NANOMETER CUTTING MACHINE EMPLOYING PARALLEL MECHANISM

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1. Introduction

Today, fabrication of nanometer-scale structures using scanning probe microscope (SPM) instruments are actively investigated [1]-[3]. A tripod or a tube type piezoelectric actuator is generally used to scan a specimen with fine *xyz*-motions. An interference among the three orthogonal motions exists for both the tripod and the tube type and it becomes significant particularly for a large displacement. Therefore, the authors has proposed a SPM type machine tool employing a parallel mechanism with 6 degrees of freedom [4]. Small angles of elevation of links is designed to make a resolution in the *z*-direction fine in the prototype. However, its motion was sometimes unstable due to singular points.

In this paper, a structure of a fine motion device employing the parallel mechanism is improved at first. Then the performance of the device is discussed. Finally, the application of the stage to a nanometer cutting machine with an atomic force microscope (AFM) structure is described.

2. Structure of nanometer cutting machine

Fig. 1 shows an overview of a fine motion stage for a nanotemer cutting machine. The stage supported with 6 links with an elevation angle of 35° stands on a base platform. The machine measures 170×170×108 mm. A table weighs 103 g. The movable range of the table is 30×40 μm in the *x*- and *y*-directions and 100 μm in the *z*-direction. Stacked piezoelectric actuators with dimensions of 5×5×20 mm are used to change the link length. They extend 16 μm at an applied voltage of 150 V. Displacement of the piezoelectric actuator is magnified over 8.6 times (approximately 100 μm) with a lever mechanism with flexure hinges made of ANSI 304 stainless steel. The generative force of the lever mechanism is 3.3 N. Its residual vibration is absorbed with a friction damper. Both ends of the links are connected with the base platform and the table by flexure joins which spring constant is 3.5×10^4 N/m. The motion of the stage is controlled by a feedback of link displacements. The displacement of each link is measured with an eddy current sensor with a frequency range up to 18 kHz.

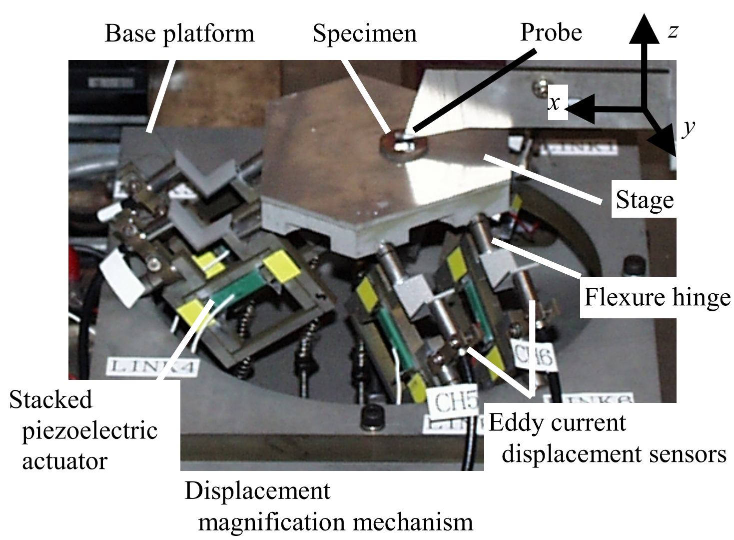

Fig. 1 Appearance of fine motion stage

Fig. 2 illustrates a block diagram of a control system. A given posture of the table is resolved into the link lengths by inverse kinematics. Then, the link lengths are given as references in each servo systems with a proportional-integral (PI) controller. In each servo systems, a digital low pass filter with a cutoff frequency of 100 Hz precedes each controller in cascade in order to prevent the vibration of the lever mechanisms which resonant frequency is approximately 300 Hz.

The controller is installed in a personal computer (80586, 100 MHz). The manipulation signal through a 12 bit D/A converter is given to the piezoelectric actuator through a voltage amplifier. The feedback signal is obtained with a 12 bit A/D converter.

