

# Precision nanometrology of a large area microstructured metrology surface

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## 1 Introduction

The authors have been working on a new surface encoder for detecting multi degree of freedom (MDOF) translational and tilt motions of precision stages<sup>[1]</sup>. The surface encoder consists of two fundamental elements: a sinusoidal microstructured metrology surface, which is referred to as the angle grid, and a two dimensional (2D) slope sensor<sup>[2,3]</sup>.

The angle grid has a 3D microstructured surface, which is a superposition of sinusoidal waves in the X- and Y-directions. Since the angle grid surface is used as the reference of position measurement, it is necessary to fabricate the sinusoidal surface in nanometer order accuracy over a large area. Considering the specifications of the surface encoder, a nanofabrication system based on the single point diamond turning with fast tool servo<sup>[4,8]</sup> was constructed to fabricate the angle grid surface. In the wavelength range of tens of microns to hundreds of microns, diamond turning, which has the advantage of producing difficult geometries with high form accuracy and good surface finish, is

superior to the electronic and optical methods, especially for fabrication of precision microstructured metrology surfaces over a large areas.

In this paper, the constructed nanofabrication system together with an efficient precision nanometrology technique for improving the fabrication accuracy is presented.

## 2 Nanofabrication system for the microstructured metrology surface

Figure 1 shows a schematic of the microstructured metrology surface (angle grid) for surface encoder consisting of the angle grid and a two dimensional angle sensor. The height profile of the metrology surface at point P, which is a superposition of sinusoidal waves in the X and Y directions, can be expressed as:

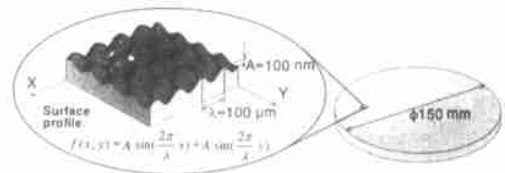


Fig. 1 Schematic of the sinusoidal metrology surface

$$f(x, y) = A_x \sin\left(\frac{2\pi}{\lambda_x}x\right) + A_y \sin\left(\frac{2\pi}{\lambda_y}y\right), \tag{1}$$

where,  $A_x$  and  $A_y$  are the amplitudes of the sine functions in the  $X$  and  $Y$  directions, respectively.  $\lambda_x$  and  $\lambda_y$  are the corresponding spatial wavelengths. These values are designed to be  $A_x = A_y = 100 \text{ nm}$  and  $\lambda_x = \lambda_y = 100 \text{ }\mu\text{m}$  based on the specifications of the slope sensor. The fabrication area is determined to be 150 mm in diameter.

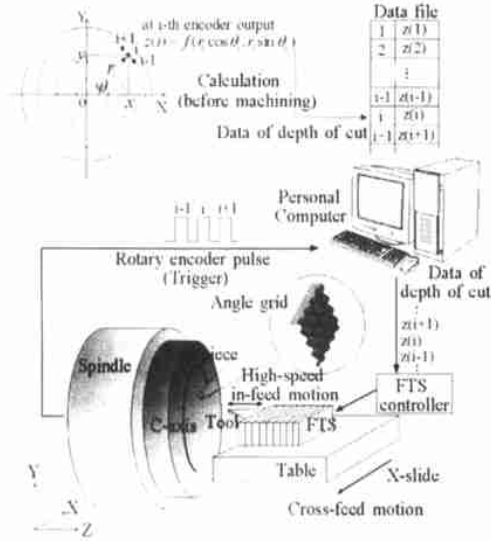


Fig. 2 Principles of the nanofabrication method

Figure 2 presents the principles of the nanofabrication method. The workpiece is mounted on the spindle with its axis along  $Z$ -direction, and the single point diamond tool is mounted on the  $X$ -slide of a diamond turning machine. The displacement of the tool along  $Z$ -direction (the depth of cut) is controlled by a fast tool servo. Assume that the rotation of the spindle and the feed of the  $X$ -slide are synchronized, the polar coordinates of the position of the tool tip in the  $XY$  plane can be expressed by

$$(r_i, \theta_i) = \left(r_0 - \frac{Fi}{PT}, 2\pi \frac{i}{P}\right) \quad i = 0, 1, N - 1, \tag{2}$$

where,  $F, P, T$  and  $i$  are the feed rate of the  $X$ -slide, pulse number of the rotary encoder of the

spindle in each rotation, rotational speed of the spindle, and  $i$ -th rotary encoder pulse, respectively. To generate the sinusoidal grid surface shown in Eq. (1), the depth of cut at each point is calculated as follows and stored in a personal computer before the fabrication.

