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On-machine measurement of a cylindrical surface with sinusoidal micro-structures by an optical slope sensor

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Abstract

This paper describes the measurement of a cylindrical surface with sinusoidal micro-structures over a large area on a diamond turning machine. The sinusoidal micro-structures, which are fabricated on the periphery surface of a cylinder by the fast tool servo-based diamond turning, are superposition of periodic sine-waves along the cylinder axis and the cylinder circumference with amplitudes of 100 nm and wavelengths of 100 μm, respectively. An optical two-dimensional (2D) slope sensor with a multi-spot light beam is developed for measurement of the 2D local slopes of the sinusoidal micro-structured surface. A cylindrical lens is employed in the sensor for removing the influence of the curvature of the cylinder surface. Experiments of fabrication and measurement of the sinusoidal micro-structured surface on an ultra-precision diamond turning machine are carried out.

Keywords: Measurement; Optical sensor; Slope; Surface profile; Micro-structure; Cylindrical surface; Diamond turning machine; Fast tool servo

1. Introduction

The authors have been developing a surface encoder [1–3] for measurement of planar motions of precision XY stages [4–13]. The surface encoder consists of a sinusoidal grid, which is referred to as the angle grid, and a two-dimensional (2D) slope sensor. The angle grid has a three dimensional micro-structured surface, which is a superposition of sinusoidal waves in the X-direction and the Y-direction. The 2D slope sensor is used to read local slope profiles of a point on the grid surface along the X-axis and the Y-axis, which are functions of the X- and Y-positions. The tilt motions (pitch, yaw, roll) can also be detected through using multiple slope sensors or a scanning laser beam slope sensor.

The sinusoidal profile of the angle grid surface is designed to have spatial wavelengths of 100 μm and amplitudes of 100 nm in both the X-direction and the Y-direction according to the specifications of the slope sensor. The corresponding amplitude of the slope profile of the sinusoidal surface is 2π mrad. Taking into consideration the moving strokes of most precision XY stages, the area of the grid surface, which determines the measurement range, is designed to be from several tens of millimeters to several hundreds of millimeters in diameter. Since the angle grid surface is used as the reference of position measurement, it is of a high priority to fabricate the sinusoidal surface accurately over a large area with a low fabrication cost.

Based on the specifications of the angle grid surface, the diamond turning with fast tool servo (FTS) [14–18] is chosen for fabrication of the angle grid surface. Single-point diamond turning has the advantage of producing difficult geometries with high form accuracy and good surface finish [19,20]. The authors have previously fabricated the sinusoidal profile on a plane surface over an area of 150 mm in diameter [21]. However, on the other hand, the diamond turning process is quite time consuming for fabricating micro-structured surface over a large area, resulting in a high fabrication cost. The maximum area of the fabricated surface is also limited by the size of the spindle and the stroke of the slide of the diamond turning machine.

One way to overcome these shortcomings is the employment of the replication technique [22,23]. Replication is widely used for low cost and mass production of various optical elements. For replication of the angle grid surface over a large area, it is necessary to accurately fabricate the sinusoidal profile on a cylinder used as the replication master. In this paper, a fabrica-

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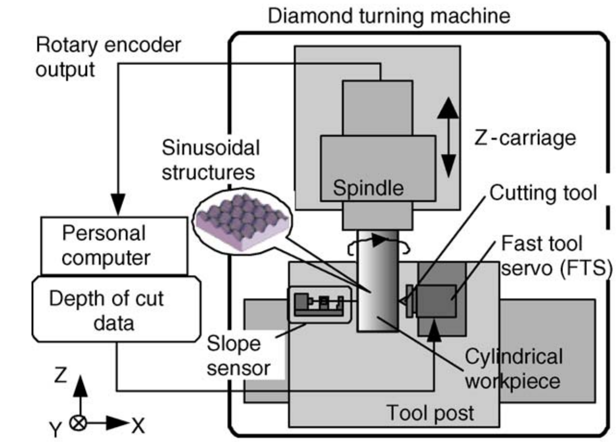

Fig. 1. Schematic of the fabrication and measurement system for the cylindrical master grid.

tion and measurement system for the cylindrical master grid is presented. To assure the fabrication accuracy, an optical slope sensor is developed for on-machine measurement of slope profile of the master grid surface.

