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Ultraprecision 4-axis positioning mechanism using flexure guide and electromagnetic actuator for topography measurement and processing system

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Abstract

A 4-axis positioning mechanism using a flexure guide and an electromagnetic actuator is developed, and a prototype of surface topography measurement and processing system is fabricated using the developed mechanism. A vertical Z-axis mechanism is integrated with a planar positioning mechanism in X-Y-θ axes. A simple stylus probe using a thin cantilever with strain gauges is attached to the Z stage, and the developed mechanism is extended to a system enabling both functions of topography measurement and surface processing by scratching. Straight lines with 0.3 mm length and fine lattice patterns with 6.25 microns pitch were scratched by the processing mode, subsequently followed by the measurement mode to derive the surface topography. The measurement results show the actual surface profile, and the potential of the system is thereby demonstrated.

Keywords: Positioning mechanism, 4-axis, Flexure guide, Electromagnetic actuator, Surface topography measurement, Scratch processing

1. Introduction

Current precise positioning mechanisms can be divided into two categories: Long-stroke positioning mechanisms and fine-positioning mechanisms with strokes measured in micrometres. To find a medium range between these two categories, the authors proposed a positioning mechanism with nanometric resolution over a 1-mm stroke using a flexure guide and an electromagnetic actuator. They previously reported about an ultraprecision positioning mechanism with four degrees of freedom [1]. In this report, the developed mechanism is extended to a system enabling both functions of topography measurement and surface processing by scratching.

2. Construction of measurement and processing system

Figure 1 shows the construction of the developed positioning mechanism. The mechanism consists of a planer positioning mechanism in X-Y-θ axes and a vertical positioning mechanism in Z-axis [2, 3]. The planer mechanism is constructed using a monolithic flexure device, and a cubic Z stage is also guided elastically using double-compound rectilinear leaf springs. The stages are driven by four pairs of voice coil motors.

To construct a surface topography measurement system using the 4-axis mechanism, a simple stylus probe using a thin cantilever with strain gauges was devised and attached to the Z stage. Figure 2 shows the arrangement of sensors around the processed or measured specimen. The motion of the planar mechanism in X-Y-θ axes is measured by three axes of laser interferometers with resolution of 0.6 nm, while the displacement of the vertical mechanism is measured by a spectral-interference laser sensor with resolution of 1 nm. To compensate for the parasitic motion of the X-Y-θ stage in Z direction, the motion Z_0 of the reference plane is measured by the capacitive gap sensors at three points around the specimen. Figure 3 shows architecture of the total system. The specimen is set on the X-Y-θ stage to move in the X-Y plane, while the Z stage moves in the vertical direction to keep contact between the stylus tip and the surface of specimen. The relative displacement S between the Z stage and the specimen measured by the stylus prove is called a 'pushing deflection'. The motions along the 4 axes are independently controlled by a full-closed feedback system as shown in Figure 4. The Z stage is controlled to keep the probe at a constant pushing deflection induced by contact force.

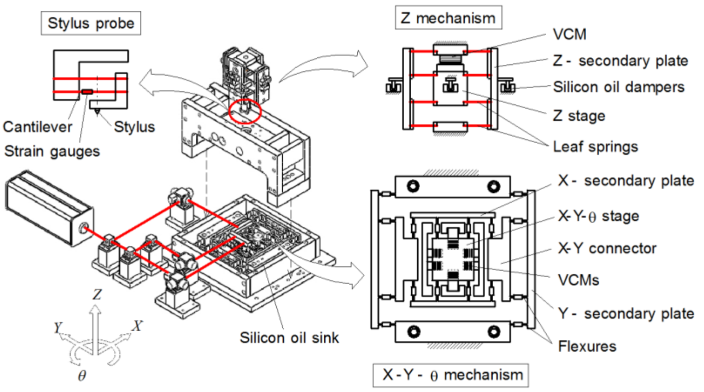


Figure 1 Schematics of 4-axis positioning mechanism and stylus probe

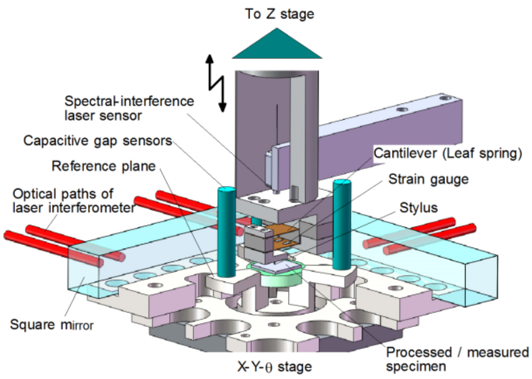
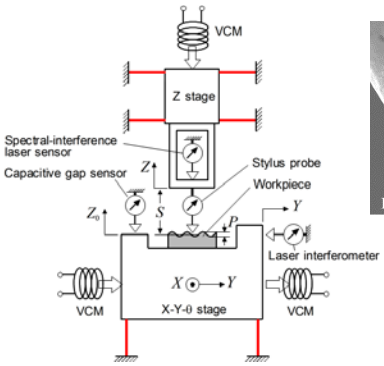
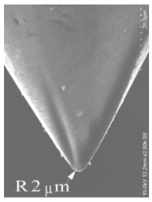


