Proc. of SPIE Vol. 2593, Microrobotics and Micromechanical Systems, ed. L E Parker (Dec 1995) Copyright SPIE

Miniature tilting mechanism using piezoelectric actuators

Satoshi Tawara* , Takayuki Goto * , Kimiyuki Mitsui **
* Advanced Technology Research Center, Mitsubishi Heavy Industries,Ltd.
8 - 1, Sachiura 1 - chome, Kanazawa - ku, Yokohama 236, Japan
**Faculty of Science and Technology, Keio University
14 - 1, hiyoshi 3 - chome, Kohoku - ku, Yokohama 223, Japan

ABSTRACT

A tilting mechanism using piezoelectric actuators which has two rotation degrees of freedom has been developed. The dimensions of the body of the tilting mechanism are 10mm in diameter and 24mm in length. We have achieved the following specifications of the tilting mechanism; ± 20 ° rotational angle in the orthogonal two axes, 30 seconds of the angular resolution, 10 ° /sec of the maximum rotation speed, and 1.75 Nmm of the maximum torque.

This paper describes the structure and the experimental results of the linear actuator and the tilting mechanism.

KEYWORDS : micromachine, piezoelectric element, linear actuator, actuator, tilt

1. INTRODUCTION

Micromachine technology is expected to have future potential applications in a wide range of fields, such as industrial machinery, plant maintenance and medical science. A micromechanical system has wide applications, such as positioning, inspection and maintenance.

We adopt piezoelectric elements as the linear actuators in the tilting mechanism because the system needs to be miniaturized for the applications.

The dimensions of the body of the tilting mechanism are fixed 10 mm in diameter and 24 mm in length for our present application. Therefore, miniature linear actuators are required such that there can be two linear actuators in the body. We have already developed a linear actuator using piezoelectric elements that is 10 mm in width, 57 mm in length, 3 mm in thickness.[1]

The present paper will describe the structure of the brand - new tilting mechanism using miniature linear actuators and its fundamental performance.

