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DEVELOPMENT OF A LASER-GUIDEDDEEP-HOLE MEASUREMENTSYSTEM: USAGE OF A LONG MEASUREMENT BAR

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Abstract*-This paper presents measurement methods of deep holes by using a measurement unitattached to the end of a long cylindrical measurement bar. The system consists of a measurement unit for scanning hole walls, a laser interferometer for detecting the topography of hole walls and an optical device for detecting the attitude of the measurement unit. The measurement unit at the end of the measurement bar is positioned along a hole'scenterline and is supported by a pair of skids. A computational analysis showed that a 3 m deep-hole with a diameter of 63mm can be measured by this measurement system.*

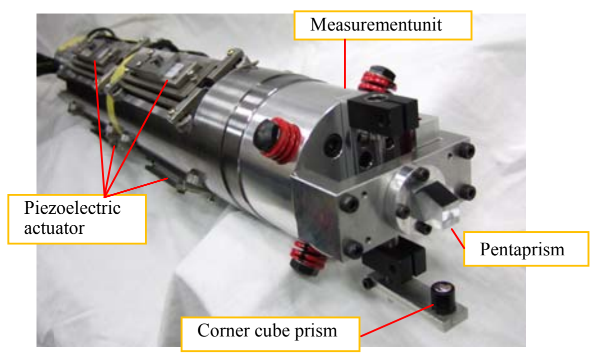
Keywords: Deep-Hole,Measurement, Accuracy, Laser Application, Probe

1. INTRODUCTION

It is essential to accurately measure the diameter, roundness, cylindricity, and straightness of a deep hole for applications such as the rotation shafts of jet engines, generators and high-speed trains; the cylinder used in plastic injection molding; and the cylindrical liners of ship engines. Existing systems have drawbacks in precisely measuring holes with large-length-to diameter ratios, in which multiple measurement devices are required.In order toaccurately evaluate the parameters of such deep holes using a single device, a laser-guided deep-hole evaluation probe was developed (Fig.1) [1]. The attitude (position and inclination) of the probe is controlled so that it stays on the measurement axis (Fig.2).A measurement unit rotates and its stylus scans the hole wall. The movement of the stylus is detected by a laser interferometer located in front of the probe.

It is difficult to measure the accuracy of deep holes of the order of a few meters with diameters varying of the order of a few millimeters, such as the rotating shaft holes of jet engines and high-speedtrains. In these cases, multiple measurement devices are required to separately measurehole accuracy.

Figure 3 shows the relationships between a measurement bar'slength and its deflection in a deep hole. One condition is a cantilever with a fixed end and a free end. Figure 3(a) isthe case in which the rigidity of the measurement bar is maintained. Many measurement devices that operate under this condition are available in the market. Figure 3(b) shows the case for which measurement is possible if the end of the measurement bar is supported. Figure 3(c) is the case in which the rigidity of the measurement bar is low andmeasurement without actuators is impossible. In this case, a measurement system as shown in Figs.1and 2 is necessary.



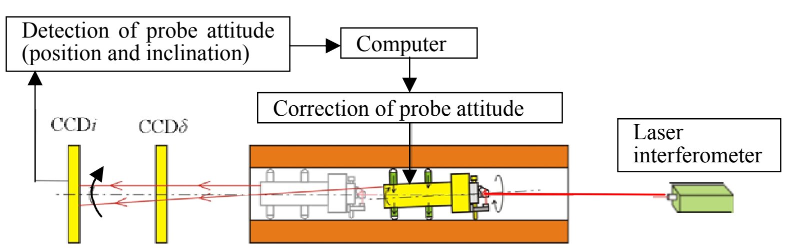


Fig.2: Structure of a laser-guided deep-hole measurement probe

In this paper, it is shown theoretically that hole accuracy can be measured when the measurement bar is a cantilever with a supported end. Further, a method for simulating measurement of a 3 m deep hole using a deep-hole measurement devicewith a small transverse length of machine table is shown. This method is very useful because a large measurement machine with a length of double the hole depth is necessaryfor evaluating the accuracy of holes with lengths of a few to several meters and is difficult to facilitate in laboratory.