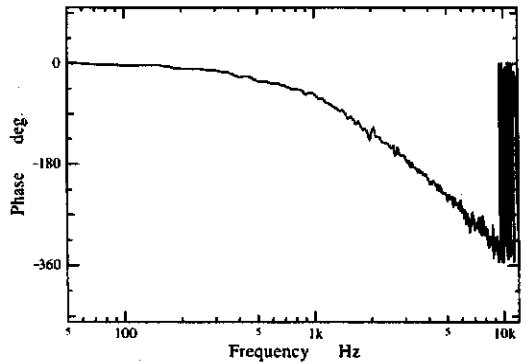
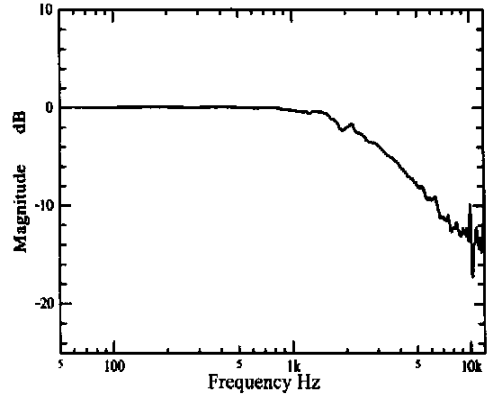


Fig. 3 Frequency response of the fast tool servo

$$\begin{aligned} z(i) &= f(r_i \cos \theta_i, r_i \sin \theta_i) \\ &= f\left(\left(r_0 - \frac{Fi}{PT}\right) \cos\left(2\pi \frac{i}{P}\right), \right. \\ &\quad \left. \left(r_0 - \frac{Fi}{PT}\right) \sin\left(2\pi \frac{i}{P}\right)\right), \end{aligned} \tag{3}$$

The nanofabrication system is composed of a commercially available CNC ultra-precision diamond turning machine, a personal computer in which the data of depth of cut are stored, and fast tool servo for fast and accurate tool positioning.

The data shown in Eq. (3) are stored in the hard disk of the personal computer as a data file before fabrication. When the fabrication starts, the data are then output to the controller of the fast tool servo one by one responding to the trigger sig-

nals from the toraty encoder of the spindle. By using the technique of DMA ring buffer<sup>[5]</sup>, data exceeding the memory capacity can also be output continuously.

In the designed and constructed fast tool servo, a piezoelectric tube actuator(PZT) is used to control the depth of cut. A round-shape tool cap flexure is employed to transmit only the PZT displacement along  $Z$ - directions to the diamond tool. A capacitance probe is installed inside the PZT tube to monitor the displacement of the PZT. An analog PID controller is constructed to feedback control the PZT displacement. Figure 3 shows the frequency response of the FTS. The bandwidth is approximately 2.5 kHz.

In the fabrication experiments, an aluminium alloy workpiece was used as the workpiece. The rotation speed of the spindle and the feed rate of the  $X$ - slide were set to be 20 rpm and 5  $\mu\text{m}/\text{rev}$ .

### 3 Results of nanofabrication and nanometrology of the microstructured surface

A great challenge in the fabrication experiment was the precision nanometrology of the profile errors of the fabricated sinusoidal microstructured metrology surface. Considering the specifications of the surface, a Zygo interference microscope was chosen as the instrument for precision surface nanometrology. However, as shown in Figure 4, it is necessary to take more than 20 000 images to evaluate the entire grid surface. For this purpose, we selected several parts along the radial direction of the workpiece as representative parts for evaluation of profile errors.