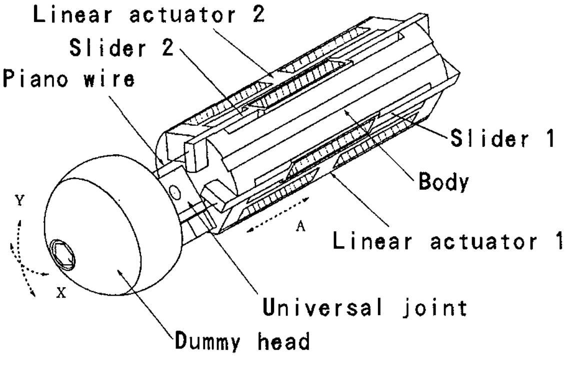


Fig.1 Isometric sketch of the tilting mechanism

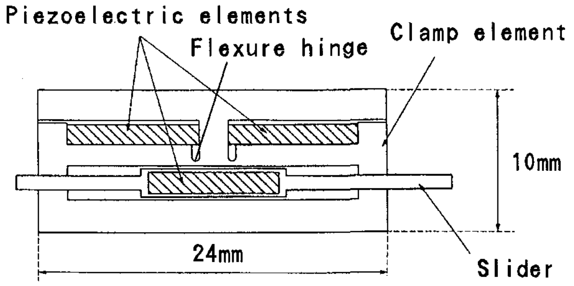


Fig.2 Structure of the linear actuator

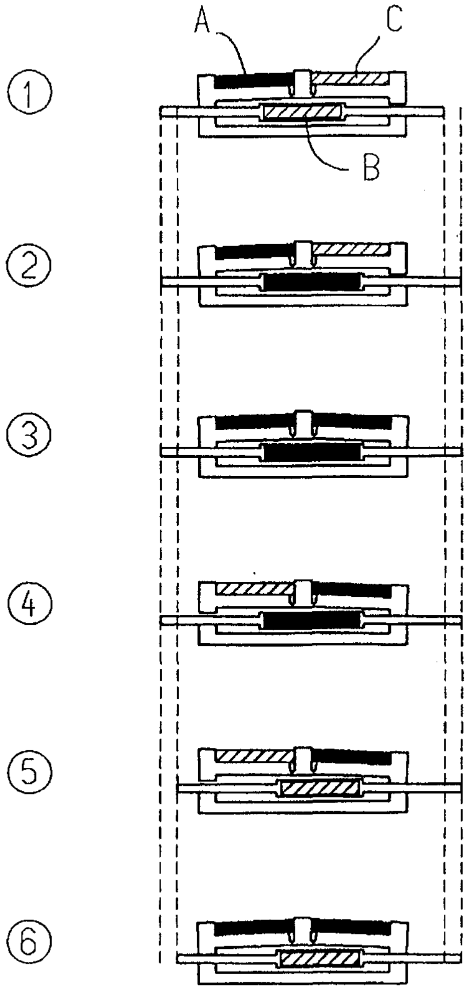


Fig.3 Principle of motion
(Black elements indicate extension.)

2. OUTLINE

2.1 Tilting mechanism

The structure of the tilting mechanism is shown in Fig.1. A left hand hemisphere in the figure, called a dummy head, is connected to the body of the tilting mechanism by a universal - joint. It is designed so that the dummy head will rotate in the direction of arrows X and Y. The dummy head can be rotated by two miniature linear actuators using piezoelectric elements in the body of the tilting mechanism.

The translational motion of the slider in the linear actuator changes into the rotational motion of the dummy head by means of the thin piano wire; if the slider(1) moves in the direction of arrow A, the dummy head rotates in the direction of the arrow X. To realize dual axis angular motion independently, the two piano wires are set on the dummy head at right angles around the center of rotation, as shown in Fig.1.

2.2 The principle of motion of the linear actuator

The structure of the linear actuator is illustrated in Fig.2. As shown in the figure, each linear actuator consists of a slider that generates displacement and two clamp elements that hold the slider. Each clamp element consist of the flexure hinges manufactured by EDM, and piezoelectric elements.

The slider has a piezoelectric element in the flexure frame. When voltage is applied to the piezoelecric element, the flexure frame is deformed under stress from the piezoelectric element and the slider has a small expansion. Each clamp element has a piezoelectric element. When voltage is applied to the piezoelectric element, the flexure hinge is bent under stress from the piezoelectric element and the clamp element grasps the slider tightly.

The principle of motion of the linear actuator is shown diagrammatically in Fig.3. A slider in the linear actuator is moved by the joint motion of two clamp elements and a slider.

When a voltage is applied to the piezoelectric element A it clamps the slider. Then a variable rate step voltage is applied to the element B causing it to change step length. At the end of the step, a voltage is applied to the element C causing it to grip the slider. Then the voltage is cut off from the element A releasing the slider. The step starts downward at which point the element A is activated again, then the element C is released, and the step starts again.[2]

Although the displacement of the slider in one cycle is very small, a long travel distance is achieved by repeating this sequence. This travel distance is limited by the length of the guide slots of the slider.

The displacement of the piezoelectric element for the clamp actuator is magnified approximately 5 times by the linkage system, so that the clamps are able to hold the slider efficiently. In order to convert the displacement generated by the piezoelectric element into the clamp element effectively, the clearances of the contact surfaces between the clamp and both rails of the slider need to be adjusted to nearly zero.

3. DESIGN

3.1 Design of the slider

The slider is required to be able to travel at high speed and to have a long travel motion for satisfaction of the specification of the linear actuator. To realize this requirement, the slider was designed by the analysis of stress and displacement using the finite element method. The thickness of the flexure frame in the slider ("t" in the figure 4) is calculated, having maximum displacement and does not exceed the allowed stress. Calculated data of the slider is as follows;

(1)The maximum displacement : 3.01 μ m,
(2)The resonant frequency : 12.5 kHz.

3.2 Design of the clamp element

The clamp element is required to be able to travel at high speed and to have a large bending transformation as well as the slider. To realize this requirement, the flexure hinge was designed by analysis of stress and displacement using the finite element method. The thickness of the flexure hinge in the clamp element is calculated, having maximum displacement and does not exceed the allowed stress. Calculated data of the clamp element is as follows;

(1)The maximum displacement : 27.0 μ m,
(2)The resonant frequency : 2.97 kHz.