Figure 2 Arrangement of sensors





Tip of stylus

Fig. 3 System architecture

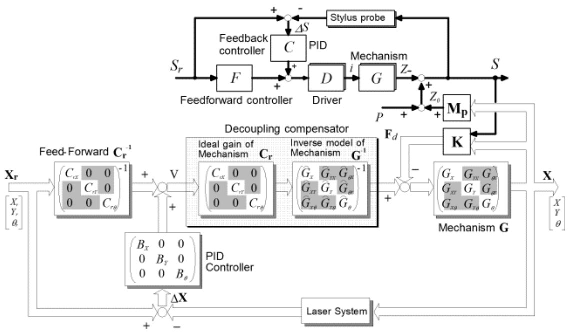


Fig. 4 Control system

3. Processing mode and measurement mode

If the contact between the stylus and the specimen is a Hertzian contact as shown in Figure 5, the pushing deflection S and maximum contact pressure $\sigma_{\max}$ are described as

$$\sigma_{\max} = \sqrt[3]{\frac{6}{\pi^3 r^2}\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}\right)^{-2} k\,S} \qquad (1)$$

where k is a spring constant of the cantilever, r is a tip radius of the stylus and E_1, ν_1, E_2, ν_2 are Young's modulus and Poisson's ratio of the stylus and specimen [4]. In processing mode, sufficient pushing deflection is applied so that $\sigma_{\max}$ is larger than the indentation hardness of the specimen, while the X-Y stage is moved in a desired direction to scratch the surface. In measurement mode, the pushing deflection is decreased to keep damage onto the specimen as slight as possible.

4. Performance

To evaluate the performance of the system, straight lines with 0.3 mm length were scratched on a standard material measures for surface roughness (HV330) by the processing mode under different values of pushing deflection S_{rk} from 1 µm to 5 µm, subsequently followed by the measurement mode under pushing deflection S_{rm} of 0.1 µm to derive the surface topography after scratching. Figure 6 (a) shows a measured result by the measurement mode of this system with scanning pitch of 0.04 mm for 100 scanned lines. The surface topography after scratching is clearly shown that the width and depth of scratched grooves become larger as the processing pushing deflection increases. Figure 6 (b) shows a measured result by an optical interference microscope for verification. The measurement results show the actual surface profile with scratched patterns, and the potential of the system is thereby demonstrated.

Figure 7 shows actual pushing force F and positioning deviation ΔX and ΔY under (a) processing mode or (b) measurement mode. Though disturbance F_d caused by pushing deflection of the stylus probe is applied to X-Y-θ stage as shown in Figure 4,

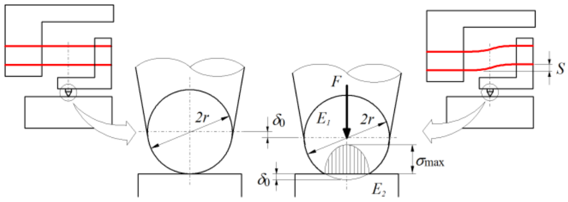
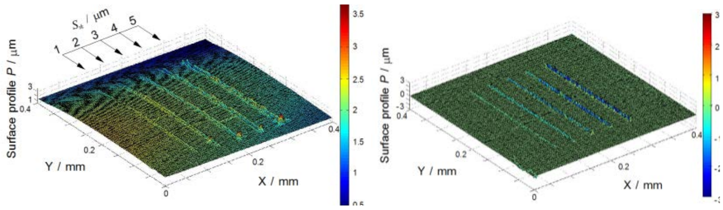
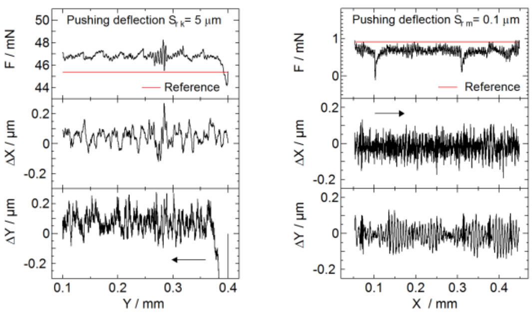


Fig. 5 Hertzian contact and pushing deflection



(a) Measured by this system (b) Measured by Zygo New View

Fig. 6 3D map of measurement results of scratched grooves



(a) Process-mode (S_{rk}=5µm) (b) Measurement-mode (S_{rm}=0.1µm)

Fig. 7 Positioning property under different mode

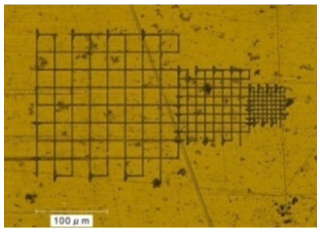


Fig. 8 Photograph of processed lattice patterns

the positioning deviations are controlled within 0.2 µm. Figure 8 shows the photograph of fine lattice pattern processed by this system. Most fine pattern has 6.25 microns pitch, and the fine performance of the developed system is shown, which has potential enabling to process and measure various fine features on a micro machine element.

5. Conclusion

A 4-axis positioning mechanism with a millimetre stroke developed previously using flexure guides and electromagnetic actuators was extended to a system enabling both functions of topography measurement and surface processing by scratching. It was shown that the system had a performance in the measurement mode reproducing surface profile. Moreover, in the processing mode, the system had a performance generating fine scratched patterns, and the potential of the prototype system was thereby demonstrated.

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