction. Fig. 6(b) is obtained when the control waveform is sinusoidal, the frequency is 300 Hz, and the direction is the CCW direction. The vertical axis is a rotational displacement and horizontal axis is a time. The rotational displacement of Leg A, Leg B and Leg C and the

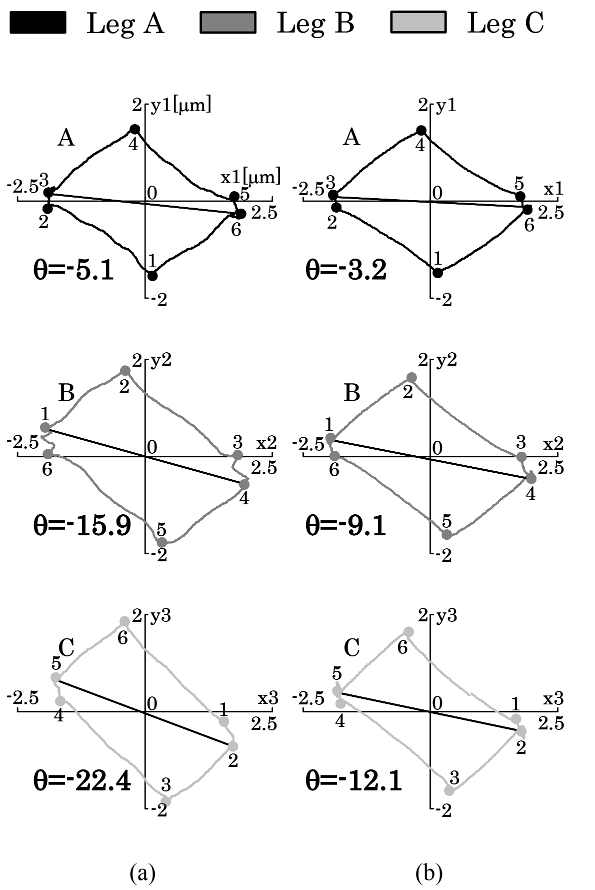


Fig. 8 Three legs' trajectories in the local xy plane and the long axis angle θ. The control waveform is rectangle. The direction is the CCW direction. The frequency is (a) 800 Hz and (b) 300 Hz.

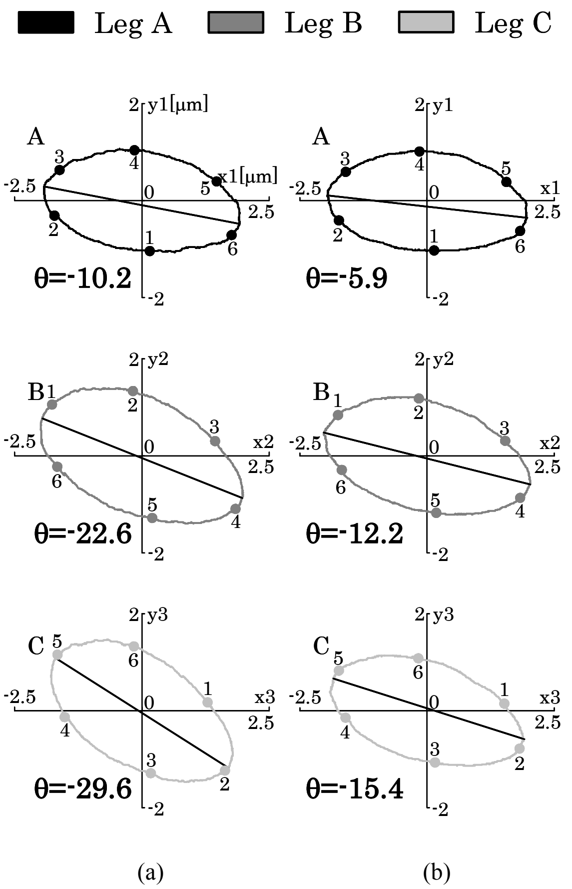


Fig. 9 Three legs' trajectories in the local xy plane and the long axis angle θ. The control waveform is sinusoidal. The direction is the CCW direction. The frequency is (a) 800 Hz and (b) 300 Hz.

input voltage applied to Piezo a are indicated in Fig. 5 and Fig. 6. Fig. 5 and Fig. 6 show 10 periods of the control waveforms. The rotational displacements of three legs synchronize with the input voltage.