3.3 Design of the tilting mechanism

The details of the tilting mechanism was designed according to the results of the slider and clamp element design as described above. The tilting mechanism is required to satisfy the conditions as follows;

(1) The body needs to contain two sets of linear actuators,
(2) The dummy head can be rotate at least ± 15° of rotation in the orthogonal two axes,

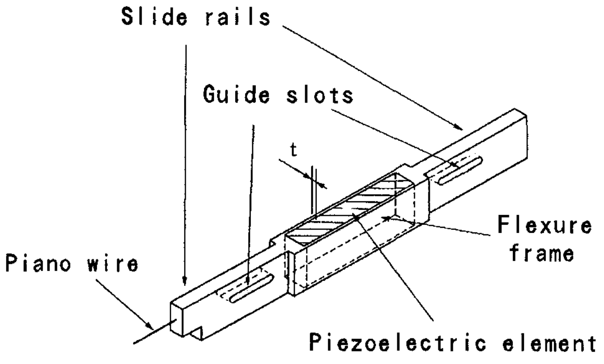


Fig.4 Slider

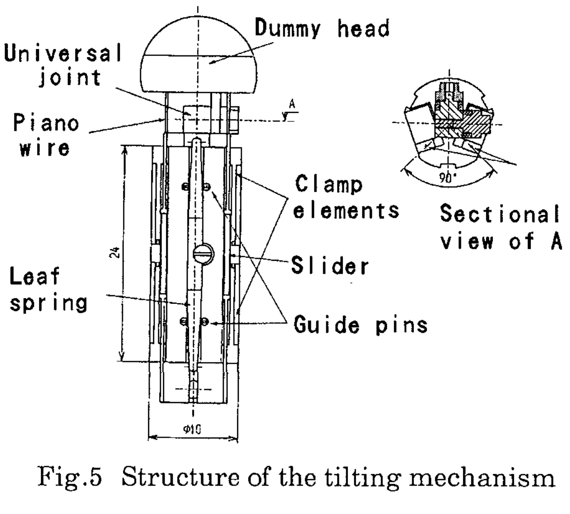


Fig.5 Structure of the tilting mechanism

(3) Easy to manufacture and made from a single part.

To satisfy these conditions described above, the body of the tilting mechanism was designed as shown in Fig.5. The smallest stack type piezoelectric element on the market was selected for the tilting mechanism. To realize dual axis angular motion independently, the two piano wires were set at a right angles around the center of the rotation. The linear actuator has a 3 mm travel that is equivalent to a ± 20° of the rotation of dummy head.

4. RESULTS & DISCUSSION

The tilting mechanism was made on an experimental basis, and the characteristics of the linear actuator and the tilting mechanism were investigated experimentally. In order to evaluate the characteristics of the linear actuator, the following basic items were tested;

(1) The characteristics of the piezoelectric element,

(2) The characteristics of the slider,

(3) The characteristics of the clamp element,

(4) The characteristics of the linear actuator.

Besides, the following basic items were tested to evaluate characteristics of the tilting mechanism;

(1) The maximum rotation angle,

(2) The minimum resolution of the rotation angle,

(3) The maximum angular velocity.

4.1 The characteristics of the piezoelectric element

Piezoelectric elements were used for the linear actuator in the tilting mechanism. We confirmed the relationship between applied voltage and displacement of the piezoelectric element. As in figure 6, the piezoelectric element has an approximately 6 μ m displacement at 100 V and the typical hysteresis that was caused by transformation of the crystal structure was observed.

