SURFACE ROUGHNESS MEASUREMENTS OF A NARROW BOREHOLE --- MEASUREMENT OF SURFACE ROUGHNESS STANDARD PIECE –

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Abstract:
In industrial fields, it is frequently necessary to measure surface roughness in confined spaces such as boreholes and grooves. However, using a small stylus, the surface roughness of a narrow borehole can be directly measured only a few millimeters from its end; alternatively, destructive measurements must be performed. We already proposed a novel surface roughness measurement sensor. To make the surface roughness sensor small, we used a stylus with a cylindrical mirror and a lensed fiber instead of a conventional inductive pick-up. The proposed sensor converts the signal obtained by measuring the surface roughness of a borehole into an optical signal, which is transferred outside the borehole by an optical fiber. Experimental results demonstrate that this system has a measurement range of 8 μm and a sensitivity of 19 nm. In this paper, a carriage to measure the surface roughness in a small borehole is proposed. The proposed carriage has two degree of freedom, displacement along the borehole axis and rotation around the borehole axis. Furthermore, surface roughness standard pieces were measured by the proposed method and the conventional method. Measurement results obtained by these methods were found to be very similar.

Keywords: Surface roughness measurement, Borehole, Lensed fiber

1. INTRODUCTION

In various industrial fields, it is frequently necessary to measure surface roughness in confined spaces such as boreholes and grooves. However, using a small stylus, the surface roughness of a narrow borehole can be directly measured only a few millimeters from its end. For example, a type I5B stylus designed from measuring the surface roughness of small boreholes[1] (Kosaka Laboratory Ltd.) has a height of 0.5 mm and a reach of 4 mm. Therefore, this stylus can measure surface roughness up to 4 mm from the end of the borehole. When it is necessary to measure the surface roughness of an area far from the end of the borehole, the borehole must be cut in the axial direction and destructive measurements performed. This major disadvantage of conventional stylus-based surface profilometers is mainly due to the inductive pick-up that is connected to the stylus. The minimum size of an inductive pick-up is approximately 20 mm. When the stylus and inductive pick-up scan inside a borehole, the smallest measureable borehole is approximately 20 mm in diameter. When only a stylus scans inside a borehole and the inductive pick-up remains outside the borehole, the measureable area is restricted to near the end of the borehole. A few studies have reported profile measurement in a small borehole[2].

We have been seeking to measure the profiles of boreholes with a diameter of less than 2 mm and a length of over 100 mm. We already proposed a novel surface roughness measurement sensor[3]. To make the surface roughness sensor small, we employed a stylus with a cylindrical mirror and a lensed fiber, instead of a conventional inductive pick-up. The proposed sensor converts the signal obtained by measuring the surface roughness of a borehole into an optical signal, which is transferred outside the borehole by an optical fiber. Measurement range of the proposed sensor was 8μm.

In this paper, a carriage to measure the surface roughness in a small borehole is shown. The carriage has two degree of freedom, displacement along the borehole axis and rotation around the borehole axis. Furthermore, surface roughness standard pieces were measured by the proposed method and the conventional method. Measurement results obtained by these methods were found to be very similar.

2. SENSING PRINCIPLE

Fig. 1 shows a schematic diagram of the surface roughness measurement system[3], which has a stylus with a cylindrical mirror and a lensed fiber. The stylus is connected to a carriage by an elastic hinge and it is used to measure the surface roughness of a narrow borehole. The cylindrical mirror is fixed on the stylus and the lensed fiber is fixed on

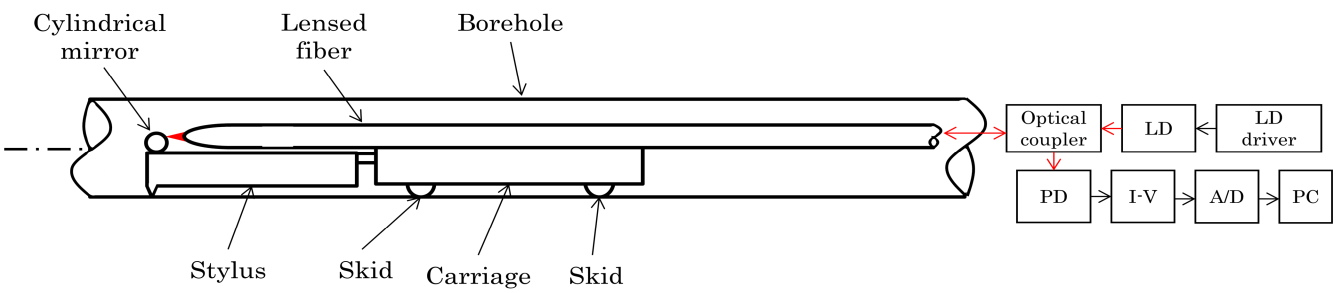

Fig.1 Schematic diagram of surface roughness measurement system in a small borehole

