Precision Positioning of a Sawyer Motor-driven Stage by a Surface Encoder

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Abstract. This paper describes the precision positioning of an XY-planar motion stage driven by a two-axis Sawyer motor. The moving part of the stage is levitated on the stage platen by an air-bearing. The X- and Y-forcers mounted on the moving part generate electromagnetic forces against the platen for the X- and Y-directional motions, respectively. The position of the moving part is feedback controlled based on the measurement result of a surface encoder, which is composed of a 2-D slope sensor mounted on the stage moving part and an angle grid film stuck on the stage platen. The angle grid film, on which sinusoidal micro-structured surface with 100 nm amplitude and 100 μm wavelength is fabricated by UV replication, is as thin as 100 μm. It is confirmed by experiments that necessary driving performance can be maintained when the forcer moves on the film. Experimental results also indicate that sub-micrometers positioning accuracy can be achieved by closed-loop positioning control based on the surface encoder output.

1. Introduction

Precision two-axis (XY) planar motion stages are widely used in semiconductor manufacturing/inspection systems, machine tools and measuring instruments [1]. Such stages are required to have high accuracy, high speed and enough stroke for assurance of product accuracy and throughput. However, conventional planar motion stages, which are constructed by superposing one-axis stages, have disadvantages of unbalanced structure and heavy moving part. On the other hand, multi-axis laser interferometers [2], which are the most popular sensor for closed-loop positioning control, are complicated, expensive and need large working space.

In this research, a new stage system, which is composed of a two-axis (XY) Sawyer motor-driven planar stage [3] and a surface encoder [4], is proposed. The Sawyer motor consists of a platen functioning as the stage guide plane, and two-axis (XY) forcers attached on the back surface of the stage moving part. The moving part, which is levitated on the platen by an air-bearing, can be moved at a high speed along the X- and Y-directions with the electromagnetic forces generated by the forcers against the platen. The surface encoder is employed for closed-loop control of the stage so that the positioning accuracy of the moving part can be improved from 10 micrometers in open-loop driving mode to sub-micrometers, which is required for a high-precision stage. The surface encoder is composed of a 2-D angle grid and a 2-D slope sensor. The 2-D angle grid surface is the superposition of sinusoidal waves in X- and Y-axes with amplitude of 100 nm and wavelength of 100 μm. The 2-D slope sensor is used for detection of the 2-D local slopes of the 2-D angle grid surface, which provides the X- and
Y-position information in an accurate and simple manner. To integrate the surface encoder in the Sawyer motor-driven stage, a film-type angle grid with a thickness of 100 μm, is stuck on the platen of the Sawyer motor. Positioning experiments of the stage system are carried out.

2. Stage system

Figure 1 (a) shows a schematic of the Sawyer motor-driven stage system integrated with a surface encoder. The stage consists of a base and a moving part. The moving part is levitated on the base by an air-bearing. Four forcers, which generate driving forces against the motor platen of the stage base, are symmetrically mounted on the back of the moving part, two in the X-direction (X-forcers) and the other two in the Y-direction (Y-forcers). The moving part also carries the sensor head of the surface encoder. A film-type of the sinusoidal grid of the surface encoder is stuck on the motor platen of the stage base.

The X-directional driving principle of the Sawyer motor is illustrated in figure 1 (b), which shows the sectional profile of S-S’. The motor consists of the forcer and the platen. The platen is a passive steel plate with teeth over the designed moving area of the stage, which is 480 mm (X) x 480 mm (Y). The pitch of the teeth (poles) is 1.2 mm. The forcer is composed of a permanent magnet and two driving coils (A,B). The forcer generates X-directional thrust force against the motor platen through passing electric currents I1 and I2 to the coils, respectively. Assume that x is the position of the forcer on the platen, P is pole pitch and k1f is the force constant. The two coils are arranged in such way that the forces are generated as follows:

\[ F_{1A} = I_1 k_1 \sin(2\pi x/P) \]
\[ F_{1B} = I_1 k_1 \cos(2\pi x/P) \]

where \[ I_{1A} = I_1 \sin(2\pi x/P), \quad I_{1B} = I_1 \cos(2\pi x/P) \]

The Y-directional thrust force can be generated by the Y-forcers in the same manner.

Figure 1 (c) shows the principle of the surface encoder to measure the X- and Y-positions of the moving part. The surface encoder is composed of a 2-D angle grid and a 2-D slope sensor. The surface profile of the 2-D angle grid is represented by

\[ f(x, y) = A \sin\left(\frac{2\pi}{\lambda} x\right) + A \sin\left(\frac{2\pi}{\lambda} y\right) \]  

As can be seen in Equation (3), the surface of the 2-D angle grid is the superposition of sinusoidal waves in X- and Y-axes. The amplitude (A) and wavelength (λ) of the sine waves are designed to be 100 nm and 100 μm, respectively. The X- and Y- positions of the moving part can be obtained from the 2-D outputs of the slope sensor shown as follows:

\[ m_x = \frac{\partial f}{\partial x} = A \frac{2\pi}{\lambda} \cos\left(\frac{2\pi}{\lambda} x\right), \quad m_y = \frac{\partial f}{\partial y} = A \frac{2\pi}{\lambda} \cos\left(\frac{2\pi}{\lambda} y\right) \]

3. Positioning experiments

Positioning experiments were carried out to evaluate the performance of the stage system. A digital PID controller was constructed for feedback control based on the measurement result of the surface encoder. A two-axis interferometer was placed outside the stage to monitor the position of the stage for comparison. For simplicity, only results of the X-directional positioning experiments are presented.

Open-loop positioning experiments were first carried out without feedback control based on the surface encoder output for investigating the influence of the grid film upon the driving characteristics of the Sawyer motor. Figures 2 and 3 are results of 300 μm step drives along the X-direction without and with the grid film on the stage base, respectively. The overshoot and the settling time in figure 2 (without the grid film) were smaller than those in figure 3 (with the grid film). The gap between the stage moving part and the stage base increased from 20 μm to 120 μm before and after the grid film was stuck on the stage base. The increase of the gap caused a decrease of the thrust force generated by the forcer, relating in increases of the overshoot and the settling time. However, the overshoot and the settling time can be shortened by the closed-loop control based on the surface encoder output. On the other hand, the positioning accuracies in figures 2 and 3 were almost the same. This was because that the positioning
accuracy was dependent on the pitch accuracies of the platen poles and the forcer poles in the open-loop positioning mode.

The results of closed-loop positioning are shown in figures 4, and 5. A command step of 0.5 μm was input to the stage controller. Figures 4 and 5 show the output of the surface encoder used as the feedback sensor and that of the interferometer used to monitor the stage movement. As can be seen in the figures, the feedback controlled stage system has a sub-μm positioning resolution, which is much better than that of the open-loop mode.

![Figure 1. Schematic of the Sawyer motor-driven stage system integrated with the surface encoder.](image)

Figure 2. A 300 μm step drive without the grid film.

Figure 3. A 300 μm step drive on the grid film.
4. Summary
A stage system, which is feedback controlled by a two-axis Sawyer motor based on the output of a surface encoder, has been constructed. The integration of the surface encoder to the stage has been realized through sticking a film-type angle grid on the stage base. Experimental results have shown that the increase of the gap between the stage moving part and the stage base caused by the film thickness does not influence the positioning accuracy of the stage. Sub-micrometer positioning has also been demonstrated by experiments.

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