Figure 4 shows the fabrication and measurement results. The spatial spectrum of each part is evaluated by the spectrum analysis through the two  $\sigma$  dimensional discrete Fourier transform (DFT) technique. Here, the  $f_x$  and  $f_y$  axes show the  $X$ -directional and  $Y$ -directional spatial frequencies, respectively;  $X$ - and  $Y$ - directions correspond to cross-feed directionl of the  $X$ - slide and cutting direction of the workpiced, respectively. The vertical axis shows the amplitude of the spectrum. The four largest components at wavelengths of 100  $\mu\text{m}$  show those of desired sinusoidal surface profile. Other components are error components. The large error components at wavelength of 50  $\mu\text{m}$  in the  $f_x$  axis, which was caused by the round nose geometry of the diamond tool, was successfully reduced to several nanometers through the compensation using the local radius of the diamond tool.

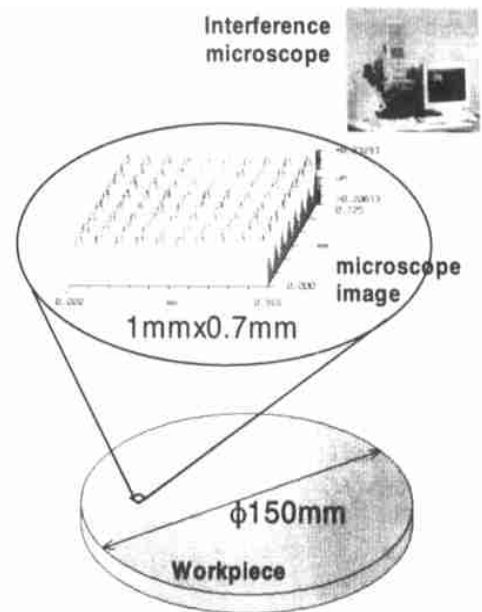


Fig. 4 Nanometrology of the microstructured surface

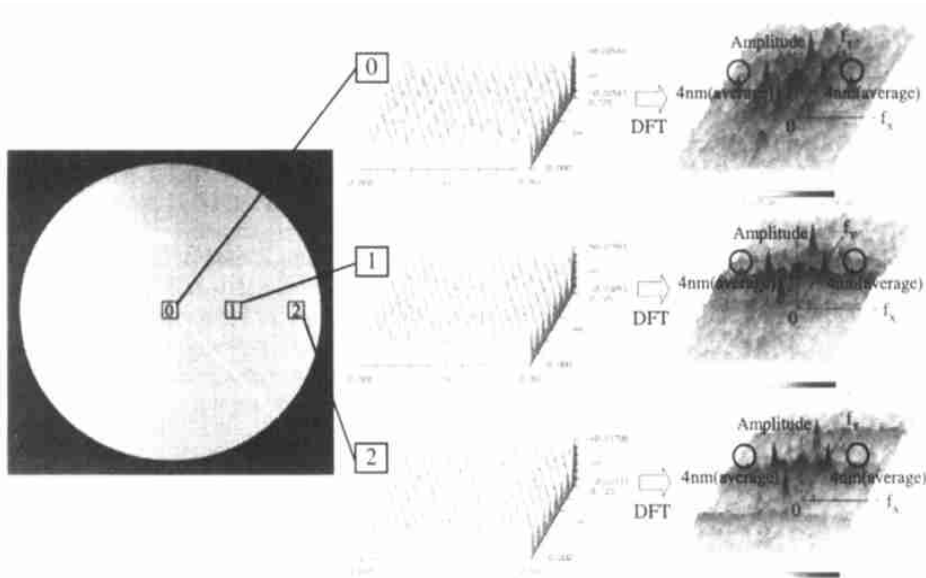


Fig. 5 Results of nanofabrication and nanometrology of the sinusoidal microstructured metrology surface

## 4 Conclusions

(1) A precision nanofabrication system consisting of an ultra-precision diamond turning machine and a fast tool servo has been constructed for a microstructured metrology surface over a large area up to 150 mm in diameter. The sinusoidal waves have been successfully fabricated on the entire grid surface.

(2) An efficient precision nanometrology technique based on the two-dimensional DFT of the ir

terference microscopy has been developed for the fabricated surfaces. The error component caused by the round nose geometry of the diamond tool has been identified and the error has also been reduced to several nanometers through a compensation procedure.

### Acknowledgments

This work was financially supported by a grant from Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

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