

# Development of an Optical Measuring Device for Rotation Accuracy of Micro-Spindle - Application to Measurements of a High-Speed Spindle -

Kengo Fujimaki, Kimiyuki Mitsui  
Keio University

Keywords: Micro-spindle, Rotation accuracy, Run-out, Optical measuring method

## Abstract

It is very difficult to measure the rotation accuracy of miniaturized spindles running at high-speed with a common measuring method which uses capacitive displacement sensors. Therefore the authors have proposed a new optical measuring method using a small reflection sphere as a measurement target. In this paper, the basic principle of the optical measuring method, the configuration of the measuring device and some of the measurement data are shown.

## 1 Introduction

The measurement of the spindle rotation accuracy is very important to verify the machining accuracy. Some measuring methods for the rotation accuracy of spindles have been proposed [1]-[14], but a measuring method for micro-spindles, which are miniaturized spindles, has not yet been established. A common measuring method uses capacitive displacement sensors and a master target, which is a high-precision ball or cylinder. However, the target attached to a micro-spindle must be small to avoid an unbalance of the spindle. In addition, capacitive displacement sensors have limitations in the applicable radius of the target [15] and are not suitable for measuring the displacement of a small target at ultra-high speed. One of the authors has developed an optical measuring method based on Holster's method [16], which evaluates the rotation accuracy by the movement of a reflected light beam from a concave mirror attached to the spindle end [17]. However, it is difficult to obtain a small and precise target and to attach it accurately to a spindle. Therefore, we have proposed a measuring method using a reflection sphere as the measurement target. For reference's sake, a similar system has been proposed for a dimensional position measurement of the CMM (coordinate measuring machine), and so on [18]. To be precise, the run-out of the spindle axis is composed of three components, which are the radial motion, the axial motion and the angular motion [19]. In this study, the measurement of the run-out composed of the radial motion and the angular motion at a point has been targeted.

In this paper, first we describe the principle of the optical measuring method and the configuration of the trial device. Then, we show some of the results of measurements with a small steel ball and a high-speed, high-precision spindle.

## 2 Measurement Principle

Figure 1 shows the optical layout of the measurement system. A target sphere is attached to the spindle end. First, the collimated laser beam goes through a beam splitter and an objective lens, and then it is reflected on the surface of the target sphere. The reflected beam goes through the lens again and is reflected by the beam splitter. Finally, it enters a quadrant photo diode (QPD). The QPD consists of four photo cells and can sense the parallel displacement of an optical spot by the difference between the outputs of each photo cell. The outputs  $V_x$  and  $V_y$  of the QPD in the directions  $X$  and  $Y$  are shown as follows with the outputs  $S_1, S_2, S_3, S_4$  of the photo cells.

$$V_x = \frac{S_1 - S_2 - S_3 + S_4}{S_1 + S_2 + S_3 + S_4} \quad (2.1)$$

$$V_y = \frac{S_1 + S_2 - S_3 - S_4}{S_1 + S_2 + S_3 + S_4} \quad (2.2)$$

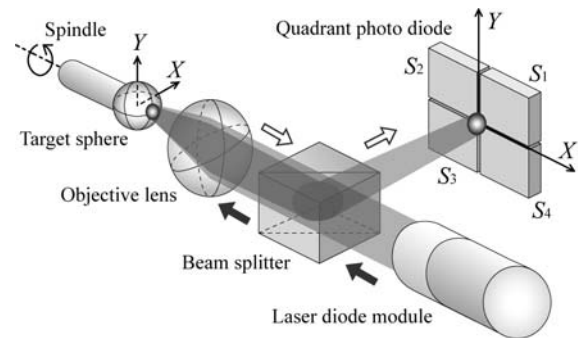


Fig. 1. Optical layout of the measurement system

Figure 2 shows an example of the relationship between the displacement  $\epsilon_x$  of the target sphere in direction  $X$  and the output  $V_x$ . It is found that this curve is non-linear, but it can be regarded as a linear curve near  $\epsilon_x = 0 \mu\text{m}$ . Therefore, the run-out of the spindle is expressed as the output divided by the measurement sensitivity  $K$ , which is the slope of the characteristic curve near  $\epsilon_x = 0 \mu\text{m}$ .