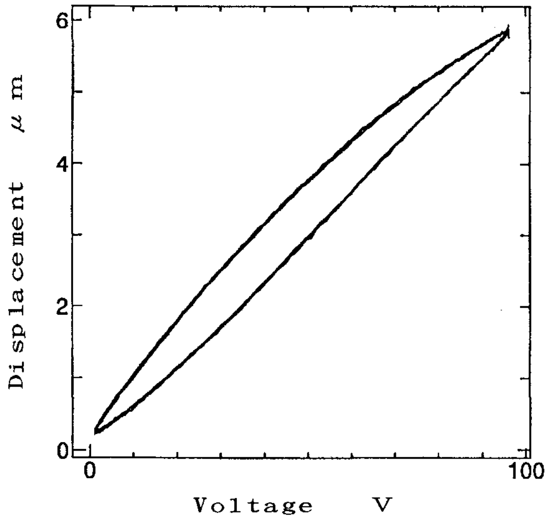


Fig.6 Characteristics of the piezoelectric element

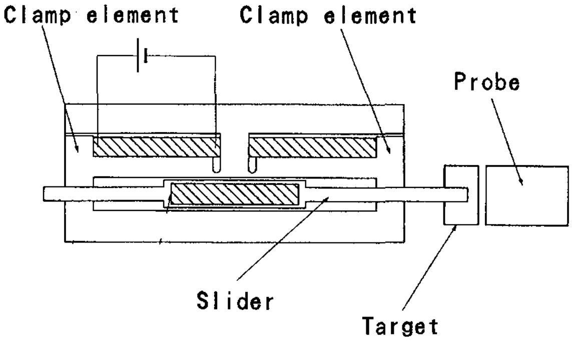
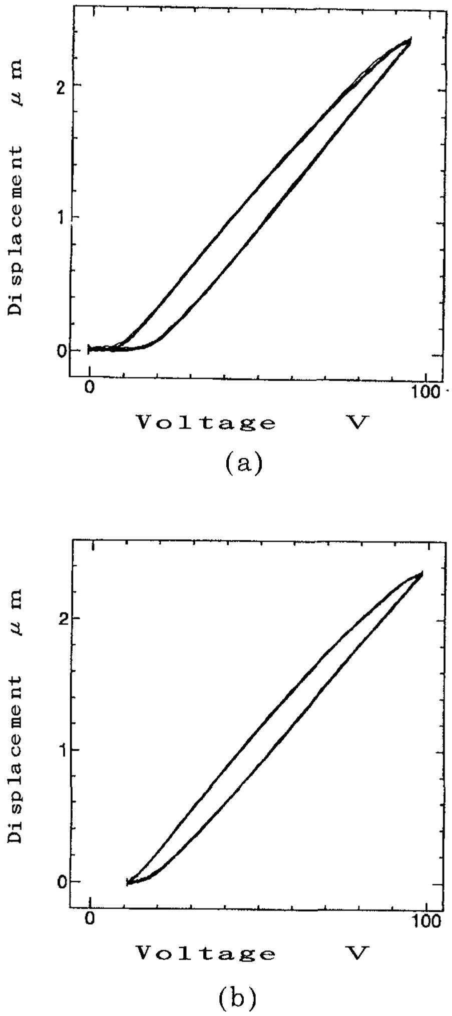


Fig.7 Experimental setup for the slider

4.2 The characteristics of the slider

The slider is one of the important elements in the linear actuator as well as the clamp element. The characteristics of the linear actuator depend strongly on the characteristics of the slider. Therefore, static and dynamic response of the slider was tested. The schematic diagram of the experimental set up for evaluation of the slider is illustrated in Fig.7. In order to measure the characteristics of the slider, the left end of the slider was fixed by clamp element, and the target for the measured point was attached to the another end of the slider, and the displacement of the slider was measured with a capacitance gage. The relation between the input voltage and the displacement of the slider is shown in Fig.8(a) for a 100 V input sinusoidal signal at 1 Hz. This result indicates that the slider has 2.4 μm displacement at 100 V and a deadband at low voltage The deadband can be considered as caused by an error in measurement in making the flexure frame of the slider. Then, the displacement of the slider was measured again for a 10 - 100 V input sinusoidal signal at 1 Hz. The deadband was improved as in Fig.8(b) by the offset voltage.

Figure 9 shows the frequency response of the slider. The slider has two resonant frequencies at 1.2 kHz and 3.0 kHz, but only the resonant frequency at 3.0 kHz is the extensional mode of the vibration considering the motion of the phase. Here, it is necessary to make corrections for the resonant frequency, because the mass of the target changes the resonant frequency. The corrected resonant frequency of the slider is 8.2 kHz. A large difference between the theoretical and experimental values of the resonant frequency was observed. But it can be considered that there is no affect on the performance of the linear actuator, because the performance is limited by the clamp element that has lower resonant frequency as described later.