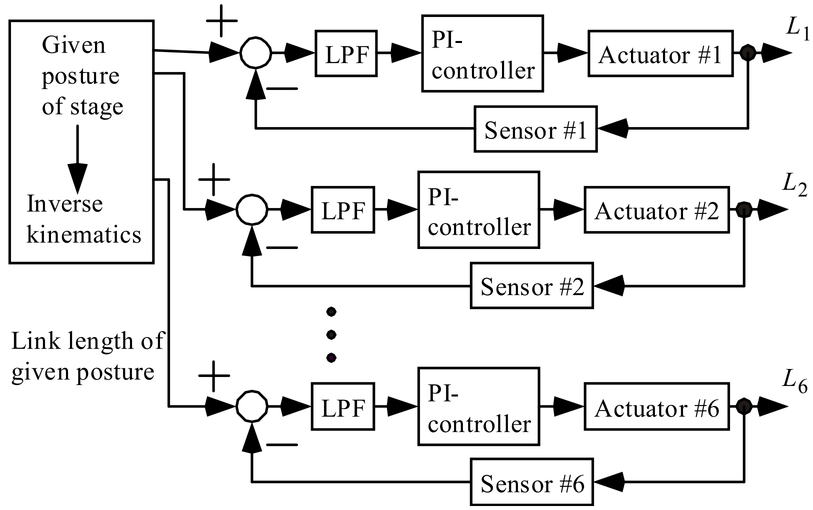

Fig. 2 Block diagram of control system

3. Displacement performance

Fig. 3 shows an example of displacement of the stage in the case of driving in the *x*-direction. Displacement of the stage is measured with capacitance displacement sensors. Interference in the *y*- and *z*-directions are 10 and 14 %p-p, respectively. A pitching error is 7.5×10^{-5} rad. Position errors of the link ends form the designed ones in assembly process cause the motion error. Though a resolution of the lever mechanism is 170 nm, resolutions of the stage are 100 nm, 143 nm and 115 nm in the *x*-, *y*- and *z*-directions, respectively.

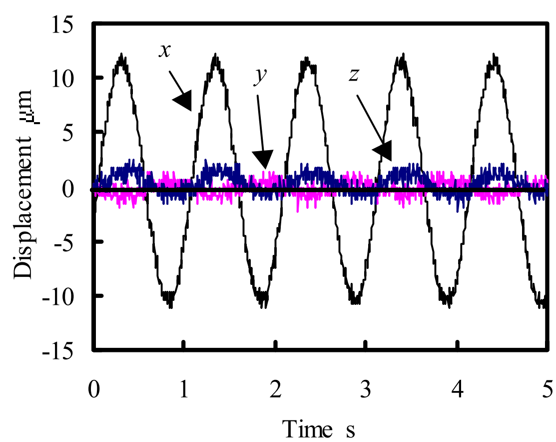

Fig. 3 Example of stage displacement driven in *x*-direction

To evaluate the displacement performance in detail, an atomic force microscope (AFM) is composed with the stage. Fig. 4 shows a configuration of the AFM. A contact mode cantilever with a length of 200 µm and a spring constant of 0.16 N/m is arranged above the stage. A probe tip mounted on the end of the cantilever is made from Si_3N_4. A beam from a semiconductor laser irradiates the back of the free end of the cantilever. A deflection of the cantilever is detected as a position of the reflected light with a quadrant photodiode. The probe is scanned within 10×10 µm on an optical flat with an accuracy of λ/20. The stage is scanned on the horizontal plane by triangular waves with frequencies of 2 and 0.05 Hz in the *x*- and *y*-directions, respectively. The standard deviation of a motion error from the plane is 34 nm.

