Dimensional Measurement of a Curved Profile by the Sensor Positioning Control*

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A laser displacement sensor with the triangular method was applied to the measurement of dimensional errors of a curved profile. Three motors control the position of this laser sensor in the x , y , and θ directions to follow the curvature of the workpiece. Fuzzy-based positioning control was found to be effective for measuring curvatures. The measuring system has an accuracy of several micrometers.

Key Words: Dimensional Measurement, Fuzzy Positioning Control, Laser Displacement Sensor, Measurement of Curved Profile

1. Introduction

Geometrical adaptive control (GAC) is the control technique for stabilizing the dimensional accuracy and for improving the profile accuracy and surface roughness in machining. Several attempts have been undertaken to make the control technique feasible, which have been based on either electrical, mechanical, pneumatic, or optical techniques. With the ever-growing demand for precision machining, the optical measurement technique^{(1)–(5)} has been preferred for highly automated machine tools, because it is a non-contact technique and provides high resolution. A stochastic approach has also been applied to manufacturing processes as a promising technique⁽⁶⁾.

For a problem restricted to the dimensional measurement of a rotary workpiece, measurement based on an indirect method can easily be applied in actual production floor. In this technique, the workpiece diameter is evaluated indirectly from a "radius change" by measuring the relative displacement between the sensor and the workpiece. In most cases, such a system is simple to construct and there is some

possibility of applying it to complex shapes such as curvatures or stepped profiles. However, the disadvantage of this method is that the measurement depends on the accuracy of the machine tool itself.

This paper presents a method for measuring dimensional errors of a curved profile in turning, in which a laser displacement sensor and indirect measurement are used. The chief advantage of this method is that no physical equipment is required in the vicinity of the workpiece. To measure the workpiece's curvature, the position of the laser sensor is controlled along three axes, x , y and θ . This positioning control of the sensor is very important^{(7)–(8)}. Fuzzy control is also applied according to the variation in the curvature. Before measurement, the parallelism between the workpiece center and the laser sensor travel along the x axis was strictly arranged within $3\mu\text{m}$ to cover the disadvantage of an indirect measurement. The experiment was constructed off-line without rotating the workpiece and resulted in an accuracy of several micrometers over the entire length of the workpiece.

2. System Construction

Figure 1 is a schematic diagram of the hardware construction in which the workpiece is set parallel to the workpiece axis of a small benched-type lathe. The overall system consists of a commercially available laser displacement sensor, driving stages, three

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Fig. 1 Hardware construction

Fig. 2 Software construction

motors, and interfaces. A low pass filter with a cut-off frequency of 20 Hz is installed in the measuring circuit, which is an advantage in preventing response to surface irregularities of a short-term character. The laser sensor is driven by the three motors in the x , y , and θ directions as shown in Fig. 1 and is controlled by computer through RS-232C and GPIB communication interfaces. The computer and motors are connected to interfaces No. 1 and No. 2. The resolution of the laser sensor and each driving part is that $0.5 \mu\text{m}$ (laser sensor), $10 \mu\text{m}$ (x -motor), $2 \mu\text{m}$ (y -motor), and 0.1° (θ -motor).

Figure 2 shows the software set up for controlling the system. The main functions are a system run which includes a run of the interface between the computer and the operator, a control strategy, and a system pause. While the system is running, each function, e.g. an update of results obtained, can be chosen at any time.

3. Measuring Method

The sensor is a commercially available semi-conductive type laser displacement sensor. A triangular method is used for evaluating workpiece profile errors. The resolution is about $0.5 \mu\text{m}$ at a wavelength

Fig. 3 Characteristic of a laser sensor

Fig. 4 Measuring principle of a curvature

of 670 nm and the spot size is a maximum of 0.2 mm. Figure 3 shows characteristics of the sensor when the object has an inclination angle of -20° to $+20^\circ$. The measured distance is proportional to the actual distance when the inclination angles are the same. This implies that the measuring error is the same if the inclinations are the same within the range shown in Fig. 3. However, a larger inclination affects the measurements. Preliminary experiments show that the limit for the inclination angle is around $\pm 20^\circ$ for this sensor. The increase of inclination angle indicates a slow declination characteristic of curves in comparison with Fig. 3.

