Displacement Analysis of Pantograph Mechanisms with Superelastic Hinges*

Mikio HORIE**, Futoshi KOBAYASHI***,
Kozo IKEGAMI** and Shinji OKABE**

For handling of a micromachine element and/or its parts, use of a micromechanical system is suitable. Thus, a pantograph mechanism is made from a plastic resin and superelastic hinges simultaneously using a small injection molding machine. The shape memory alloy having an effect of superelasticity is used as superelastic hinges. Therefore it is possible for superelastic hinges to have large bending displacements. The input and output displacements of the pantograph mechanism with superelastic hinges are measured and their linear relationship is confirmed. Then a micromechanical system for microbonding by adhesives is constructed using piezoelectric actuators, the pantograph mechanism and a needle. We confirmed that the proposed mechanical system performs well for microbonding by adhesives.

Key Words: Design, Machine Element, Robotics, Manipulator, Micromachine, Mechanisms, Superelastic Hinge, Pantograph Mechanism, Microbonding by Adhesive, Micromechanical System

1. Introduction

We have already discussed a method of spreading a small amount of adhesive, and a method of microbonding between a floating head slider and an arm in a hard disk by making use of a new shape of needle and a displacement sensor^{(1),(2)}. In the present work, a mechanical system for microbonding to make the needle point move in a plane has been developed. We used a pantograph mechanism with a linear relationship between the input and output displacements as the mechanism of the mechanical system for microbonding. Moreover, considering energy utilization and the useless of movable space dimension of the mechanism, etc., a small pantograph mechanism was designed from the viewpoint that a small-dimension mechanism is good for treatment of microdimension

machine elements. When we consider a production of very small parts, it is necessary to take into account the ease of manufacture and to simplify the production process to the greatest degree possible.

We consider a hinge (hereafter called a superelastic hinge) instead of a kinematic pair composed of two elements such as an axis and a hole in the mechanism. The hinge is a thin plate which is made of a shape memory alloy having superelasticity. It is possible for the superelastic hinge to endure relatively large bending displacements between two links, though it is impossible to endure large bending displacements in the case of a traditional elastic hinge⁽³⁾.

In this research, the pantograph mechanism is designed and is produced using a small injection molding machine, with clarification of the displacement characteristics of the superelastic hinge in the pantograph mechanism. Next, the displacements of the mechanism are clarified, for the case of driving of this mechanism by piezoelectric actuators with the displacement expansion mechanism.

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** Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226, Japan

*** Graduate Student, Tokyo Institute of Technology

2. Displacement Characteristics of Pantograph Mechanism

2.1 Principle of pantograph mechanism

Pantograph mechanisms are frequently applied to robot arms and legs with two degrees of freedom because of the good controllability of mechanisms due to the linear relationship between the input and output displacements. In the pantograph mechanism shown in Fig. 1, $\triangle ABF$, $\triangle FDE$, and $\triangle ACE$ are mutually similar. The shape of the mechanism is determined by the length of segment AB, ratio $k_1(\equiv BC/AB)$, and ratio $k_2(\equiv AC/CE)$. Moreover, when point F is fixed on the frame and point A is driven, the direction of motion of point E differs by 180° from that of point A. When point A is fixed on the frame and point F is driven, the direction of motion of point E is same that of point F⁽⁴⁾.

2.2 Pantograph mechanism with superelastic hinge

We replaced a revolute pair with the superelastic hinge as shown in Fig. 2. In the pantograph mechanism, binary pairs and a ternary pair which contains a fixed link are used. The binary pair shown in Fig. 3(a) is examined first. Figure 3(b) shows a binary revolute pair composed of an axis and a hole. The rotating center corresponds to the center of the axis or the hole in the case of this pair. Figure 3(c) shows

Fig. 1 Pantograph mechanism

Fig. 2 Replacement of revolute pair with superelastic hinge

a superelastic hinge which is equivalent to a revolute pair. The rotating center of this hinge in the moving state is located at the position which is different with the cross point of neighboring two link center lines although it is located at the center of the hinge in the initial state in which the hinge is unbent. Moreover, the transmission of the moment does not occur in case of the revolute pair, but does occur in the case of the superelastic hinge; however, power is transmitted in both cases.

Next, the ternary pair shown in Fig. 4(a) is examined. Figure 4(b) shows a revolute pair in which two moving links are connected to an axis and a hole on a frame. The rotating center corresponds to the center of the axis or the hole for this kinematic pair, too. Figure 4(c) shows a ternary pair which is composed of two elastic hinges. It is equivalent to a revolute pair which contains the frame. Here, the superelastic hinges 1 and 2 are made, and a ternary pair is composed as shown in Fig. 5. The rotating center of this pair is located at the center of the length of the elastic hinge. In the case of this hinge, power is transmitted between a moving link and a fixed link, though the power is not transmitted between the two moving links. Transmission of the moment does not occur for a normal ternary pair. However, it does occur at the superelastic hinge between the moving link and the frame.