A force curve is also measured to evaluate the *z*-motion. Fig. 5 shows an example of the force curve measured in air. The vertical and horizontal axes indicate the output of the quadrant photodiode and the commanded displacement of the table in the z-direction, respectively. A silicon wafer cut along (001) plane is used for a specimen. The stage is driven by a triangular wave with a frequency of 1 Hz and an amplitude of 4 µmp-p in the *z*-direction. The output of the photodiode is proportional to the deflection of the cantilever. The positive deflection corresponds to the repulsive force between the probe and the specimen. The probe approaches the specimen when the table moves upward. The linearity of the motion is 3.8 % between 1.3 (A) and 1.8 µm (B).

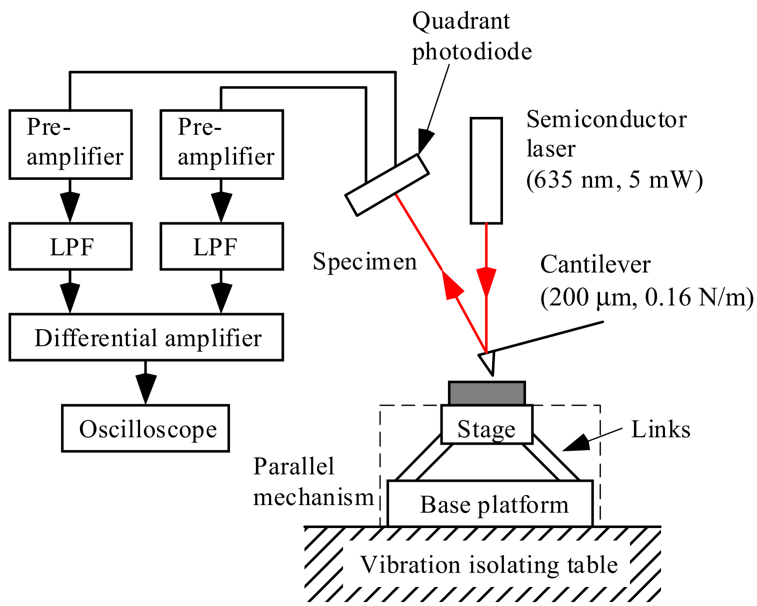

Fig. 4 Configuration of AFM

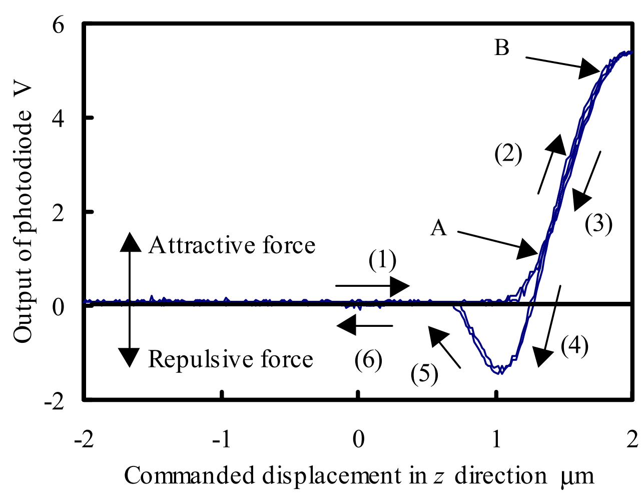

Fig. 5 Example of force curve

4. Nanometer cutting experiments

Because polymer resin is light, and has good machinability and chemical stability, it is expected to apply to precision parts and materials for micro-machines. Acrylic resin is scratched with the probe. At first, an inclination of a workpiece is measured by scanning roughly. Then the stage is moved in parallel to inclined surface of the workpiece and the probe scratchs it. Finally, the scratched area is observed.

Fig. 6 shows an example of scratching. The probe is scanned within 10×10 µm for the observation and within 5×5 µm for the scratching with a pressing force of 450 nN. The scanning frequencies are 2 and 0.05 Hz in the *x*- and *y*-directions, respectively. A pocket with a depth of 28 nm can be machined after 100 scratches. A stack of debris is observed near the pocket. Fig. 7 shows a change of depth against the number of scratch. The surface is seldom machined below 25 times. However, the depth of the pocket is linearly increased over 25 times. Once a scratch occurs by some reason, machining proceeds constantly.

