

Development of a Micro-Displacement Table for Ultra-Precision Machining and Grinding for Curved Surfaces by the Use of It*

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This paper describes a positioning system and reports experimental results of the grinding for curved surfaces by using the system. In order to control the shape accuracy of ultra-precision grinding surfaces, a micro-displacement table and its control system have been developed. The table has three non-contact capacitive displacement transducers as sensors and three stacked piezoelectric ceramic actuators. In the grinding process, a microcomputer dynamically and precisely controls the positioning micro-displacement table so that it changes the relative position of the ground surface and grinding wheel. It is confirmed that three-dimensional curved surfaces with large curvature radii can be precisely obtained by means of automatic grinding operations with the table and its control system. Thus, it is expected that mirror surfaces having high shape precision can be ground on conventional grinding or cutting machines such as machining centers or surface grinders by attaching the system to them.

Key words : ultra-precision grinding, piezoelectric ceramic actuator, grinding for curved surfaces, large curvature radius

1. Introduction

SiC reflectors used in synchrotron orbital radiation facilities and optical lenses, made of advanced ceramics or glass, are very difficult to machine and shape because of their extreme hardness and brittleness. They are usually required to be of high precision in shape accuracy and in surface roughness. Conventionally, several complicated manufacturing processes are necessary to machine them. When three-dimensional curved surfaces are finished, loose abrasives are usually used by means of lapping or polishing. Because the finish machining is not automatic, the time consumed in the process is very long, the productivity is low and the shape accuracy of the curved surface cannot be guaranteed. Particularly, it has been extremely difficult to manufacture, by means of automatic grinding operations, SiC reflectors that have high precision in shape accuracy and low surface roughness and are spherical or nonspherical surfaces with large curvature radii.

Recently, it has become possible to grind a surface whose roughness is of several nanometers because of the rapid advance of mirror grinding techniques. However, it is still very difficult to grind a three-dimensional curved surface and control its shape accuracy. A grinding method has not yet been developed for machining three-dimensional curved surfaces with high precision in shape accuracy and low surface roughness. There is a

great demand to develop a technique automatically generating a desired three-dimensional curved surface using bonded abrasive wheels and precisely controlling the shape accuracy.

The authors considered that it is possible to generate and control the shape of ultra-precision ground surfaces by developing a positioning system to dynamically and precisely control the relative position of the ground surface and the grinding wheel. Combining this positioning system with the technique of mirror grinding makes it possible to obtain high-accuracy shape and mirror surfaces. It becomes possible to generate spherical or nonspherical ceramic or glass surfaces with large curvature radii, with high precision in shape accuracy and low surface roughness, by means of grinding operations. This has been extremely difficult so far. Moreover, this technique can innovate conventional manufacturing processes, and satisfies the demand of advanced automation for ultra-precision machining.

While there may be other methods for realizing this positioning system, the authors developed a table with stacked piezoelectric ceramic actuators. To dynamically and precisely control this table, we also developed its control system. The table having three stacked piezoelectric ceramic actuators was developed using three non-contact capacitive displacement transducers as sensors. In the grinding process, a microcomputer dynamically and precisely controls the table so that it changes the relative position of the ground surface and grinding wheel. Thus, using this system, we expect to precisely control the shape accuracy of ultra-precision grinding surfaces. Henceforth this table is referred to as micro-displacement table.

In this paper, the design of the micro-displacement table and its control system is

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described. Experimental results of the mirror grinding of concave mirrors by means of this system are reported.

2. Design of Micro-Displacement Table

2.1 Design Concepts

Studies on the use of piezoelectric ceramics as actuators of micro-displacement mechanisms have been carried out actively in recent years¹⁾²⁾. However, a micro-displacement table using piezoelectric actuators as a precise positioning servomechanism for grinding has not yet been seen.