K. Fujimaki and K. Mitsui

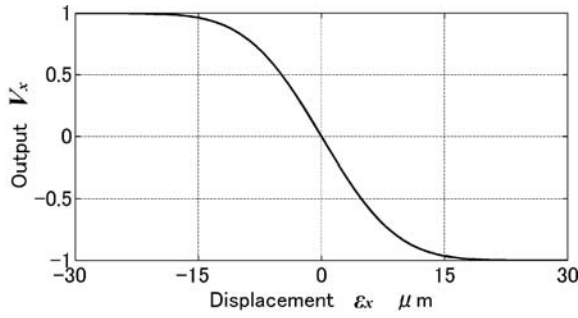


Fig. 2. An example of a characteristic curve of the output

In this measuring method, the resolution and the response speed is very high because the QPD is used as a position detector of the optical spot. And, a small sphere can be targeted because the laser beam is condensed by the objective lens. Therefore, this measuring method is suitable for evaluating the rotation accuracy of micro-spindles.

### 3 Analysis of the Basic Characteristics

Here, the analysis of the basic characteristics of this measurement system is described. It is assumed that the movement of the optical spot on the QPD follows a parallel displacement in proportion with the displacement of the target sphere.

The displacement rate  $k$  is given by the following equation.

$$k = \frac{\text{displacement of optical spot on QPD}}{\text{displacement of target sphere}} \quad (3.1)$$

Figure 3 shows the light intensity distribution on the QPD. This is a Gaussian distribution with radius  $r$  when the displacement of the target sphere in the direction  $X$  is  $\epsilon_x$ . The light intensity distribution  $I$  is

$$I(x, y) = I_0 \exp\left(-\frac{2}{r^2} \left\{ (x - k\epsilon_x)^2 + y^2 \right\}\right) \quad (3.2)$$

Here, the peak  $I_0$  of the light intensity distribution is expressed as the following, where  $P$  is the light power.

$$I_0 = \frac{2P}{\pi r^2} \quad (3.3)$$

In addition, the light power  $P$  is

$$P = S_1 + S_2 + S_3 + S_4 \quad (3.4)$$

The output  $V_x$  of the QPD in the direction  $X$  is derived as the following with the above equations.

$$\begin{aligned} V_x &= \frac{S_1 - S_2 - S_3 + S_4}{S_1 + S_2 + S_3 + S_4} \\ &= \frac{2 \int_{-\infty}^{\infty} \int_0^{\infty} I(x, y) dx dy - P}{P} \\ &= \frac{2}{r} \sqrt{\frac{2}{\pi}} \int_0^{\infty} \exp\left(-2 \frac{(x - k\epsilon_x)^2}{r^2}\right) dx - 1 \end{aligned} \quad (3.5)$$

Therefore, the differentiation of  $V_x$  with respect to  $\epsilon_x$  is

$$\frac{dV_x}{d\epsilon_x} = 2\sqrt{\frac{2}{\pi}} \frac{k}{r} \exp\left(-2 \left(\frac{k\epsilon_x}{r}\right)^2\right) \quad (3.6)$$

Because this is constant at  $|k\epsilon_x| \ll r$ , the measurement sensitivity  $K$  is expressed with the radius  $r$  of the optical spot on the QPD and the displacement rate  $k$ .

$$K = 2\sqrt{\frac{2}{\pi}} \frac{k}{r} \quad (3.7)$$

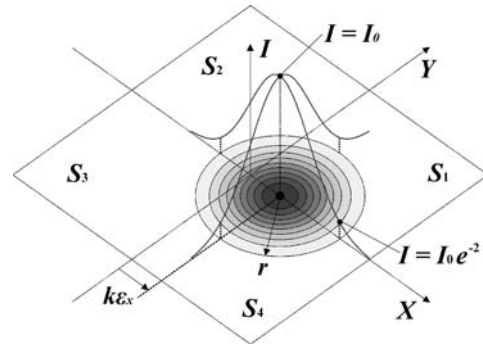


Fig. 3. Light intensity distribution on the QPD

Figure 4 shows the characteristic curve of the QPD in the direction  $X$ , which is computed by the numerical integration in Equation (3.5). The reason that this curve inverts in comparison with Figure 2 is that an optical spot on the QPD normally moves in a direction opposite to the target sphere.