2. DESIGN OFTHE MEASUREMENT SYSTEM

2.1 Deep-Hole Measurement System

Figure 4 showsthe deep-hole measurement system, which uses a hollow shaft as the long measurement bar **3**[2]. A conventional lathe is used, withone end of the measurement bar fixed bythecollet chuck and the other end supported by a pair of skids **10** behind the measurement unit **1** [3]. Workpiece**2**is fixed on a machine table. The hole wall is scanned spirally byrotatingthe measurement unit and feeding the workpiece along the measurement unit, which is rotated by a stepping motor**7**.Up and down movement of a stylus is detected by alaser interferometer **4**, which

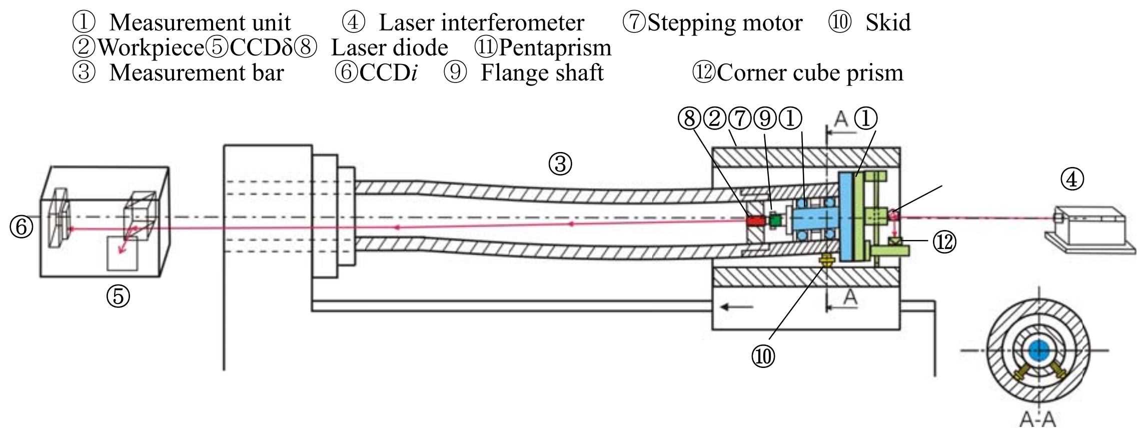
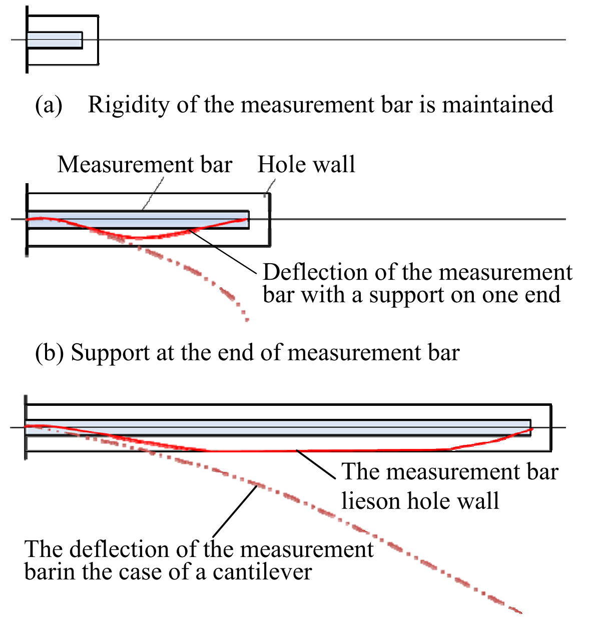


Fig.4: Laser-guided deep-hole measurement systemwithout actuators

isplaced in front of the measurement unit, via pentaprism**11** and corner cube prism **12**,which are attached to the measurement unit.

A laser diode **8** is located at the front end of the measurement bar in order to detect the attitude (position and inclination) of the measurement unit. A laser beam passes through the measurement bar and reaches optical devices**5** and**6**to detect the attitude of the measurement unit.