A micro-displacement table was designed, taking account of the following considerations which are the special features of it and are different from conventional tables. A micro-displacement table for the purpose mentioned above must withstand severe conditions in the grinding process. Even the load (grinding force) changes substantially in the grinding process, the output of the system must always track the reference input. Consequently, it is necessary to perform a feedback control dynamically and precisely, detecting the output of the system in the machining process. In view of the mechanism of the grinding operation and the use of coolant, small high-accuracy displacement sensors are required in the table. Piezoelectric actuators are strong enough against compressive force, but are very weak against shear force and humidity. Therefore, the table must have enough stiffness against not only compressive force but also transverse force, and must be waterproof. It must be easily attachable to machine tools horizontally or vertically, because a cup wheel or a peripheral wheel is often used. Moreover, it is possible to incline the ground surface with a small angle in the designated direction, as well as hold the ground surface horizontally, by controlling each of the three piezoelectric actuators independently.

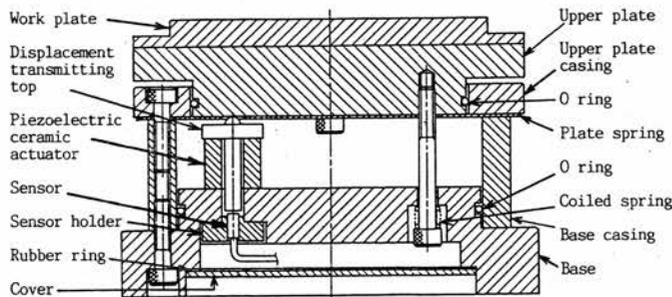


Fig. 1 Micro-displacement table

Table 1 Specifications of stacked piezoelectric ceramic actuator

Shape	Ring	Rated displacement	16μm/150V
Outer diameter	18.4mm	Rated force	800kgf/150V
Inner diameter	7.4mm	Compressive strength	6000kgf/cm ²
Height	18.0mm	Tensile strength	100kgf/cm ²

2.2 Structure of Micro-Displacement Table

The structure of the micro-displacement table is shown in Fig. 1.

Three stacked piezoelectric ceramic actuators are fixed on the base by using bonding material. They are located at the points that trisect a circle centered at the axis of the table. Displacement transmitting tops are set on the piezoelectric actuators in order to transmit displacement to the upper plate and detect displacement using sensors. The middle tops of these displacement transmitting tops are hemispherical for transmitting displacement of the piezoelectric actuators to the upper plate even when the upper plate is inclined. These three piezoelectric actuators are controlled independently by three dynamical compensators which are described in § 3.2. Table 1 shows the specifications of the stacked piezoelectric ceramic actuators used in the table.

As for sensors, three noncontact capacitive displacement transducers are placed, with the sensor holders, facing the rods of the displacement transmitting tops. The sensor holders are designed so that the distance between the rods and the sensors can be adjusted. It is necessary to keep the displacement transmitting tops in continual contact with the upper plate at a fixed pressure. Therefore, the fixed pressure is provided by a plate spring, three bolts and three coiled springs. In order to prevent the inundation of coolant into the table, two O-rings and a rubber ring are used. The table needs to have enough transverse strength in case shearing force is incurred between the upper plate and the base in the machining process. Thus, the upper plate, the upper plate casing, the base casing, the plate spring and the base are secured by bolts. The table was designed so that it is easily attachable to machine tools horizontally or vertically by means of a simple attachment.

3. Design of Control System

To make a precise positioning servomechanism of the micro-displacement table, its control system was designed.

3.1 Mathematic Model of Control Object

If the nonlinear characteristics and hysteresis of the piezoelectric actuator and the mass of the upper plate are neglected, y , the displacement of the piezoelectric actuator from the operating point, is given by

$$y = aV - bW, \quad (1)$$

where,

$$a = dAY / (AY + kL) \quad (2)$$

$$b = L / (AY) \quad (3)$$

and the symbols represent the following:

- k = Spring constant of the springs used in the table
- V = Terminal voltage of the piezoelectric actuator
- W = Load (grinding force) in the direction of the axis of the piezoelectric actuator
- A = Sectional area of the piezoelectric actuator
- Y = Young's modulus of the piezoelectric actuator
- L = Height of the piezoelectric actuator
- d = Piezoelectric strain constant of the piezoelectric actuator.

