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

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Abstract
A 4-axis positioning mechanism using flexure guide and electromagnetic actuator is developed, and a prototype of surface topography measurement system is fabricated using the developed mechanism. A vertical Z-axis mechanism is newly developed, and it is integrated with a planar positioning mechanism in X-Y-θ axes that had been previously developed. A simple stylus probe using a thin cantilever with strain gauges is devised and attached to the Z stage to construct a topography measurement system. Standard material measures for surface roughness are measured, and the potential of the prototype system is then demonstrated.
Keywords: Positioning mechanism, 4-axis, Flexure guide, Electromagnetic actuator, Surface topography measurement

1. Introduction

Current precise positioning mechanisms can be divided into two categories: Long-stroke positioning mechanisms ranging from millimeters to meters and fine-positioning mechanisms with strokes measured in micrometers. To find a medium range between these two categories, the authors attempted to create a positioning mechanism with nanometric resolution over a 1-mm stroke using a flexure guide and an electromagnetic actuator [1][2]. They previously reported an ultraprecision planar positioning mechanism with three degrees of freedom in X-Y-θ axes. To apply that mechanism to practical applications, such as surface topography measuring or processing systems, a fourth axis was needed to move a terminal effector in Z direction. In this report, a Z-axis mechanism is newly constructed to make a 4-axis positioning mechanism, and a prototype of the topography measurement system is fabricated to demonstrate the capability of the mechanism. To realize the measurement system for the target of measureable topography with wavelength and amplitude from 10s nm to 1 mm, the Z-axis mechanism is also required to move over a 1-mm stroke with nanometric resolution.

2. Mechanism

Figure 1 shows the construction of the developed positioning mechanism and the structure of each part. The developed mechanism consists of a planar positioning mechanism in X-Y-θ axes and a vertical positioning mechanism in Z-axis. The X-Y-θ planar mechanism consists of two parts of a monolithic flexure device that forms a positioned stage of cube configuration with 60 mm sides, and flexure thin beams of double compound rectilinear springs supporting the stage [2]. Three pairs of voice coil motors are set around the stage: these motors independently generate driving forces, or yaw moment, in the X, Y and θ directions. To compensate for any damping effect, the mechanism is sunk in silicone oil of 1000 cSt. The newly developed Z-axis mechanism has a cubic stage with 50 mm sides, and it is guided elastically using double-compound rectilinear leaf springs. The Z stage is driven by a voice coil motor in the vertical direction. The vibration of the Z stage and two secondary plates are controlled passively by each damper with silicon oil of 1×10^5 cSt.

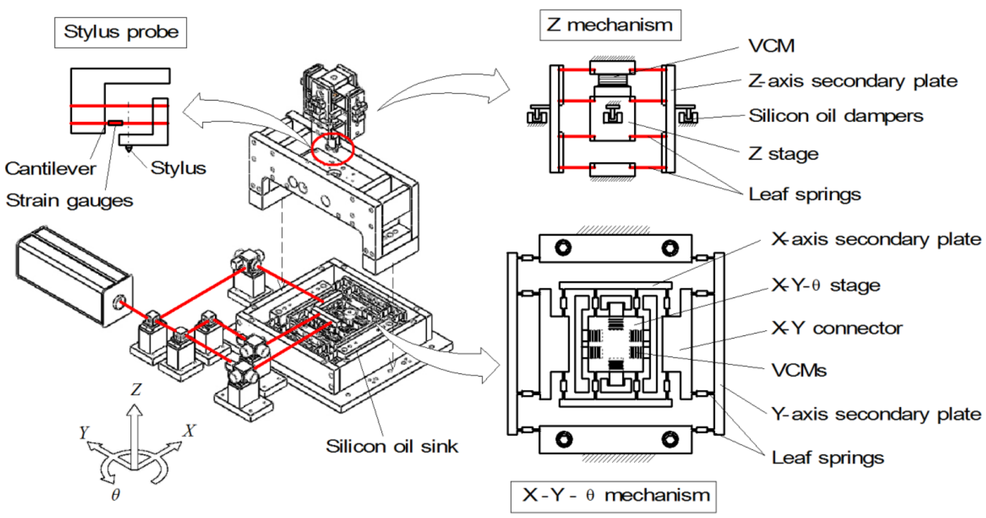


Figure 1. Schematics of 4-axis positioning mechanism and stylus probe.

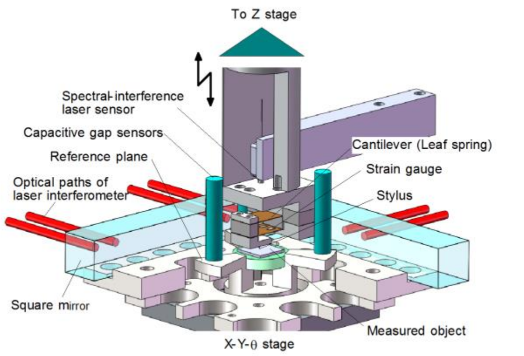


Figure 2. Arrangement of sensors around measured object.