(a)

(b)

Fig.8 Static characteristics of the slider

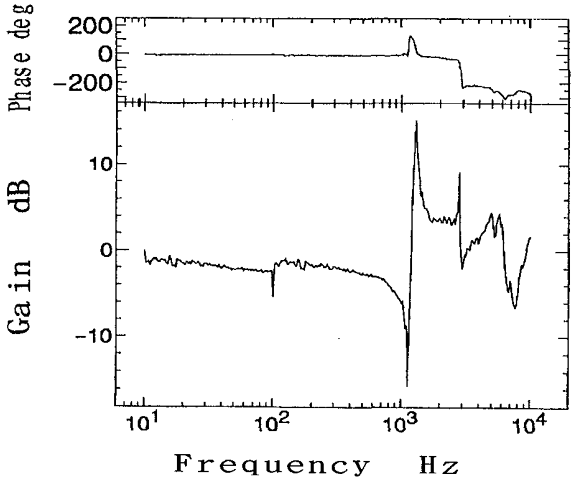


Fig.9 Frequency response of the slider

4.3 The characteristics of the clamp element

The clamp element (Fig.10) is one of the important elements of the linear actuator as well as the slider as before. The characteristics of the linear actuator depend strongly on the characteristics of the clamp element. Therefore, the static and dynamic response of the clamp element were tested.

Figure 11 shows the static characteristic of the test piece of the clamp element. It is seen from this figure that the test piece has approximately 5 μ m extensional displacement in the direction of the arrow A and approximately 25 μ m displacement in the bending direction of the arrow B by 100 V supply.

Figure 12 shows the frequency response of the test piece. As it is clear from the figure, the test piece has a resonant frequency at 3.8 kHz. These results obtained are in agreement with the calculated performance.

The endurance test of the test piece was put in operation for 1000 hours. After the endurance test, neither deformation nor cracks were found at the flexure hinge.

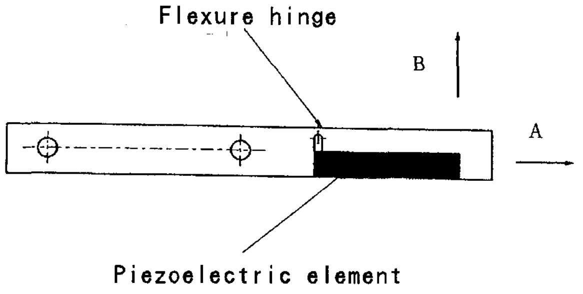


Fig.10 Test piece of the clamp element

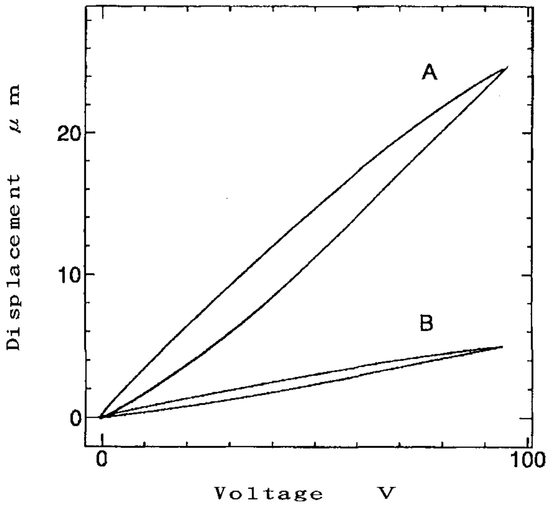


Fig.11 Static characteristics of the clamp element

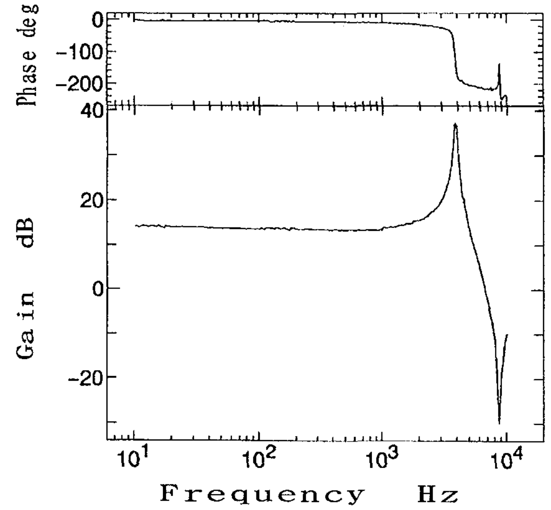


Fig.12 Frequency response of the clamp element

4.4 The characteristics of the linear actuator

The linear actuator was tested to evaluate the following characteristics;

(1)The displacement of the linear actuator for one step,

(2)The relation between the motion speed of the slider and the control frequency,

(3)The relation between the motion speed of the slider and the load.