Let u be the controlling input of the driving circuit of the piezoelectric actuator, α and T be the gain and time constant of the driving circuit respectively. Since

$$V = \alpha u / (1 + Ts), \tag{4}$$

then eq. (1) can be rewritten as follows:

$$y = (n_p / d_p) u - bW, \tag{5}$$

where constant $c > 0$,

$$n_p = (\alpha \alpha / T) / (s + c) \tag{6}$$

$$d_p = (s + 1/T) / (s + c). \tag{7}$$

Choose x_p and y_p as

$$x_p = (cT - 1) / (\alpha \alpha) \tag{8}$$

$$y_p = 1. \tag{9}$$

Then the following Bezout identity equation is satisfied:

$$x_p n_p + y_p d_p = 1. \tag{10}$$

3.2 Design of Compensators

The mathematic model of the control object mentioned in the previous section is obtained by neglecting the mass of the upper plate and the nonlinear characteristics and hysteresis of the piezoelectric actuator. The characteristics of three piezoelectric actuators are usually different. When one has trouble, it needs to be exchanged for a new one. It is desirable to control the three actuators using three identical robust compensators without redesigning and investigating the characteristics of each actuator. Therefore, we designed the compensators based on the H_∞ control theory which is prominent in robust control.

Let r be reference input of the system and

$$u = C_1 r - C_2 y. \tag{11}$$

From ref. 3), all the stabilizing compensators C_1, C_2 are given by

$$C_1 = (d_p + C_2 n_p) Q_1 \tag{12}$$

$$C_2 = (x_p + d_p Q_2) / (y_p - n_p Q_2), \tag{13}$$

where $Q_1, Q_2 \in RH_\infty$, RH_∞ is the subset of H_∞ consisting of real-rational functions and H_∞ is the Hardy space. The H_∞ -norm of F is defined as

$$\|F\|_\infty = \sup \{ |F(s)| : \text{Re } s > 0 \}. \tag{14}$$

Assume

$$r = r_0 / s \tag{15}$$

$$W = W_0 / s. \tag{16}$$

Here r_0 and W_0 are constants. Choosing

$$Q_1 = cT / (\alpha \alpha) \in RH_\infty \tag{17}$$

$$Q_2 = (s + c) / [\alpha \alpha (s + 1/T)] \in RH_\infty. \tag{18}$$

From eqs. (12) and (13), we obtain

$$C_1 = C_2 = c(Ts + 1) / (\alpha \alpha s) \tag{19}$$

$$[(r - y) / r_0] = 1 / (s + c) \in RH_\infty \tag{20}$$

$$[(r - y) / W_0] = b / (s + c) \in RH_\infty. \tag{21}$$

Therefore, the steady state error is 0. And the larger c is, the better the characteristics of robust regulation (i.e. stabilization plus tracking and/or disturbance rejection) are.

3.3 Configuration of Control System

The configuration of the control system is illustrated in Fig. 2 and the specifications of the units used in this system are shown in Table 2.

The power for the stacked piezoelectric ceramic actuators is supplied from a direct-current power supply through a driving circuit. The displacement signals detected by noncontact capacitive displacement transducers are input to the CPU of a

