In-process roundness measurement system for cylindrical machine parts of small diameter with run-out error compensation

Ryuichi YAMADA*, Takanori TAKEI**, Kazuhisa YANAGI**
*Nagaoka National College of Technology, Department of Mechanical Engineering, Nishikatakai 888, Nagaoka, 940-8532, Japan
**Nagaoka University of Technology, School of Mechanical Engineering, Kamitomioka 1603-1, Nagaoka, 940-2188, Japan

Introduction
A number of cylindrical machine parts of small diameter are widely used in the information storage devices and information processing instruments. The functional performances of such devices can be attributed to the overall accuracy of those mechanical components. It has been demanded that the diameter error and out-of-roundness of the cylindrical machine parts are small enough from a practical point of view. Quality control technology in the production line is an issue to meet the requirement. Not only the geometrical accuracy of the products but also the mechanical accuracy of the machine tools are important. An objective of our study is to develop an in-process measurement system which can evaluate both the roundness of turned cylinder and the rotational error of lathe spindle. Cylinders to be measured are smaller than 2 mm in diameter and the target measurement accuracy of the system is the range of sub-micrometer.

Measurement principle
The measuring instrument of the developing system consists of three optical sensing units. Each unit has a parallel light beam and twin photo diodes to detect the asymmetrical beam power distribution. The parallel light beam is produced using a super luminescent diode (SLD) and a collimator lens. A cylindrically turned work is set within the crossing of the three light beams, where two of them are orthogonal. The work displacement perpendicular to each beam axis can be detected from the difference signal of the related twin photo diodes. Then the run-out locus of the work can be drawn as a Lisajous figure using the two orthogonal sensing units. As to the roundness measurement of the work itself, so-called V-block method was adopted. The two sensing units may be regarded as an optical virtual V-block and the remaining sensing unit as a tangential type displacement sensor. Following the measuring principle of the V-block method, the roundness profile can be evaluated by knowing a series of correction factors for the corresponding numbers of undulation per revolution. A practical design procedure for the optical and mechanical configuration was shown in Fig. 1.

Fig. 1  Schematic of measurement system
Effect of setting angle of the optical axes on the fluctuation of the correction factors

In roundness measurement by the V-Block method, the correction factor $\mu$ depends on the number of undulation per revolution of measured signal. When the value of $\mu$ is small, the signal of its undulation per revolution is reduced, and the measurement becomes difficult. Then, the effect of the measurement noise becomes easy to be received. The correction factor is expressed by the equation (1)

$$\mu_{n,\alpha,\beta} = \sqrt{\left(1 + l_{n,\alpha,\beta}\right)^2 - f_{n,\alpha,\beta}}$$

(1)

where

$$l_{n,\alpha,\beta} = \left[\cos\beta \cos\left(n \frac{\pi + \alpha}{2}\right)\right] \cos n\beta - \left[\sin\beta \sin\left(n \frac{\pi + \alpha}{2}\right)\right] \sin n\beta$$

$$f_{n,\alpha,\beta} = \left[\cos\beta \cos\left(n \frac{\pi + \alpha}{2}\right)\right] \sin n\beta - \left[\sin\beta \sin\left(n \frac{\pi + \alpha}{2}\right)\right] \cos n\beta$$

In equation (1), $\alpha$ is the angle which forms V-Block, and $\beta$ is a tilting angle of displacement sensor in making bisector of $\alpha$ to be base line. $\alpha$ and $\beta$ are shown in Fig. 1.

In this study, $\alpha$ was fixed at 90°, because run-out error and roundness profile are measured simultaneously. After the decision of $\alpha$ value, adequate $\beta$ was examined. Concretely, $\beta$ at which a series of correction factors became over 0.5 was searched under the condition that the numbers of undulation per revolution were from 2 within 20. As a result, it satisfied this condition that the absolute values of $\beta$ are 3.7° ~ 7.3°. For 3.7° $\leq \beta \leq 7.3°$, a series of correction factors for the numbers of undulation per revolution was calculated. The results are shown in Fig. 2 and Fig. 3. The 19th undulation per revolution has the biggest fluctuation of a series of correction factors. However, the deviation of the value of $\mu$ is about 0.15 and small enough when the value of $\beta$ is deviated by 0.5°.

**Fig. 2 Correction factor**

**Fig. 3 Correction factor (UPR19)**

Selection of the light source

It is supposed that this measuring instrument measures cylindrical parts of 2 mm diameter or less. Therefore, light source of the good blocking-off property was necessary when a pin gage was inserted on the cross section of light beam.

SLD was selected as a light emitting device which is able to satisfy above-mentioned property. SLD generates the stimulated emission light similarly to LD (Laser diode) and possesses fairly good wavelength-
selectivity. However, it is an incoherent light source because there is no resonator. It has medium luminescent characteristics between LED and LD.

The intensity distribution along a normal line passing through the optical axis was measured for SLD and LED. (The distance from the devices was 35 mm.) From the experimental results shown in Fig. 4, we can see that SLD gives the maximum intensity near the optical axis and high frequency components with small amplitude are superimposed. For the case of LED, the intensity distribution is almost flat. When a pin gage was inserted on the cross section of light beam, the blocking-off property of SLD seems to be much better than LED as shown in Fig. 5. It is obvious that SLD is suitable for the measurement of pin gage displacement in the horizontal direction, if the output signal and the displacement are practically linear to each other.

![Fig. 4 Intensity of light beam](image)

![Fig. 5 Intensity of light beam cut off by pin gage of the 1 mm diameter](image)

**Modulation of the light source**

To avoid the interference of the three light sources to each other, the lock-in measurement technique was adopted. First, the signal to be detected is distinguished from the noise by giving a modulation. Then, by synchronizing the modulated signal to the reference signal, the noise can be removed, and only desired frequency component is functionally taken out.

The electronic circuit structure for this measurement is shown in Fig. 6. Function generator (MAX038) makes the square wave signal arise. This signal is used for the modulation of the light source and also as the reference signal of the phase detector (CD-505R2). First, the phase detector amplifies modulated signal, and it does the BPF processing. The BPF processing removes odd number harmonics by the square wave modulation. After the synchronization by the phase sensitive detector (PSD), the desired displacement signal can be obtained through a low pass filter (LPF).
Measurement Result

Since the modulation limit of SLD light source is 10kHz, the modulation frequencies of 5, 7 and 9 kHz were adopted for the three beams. These can be no interference among the higher harmonics. The output signals of twin photo diode against pin gage position (1 mm in diameter) are shown in Fig. 7 respectively corresponding to three modulation frequencies. The distance between the pin gage and the twin photo diodes to detect was 15 mm, and that between the pin gage and SLD was 20 mm. The three cases in Fig. 7 show good linearity between the output signal and the pin gage position. Therefore, the run-out error can be measured from the difference signal of two twin photo diodes which are set orthogonal, and the roundness profile can be obtained by harmonic analysis of the output signal from the corresponding diode.

Conclusions

(1) An in-process roundness measurement system for cylindrical machine parts of small diameter with run-out error compensation was proposed.
(2) The adequate arrangements of the sensing units were found out theoretically for the measurement of roundness profile and run-out error simultaneously.
(3) The blocking-off property of SLD by a pin gage is much better than LED, and so SLD is suitable for the in-process roundness measurement.
(4) The lock-in measurement technique was utilized so that the three light sources might not functionally interfere to each other.

Reference