The schematic diagram of the experimental set up for evaluation of the linear actuator is illustrated in Fig.13. The voltage signals were output from a personal computer, and they were amplified by a high voltage amplifier and then supplied to the piezoelectric elements. The displacement of the slider was measured with a capacitance gage and an axial load was added to the slider by hanging a weight.

The relation between the input voltage of the piezoelectric element in the slider and the displacement of the slider is shown in Fig.14. In this case, the slider was moved rightward and leftward 30 steps each with no load.

The displacement of a single cycle of the slider was calculated based on the previous data as shown in Fig.15. According to this result, the maximum displacement of the slider is 0.9 μ m and the minimum displacement is 0.3 μ m with stable motion.

Figure 16 indicates the relation between the motion speed of the slider and the control frequency. The control frequency means the step number in a second. As shown in the figure, with an increase in the control frequency the motion speed of the slider increases linearly until 1200 Hz. Over 1200 Hz, the motion speed of the slider decrease rapidly. It is satisfactory to consider that the frequency response of the slider causes the rapid decrease over 1200 Hz of the motion speed. In the chapter of the characteristics of the slider, we ignored the lateral resonant mode at 1200 Hz of the slider, but the motion speed has direct effects upon this mode in practice.

Figure 17 shows the relation between the motion speed of the slider and the control frequency under