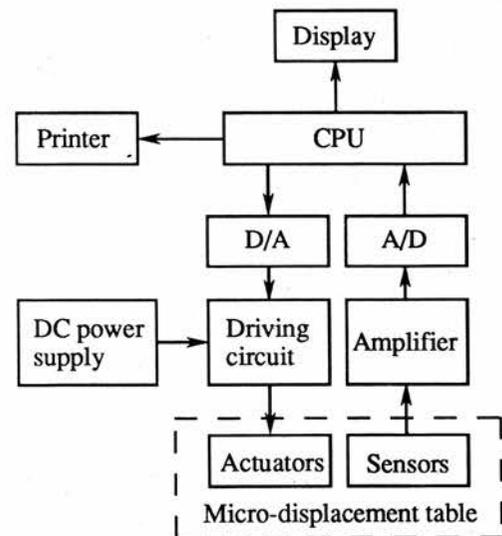


Fig. 2 Schematic illustration of control system

Table 2 Specifications of units used in control system

CPU	80286 or 80386
D/A converter	DA12-4(98) (CONTEC)
A/D converter	AD12-8R(98) (CONTEC)
Driving circuit	Originally developed, Three channels
Amplifier	PC-1001 (Photonics)
DC power supply	4042 High speed power amplifier / bipolar power supply (NF Electronic Instruments)
Actuators	Three stacked piezoelectric ceramic actuators (NEC)
Sensors	Three noncontact capacitive displacement transducers, (Photonics) Range: 50 μ m Resolution: 50nm
Display	PC-KD852 (NEC)
Printer	PC-PR201F (NEC)

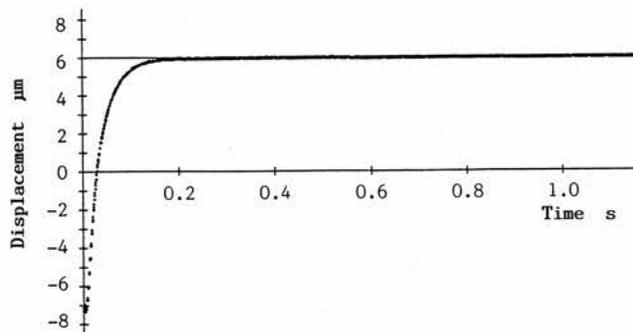


Fig. 3 An example of step responses of system

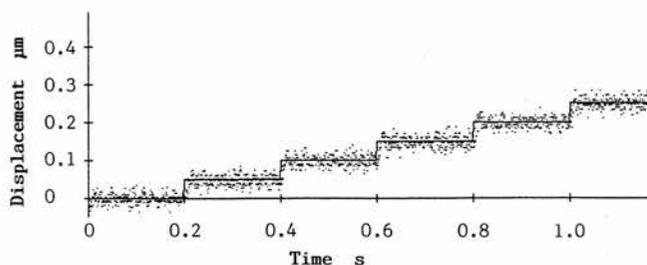


Fig. 4 Response of system to a reference input in tiers

microcomputer through an A/D converter. The dynamic compensators shown by eq. (19) were realized as soft servos by programs. The controlling inputs are output to the driving circuit through a D/A converter. The controlled output of the system is shown on the display so that it can be monitored in the machining process. The ground surface can be held horizontally and inclined with a very slight angle in the designated direction, by controlling each of the piezoelectric actuators independently.

3.4 Characteristics of Positioning System

3.4.1 Step Response

An example of the step responses of the positioning system is shown in Fig. 3. The steady

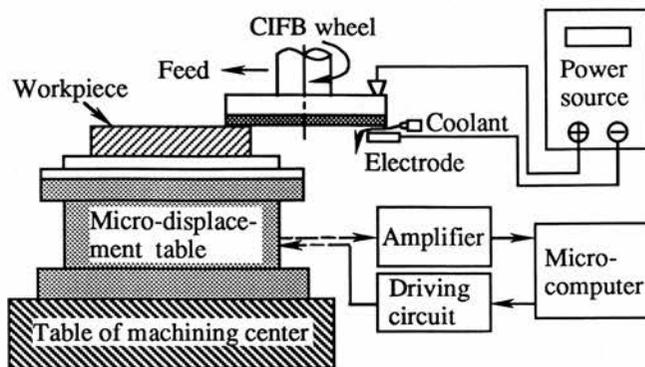


Fig. 5 Schematic illustration of grinding system

Table 3 Specifications of grinding system

Grinding machine	Machining center: VQC-15/40 (YAMAZAKI MAZAK)
Micro-displacement table	Originally developed. Actuators: Three stacked piezoelectric ceramic actuators (NEC) Sensors: Three noncontact capacitive displacement transducers (Photonics)
Grinding wheel	Cast-iron fiber-bonded diamond wheel (Cup wheel, SINTOBRATOR) Diameter: 200mm, Width: 5mm, Mesh number: #5000
Elid power source	Electro-discharge machine SUE-87 (Sodick)
Workpiece	Silicon (54X20X20) (SHIN-ETSU HANDOTAI)
Liquid	AFG-M NORITAKE-Cool 50 (NORITAKE)

state error is 0 and the output of the system precisely tracks the step reference input.

