Fine Motion Performance of L-shaped Seal Mechanism with 3 Degrees of Freedom

Katsumi Kawagoe and Katsushi Furutani
Toyota Technological Institute
12-1, Hisakata 2-chome, Tempaku-ku, Nagoya 468-8511 JAPAN

1. INTRODUCTION

Multiple degrees of freedom (DOFs) devices with a wide movable range and a high resolution are required for a fine motion stage in scanning probe microscopes (SPMs). A coarse motion device is generally combined with a fine motion one to build such a positioning device. Inchworm Mechanism [1][2] and Impact Drive Mechanism [3][4] have been developed for a coarse motion mechanism for SPMs. With an increase of DOFs of the devices, the number of controlled actuators is increased, the size of a whole device becomes large and its structure becomes complex.

The authors have proposed Seal Mechanism with 3 DOFs. Though the mechanism has a smaller number of controlled devices, it can move with micrometer order steps in the *x*-, *y*- and θ-directions. Though Seal Mechanism has smaller number of controlled actuators than Inchworm mechanism, it performs as well as Inchworm mechanism [5][6]. An L-shaped device of Seal Mechanism has been proposed and its positioning performance in Coarse mode has been investigated [6]. In this paper, positioning performance of Seal Mechanism in the combination of Coarse mode with Fine one is described.

2. PRINCIPLE OF MOVEMENT

2.1 Movement Principle of 3-DOF Device in Coarse Mode

Fig. 1 shows a structure of a 3-DOF device of Seal Mechanism [6]. This device consists of two controlled Friction devices CA and CB, connected by two Extension devices PA and PB with Friction devices CC constant friction. Two Extension devices cross at right angle. Extension devices are alternated by on-off control in Coarse mode. It can move in a wide range. A Friction device CC that generates a constant frictional force works as a passive element. Therefore, it is possible to move with 3 DOFs by using two Friction devices and two Extension devices as the controlled elements. The following relation must be satisfied:

$$F_{XOff} < F_C < F_{XOn} \qquad (1)$$

where F_C is a constant frictional force at Friction device CC, and F_{XOn} and F_{XOff} are frictional forces at Friction device CA or CB in the cases of adhering and releasing, respectively. Fig. 2 shows the movement principle of a 3-DOF device. The device can move in the +*x*-direction as shown in Fig. 2 (a). Figs. 2 (b) and (c) illustrate the movement principle in the *y*- and θ- directions. Either PA or PB is used to rotate in the θ-direction.

2.2 Movement Principle of 3-DOF Device in Fine Mode

The step like movement can be interpolated by changing the length of Extension device continuously, which is similar to Walking Drive Mechanism [7]. Friction device CC can move when this device adhered onto a base with CA and CB, and two Extension devices expand and contract continuously. It can draw various loci with the input signal. For example, a locus will become a circle when a sine wave is applied to PA, a cosine one is applied to PB simultaneously. 2 DOFs, the *x* and *y*-directions are controllable in this mode.

3. STRUCTURE OF DEVICE EMPLOYING SEAL MECHANISM

Fig. 3 shows an appearance of a 3-DOF device. Stacked piezoelectric actuators and electromagnets were used for Extension devices and Friction device, respectively. The whole device measures 63×63×16 mm and weighs 34 g. The piezoelectric actuator with dimensions of 5×5×20 mm expands 11.6 μm at the applied voltage of 100 V.

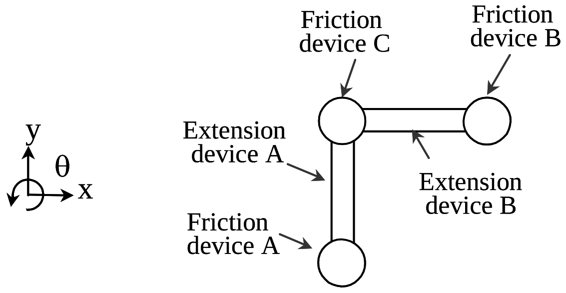


Fig.1 Structure of Seal Mechanism with 3 DOFs

The waveforms were given through drive amplifier generated with a personal computer. The signal from an additional capacitor to pick up noise was subtracted from the signal from the charge amplifier to reduce the noise from power lines in the induced charge feed back control [8][9]. The phase of the signal from the pick up capacitor was adjusted by using a filter to each piezoelectric actuator.

Displacements were measured with eddy current displacement sensors with a measurement range of 1 mm and a resolution of 0.4 μm, and capacitance displacement sensors with a measurement range of ± 25 μm and a resolution of 8 nm. A rectangular wave was applied to Electromagnets CA and CB. An applied voltage to Electromagnet CC was determined to 1 V experimentally.