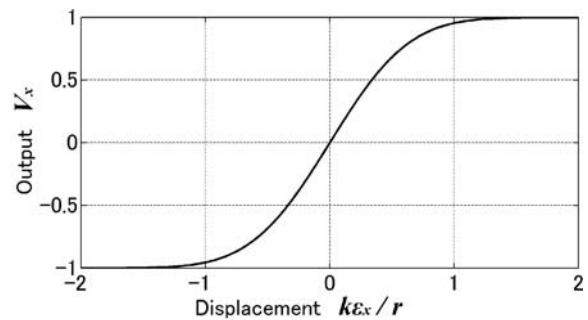


Fig. 4. Characteristic curve of the output in the direction  $X$  on the QPD

## Development of an Optical Measuring Device for Rotation Accuracy of Micro-Spindle

The values  $r$  and  $k$  are derived as follows by geometric optics theories with five parameters, which are the radius  $R$  of a target sphere, the focal distance  $f$  of an objective lens, the beam radius  $r_0$  of a light source, the distance  $L_s$  between a QPD and an objective lens, and the distance  $L_t$  between an objective lens and the center of a target sphere. At  $\varepsilon_x \ll R$ ,

$$k = \frac{2}{fR} \{ (L_s - f)(L_t - R) - fL_s \} \quad (3.8)$$

$$r = \left| r_0 - 2(L_t - f) \left\{ \left( \frac{L_s}{f} - 1 \right) (x_B - L_t) + L_s \right\} \frac{ \left\{ (f^2 + r_0^2) x_B - r_0^2 (L_t - f) \right\} }{ 2r_0^2 (L_t - f) x_B - 2r_0^2 (L_t - f)^2 + f^2 R^2 } \right| \quad (3.9)$$

Here,  $x_B$  is

$$x_B = \frac{r_0^2 (L_t - f) + \sqrt{(f^2 + r_0^2) f^2 R^2 - f^2 r_0^2 (L_t - f)^2}}{f^2 + r_0^2} \quad (3.10)$$

### 4 Validation Testing

The configuration of the optical measuring device is shown in Figure 5. This is almost the same layout as in Figure 1. The outputs from the photo cells of a QPD are faint current signals and must be converted to voltage signals by trans-impedance amplifiers before being sampled by the A/D converter. Therefore, the QPD and amplifier ICs are placed on one circuit board because the outputs are susceptible to electric noises between the QPD and the amplifiers. The response frequency is about 1 MHz after considering the specifications of these electronic components. Calculations of Equations (2.1) and (2.2) are done on a PC.

In this paper, a high-speed, high-precision spindle is used as the measuring object in order to validate the measuring results of this trial device; this method is compared with the conventional method, which uses a high-precision master ball and two capacitive displacement sensors.

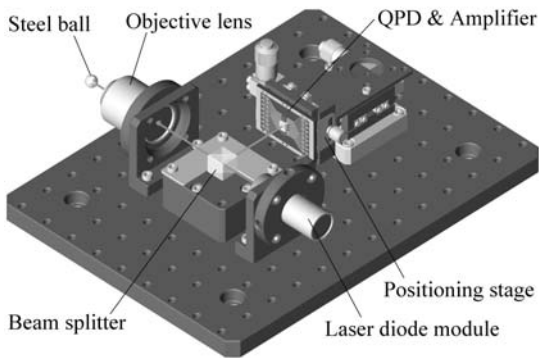


Fig. 5. Configuration of the optical measuring device

Figure 6 shows the simultaneous measurement method in the optical measuring device and the capacitive displacement sensors. The measurement sensitivity  $K$  of the optical measuring device is  $-0.20 \mu\text{m}^{-1}$ , and the resolution is about 3 nm. In addition, the steel ball has a diameter of 11.90 mm, the spindle speed is 2447 rpm and the sampling frequency of the A/D converter is 1 MHz. The resolution of the capacitive displacement sensor is 3 nm and the response frequency is 40 kHz.

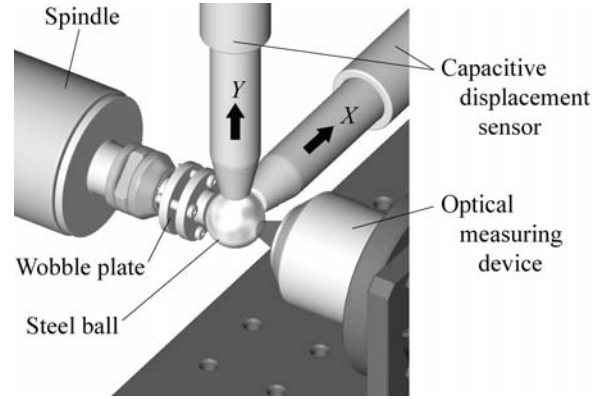


Fig. 6. Simultaneous measurement in the optical measuring device and the capacitive displacement sensors