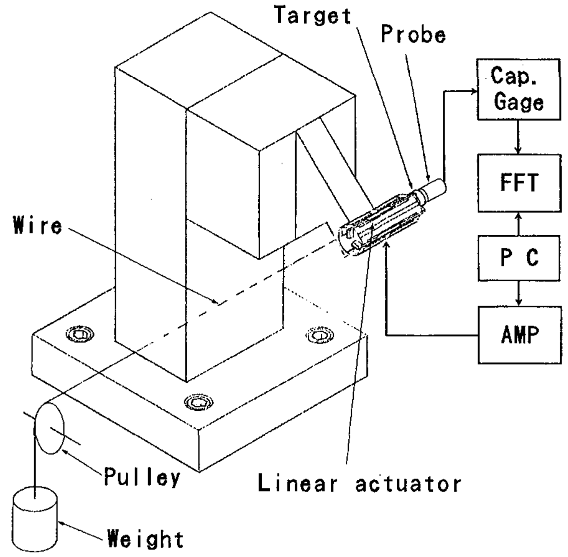


Fig.13 Experimental setup for the linear actuator

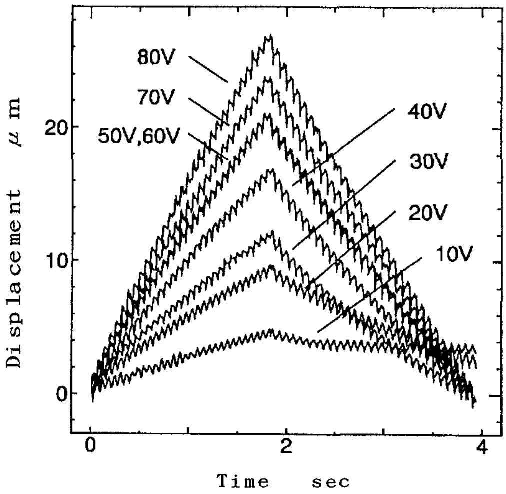


Fig.14 Motion of the slider

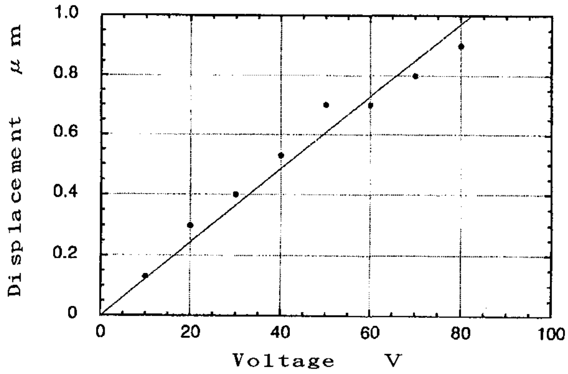


Fig.15 Displacement of the one cycle

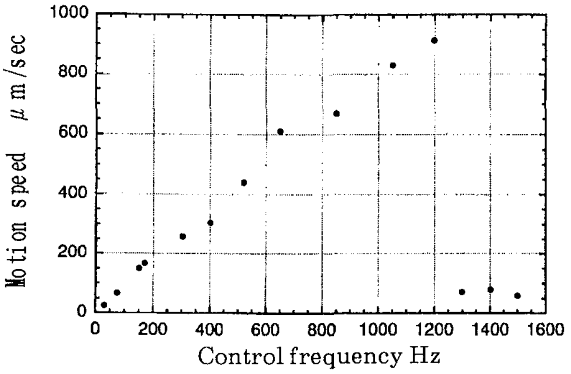


Fig.16 Relation between motion speed and control frequency

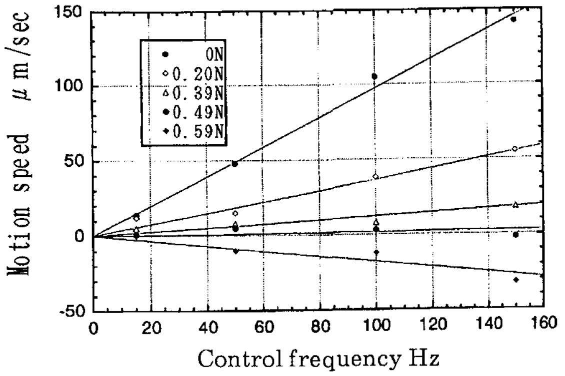


Fig.17 Relation between motion speed and load

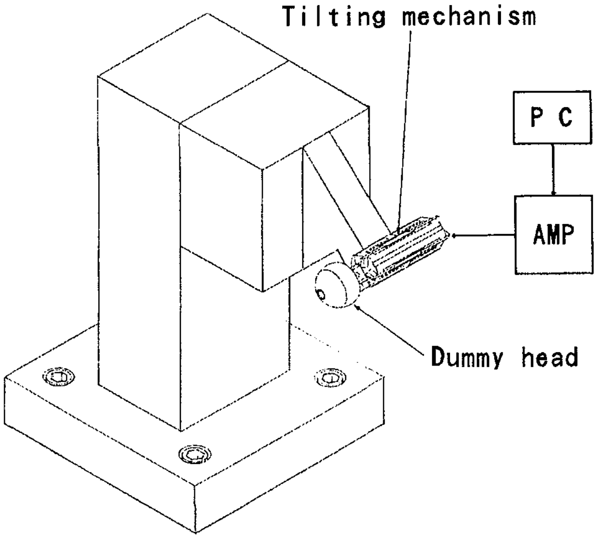


Fig.18 Experimental setup for the tilting mechanism

the condition that the load is changing. According to this result, the force generated by linear actuator balance the lad at 0.49 N.

4.5 The characteristics of the tilting mechanism

To evaluate the performance of the tilting mechanism, the set up of Fig.18 was used. The voltage signals were output from a personal computer, and they were amplified by a high voltage amplifier and then supplied to the piezoelectric elements as well as the linear actuator experiments.

The following performance was confirmed by experiments, the tilting mechanism has ± 20° rotational angle in the orthogonal two axes, 30 seconds of the angular resolution, 10° /sec of the maximum speed, and 1.75 Nmm of the maximum torque.

5. CONCLUSIONS

This paper has described the structure and the experimental results of the linear actuator and the tilting mechanism using piezoelectric actuators. We have achieved the following specifications of the tilting mechanism; ± 20° rotational angle in the orthogonal two axes, 30 seconds of the angular resolution, 10° /sec of the maximum speed, and 1.75 Nmm of the maximum torque.

ACKNOWLEDGMENT

The authors would like to thank for the assistance of Mr.Suzuki who was a graduate student of Keio University.

REFERENCES

1. T.Goto, S.Tawara, K.Mitsui and N.Suzuki,"Miniature linear actuator using piezoelectric elements," Proceedings of ASPE Annual Meeting, pp.242, 1994.
2. Burleigh Instruments,Inc.,"The piezo book," Burleigh Instruments,Inc., Catalog No.330288, pp.10, New York, 1983.