3.4.2 Positioning Accuracy

Figure 4 shows the response of the system to a reference input in tiers whose individual steps equal 50 nm, the resolution of the displacement sensors used in the micro-displacement table. The system has a positioning accuracy equal to the resolution of the sensors used. Thus, it appears to be possible to improve the positioning accuracy by using higher-resolution sensors.

4. Experimental Method

It is possible using the micro-displacement table and its control system to grind spherical and nonspherical mirrors, and so on. The experimental results of generating concave mirrors with large curvature radii by means of the grinding operation using the system to change the relative position of the ground surface and grinding wheel, are reported in this paper.

The grinding system is schematically illustrated in Fig. 5 and its specifications are shown in Table 3.

4.1 Grinding Machine

A machining center was used as a grinding machine. The micro-displacement table and

electrolytic dressing electrodes were attached to the machining center. Figure 6 shows a part of the grinding system.

4.2 Electro-Discharge Machine

An electro-discharge machine was used as the power source for grinding with electrolytic in-process dressing⁴). The electrolytic conditions were voltage $E_0 = 60$ V, width of pulse $\tau_{on} = 12$ μ s, $\tau_{off} = 3$ μ s, short current $I_p = 16$ A.

4.3 Grinding Wheel

A cast-iron fiber-bonded diamond abrasive wheel (CIFB-D abrasive wheel) whose mesh number is #5000 was used as a finish grinding wheel. This micro-grain wheel was dressed by using the electrolytic dressing attachment before grinding. For rough grinding, #325 and #1200 CIFB-D abrasive wheels were used.

4.4 Grinding Conditions

The finish grinding conditions were peripheral velocity of grinding wheel $V = 1200$ m/min, feed speed of the machine table $f = 60$ mm/min, and depth of cut $d = 1$ μ m.

Mirror grinding was carried out for machining concave silicon mirrors with large curvature radii. The silicon workpiece had been previously ground to a plane with a lustrous surface. Then the relative position of the grinding wheel and the ground surface was controlled by using the micro-displacement table and its control system. The aim was to generate a three-dimensional curved surface with a large curvature radius of 60 m. The largest displacement is 6.1 μ m in a machining distance of 54 mm. To be more precise, the workpiece is fixed on the micro-displacement table. While the feed is given, micro-displacement is exactly given to the workpiece in the direction of the micro-displacement table's axis in accordance with the relative movement of the grinding wheel and the workpiece. The reference input of the control system is to increase the displacement and raise the workpiece after the grinding operation starts, give the maximum displacement at the center of the workpiece, then decrease the displacement and lower the workpiece. In calculation of the reference input of the control system, the shape and size of the grinding wheel must be taken into consideration.

5. Experimental Results

5.1 Result of On-Machine Measurement

Since it is a grinding process of a three-dimensional curved surface with a large curvature radius, it is necessary to measure the machined surface before removing the workpiece from the grinding machine. Figure 7 shows the profile of a machined surface measured with a dial gauge.