Figure 7 shows the results of the run-out in the directions  $X$  and  $Y$ , simultaneously measured by the optical measuring device and the capacitive displacement sensors. Figure 8 shows the trajectories of the center of the steel ball. The frequency components above 30 upr (undulations per revolution) in these results have been cut off. Considering that the results measured by the capacitive displacement sensors could have errors of about  $0.08 \mu\text{m}$ , which is the sphericity of the steel ball, the result of the optical measuring device is in excellent agreement with the result of the capacitive sensors. The differences between these results are about  $0.1\text{--}0.2 \mu\text{m}$  at a maximum. Therefore, the accuracy of the optical measuring device is at least on a sub-micrometer order.

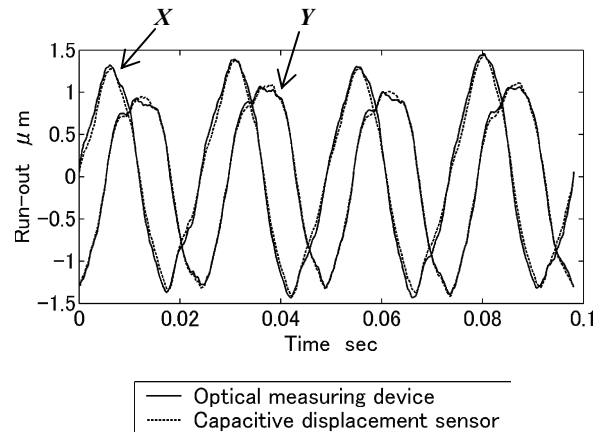
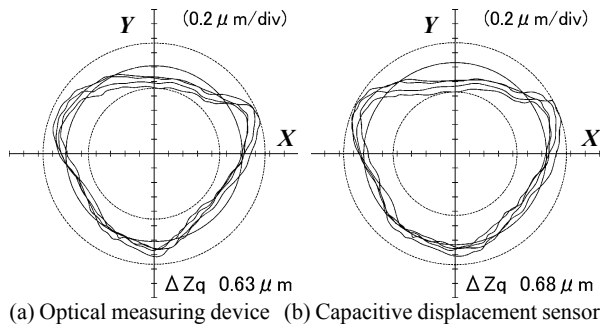


Fig. 7. Comparison of the measurement results of the run-out (4 revolutions)

K. Fujimaki and K. Mitsui

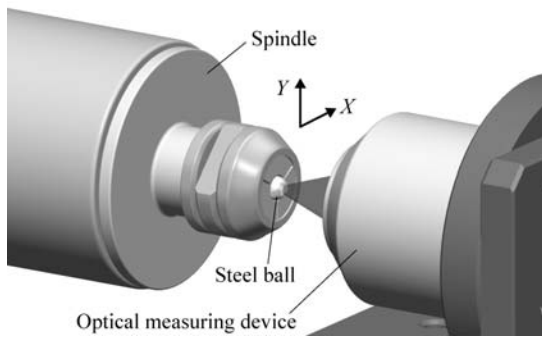


**Fig. 8.** Measurement results of the run-out (Lissajous display, 4 revolutions)

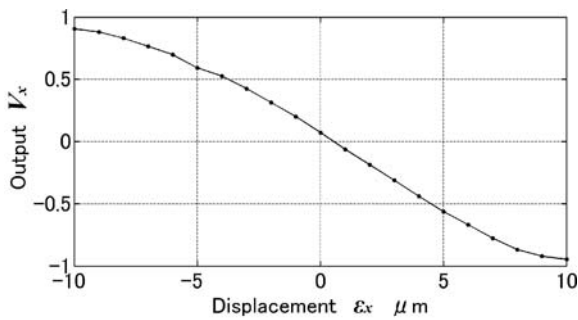
## 5 Measurement of a High-speed Spindle

The validation of the optical measuring device mentioned above was made by measuring the spindle running at about 2000 rpm. Here, the optical measuring device is applied to the spindle running at a much higher speed.

A small steel ball of diameter 3 mm is attached to the collet chuck of the high-speed, high-precision spindle (Figure 9). This condition is almost the same as that for the measurement of the micro-spindle. The characteristic curve of the output with respect to the displacement  $\varepsilon_x$  of the spindle in the direction  $X$  is shown in Figure 10, and the measurement sensitivity is  $-0.11 \mu\text{m}^{-1}$ . The resolution evaluated by the bit number and the input range of the A/D converter is about 7 nm.