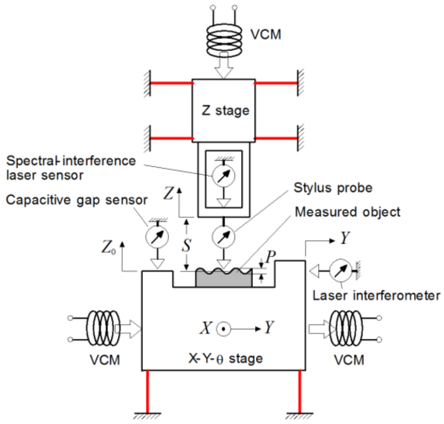


Figure 3. Measurement principle.

The motion of the planar mechanism is measured by a laser interferometer with resolution of 0.6 nm, while the displacement of the vertical mechanism in Z axis is measured by a spectral-interference laser sensor with resolution of 1 nm. The motions along the 4 axes are controlled independently by a fully closed feedback system.

3. Application to surface topography measurement system

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 as shown in Figure 1. Figure 2 shows the arrangement of sensors around the measured object. The measured object is set on the X-Y-θ stage, as shown in Figure 3, and the stage is moved with a scanning motion in the Y direction and a stepping motion in the X direction, while the Z stage is controlled to keep the probe at a constant deflection. To compensate for the parasitic motion of the X-Y-θ stage in Z direction, a reference plane is set at identical height with the measured object, and the motion Z_0 of the reference plane in Z direction is measured at three points around the object.

Figure 4 shows the block diagram of the control system for Z axis motion. The surface profile P of the object is derived by calculating the measured values of probe deflection S, motion of reference plane Z_0 and the motion of the stages Z using the following equation at every X-Y position of the object.

$$P = (Z + S) - Z_0 \qquad (1)$$

Figure 5 shows the characteristics of the stylus probe: The relation between the deflection S of the probe and the displacement Z shows sufficient linearity.

4. Performance

To evaluate the performance of the system, standard material measures for surface roughness were used. Figure 6 shows experimental results of measurement on standard measures with surface roughness of R_z=6 μm and R_z=1.5 μm. (a) shows motions of each parts being measured, and (b) shows surface profile P derived by eq. (1). The obtained curve of profile reproduces the actual surface profile that is verified by usual stylus instrument. Figure 7 shows 3D-map of the standard measures obtained by the developed system: The surface profile was reproduced over X×Y = 1×1 mm area with resolution of several 10s nm in Z direction.

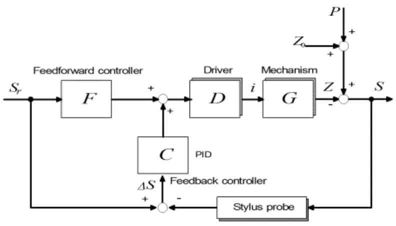


Figure 4. Z-axis control system.

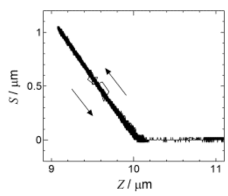
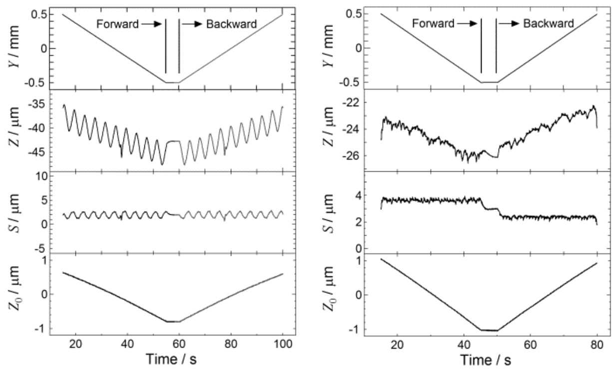
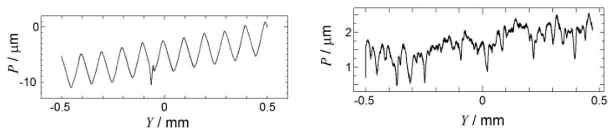


Figure 5. Probe characteristics.

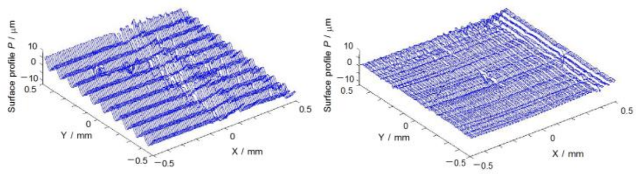


(a) Motion of each part (Left: R_z=6 μm, Right: R_z=1.5 μm)



(b) Derived surface profile (Left: R_z=6 μm, Right: R_z=1.5 μm)

Figure 6 Performance



(a) R_z= 6 μm (Nominal) (b) R_z=1.5 μm (Nominal)

Figure 7. 3D-map of standard material measures.

5. Conclusion

A 4-axis positioning mechanism with a millimeter stroke was developed using flexure guides and electromagnetic actuators, and a surface topography measurement system was constructed by adopting a stylus probe to the mechanism. The system has performance reproducing surface profile over X×Y = 1×1 mm area with resolution of 10s nm, and the potential of the prototype system is thereby demonstrated.

References

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