2. The fabrication system and the optical slope sensor for the cylindrical master grid

Fig. 1 shows a schematic of the fabrication and measurement system. The fast tool servo (FTS) is mounted on the tool post of a diamond turning machine to cut the surface of a cylindrical workpiece. The workpiece is mounted on the spindle with its axis along the Z-direction. The spindle is moved along the Z-axis by the carriage of the diamond turning machine. The carriage movement and the spindle rotation are synchronized so that the $Z-\theta$ coordinates of the cutting point can be determined by the rotary encoder output of the spindle as follows:

$$z(i) = \frac{V_Z}{PT}i,\ \theta(i) = \frac{2\pi}{P}i, \quad i = 0, 1, 2, \ldots, N-1 \qquad (1)$$

where V_Z, P, T and i are the feed speed of the Z-carriage, pulse number of the rotary encoder in each rotation, rotational speed of the spindle and i-th rotary encoder pulse, respectively. The micro-structured cylinder surface for replication is a superposition of periodic sinusoidal structures along the axial direction (Z-direction) and the circumferential direction (θ_Z-direction) of the cylindrical workpiece. The X-directional depth of cut data at each cutting point for generating the surface is calculated as follows and stored in the memory of a personal computer before fabrication.

$$\begin{aligned} f(i) &= A_Z \sin\left(\frac{2\pi}{\lambda_Z} z(i)\right) + A_\theta \sin\left(\frac{2\pi r}{\lambda_\theta}\theta(i)\right) \\ &= A_Z \sin\left(\frac{2\pi}{\lambda_Z}\frac{V_Z}{PT}i\right) + A_\theta \sin\left(\frac{2\pi r}{\lambda_\theta}\frac{2\pi}{P}i\right) \end{aligned} \qquad (2)$$

where A_Z, λ_Z, A_θ, λ_θ are the amplitudes and wavelengths in the two directions, respectively. r is the radius of the cylinder. When the fabrication starts, the tool is actuated by the FTS based on the $f(i)$ data in Eq. (2) in responding to the rotary encoder output of the spindle. In the experiment described in the following section, both A_Z and A_θ are set to be 100 nm (A). λ_Z and λ_θ are set to be 100 μm (λ).

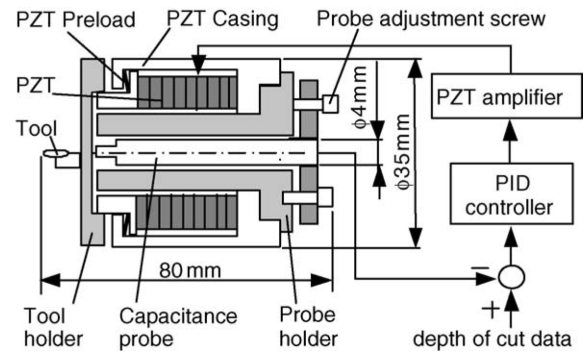

Fig. 2. Schematic of the FTS-unit.

Fig. 2 shows a schematic of the FTS-unit developed for fabricating sinusoidal micro-structures on cylindrical surfaces. Fig. 3 shows a photograph of the FTS-unit. Since the size of the FTS-unit in the Z-direction will limit the fabrication area of the cylindrical workpiece on the spindle side as shown in Fig. 1, a compact design of the FTS-unit is carried out for larger fabrication area. The compact size is also helpful for improvement of the FTS-unit in thermal and dynamic characteristics, which are important for long-time fabrication of large area micro-structured surfaces.

As can be seen in Figs. 2 and 3, the FTS-unit consists of a hollow-type piezoelectric (PZT) ring actuator and a capacitance displacement probe. The PZT actuator with an internally pre-stressed stainless casing has characteristics necessary for the FTS-unit, including compact size (35 mm diameter × 34 mm length), high stiffness (450 N/μm), large bandwidth (30 kHz) and high displacement resolution (0.24 nm). A small capacitance probe (4 mm diameter × 34 mm length) is mounted in the hollow of the PZT actuator with a diameter of 14 mm so that the FTS-unit has almost the same size as the actuator, which is half of the first-generation FTS-unit used for fabrication of sinusoidal micro-structures on plane surfaces [21]. The sub-nanometer resolution and 20 kHz bandwidth of the capacitance sensor also match those of the actuator. Figs. 4 and 5 show the static response and the dynamic response of the FTS-unit, respectively. The bandwidth of the closed-loop controlled FTS-unit is approximately 3 kHz (−3 dB).

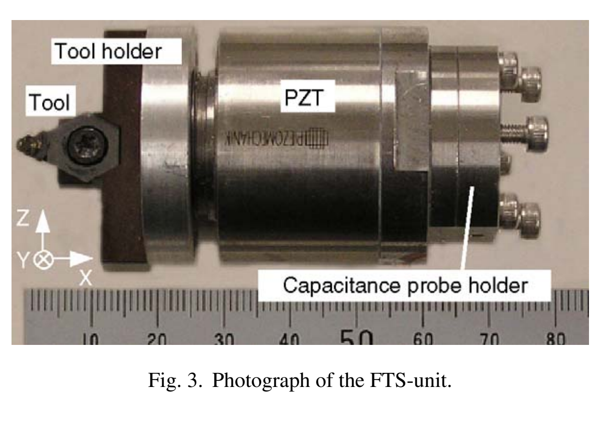

Fig. 3. Photograph of the FTS-unit.