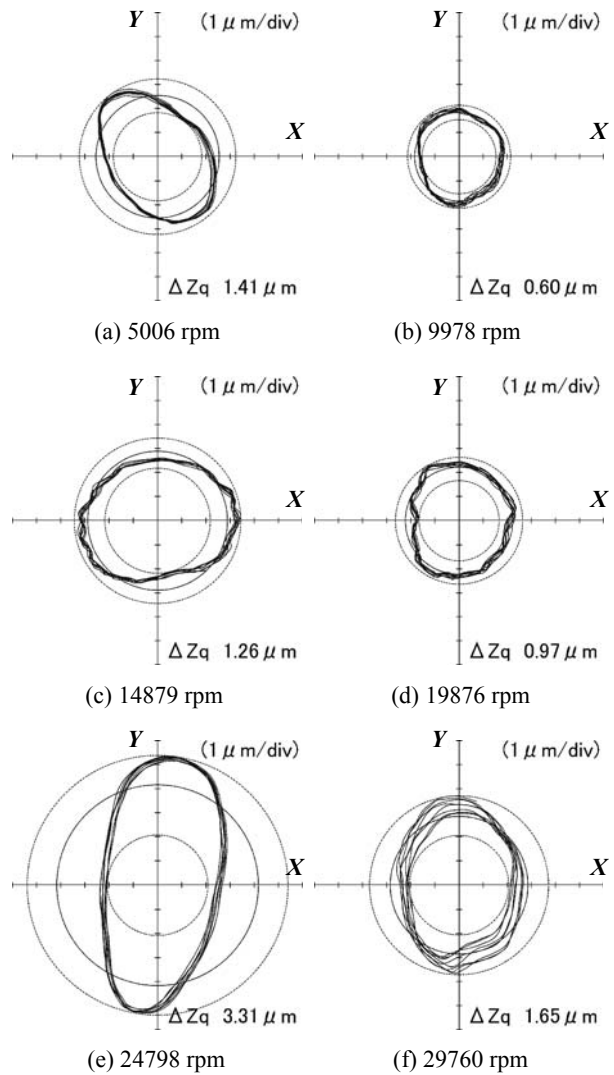


**Fig. 9.** Measurement using a small steel ball



**Fig. 10.** Characteristic curve of the output

Figure 11 shows the measurement results of the run-out at a rotational speed of about 5000-30000 rpm in increments of about 5000 rpm, where the cut-off frequency is 30 upr. Because the validity of the optical measuring device at a low rotational speed has been verified and the response speed is enough, it can be regarded that this optical measuring device can measure the rotation accuracy of a high-speed, high-precision spindle attached to a small steel ball, which is almost the same in measurement conditions as those for a micro-spindle. Here, because a wobble plate is not used, unlike in the above validation testing, the eccentricity of the steel ball has widened.



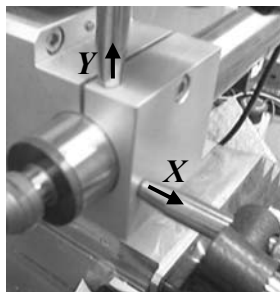
**Fig. 11.** Measurement results of the run-out (Lissajous display, 8 revolutions)

The results of the measurement of the vibration of the spindle holder by the capacitive displacement sensors (Figure 12) are shown in Figure 13. From these results, it is found that the spindle vibrates mechanically at high rotational speeds, and this is the reason that some of the results in Figure 11

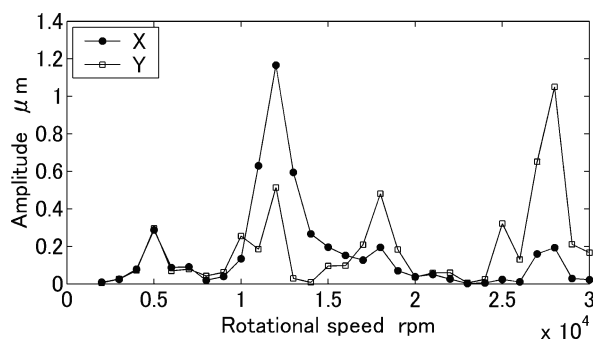


## Development of an Optical Measuring Device for Rotation Accuracy of Micro-Spindle

show elliptical trajectories. Therefore, the holding method of the spindle should be reconsidered in future work in order to measure the pure run-out of the spindle running at a high rotational speed.