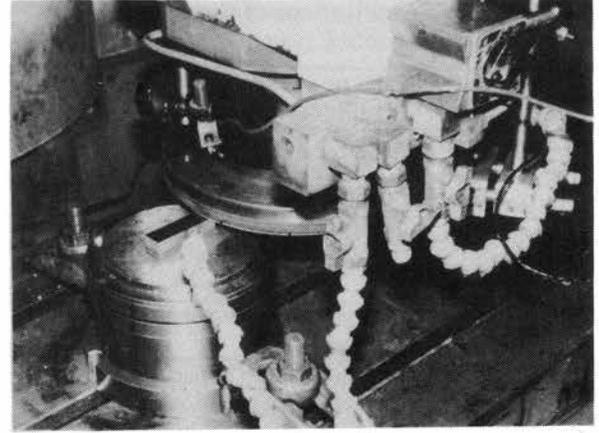


Fig. 6 A part of grinding system

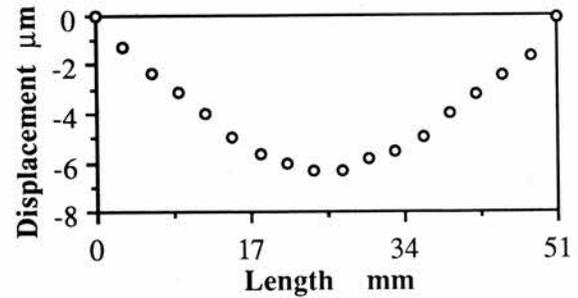


Fig.7 Profile of machined surface measured with dial gauge

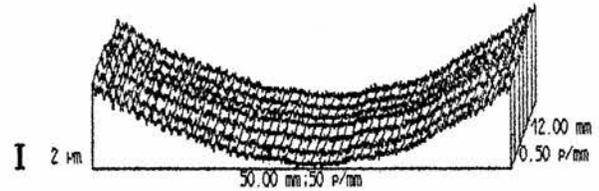


Fig.8 Contour of machined surface measured with precision optical length-measurement system

Thus, it was confirmed by on-machine measurement that the profile of the machined surface as the aim was obtained.

5.2 Results of Precision Measurement

5.2.1 Contour measured with optical length measurement system

Figure 8 shows the contour of the machined surface measured with a precision optical length-measurement system. The curvature radius was 60.164 m by analysis using this measurement system. This result coincides with the reference value of 60 m.

5.2.2 Fringe and contour measured with interferometer and fringe analyzing system

The fringe and contour of the machined surface

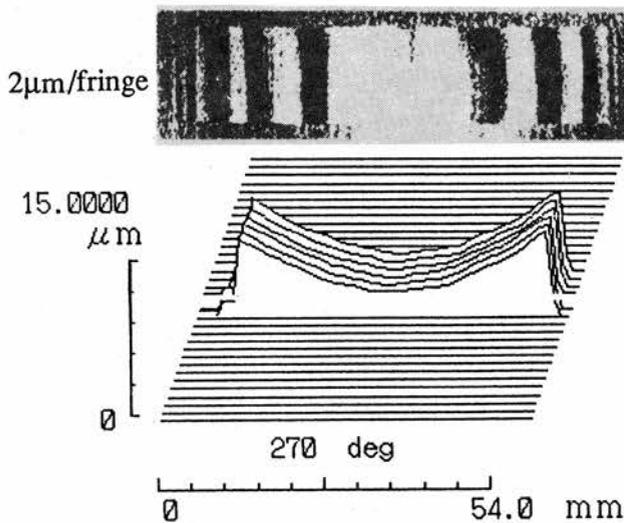


Fig.9 Fringe and contour of machined surface measured with interferometer and fringe analyzing system

measured with an interferometer and fringe analyzing system is shown in Fig. 9. It is also confirmed that three-dimensional curved surfaces with large curvature radii can be precisely obtained by using the micro-displacement table and its control system.

6. Conclusions

A micro-displacement table with stacked piezoelectric ceramic actuators was designed. A control system was also designed to dynamically and precisely control this table. By using the system, we successfully obtained nonspherical mirrors (concave mirrors) with large curvature radii, with high precision in shape accuracy and low surface roughness.

This technique has the following features:

(1) Three-dimensional curved surfaces with large curvature radii can be precisely obtained by means of grinding operations with high precision in shape accuracy and low surface roughness. This has been very difficult so far.

(2) This technique can innovate conventional manufacturing processes, and satisfies the demand for advanced automation. The time consumed in the processes becomes very short and the productivity is high.

(3) It can be used to grind plane mirrors and spherical or nonspherical mirrors represented by SiC reflectors used in synchrotron orbital radiation facilities. It has not only originality but also adaptability.

(4) The machines to which the system is attached are conventional and not specially designed for the purpose of ultra-precision grinding. That is, mirror surfaces having high shape precision can be ground on conventional grinding or cutting machines such as machining centers or surface grinders by attaching the system to them.

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