the carriage. A laser beam from a laser diode (LD) passes through an optical coupler and the lensed fiber. The laser beam from the lensed fiber is focused on a cylindrical mirror. A part of the beam reflected from the cylindrical mirror enters the lensed fiber and is detected by a photodiode (PD). The PD output is transformed into a voltage and digitized by an A/D converter. As the cylindrical mirror moves in response to the surface roughness in the borehole, the surface roughness can be converted into an electrical signal.

Fig. 2 shows a schematic diagram of the lensed fiber and the cylindrical mirror. When the cylindrical mirror moves 1 μm in the height direction of the surface roughness, the incident angle of the laser beam on the cylindrical mirror changes by θ rad. which is given by:

$$r\theta = 1 \quad (1)$$

where r is the radius of the cylindrical mirror. The beam reflected from the cylindrical mirror to the lensed fiber is deviated by d μm, which is given by:

$$d = f\,2\theta \quad (2)$$

where f is the focal length of the lensed fiber. Consequently, the relationship between r and d can be written as:

$$d = \frac{2f}{r} \quad (3)$$

Therefore, when variable f increases, variable d increases. Further, when variable r decreases, variable d increases. That is, to make high sensitivity, variable f should be large and variable r should be small.

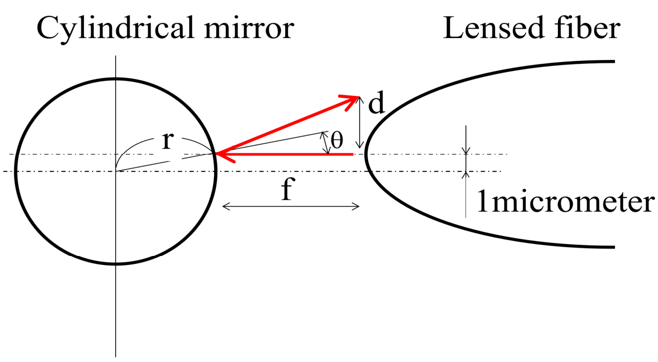

Fig.2 Lensed fiber and cylindrical mirror

3. FUNDAMENTAL CHARACTERISTICS

Figs. 3 shows a schematic diagram of the experimental system of the surface roughness sensor with the stylus having a cylindrical mirror and a lensed fiber. A stylus (Mitsutoyo, 12AAB406) is used to trace the surface roughness. The V-groove of the stylus is placed on the knife edge of the carriage. The cylindrical surface of an optical fiber (diameter: 125 μm; length: 2 mm) coated with Cr is used as the mirror. The cylindrical mirror is fixed on the stylus. A lensed fiber (Moritex Co., Circletran MST-CT1310G11W320/BS10FAd; focal length: 320 μm; spot diameter: 11 μm) is fixed on the carriage using a shallow V-groove formed by a scriber.

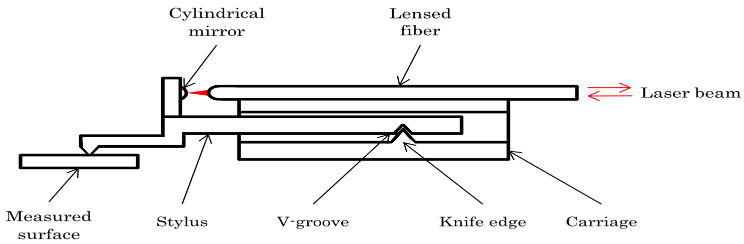

Fig.3 Schematic diagram of the experimental system

The sensor is set on a Z-stage (Chuo Precision Industrial Co. Ltd., NPZ-347-S1). The Z-stage can be finely translated in a 10 μm range and it is driven by a PZT actuator. It can be roughly translated by a micrometer. The tip of the stylus is placed on the surface to be measured. The Z-stage is driven by a triangular wave (period: 2 s; peak-to-valley amplitude: 8.5 μm) generated by a function generator (Agilent, 33120A) and the output of the stage driver, the displacement of the Z-stage (measured by a strain gauge), and the output of the surface roughness sensor are acquired by A/D converters (Agilent, 34410A). These A/D converters are double integration type and integration times are set to 0.02 s to eliminate noise from the power line cycle that has a frequency of 50 Hz.