In this measurement system, the laser diode is placed on the measurement axis,which is the center line of the spindle of the headstock,so the attitude of the measurement unit can be accurately detected. On the other hand, in the measurement system described in [1,3], a laser diode is fixed on the measurement probe apart from the measurement axis as shown in Fig.2.Therefore, the rotational deviation of the laser



(a) Rigidity of the measurement bar is maintained

(b) Support at the end of measurement bar

(c) Rigidity of measurement bar is not maintained.

Fig.3: Deflections of measurement bars of varying lengths in deep holes with support at one end.

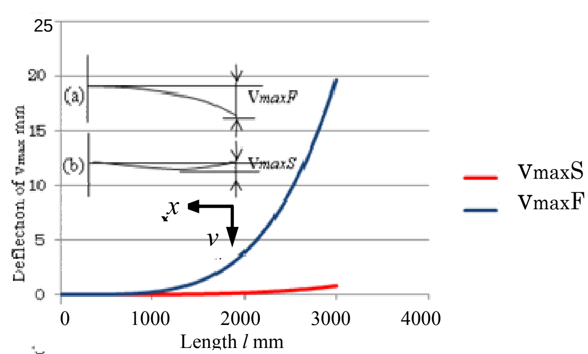


Fig.5: Maximum deflections of measurement bar

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diode due to the rolling of the measurement probe affects the detection accuracy of the probe's attitude [4].

2.2Relationship between Measurement Bar-Length and its Deflection

Figure 5 shows the relationship between the overhang length of a cantilever and its maximum deflection [4]. The beam hasthe following characteristics: steel material, Young's modulus *E*is2.05GPa, and the outside and inner diameters are 50 mm and24mm, respectively . Figure 6 shows the relationships between overhang length and inclination of the free end of the beam [5].

The following two conditions are illustrated: (a) is a cantilever with a free end, and (b) is a beam with a supported end.

(a) In the case of a cantilever with a free end

— (1)

— (2)

(b) With a supported end

— (3)

—(4)

where*E* is Young's modulus,*I*is the geometrical moment of inertia, and *l* is the length of the beam.When the length of the overhang is 3 m, maximum deflections are 19.66 mm and 0.85 mm in cases (a) and (b), respectively. In the case of (b), the maximum deflection of the beam occurs at1.2645 m from the supported end.In this case, it should be noted that the hole wall does not block the laser beamat that position. At the end of the measurement bar, deflection *v* does not occurowing to support. Inclination angles*i* are -0.0087 and 0.00109 in cases (a) and (b), respectively.

3. FACTORS THAT AFFECTMEASUREMENT ACCURACY

Problems that occur during deep-hole measurement are solved analytically and discussedbelow.

3.1 Inclination of the Measurement Unit

Section 2.2 shows the inclination angle at the supported endof a 3 m measurement bar.

Figure 7 shows the measurement parameters for deep-hole wall scanning.Sections AB and CD are the results of scans under normal and inclined conditions, respectively. If the hole wall is scanned when the measurement unit is inclined, the shape of the scanned hole is an oval. However, thedata acquired by a laser interferometer indicates acircular shape even though the measurement unit inclines.The laser path between the laser interferometer and the corner cube prism does not change when the inclination angle is small [2].

When the diameter of the reference hole is

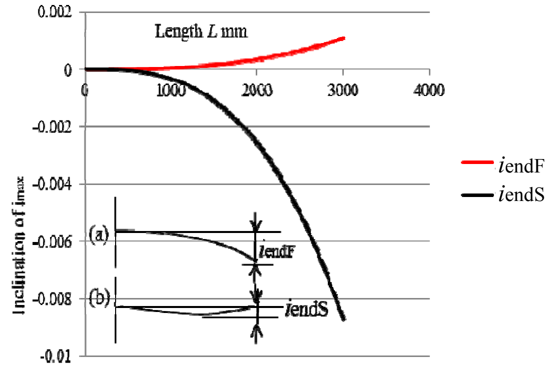
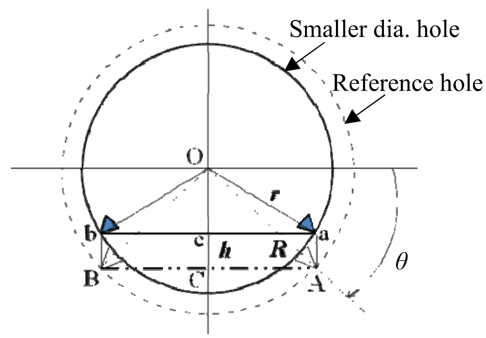