In Fig. 5 and Fig. 6, the miniature robot can rotate properly in the CCW direction when the rotational displacement of three legs are positive. The miniature robot rotates in the wrong direction, i.e. the CW direction when the rotational displacement of three legs are negative. In Fig. 5(a), the miniature robot can rotate properly because the rotational displacement of three legs are positive. In Fig. 5(b), the miniature robot rotates in the wrong direction because the rotational displacement of three legs are negative. Fig. 6(a) shows that the miniature robot can rotate properly and Fig. 6(b) shows the miniature robot rotates in the wrong direction. Therefore when the input frequency is 800 Hz, the miniature robot can rotate properly, and when the input frequency is 300 Hz, the miniature robot rotates in the wrong direction.

Fig. 7 shows the miniature robot and three legs' trajectories indicated in the local xy plane. The coordinates in Fig. 7 are introduced in Fig. 1(a). The horizontal and vertical axis denote the local coordinate xi and yi (i=1, 2, 3) of the legs. Numbers in Fig. 7(a) correspond to those in Fig. 4(a) and numbers in Fig. 7(b) correspond to those in Fig. 4(b). In Fig. 7(a), the control waveform is rectangle, the frequency 800 Hz, and the direction is the CCW direction. The three legs' trajectories are similar to hexagonal trajectories in the CCW direction. In Fig. 7(b), the control waveform is sinusoidal, the frequency 800 Hz, and the direction is the CCW direction. The three legs' trajectories are similar to ellipse trajectories in the CCW direction. In Fig. 7(a) and Fig. 7(b), θ is long axis angle. The long axis of the hexagonal trajectories is defined as the maximum distance between the vertexes. The angles differ by changing frequency. We investigate the relationship between the angle and the motion of the miniature robot.

Fig. 8 and Fig. 9 show the three legs' trajectories. In Fig. 8(a), the trajectories are obtained by using Fig. 7(a). When the control waveform is rectangle, the frequency is 300 Hz, and the direction is the CCW direction, Fig. 8(b) is obtained. In Fig. 9(a), the trajectories are obtained by using Fig. 7(b). Fig. 9(b) is obtained when the control waveform is sinusoidal, the frequency is 300 Hz, and the direction is the