Fig. 3 Binary pair

Fig. 4 Ternary pair

Fig. 5 Structure of ternary pair with superelastic hinge

Fig. 6 Displacement X_h of rotating center and slope θ of superelastic hinge

In the pantograph mechanism with normal joints, the rotating centers of four kinematic passive pairs form a parallelogram. In the pantograph mechanism with superelastic hinges, it is assumed that the four rotating centers of each hinge in the initial state when superelastic hinges of the pantograph mechanism do not bend make the parallelogram.

2.3 Displacement characteristics of superelastic hinge

The difference in maximum slope among stainless steel SUS304, phosphorus bronze PBSP-SH and shape memory alloy Ti-Ni is investigated for the case in which their materials are bent to their elastic limit. Figure 6 shows the displacement X_h of a rotating center and the slope θ when a bending moment M is applied to links in a four-point bending test. Figure 7 shows the maximum slope determined according to the large-deflection nonlinear bending theory⁽²⁾ for a non-dimensional beam length t_n divided by a beam thickness for a shape memory alloy Ti-Ni, phosphorus bronze PBSP-SH, and stainless steel SUS 304. From this figure, it is found that a large slope is

Fig. 7 Elastic limit of hinge

obtained in the case of the shape memory alloy as compared to other normal materials. Therefore, the shape memory alloy is suitable for use to make superelastic hinges.

Figures 8 and 9 show the relationship between the displacement X_h of the rotating center and the bending moment M and the relationship between the slope θ and bending moment M , respectively. In the pantograph mechanism, superelastic hinges 1 mm or 2 mm in length l and 2 mm in width b are used. In this case, it is known that it is possible to disregard the displacement X_h of the rotating center.

2.4 Design and manufacture of the pantograph mechanism

When the pantograph mechanism is designed, miniaturization is our aim as described in the introduction. Therefore, an injection molding machine is used to facilitate the manufacture. When the pantograph mechanism is made, the superelastic material is set beforehand at the required position in the mold, and it is considered that the pantograph mechanism can be manufactured simply by pouring of the resin into the mold. Concerning the miniaturization, the thickness of the superelastic hinge represents the constrained condition. The thickness is determined as 0.16 mm. The 0.16 mm is a limit thickness made by manufacturing process to make a plate type SMA from a wire type SMA. A pantograph mechanism having dimensions appropriate to this hinge thickness was designed.

Next, the work space is discussed. In general, the output point of a pantograph mechanism composed of revolute pairs can be displaced only in the plane. Therefore, only the positioning of the pantograph mechanism in this plane is examined here. Therefore, the work space of the mechanism is designed accord-

Fig. 8 Relationship between bending moment M and moving displacement X_h when hinge lengths are varied

Fig. 9 Relationship between bending moment M and slope θ when hinge lengths are varied

Fig. 10 Fabricated pantograph mechanism with superelastic hinges
($AB=7.0$ mm, $BC=DF=24.5$ mm, $CD=BF=6.5$ mm, $DE=23.2$ mm)

ing to the above, assuming the work space to be $8\text{ mm} \times 8\text{ mm}$ square obtained by the discuss with the dimension of the spreading area with respect to the dimension of the pantograph mechanism.

Figure 10 shows the mechanism which was manufactured using links made of polyethylene resin and hinges made of Ti-Ni SMA using a small injection molding machine. Points A and F are input points in the pantograph mechanism, and a needle is fixed at output point E.

3. Experimental Apparatus and Experimental Method

Operation of the pantograph mechanism is described here and the relationship between the input-output displacements is clarified. Figure 11 shows a schematic of the entire mechanical system used in the experiments. In this system, an actuator outputs a displacement of about 2 mm, expanding the displacement of the piezoelectric actuator 40 times with the displacement expansion mechanism. The strain gages are bonded to the side of the piezoelectric actuator and the displacement of the actuator is calibrated using the strain gages.

The length of each link of the pantograph mechanism used in the experiments is shown in the caption of Fig. 10. The superelastic hinge at points B and D is 2 mm wide and 1 mm long. One at point C is 2 mm wide and 2 mm long. Point F has the structure shown in Fig. 5, and the lengths of superelastic hinges 1 and 2 are equal. In the case of hinge 1, the total width is 2.5 mm and the width of space d_1 is about 1.0 mm. The width of hinge 2 is 0.8 mm.

As for the pantograph mechanism, point E directly moves in two directions when input points A and F are driven in the horizontal and vertical directions, respectively. In the installation of the pantograph

Fig. 11 Mechanical system for microbonding by adhesives

mechanism on the actuator, first the actuator is located in the middle position of the displacement range, and the pantograph mechanism is installed in this initial state.