As the Z-stage has a short fine motion range, it was roughly translated by approximately 5 μm by the micrometer and calibration was performed. This process was repeated five times. Fig. 4 shows the calibration results, where the abscissa is the displacement in the Z direction and the ordinate is the output of the surface roughness sensor. It shows that the sensor output changes when the displacement is changed. A small amount of hysteresis was observed. The sensor output was small (–5 V) when the laser beam was focused lower side of the cylindrical mirror, whereas when the laser beam was focused near the center of the cylindrical mirror, the sensor output was large (–7 V). Furthermore, when the laser beam was focused upper side of the cylindrical mirror, the sensor output was small (–5 V). The two areas indicated by the

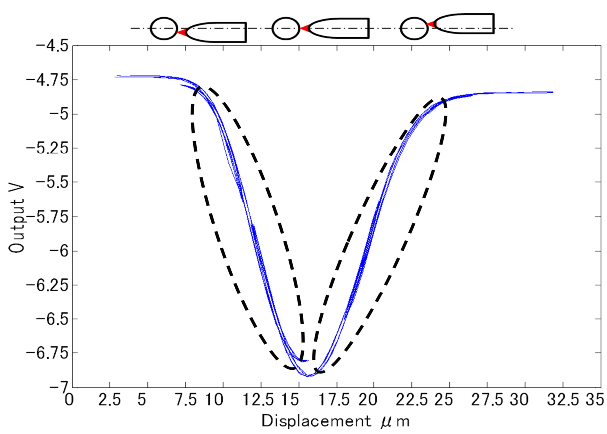

Fig. 4 Calibration results

dashed ellipses in Fig. 4 are suitable for surface roughness measurements. Since it is nonlinear, a least-squares by a third-order polynomial is used as the calibration curve. The measurement range was 8 µm.

Fig. 5 shows the noise of the proposed surface roughness sensor for a sampling interval of 0.04 s and 50 sampling points. This figure shows that the proposed system has a noise of 5.2 mV(±2σ). In practical measurements, the noise determines the sensitivity of the roughness sensor. Since the noise was 5.2 mV(±2σ), the sensitivity was 19 nm.

Fig. 6 shows the thermal drift of the surface roughness sensor. The sampling interval was 1 s and number of sampling points was 3600. The sensor output varies sinusoidally with a period of 18 min. This drift is caused by temperature control in the laboratory. In the worst case, the thermal drift was 1 mV/s.