**Fig. 12.** Measurement of the vibration of the spindle holder by the capacitive displacement sensors



**Fig. 13.** Vibration of the spindle holder with respect to the rotational speeds

## 6 Conclusions

In this paper, the principle of the measurement method for the rotation accuracy of micro-spindles has been described, and the results of the analysis and experiments have been shown. The results are summarized as follows.

1. With the analysis of the light intensity distribution, it was derived that the characteristic curve of the output in this optical measuring method is determined by the displacement rate and the radius of an optical spot on the QPD.
2. It was shown that the displacement rate and the radius of an optical spot on a QPD can be expressed by five parameters of the optical system.
3. By integrating the QPD and high-speed amplifier ICs into one circuit board, the reduction of noises and the high-speed response of output signals were realized.
4. The validity of the optical measuring device was verified by the simultaneous measurement with capacitive displacement sensors. The accuracy of this trial device was at least on the order of sub-micrometers.

5. By applying the optical measuring device to a high-speed, high-precision spindle attached to a small steel ball, which is almost the same in measurement conditions as those for a micro-spindle, it was shown that the optical measuring device can measure the rotation accuracy of a micro-spindle.

## 7 References

- [1] R. R. Donaldson : A Simple Method for Separating Spindle Error from Test Ball Roundness Error, *Ann. CIRP*, Vol.21, No.1 (1972) pp.125-126.
- [2] K. Mitsui : Development of a New Measuring Method for Spindle Rotation Accuracy by Three Points Method, *Proc. Int. Mach. Tool Des. Res. Conf.*, Vol.23rd, (1983) pp.115-121.
- [3] P. D. Chapman : A Capacitance based Ultra-precision Spindle Error Analyser, *Prec. Eng.*, Vol.7, No.3 (1985) pp.129-137.
- [4] H. Shinno, K. Mitsui, Y. Tatsue, N. Tanaka, T. Omio and T. Tabata : A New Method for Evaluating Error Motion of Ultra-Precision Spindle, *Ann. CIRP*, Vol.36, No.1 (1987) pp.381-384.
- [5] N. Ozawa, Y. Okazaki, Y. Kitamura, T. Kohno and K. Mitsui : A New Measuring Method for Spindle Error Motion Using a Cube-corner Prism and Laser Interferometers, *Proc. of the 28th International MATADOR Conf.*, (1990) pp.515-521.
- [6] G. X. Zhang and R. K. Wang : Four-Point Method of Roundness and Spindle Error Measurements, *Ann. CIRP*, Vol.42, No.1 (1993) pp.593-596.
- [7] G. X. Zhang, Y. H. Zhang, S. M. Yang and Z. Li : A Multipoint Method for Spindle Error Motion Measurement, *Ann. CIRP*, Vol.46, No.1 (1997) pp.441-445.
- [8] E. Marsh, R. Grejda : Experiences with the Master Axis Method for Measuring Spindle Error Motions, *Prec. Eng.*, Vol.24, No.1 (2000) pp.50-57.
- [9] W. Gao, S. Kiyono, E. Satoh : Precision Measurement of Multi-Degree-of-Freedom Spindle Errors Using Two-Dimensional Slope Sensors, *Ann. CIRP*, Vol.51, No.1 (2002) pp.447-450.
- [10] H. J. Ahn, S. Heon, D. C. Han : Error Analysis of the Cylindrical Capacitive Sensor for Active Magnetic Bearing Spindles, *Trans. ASME J. Dyn. Syst. Meas. Control*, Vol.122, No.1 (2000) pp.102-107.
- [11] C. H. Liu, W. Y. Jywe and H. W. Lee : Development of a simple test device for spindle error measurement using a position sensitive detector, *Meas. Sci. Technol.*, Vol.15, No.9 (2004) pp.1733-1741.
- [12] W. Y. Jywe and C. J. Chen : The development of a high-speed spindle measurement system using a laser diode and a quadrants sensor, *Int. J. of Mach. Tools Manuf.*, Vol.45, No.10 (2005) pp.1162-1170.
- [13] C. H. Liu, W. Y. Jywe, Y. S. Lin and S. C. Tzeng : Development of a novel optical measurement system for the error verification of a rotating spindle, *Opt. Eng.*, vol.44, No.9 (2005) pp.097003.1-097003.6.