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Development of nano-Probe System Using Optical Sensing

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Abstract

Nano-probe system is described in this paper. Recently industrial parts have been smaller in size of sub-micron order. Therefore it is important to measure such small mechanical parts in high accuracy. For this purpose, there are some measuring machines that are capable of measuring these parts high accurately today. Scanning probe microscopes have been developed and widely used. However, they can measure profiles only in vertical narrow range and cannot measure three dimensional small industrial parts. It is important to develop the measuring system that can measure such small parts in wider range and three dimensionally. We have developed nano-CMM, whose resolution is nano-meter order. The probe attached to nano-CMM must be small enough and be able to detect a touch of an object with high sensitivity. We proposes a novel optical sensing system, this system can detect movements of a metal ball. Experiment that inspects availability of the optical sensing system is done.

Keywords: coordinate measuring machine, probing system, nano meter measurement, coordinate metrology

1. Introduction

Recently, industrial parts have been smaller in size of sub-micron order. Therefore, it is important to measure such small mechanical parts in high accuracy. For this purpose, there are some measuring machines that are capable of measuring these parts high accurately today. Scanning probe microscopes such as AFM (Atomic Force Microscope) and STM (Scanning Tunneling Microscope) that detect physical force or tunneling current between a probe and a target have been developed and widely used. The vertical resolution of these measuring systems is up to sub nano-meter. However, they can measure profiles only in vertical narrow range and cannot measure three-dimensional small industrial parts. It is important to develop the measuring system that can measure such small parts in wider range and three dimensionally.

We have developed nano-CMM (Coordinate Measuring Machine with nano meter resolution) [1][2][3], whose resolution is nano-meter order and specifications are 1/100 of these of a traditional CMM (Table 1). The probe system attached to nano-CMM must be small enough and be able to detect touch of an object with high sensitivity. We call such a probe system as "nano-Probe System" and are developing it.

For the nano-Probe system, a contact type probe is better because noncontact type probe such as an optical probe may be influenced by the surface of an object. The ball probe consisted of a thin stylus and a probe ball can be applied to various measurements. For these reasons, we adopt the contact type ball probe system as nano-Probe System.

Table 1 Comparison of specification of measuring devices

	SPM	CMM	nano-CMM
volume	$(1m)^3$	$(2m)^3$	$(200mm)^3$
mass	200kg	1000kg	10kg
measuring range	$(100\mu m)^3$	$(1m)^3$	$(10mm)^3$
measuring resolution	under 1nm	1mm	10nm
measuring accuracy	10nm	10mm	100nm
probe radius		10mm	100μm
measuring pressure	10^{-8}N	0.1N	10^{-3}N
accuracy of scale		1mm	10nm
sphericity of probe		0.1mm	10nm
working environment	vacuum	thermostatic chamber	thermostatic chamber

2. Principle of Optical Sensing

2.1 Configurations

Figure.1 illustrates configurations of nano-Probe System that we purpose in this paper. A laser beam through an optical fiber is made parallel by a collimator lens mounted at the end of the fiber. The laser beam is focused and goes in a hollow stylus. The reflected beam at the surface of a metal ball is focused at a QPD (Quadrant Photo Diode). Outputs of the QPD are sent to PC by an A/D converter and processed.

2.2 Optical Sensing System

The way to detect the movement of probe ball is following; at first, the collimated laser beam goes toward the metal ball. The beam is focused at the center of the metal ball by the objective lens and reflected at the surface of the ball. When the focus is coincident with the center of ball exactly, the virtual light source of the reflected beam with the focus of the original beam. If the ball shifts normal to the beam, the virtual light source also shifts. If the movement of a ball b is smaller enough than radius of the ball, the virtual light source moves by the distance of $2b$ to the same direction (see Figure 2).

The displacement of light spot y_2 is amplified using the objective lens and the focus lens as equation (1) from the displacement of the virtual light source y_1. The amplitude ratio equals to the ratio of the focal distances of the two lenses (Figure 3).

$$y_2 = \frac{f_2}{f_1} y_1 \qquad (1)$$

Where f_1 is the focus distance of the objective lens, f_2 is the focus distance of the focus lens, y_1 is the displacement of the virtual light source, and y_2 is displacement of the light spot.