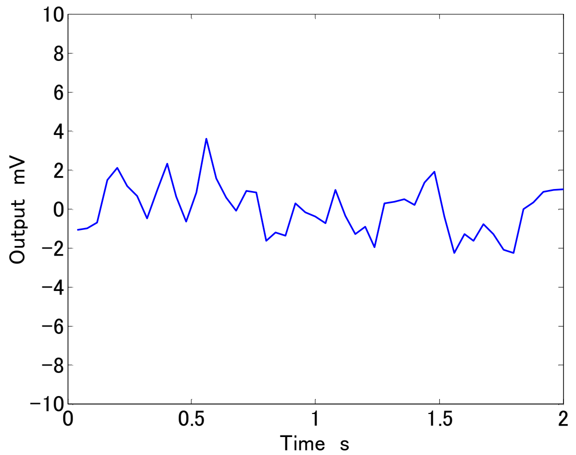

Fig.5 Noise of the sensor

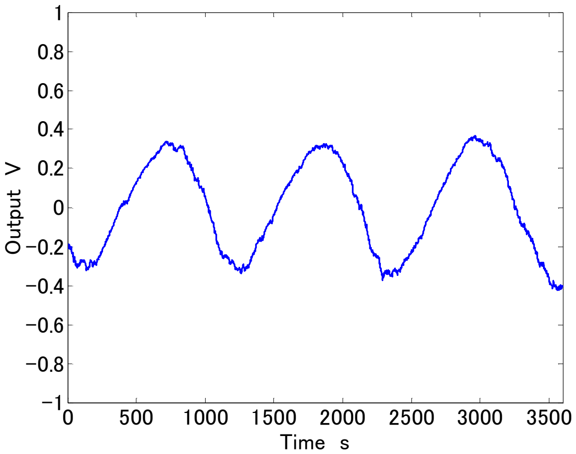

Fig.6 Drift of the sensor

4. CARRIAGE

In case of surface roughness measurement system, a skid is used to eliminate lower spatial frequency component, i.e., surface waviness. In the proposed system, two skids are set to the carriage and the carriage scans along the borehole axis. Therefore, degree of freedom of the carriage should be constrained properly[4]. The borehole axis is X-axis. Required motions of the carriage are scanning along X-axis and rotation around X-axis. Originally, the carriage has six degree of freedom. Then, four degree of freedom should be constrained. Consequently, number of contact point between the carriage and the borehole is four. Two skids are set at both ends of the carriage and they make two contact points. Furthermore, two springs are set at upper position of the carriage to make two contact points.

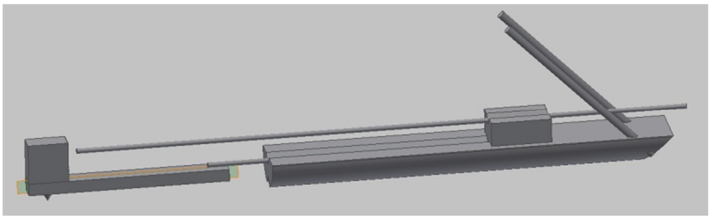

Fig.7 Draught of the carriage with the stylus

Fig.7 shows a draught of the carriage with the stylus and the lensed fiber. Length of the carriage along X-axis is 10mm. Height is 1.3mm and width is 1.5mm. V-groove is made at the lower part of the carriage and two steel balls with 0.15mm diameter are set in the V-groove as the skid. The end face of the carriage is cut as an inclined plane and two small through holes with 0.18mm diameter are made. Furthermore, two springs are set to the carriage using these through holes. Upper part of the carriage is two stage. Each stage has a V-groove. A spring is set in the lower V-groove and the stylus is set to the spring. The lensed fiber is set at the higher V-groove.

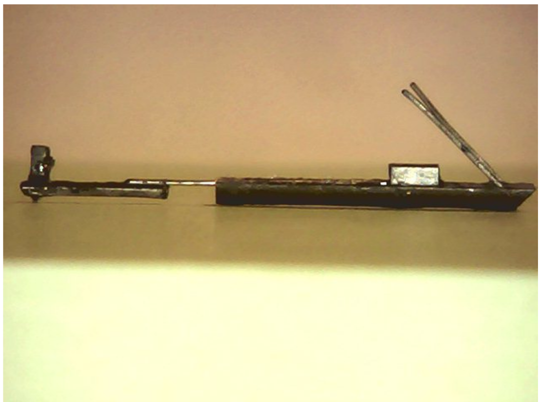

Fig.8 Trial manufacture of the carriage with the stylus

Fig.8 shows photograph of the trial manufacture of the carriage with stylus. The stylus, Kosaka Laboratory I5B, with cylindrical mirror is connected to the carriage using a guitar string. A string of an electric guitar, D’Addario 0.07(0.178mm diameter), is used as the spring.