4. *EXPERIMENTS*

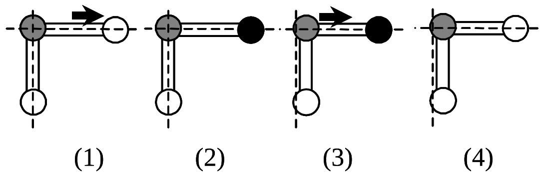
4.1 Displacement control by feedback of induced charge

The elliptically moving device consists of two piezoelectric actuators crossing at right angle. When the voltage of a circular locus was applied to it, its tip moves elliptically because of an isotropic stiffness and the hysteresis of piezoelectric actuators [10][11]. This device had some interference among the axes in Fine mode. Therefore, displacement control by the feedback of the induced charge was tried. Equation (2) predicts the displacement of this device from the extension of the piezoelectric actuators.

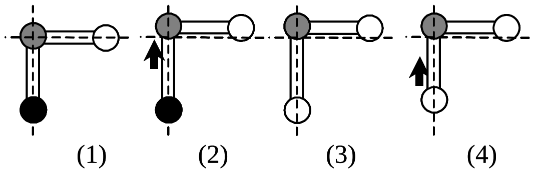
$$x = AC = \begin{pmatrix} 3.71 & 0.39 \\ 0.24 & -2.71 \end{pmatrix} \begin{pmatrix} C_{PA} \\ C_{PB} \end{pmatrix} \qquad (2)$$

where $x = [x \;\; y]^T$ is a position vector with 2 DOFs, A is a coefficient matrix obtained from experimental results, and C indicates the induced charges vector with 2 DOFs. The generalized inverse matrix of C is used for the displacement control.

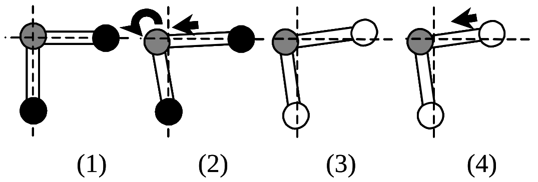
Fig.4 shows an example of positioning when the reference positions were set to x = -1 μm and y = 1 μm at the same time. In 10-time positioning, the maximum errors in x and y-directions were 0.09 and 0.11 μm, respectively. Noise, impulsive force and stick- slip caused this error.



(a) +x motion



(b) +y motion



(c) +θ motion

Fig.2 Principle of movement of Seal Mechanism

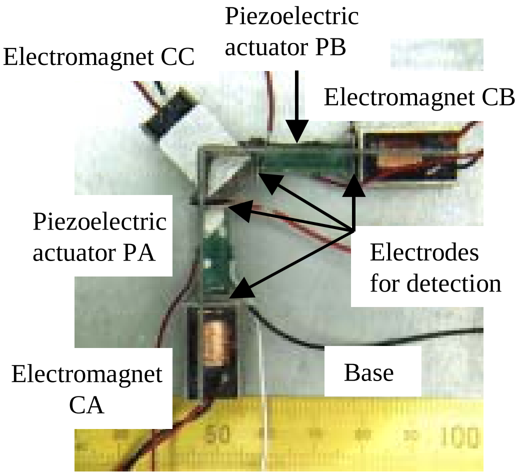


Fig.3 Appearance of Seal Mechanism with 3 DOFs

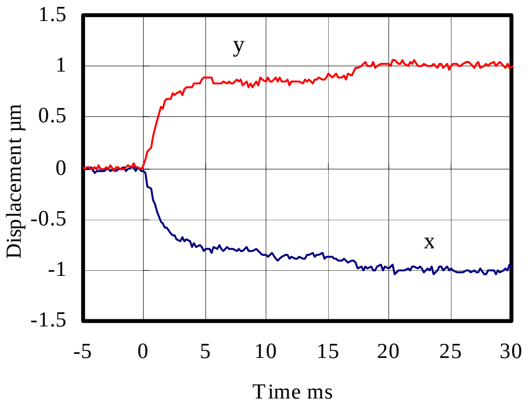


Fig.4 Positioning by induced charge feedback control

4.2 Coarse and Fine positioning by displacement feedback control

Positioning by the feedback of the displacement was carried out by the combination of Coarse and Fine modes in absolute coordinate system. The mode is switched from Coarse to Fine when the device reaches the movable range of Fine mode in the x- and y-direction and the tolerance in the θ–direction. The displacements was measured with eddy current displacement sensors. The reference positions was independently set to x = 100 μm or y = 100 μm and the others was set to zero. Fig. 5 shows an example of positioning in the y-direction. Fig. (a) shows the whole positioning process and Fig. (b) shows expanded at switching from Coarse mode to Fine one. Table 1 shows results of 10-time positioning in each direction. Positioning accuracies in the x- and y-directions were smaller than the resolution of the displacement sensor. The error in the θ-direction was less than the tolerance in the θ-direction in Coarse mode.

4.3 Control of circular motion

The circular motions of 10 revolutions were carried out after the applied voltage was gradually raised to reduce the impulsive force at its beginning. Fig. 6 shows results at a frequency of 3.3 Hz. Table 2 shows results of tracking by the open loop, the displacement feedback and the induced charge feedback control. Because of the influence of the noise, the induced charge feedback could not perform with the same accuracy as the displacement feedback control. Therefore, the treatment of the noise is required in order to improve the motion accuracy by the induced charge feedback.