QPD is used to detect the displacement of the laser spot. The displacement is derived from outputs r_x and r_y, which are calculated by each output of diode as follows (see equation (2) and Figure 4).

$$r_x = \frac{(p_1 + p_4) - (p_2 + p_3)}{p_1 + p_2 + p_3 + p_4}$$
$$r_y = \frac{(p_1 + p_2) - (p_3 + p_4)}{p_1 + p_2 + p_3 + p_4} \qquad (2)$$

2.3 Laser guide fiber

He-Ne laser tube must be separated from the stylus part for following two reasons; firstly, the stylus part must be as small as possible because the nano-Probe system is attached with nano-CMM whose size is only (200mm)^3. Secondly, the heat of laser tube can influence the results of measurement. Therefore the laser beam is guided from the He-Ne laser-tube to the probe through the optical fiber.

We choose a single mode fiber as the laser guide from three kinds of optical fiber (multi mode fiber, single mode fiber and polarization maintaining fiber). Single

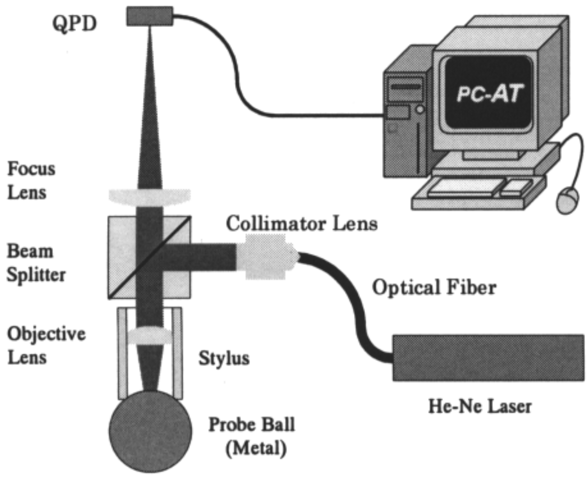

Fig.1 Configurations of nano-Probe system

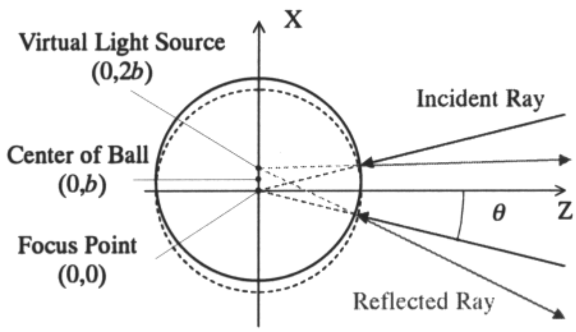

Fig.2 The displacement of the virtual light source

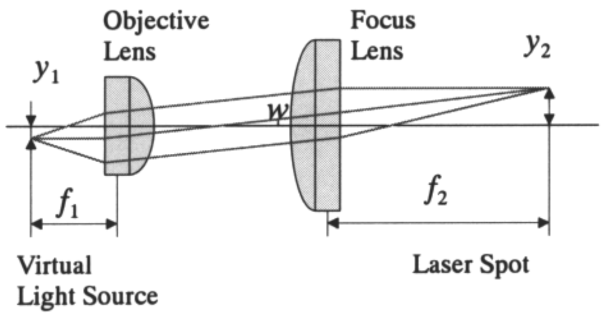

Fig.3 Amplification of the displacement of the virtual light source

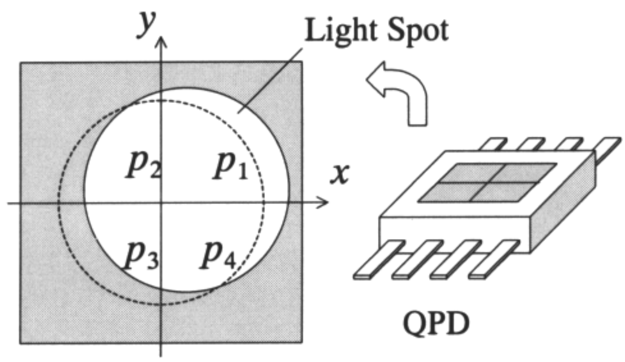

Fig.4 Detection of the displacement of a spot using QPD

mode fiber can guide less light than a multi mode fiber, but a shape of light spot and quantity of light are stable even if fiber is bent. A multi mode fiber can guide a beam easily and its loss of light is very low. But this is unavailable because a shape of light spot and quantity of light vary with the bend of fiber. Polarization maintaining fiber can keep the polarization of light. But its loss of light is very high and polarization is disturbed by the bend of fiber.

3. Simulation