Through use of the above-mentioned experimental apparatus, the loci of the output point are measured with the CCD camera when the pantograph mechanism is operated. The measurement data are analyzed with the computer. The static characteristics of the pantograph mechanism with superelastic hinges can be determined from the relationship between the loci and displacements of the actuators.

4. Automated Experiment of Mechanical System for Microbonding

A needle and a pantograph mechanism are combined for experiments, and a mechanical system for spreading a small amount of adhesive and automated microbonding, which is done manually, are discussed here. In the automated experiment, the displacement of the needle point installed at output point E of the pantograph mechanism is measured. Output point E can move in the horizontal and vertical directions, and the computer calibrates the output displacements using the measured data.

4.1 Input-output displacement characteristics

The displacements of output point E of the pantograph mechanism when input points A and F are driven horizontally and vertically by the actuators are shown in Figs. 12 and 13 with the ideal expanded loci of input points A and F, respectively. In these figures, the initial position of output point E is the position where input points A and F are situated at the centers of those displacement ranges. From these figures, it is known that the relationship between the input-output displacements is linear in the range of displacements in the experiments, because the data are observed linearly.

4.2 Positioning accuracy and repeatability of the proposed pantograph mechanism

The positioning accuracy of the needle point is measured as the difference between the desired value 1 mm and the real displacement of the needle point when the needle point was moved the desired value 1 mm in the horizontal or vertical direction. Moreover, the repeatability shows the deviation of the real displacement of the needle point when the same needle point is moved the desired value 1 mm in the horizontal or vertical direction many times. Table 1 shows the positioning accuracies and repeatabilities. The positioning accuracy is not good; because we wish that accurate movement of the needle in the horizontal or vertical direction is essential in calibration of the input-output displacements. However, the

Table 1 Positioning accuracy and repeatability of the proposed mechanical system

		Horizontal displacement	Vertical displacement
Positioning accuracy	Horizontal direction	0.179 mm	0.029 mm
	Vertical direction	0.012 mm	-0.394 mm
Repeatability	Horizontal direction	0.038 mm	0.000 mm
	Vertical direction	0.000 mm	0.082 mm

Fig. 12 Input-output displacements in the horizontal direction when the controller is acting

Fig. 13 Input-output displacements in the vertical direction when the controller is acting

repeatabilities of the proposed pantograph mechanism are good. The input displacement calculated using the data of strain gages on piezoelectric actuators and the output displacement of the actual needle point have a one-to-one correspondence.

4.3 Automation experiment for microbonding

For automation of microbonding which is currently performed manually, automation to decrease the amount of the adhesive spreading deviation is attempted. In the automation experiment, the adhesive is spread using open loop control. First, for

Table 2 Standard deviation of adhesive volume

Application method	Standard deviation of adhesive volume
This mechanical system	$1.08 \times 10^{-3} \text{ mm}^3$
Manual operation system with displacement sensor	$1.02 \times 10^{-3} \text{ mm}^3$

application of the adhesive to the needle, the container which is used to place the adhesive in the work space of the needle point is positioned appropriately. In the case of the first spreading, the height of the adhesive in the container is confirmed and the needle point is displaced so that the needle point touches the surface of the adhesive. In every spreading after the second one, the needle point is displaced automatically and contact of the needle point with the adhesive is not confirmed. Thus, the spreading is performed many times, and the amount of adhesives is measured for each spreading. Table 2 shows the experimental results. The amount of the adhesive is measured as the area of adhesive after the spread adhesive is expanded by application of a constant load for a given time⁽¹⁾ because the amount of adhesive spread is extremely small.

4.4 Experimental results

Table 2 shows standard deviations of adhesive volumes when the proposed mechanical system and a manual operation system with an optical fiber displacement sensor are used. From Table 2, in the case of the proposed mechanical system, it is found that the standard deviation of adhesive volume nearly equals that in the case of manual operation with the optical fiber displacement sensor. Therefore, it is possible to bond the floating head slider and the arm in a hard disk using the proposed mechanical system. This mechanical system exhibits no backlash and facilitates smooth displacement of the needle. Our results demonstrate the usefulness of this mechanical system.

5. Conclusions

The characteristics of the pantograph mechanism with superelastic hinges are analyzed, for the purpose of development of a micromanipulator which can be used to manipulate a needle for microbonding. Our results are as follows.

(1) From the analytical results for the superelastic hinge made of the shape memory alloy, little movement of the rotating center of the hinges was demonstrated and the superelastic hinge was applied to the joints of the pantograph mechanism.

(2) It was confirmed that the relationship between the input-output displacements is linear in the range of displacements in the experiments when the input points A and F are driven horizontally and vertically, respectively.

(3) The mechanical system for microbonding was composed of piezoelectric actuators, the pantograph mechanism with a needle and superelastic hinges. When open loop control was applied to this mechanical system and the adhesive was spread, microbonding was achieved.

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