5. CONCLUSIONS

In this paper, the performance of Seal Mechanism in Fine mode was investigated experimentally and it positioned by the combination of Coarse mode and Fine one. The conclusions can be drawn as follows.

(1) The relative positioning within an extendable range of the piezoelectric actuators was possible by the induced charge feedback.

(2) The absolute positioning that combined the coarse mode and fine mode was possible by the displacement feedback.

(3) Only 2 DOFs, the x- and y-directions were controllable in Fine mode. However the final error of the θ-direction is less than the tolerance in the θ–direction in Carouse mode.

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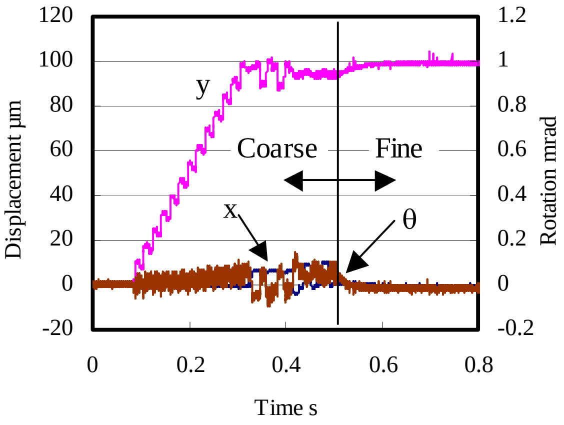
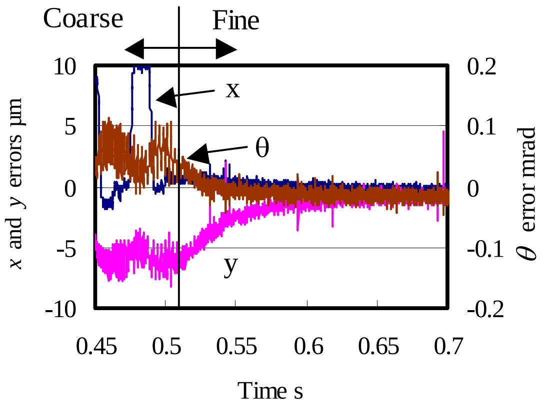


(a) Whole process



(b) Switching from coarse mode to fine

Fig.5 Positioning by displacement feedback control

Table 1 Results of positioning

Reference position		x=100 μm		y=100 μm	
		μ	σ	μ	σ
Error	x μm	0.0	0.2	-0.1	0.1
	y μm	0.0	0.3	0.0	0.3
	θ mrad	0.014	0.024	0.021	0.019
Time ms	Coarse	581	161	285	57
	Fine	292	70	237	65
	Total	872	156	523	103

μ: average, σ: standard deviation

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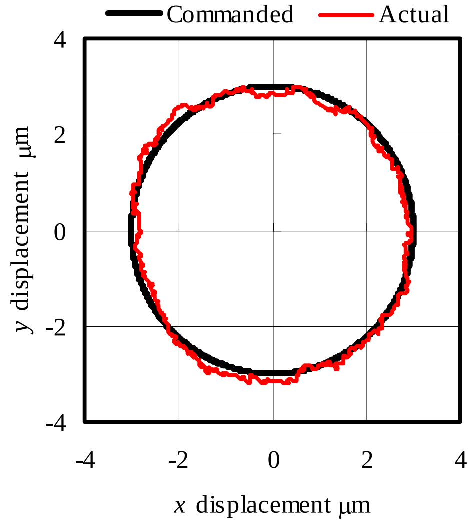
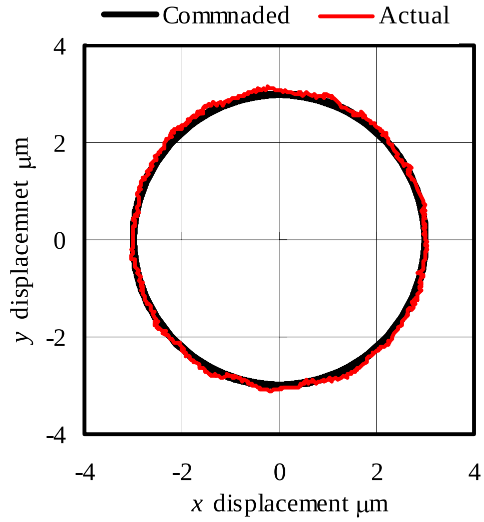


(a) Induced charge feedback control



(b) Displacement feedback control

Fig.6 Circular motions

Table 2 Accuracy of circular motion

Feedback	Radius μm	Roundness μm
None (open)	2.90	0.87
Displacement	3.05	0.26
Induced charge	3.06	0.51