We simulated the behavior of nano-Probe system based on principle. In these simulations, we assume the following conditions;

○the incident ray of light is regarded as a paraxial ray,

○the surface of the metal ball is mirror finished surface, and

○the optical system is ideal.

We simulated the influence of following effects.

3.1 Influence of probe ball radius

Figure 5 shows a result of the simulation for the influence by probe ball radius. The displacements of the virtual light source and the differences from approximate values are plotted. The ball radius D varies in 10mm, 5mm, 3mm under the conditions of $\tan\theta = 0.1$, where θ is the maximum incident angle of ray (see figure 2). The larger ball radius is, the smaller difference from the approximate value is.

3.2 Influence of max incident angle

Figure 6 displays a result of the simulation for the influence by the maximum incident angle. Tangent of the maximum incident angle of ray, $\tan\theta$ varies in 0.05, 0.1, 0.2 under the conditions of the ball radius D = 5mm. Under these conditions, the maximum incident angle makes only little effect to the difference from approximate values.

3.3 Influence of movement in z-axis

Figure 7 shows a result of the simulation for the influence of the movement of the ball in z-axis. The movement of the ball varies in −100μm, −10μm, 10μm, 100μm under the conditions of D = 5mm, $\tan\theta = 0.1$. The movement of the ball in z-axis influences the virtual light source.

3.4 Appropriateness of approximation

For the real operating condition, the maximum movement of the probe ball is only 100nm. Under such a condition, the maximum difference is under 1nm from these simulations (see figures 5, 6 and 7). It satisfies the specifications of nano-Probe. We conclude that the approximation of the displacement of the virtual light source is appropriate.

