INTRODUCTION

Along with the miniaturization of optical devices such as medical endoscopes and fiber-optic communication systems, micro-aspheric lenses (1 mm in diameter) have become very important parts [1]. Micro-aspheric lenses are necessary for downsizing and higher image quality. Form accuracy of micro-aspheric lenses is required to be better than 100 nm to make the most of those devices. However, the 100 nm form accuracy is very hard to achieve because aspheric surface profiles are complicated. On the other hand, accurate profile measurement of the aspheric surfaces for realizing on-line assessment is a big challenge. Scanning probe measurement systems with a contact stylus are practical and suitable for profile measurement of aspheric surfaces [2]. We have developed a novel measurement system for micro-aspheric profiles that employs a contact stylus [3]. Contact styli are capable of measuring complicated surfaces that have steep slope such as aspheric surfaces as long as the probe spheres at probe tips contact with the measuring objects. However, lateral resolution of measuring instruments that employ contact styli is restricted by the radius of probe sphere. Most of commercial styli do not have high enough resolution to be employed for micro-aspheric surface scanning. In this research, a micro-stylus, which is composed of a micro-glass-ball and a microstylus, is fabricated and it is applied to the micro-aspheric profile measurement system.

DESIGN OF THE MEASUREMENT SYSTEM

The measurement system is schematized in Figure 1. The design is based on a concept: “A small-scale and high precision measuring instrument”. The footprint of the machine is 400 mm × 275 mm and the weight of the machine is 57 kg. An aspheric workpiece is mounted on the spindle turntable and a contact-type sensor is mounted on the slide. The aspheric surface is scanned spirally by rotating the spindle and feeding the slide in radial direction of the aspheric workpiece. The surface of a ring artifact surrounding the aspheric workpiece is scanned by two capacitance sensors mounted both sides of the contact-type sensor for the purpose of error motion compensation. Characteristics and specifications of the measurement system are listed below.

Spindle

An air bearing is employed for the spindle. A rotary encoder whose resolution is 0.0038 arc seconds enables positioning accuracy of 1 arc second.

Slide

An air bearing is also employed for the slide. Both the table and the guide are made of ceramics, which is so light and hard that the deflection can be reduced. The stroke of the slide is 70 mm and the resolution of the linear encoder is 0.28 nm. To avoid Abbe error, the scale of the linear encoder is set just below the aspheric workpiece. The vertical and horizontal straightness errors of the slide motion are less than 1 µm within the full stroke.

Contact-type Sensor

A contact-type sensor is employed for the aspheric surface scanning. A shaft of the sensor is fed forward and a ball at the tip of the stylus is pressed to the aspheric object to follow the variation of the surface profile. An air bearing is employed to levitate the shaft so that the shaft can move smoothly. To feed the shaft forward, a technology called inclined self-weight is used [4]. A linear encoder whose resolution is 0.5 nm is attached at the exact center of the shaft to avoid Abbe error.

Vibration Isolation Table and Chamber

The whole measurement system is mounted on a vibration isolation table and covered by a chamber. So it is less affected by vibration and temperature variation.
ERROR COMPENSATION
For scanning probe measurement system, it is important to compensate error motions of the scanning stage. In this measurement system, the error motions including drifts and vibration between the slide and the spindle can be measured at the same time when the aspheric profile is measured. The error motions are measured by scanning the surface of the ring.
artifact by the two capacitance sensors. The output of the contact-type sensor (Sensor C) can be expressed as

\[ m_c(x,\theta) = g(x,\theta) + e_{ct}(x,\theta) - x(e_{ct}(x,\theta) + e_{ct}(x,\theta)) \],

(1)

where \( m_c(x,\theta), g(x,\theta), e_{ct}(x,\theta), e_{ct}(x,\theta) \) and \( e_{ct}(x,\theta) \) represent the output of the Sensor C, the aspheric surface profile, axial motion of the spindle, horizontal straightness error of the slide, tilt motion of the spindle and yaw error of the slide respectively. The mean output of the two capacitance sensors (Sensor A and Sensor B) can be expressed as

\[ \frac{m_A(x,\theta) + m_B(x,\theta)}{2} = f(d/2 + x,\theta) + f(-d/2 + x,\theta + \pi)/2 \],