Figure 4 illustrates the principle for measuring curvature based on the characteristic given in Fig. 3. In theory, if the inclination angle of a workpiece is within -20° to $+20^\circ$, the profile can be measured precisely. An error beyond these limits should be considered in regard to the whole system to determine whether it has a large influence or not. When the laser beam is perpendicular to the object surface, the intensity of the reflected light is greatest. The relationship between the laser beam and the object surface

Table 1 Control variables of $\Delta\theta$ and X_{step}

$\Delta\theta$	-3	-2	-1	0	1	2	3
X_{step}	3	2	1	0	-1	-2	-3

Fig. 8 Block diagram of a fuzzy control

Fig. 9 Membership function for fuzzy control

$$\{X_{step}\} = \{NB, NS, O, PS, PB\}$$

where

NB: negative large

NS: negative small

O: zero

PS: positive small

PB: positive large

The interval $\Delta\theta = \{0^\circ, 30^\circ\}$ changes according to the fuzzy set in the range of $X (= \Delta\theta \text{ or } X_{step}) = \{-3, -2, -1, 0, 1, 2, 3\}$. The membership function (μ) in this case is shown in Fig. 9, where the control strategy is determined as follows:

If $\Delta\theta$ is NB, then X_{step} is PB

If $\Delta\theta$ is NS, then X_{step} is PS

If $\Delta\theta$ is O, then X_{step} is O

If $\Delta\theta$ is PS, then X_{step} is NS

If $\Delta\theta$ is PB, then X_{step} is NB

The control law, given in Table 1, is that when an X_{step} is large enough to pass an irregular point, then the control algorithm sets the X_{step} as a small one again.

5. Experimental Results

All the tests were conducted on aluminum bars, 350.5 mm in length, supported by the tail stock. A typical workpiece profile and an example of its measurement results are shown in Fig. 10. In order to compare with the fuzzy control, the interval control of X_{step} is also accomplished with the same workpiece. Because the larger the interval X_{step} is, the lower the measuring accuracy is, and vice versa.

(a) Dimension of a workpiece

(b) $X_{step} = 2$ mm, time = 514 s

Fig. 10 Experimental result

(a) Concave profile

(b) Convex profile

Fig. 11 Close up view of Fig. 10

Three measurements were accomplished:

(a) a large step of $X_{step} = 2$ mm with a measuring time of 514 seconds,

(b) a minimum step of $X_{step} = 0.5$ mm with a measuring time of 1 152 seconds,

(c) a fuzzy control with steps from 0.5 mm to 2 mm with a measuring time of 624 seconds, by adjusting the steps of the measuring system subject to the change of a curvature.

Figure 10(a) shows the dimensions of the workpiece and Figure 10(b) shows the measurement result of 10 (a). To evaluate three measurement results clearly, close measurement views of the concave and convex profiles are illustrated in Figs. 11(a) and 11(b). In the convex profile, the measurement result by fuzzy

control shows the same trace with a minimum step of $X_{\text{step}}=0.5$ mm which can provide a highest accuracy among three methods. The measuring time in that case is, however, a half of the minimum step method. These results show that the large step saves measuring time, but sacrifices measuring accuracy. Fuzzy control is especially effective in measuring concave profiles by saving measuring time and, at the same time, by keeping measuring accuracy, as illustrated in Fig. 11(a).

Owing to the use of a low pass filter, the measurements are not seriously affected by roughness values. The problem is the robustness to the change of workpiece properties such as color and glossiness. Generally, to avoid these effects, the ratio measurement is performed by taking the ratio of, for example, the specular intensity to the intensity at one off-specular angle. This method theoretically cancels the change of workpiece properties between the numerator and the denominator but does not exactly succeed in the practical system. Therefore, the measurement system needs a set of calibration when a workpiece material is changed.

6. Summary

A commercially available laser displacement sensor which has a measurement limitation for the inclination angle of $\pm 20^\circ$ was used to evaluate the dimensional errors of the curved profile of workpieces. To measure the profile, the laser sensor is driven by using three motors in the x , y , and θ directions. The measuring step and the interval along the x axis is very important for this measurement. Fuzzy control was used for the positioning the laser sensor along the curvature of the workpiece. The experimental results show that the measuring system can be applied to workpieces having inclination angles of up to around $\pm 20^\circ$. The system has a measuring accuracy of several micrometers.

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