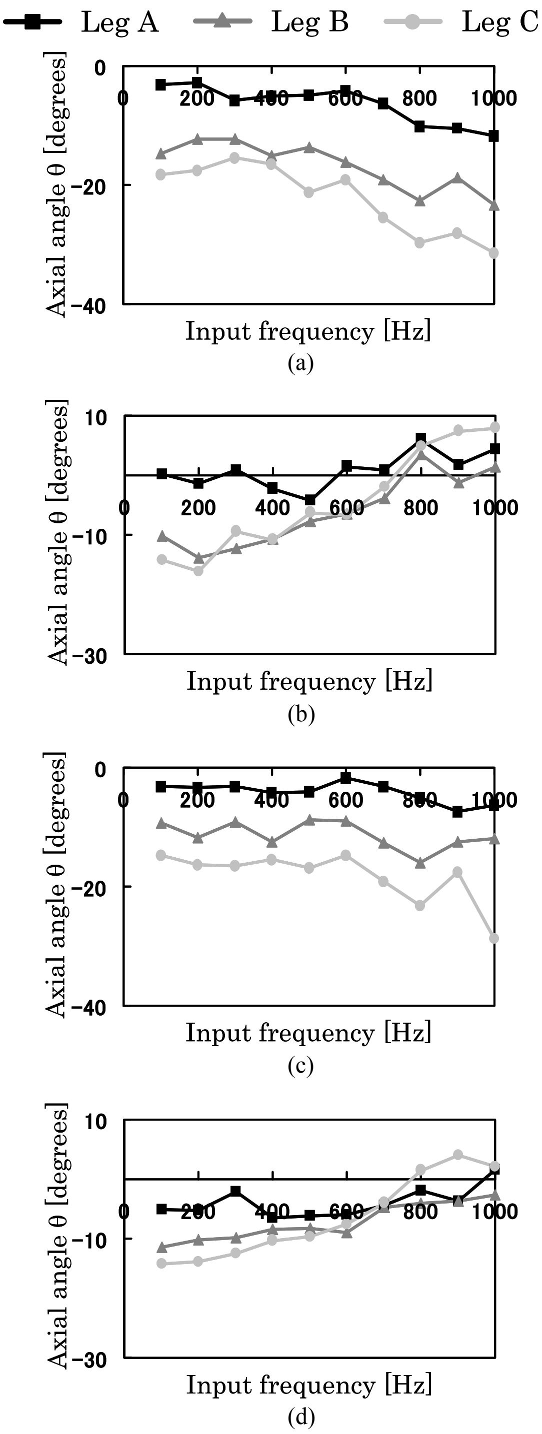


Fig. 10 θ of the legs of each frequency. (a) The control waveform is rectangle, and the direction is the CCW direction. (b) The control waveform is rectangle, and the direction is the CW direction. (c) The control waveform is sinusoidal, and the direction is the CCW direction. (d) The control waveform is sinusoidal, and the direction is the CW direction.

CCW direction. The difference between Fig. 8(a) and (b) is frequency. The difference between Fig. 9(a) and (b) is also frequency. The lines in the trajectories indicate long axis. The numbers in Fig. 8 correspond to those in Fig. 4(a) and numbers in Fig. 9 correspond to those in Fig. 4(b). The trajectories of Fig. 8(a) and Fig. 8(b) are similar. However, the angles of the long axis of Fig. 8(a) are larger than that of Fig. 8(b). The trajectories of Fig. 9(a) and Fig. 9(b) are similar. However, the angles of the long axis of Fig. 9(a) are larger than that of Fig. 9(b). The tendency of the angles in Fig. 9 are similar to Fig. 8. When the frequency changes, the angles differes.

Fig. 10 shows θ of the legs of each frequency. The vertical axis denotes the long axis angle and horizontal axis denotes frequency. Fig. 10 is obtained by changing the direction, the waveform, and the frequency. Fig. 10(a) and Fig. 10(b) are obtained when the control waveform is rectangle, and the direction is the CCW direction. Fig. 10(c) and Fig. 10(d) are obtained when the control waveform is sinusoidal, and the direction is the CCW direction. In Fig. 10(a) and Fig. 10(c), as frequency becomes higher, the angles of long axes decrease. In Fig. 10(b) and Fig. 10(d), as frequency becomes higher, the angles of long axes increase. From these results, when the control waveforms is the CCW direction, the angles of long axes decrease as frequency becomes higher, and when the control waveforms is the CW direction, the angles of long axes increase as frequency becomes higher. We suppose that the angle of long axis affect the motion of the miniature robot.

6 Conclusions

By changing the input waveforms, we studied the motion of the miniature robot and its legs. In the experiments, the miniature robot, which uses the input frequency of 800 Hz, can rotate properly, and the miniature robot, which uses the input frequency of 300 Hz, can rotate in the wrong direction. The angle of the long axis in each frequency was measured. The angle of the long axis differs according to the frequency and waveform. When the control waveforms is the CCW direction, as frequency becomes higher, the angles of long axes increase. When the control waveforms is the CW direction, as frequency becomes higher, the angles of long axes decrease.

7 References

[1] Akihiro Torii, Yoshiyuki Fukaya, Kae Doki, Akiteru Ueda, (2003) Motion of a Miniature Robot Using Three Piezoelectric Elements Controlled by Rectangular Voltage: Journal of Robotics and Mechatronics Vol. 15 No. 6. 602-608