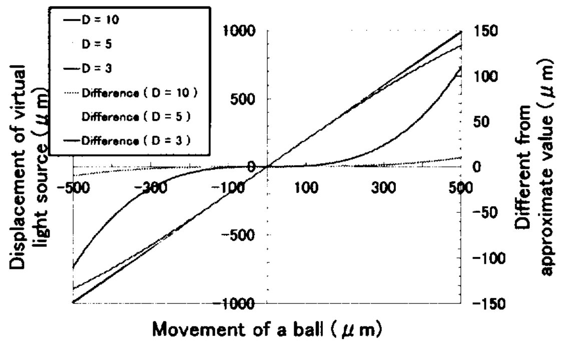

Fig.5 Influence of probe ball radius

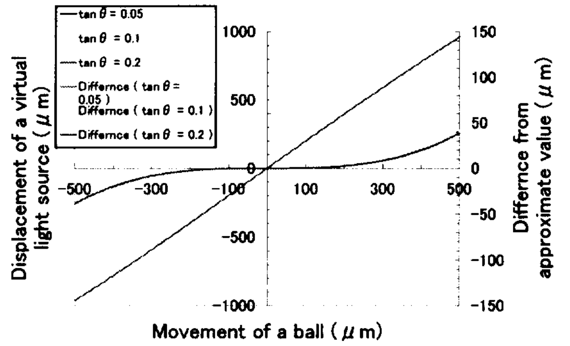

Fig.6 Influence of max incident angle

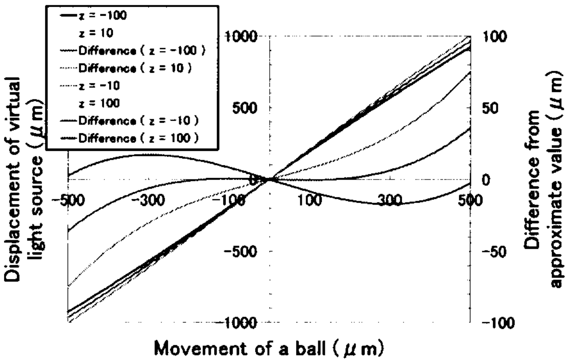

Fig.7 Influence of the movement of a ball in z-axis

4. Experiment

Figure 8 illustrates experimental equipment. A Piezoelectric stage moves the metal ball in x-axis. The movement of the metal ball is measured by optical scale system (holo-scale, Mitutoyo). We recorded outputs of QPD and measured the values from holo-scale with the increasing voltage applied to the piezoelectric stage. The conditions are following; the radius of the ball D=3mm, the focal distance of the objective lens f_1=10mm and the focal distance of the objective lens f_2=100mm. The experiment is done in a normal temperature.

Figure.9 shows the result of experiment. The resolution calculated from the gradation and the deviation is shown in table 2. The resolution of 7.1nm is less than the target resolution of nano-Probe system (10nm).

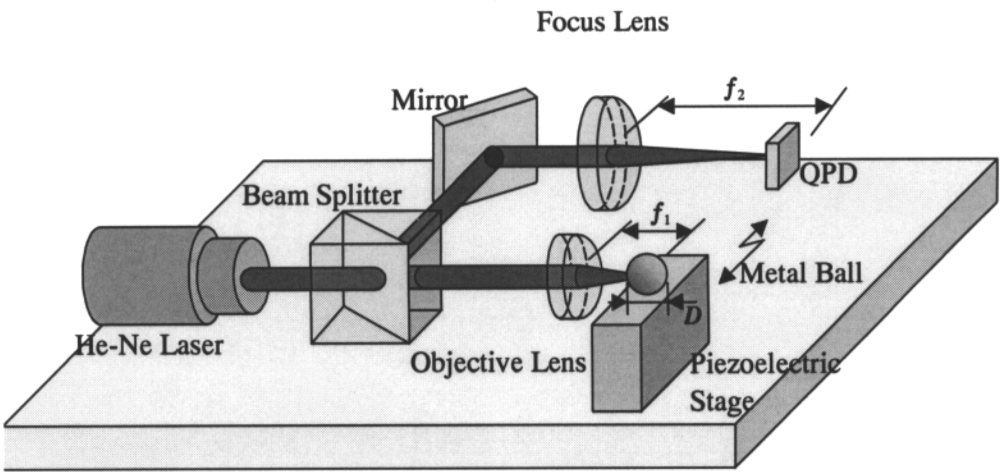

Fig.8 Experimental equipment

5. Conclusion

We proposed a novel optical sensing system, which uses a laser beam to detect the movement of the metal ball. Using this optical sensing system, we can detect the movement of the probe ball by nano-meter order. We conclude that the optical sensing system can be applied to the probe system for nano-CMM.

In future, we plan to make nano-Probe which is small enough to be attached to nano-CMM.

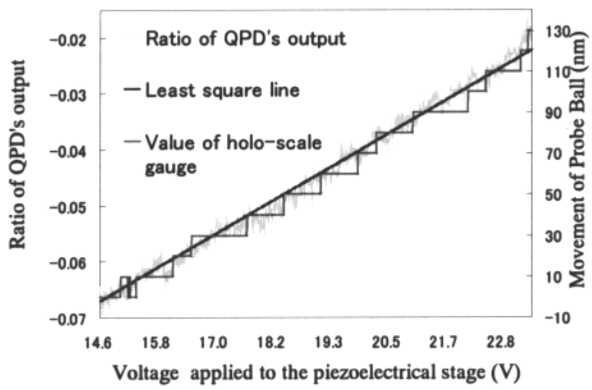

Fig.9 Ratio of output of QPD to the movement of the ball

Table 2 The gradient, deviation and resolution of the experimental result

gradient	3.9×10^{-4} (nm/V)
deviation	1.4×10^{-3}
resolution	7.1 (nm)

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