5. Conclusions

The following conclusions can be drawn through the experiments.

(1) A stage for an AFM by using a parallel mechanism with 6 degrees of freedom is build as a trial.
(2) The movable range of the prototype is 40×30×100 μm in the *x*-, *y*- and *z*-directions.
(3) A pocket with dimensions of 5×5×0.03 μm is machined by scratching 100 times.
(4) The motion performance is evaluated by composing an AFM.

The authors will improve the motion accuracy of the stage.

Acknowledgment

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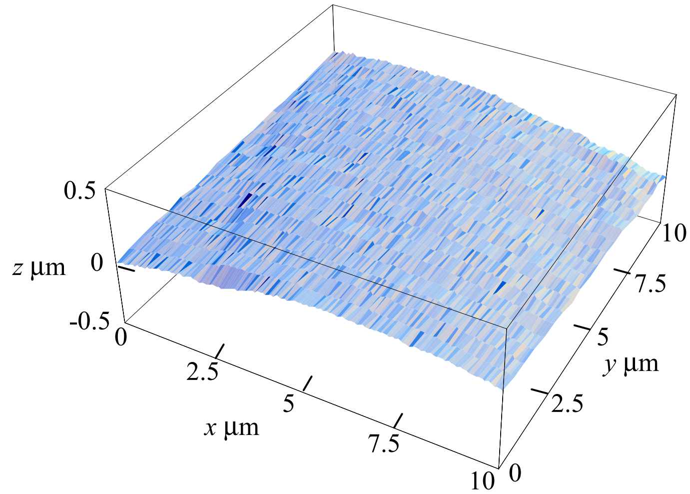
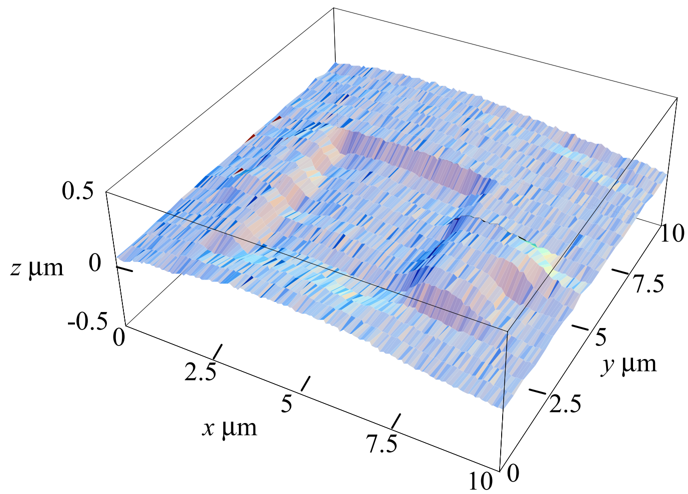


(a) Before scratching



(b) After 100th scratching

Fig. 6 Example of scratching

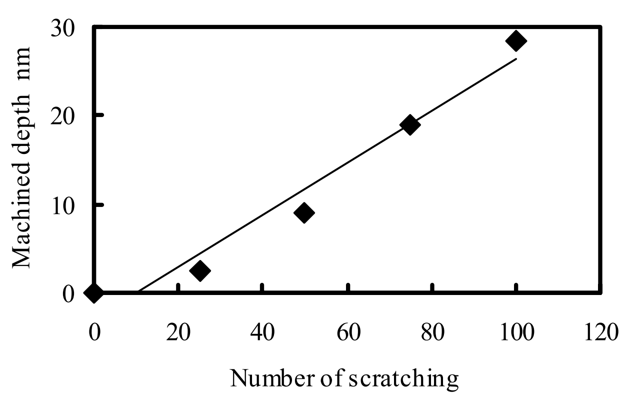


Fig. 7 Progress of machined depth