Fig.6: Inclinations at the end of a measurement bar

$d = e\cos\theta$

Fig.7: Influence of measurement unit inclination on measurement accuracy



A, B: Skid positions on reference hole
a, b: Skid positions after sliding up on wall of smaller diameter hole

Fig.8: Two skids positions when entering small hole

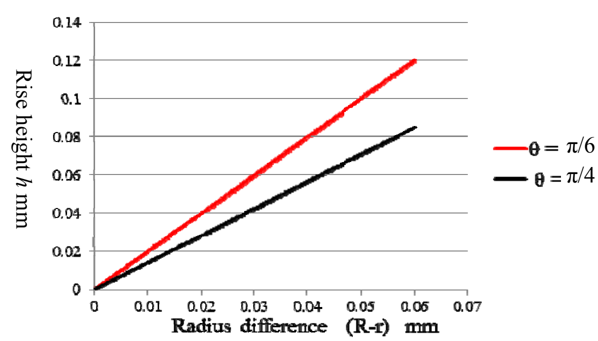


Fig.9: Relationship between skid rise and radius difference when entering small hole

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2R=63mm,the length of the longer axis of the oval is longer by 0.037 µm than diameter of the reference hole. The longitudinal shift δZ of the scanning location is Thislongitudinal shift does not affect the accuracy of the hole measurement.

3.2Effect of Changing the HoleSize

Figure 8shows that skids A and B slide up on the wall of a hole with a diameter less than that of the reference hole.R and $r$are the radii of reference and smaller diameter holes, respectively.R=31.5 mm,h is the height difference of the measurement unit when skids A and B slide up on the wall of a hole with a smaller diameter than the reference hole. From thePythagorean theoremfor a righttriangle, Eq. (5) can be obtained.

$$\overline{} \qquad (5)$$

Figure 9 shows the relationship between radius difference (R-r) and height of rise h, which is obtained from Eq. (3). The relationship is obtained when the position anglesθ areπ/6 and π/4 rad.When the radius difference is 0.06 mm, the skid rises are 0.12 mm and 0.085 mm at skid positions of π/6 and π/4, respectively. However, these values can be corrected using acquireddatathrough an optical device for detecting the attitude of the measurement unit behind the headstock (Figs. 2 and 3).

4. GUIDELINES FOR A SIMULATION EXPERIMENT

It is very difficult to carry out an experiment using a measurement bar with outer and innerdiameters of 50 and 24 mm, and a length of more than 3m in the laboratory. In this experiment, the workpice length, as well as the longitudinal feeding length,is 3 m. The total length of the machine becomes 7 to 8m when the headstock length is included. In order to carry out similarmeasurement experiment for a bar with a diameter of 50 mm and a length of 3m, a measurement bar with a diameter of 18mm is taken into consideration, because a bar with this diameter is easier to bend than onewith a diameter of 50mm.

4.1Calculation of Inclination Angle

Figure 10 shows a cantilever with a support at its end. At the location of 0.5785l mm from the fixed end, weight P is loaded. In these conditions, the inclination angle i of the free end and supporting force R on the free end are written as:

$$—(\ 3P \quad w \ \ +3R \ ) \qquad (6)$$

$$R= — \ [4P \quad (3 \quad a) + 3w \ \ ] \qquad (7)$$

Using Eqs. (6)and(7), measurement bar length l is determined under the condition that the slope angle $i$remains constant at 0.00109. Outer and inner diameters of the measurement bar are 18 mm and 12mm,