(2)

where \( m_A(x,\theta), m_B(x,\theta), d \) and \( f(x,\theta) \) represent the output of Sensor A, the output of Sensor B, distance between Sensor A and Sensor B and the surface profile of the ring artifact respectively. By subtracting equation (2) from equation (1), the aspheric surface profile can be calculated by using the outputs of the sensors and the surface profile of the ring artifact as follows

\[ g(x,\theta) = m_c(x,\theta) - \frac{m_A(x,\theta) + m_B(x,\theta)}{2} + \frac{f(d/2 + x,\theta) + f(-d/2 + x,\theta + \pi)}{2} \],

(3)

The surface profile of the ring artifact can be measured precisely by reversal technique [3].

**EXPERIMENTS**

Fabricated micro-styli are attached to the contact-type sensor with a jig and used to scan the micro-aspheric surface. Figure 3 shows the photograph of the measurement system with the micro-stylus. The contact-type sensor with the micro-stylus is mounted on the slide along with the two capacitance sensors. Measurement range of the capacitance sensor is –25 µm to 25 µm which corresponds to –10 V to 10 V. Diameter of the electrode is 1.7 mm. A micro-aspheric object and the ring artifact are mounted on the spindle. The surface of the ring artifact is mirror finished by diamond turning. The micro-aspheric object is mounted on the spindle with a jig which makes it possible to adjust the attitude of the object.

Figure 4 shows the stability of the measurement system. The outputs of the contact-type sensor and the two capacitance sensors are sampled at the same time while the slide and spindle are kept stationary. Left vertical axis represents output of sensors and right represents temperature. 4 lines represent the output of the contact-type sensor, the mean output of the capacitance sensors, differential output between above two outputs which corresponds to equation (3) and temperature. It seems that by applying equation (3) to the sensor outputs displacement variation between the slide and the spindle can be cancelled.

**FABRICATION OF MICRO-STYLUS**

Micro-shafts for the micro-styli are made from glass tubes. Glass tubes are stretched to thin the tip of the shaft by heating. Utilizing capillary phenomenon, adhesion bond is filled at the tip of the shaft. Alignment of the probe shaft and micro-glass-ball is conducted by using CCD cameras. The position of the micro-glass-ball is easily set to be centered, because the position is decided by the inner diameter of the micro-styli. In this paper, two types of the shaft are fabricated for two kinds of diameter of micro-glass-ball (50 µm and 100 µm in diameter) (described as 50 µm-diameter stylus and 100 µm-diameter stylus respectively below). Figures 2(a) and (b) show the photographs of the fabricated micro-styli.

**FIGURE 2** Microscopic image of the micro-stylus (a) 50 µm-diameter stylus (b) 100 µm-diameter stylus

**FIGURE 3** Photograph of measurement system
To measure the X-sectional surface profile of the micro-aspheric object, the slide is fed in the X-direction and the micro-aspheric surface is scanned by the contact-type sensor. Traveling speed of the slide is 0.03 mm/s and sampling interval is 10 µm. The profile data is fit to 10th polynomial. Figure 5 shows the measured profile and measurement repeatability. The measurement repeatability is evaluated as standard deviation for 10 times of measurements. Solid line, dashed line and chain line represent measured profile, measurement repeatability with 100 µm-diameter micro-stylus and that of 50 µm-diameter micro-stylus respectively. It would appear that difference of repeatability between 50 µm-diameter and 100 µm-diameter mainly due to the difference of lateral stiffness of the stylus.

Finally, 100 µm-diameter stylus is used for spiral scanning of the micro-aspheric surface. Traveling speed of the slide and revolution speed of the spindle are 0.015 mm/s and 10 rpm respectively. The ring artifact was scanned by the capacitance sensors and error motions were compensated. Figure 6 shows the measured profile of the micro-aspheric surface. The measurement repeatability is smaller than ±20 nm all over the surface.

**CONCLUSION**

Micro-styli are fabricated for scanning of micro-aspheric surface. X-sectional scanning and spiral scanning with the fabricated micro-stylus are conducted for profile measurement of the micro-aspheric object. The measurement repeatability of micro-aspheric X-sectional scanning and spiral scanning by 100 µm-diameter stylus are smaller than ±15 nm and ±20 nm respectively.

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**REFERENCES**