5. SURFACE ROUGHNESS MEASUREMENTS USING THE PROPOSED SENSOR

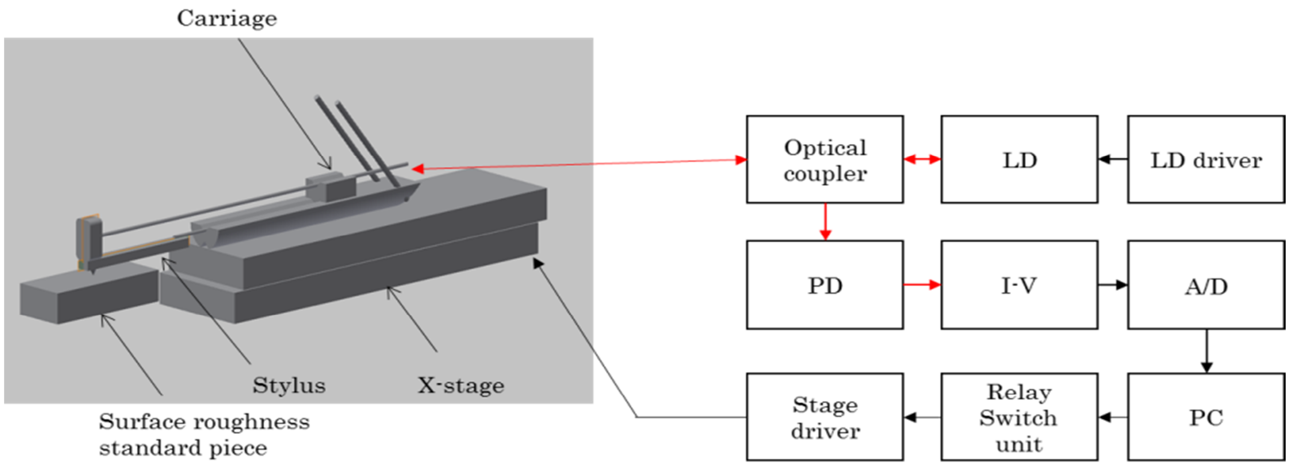

Fig. 9 Block diagram of the experimental system to measure the surface roughness standard pieces

Fig. 9 shows a block diagram of the experimental system to measure the surface roughness standard pieces using the proposed surface roughness sensor. The surface roughness standard piece was set on a table and the carriage of the proposed system was set on an X-stage (Suruga Seiki, PG430-L05AG-UU). The X-stage is driven by a PC via a relay switch unit (Agilent 34970A and 34903A).

Two surface roughness standard pieces, Ra were 0.2 μm and 0.4 μm(NIHON KINZOKU DENCHU CO., LTD.), were measured.

The scan speed of the X-stage was set to 3 mm/min (i.e., 50 μm/s). Since the A/D converter had an integration time of 0.02 s, the spatial sampling interval was 1 μm. The number of sampling points was set to 1000, which gave a sampling length of 1 mm and a sampling time of 20 s.

Fig.10 shows measurement result of surface roughness standard that has Ra 0.2μm using the proposed system. Further, the surface roughness standard piece was measured by conventional method, Kosaka laboratory LTD SE300-29. Thin line in Fig.10 is the measurement result by the proposed method and thick line is the measurement result by the conventional method. The abscissa is X-direction position and the ordinate is the height of the surface profile. These results were found to be very similar.

Fig.11 shows measurement result of surface roughness standard that has Ra 0.4μm. Thin line is the measurement result by the proposed method and thick line is the measurement result by the conventional method. The abscissa is X-direction position and the ordinate is the height of the surface profile. These results from 200mm to 1000mm were found to be very similar.

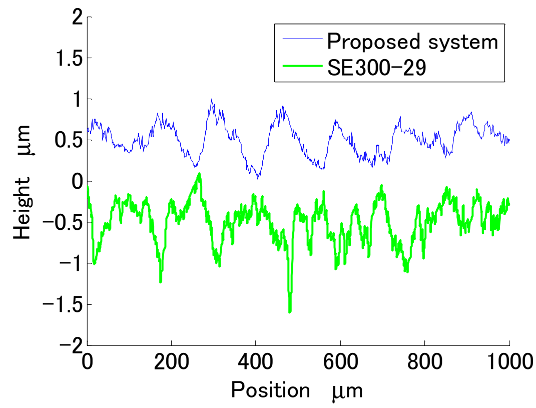

Fig. 10 Surface roughness measurement results (Ra=0.2μm)

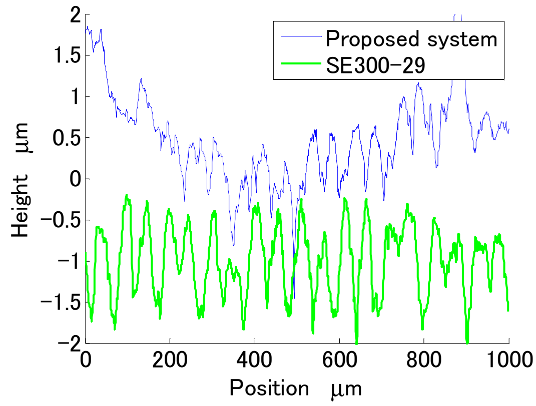

Fig. 11 Surface roughness measurement results (Ra=0.4μm)

4. CONCLUSIONS

A novel sensor that uses a stylus with a cylindrical mirror and a lensed fiber, is proposed to measure the surface roughness in a small borehole.

The carriage that has two degree of freedom, displacement along the borehole axis and rotation around the borehole axis, was developed. Furthermore, surface roughness standard pieces were measured by the proposed method and the conventional method. Measurement results obtained by these methods were found to be very similar.

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