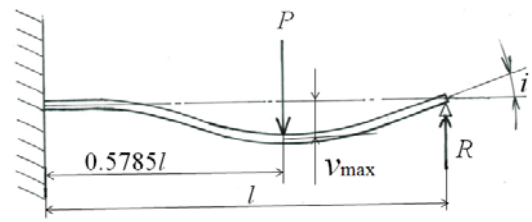

Fig.10: Cantilever with a support at free end.

respectively. The inclination angle atthe end of the

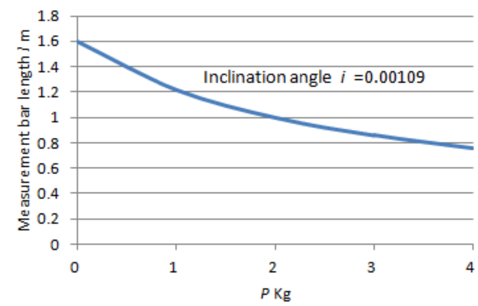

Fig.11:Relationship between load P and measurement bar length l

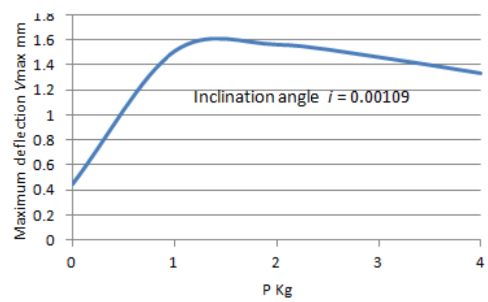

Fig.12: Relationship between load P and measurement bar deflection v_{max}

measurement bar with outer and inner diameters of 50

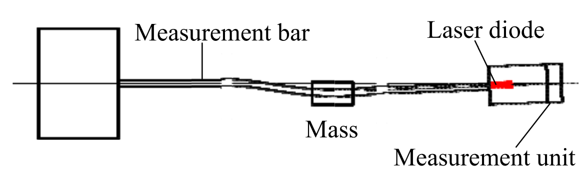

Fig.13: Simplified simulation model

and 24 mm, respectively, and length of 3m is 0.00109. The end of the measurement is supported.

4.2Determination of Load

Figure 11 showsthe relationship between the length l of the measurement bar and the load P.The length of the measurement bar for obtaining inclination angle i

(0.00109) at the supported end decreases exponentially as the load *P*increases.Figure 12 shows the relationship between the maximum deflection of a boring bar and the load *P*. When a 1 kg mass is loaded, the length and maximum deflection of the measurement bar are 1220 mm and 1.5 mm, respectively. Under thesemeasurement bar conditions, a simulation experiment using a lathe is easily carried out.

4.3Apparatus for a Simulation Experiment

The load *P* is applied by attaching a masstothe measurement bar. A laser diode is fixed in the measurement probe (Fig.13).The measurement probe consists mainly of a measurement unit, stepping motor, and laser diode. The hollow, slender measurement bar is also connected to the probe.

5. COMPARISON WITH LASER-GUIDED PROBE

A laser-guided deep-hole measurement system is particularly effective in cases wherethe holelength is quite large (Figs.1and 3(c)). The probe is always kept on the measurement axis by using six piezoelectric actuators, even though the hole diameter varies along the length of the hole. The probe's attitude is constantly monitored by the probe attitude detector and controlled so that the probe always remains on the measurement axis. In this case, high measurement accuracy levels can be obtained but the fabrication cost is very high.

On the contrary, the present probe is inexpensive to fabricate. By compensatingusing acquired data, accurate measurement can be obtained.

6. CONCLUSION

The accuracy of deep-hole measurementsis discussed for the regionwhere thebending rigidity of a measurement bar is low and the effects on measurement are easily compensated. The following results are obtained.

1. The developed system can measure the accuracy of ahole with a length of 3 mand diameter of 63 mm.
2. The effect of the changing attitude of the measurement unit on measuring accuracy is explained.
3. A method is presented for performing a simulation experiment by applyinga load and using a small measurement bar with outer and inner diameters of 18 mm and 12 mm, respectively.

In the future, we will focus onthe implementation of this method for measuring the accuracy of a deepholea few metersin length through simulation.

7. ACKNOWLEDGEMENT

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