High-Precision Angle Measuring Technology and High-Precision Angle Sensor

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High-resolution and high-precision angle sensors are expected for nanotechnology control system. The technology for manufacturing high-precision disks, and the measurement evaluation technology through the angle calibration system, and the development of a high-resolution optical angle sensor with high-precision and a self-accuracy calibrating function was achieved. This was accomplished using fundamental technology such as the high-precision disk that forms the core part of the angle sensor, and a high-precision measuring instrument and the self-calibrating technology of an angle sensor. A high-precision angle calibration system and a high-precision angle sensor with a resolution of 0.001 seconds were achieved.

Keywords: 2-dimensional length measurement; High-precision disk; Angle calibration apparatus; Self-accuracy calibration; High-precision angle sensor

1. Introduction

The measurement resolution of 0.001 seconds is essential for angle sensors used in nanotechnology control systems. The component engineering for realizing the measurement of 0.001 seconds consists of six types of technology: (1) High-precision technology with disk accuracy of 0.3 seconds accuracy disk [1], (2) the CAE (Computer Added Engineering) analysis technology for the mechanism section and high-precision coupling technology, (3) the signal dividing technology developed using R/D (Resolver / Digital Conversion) technology, (4) accuracy compensation technology through the efficient use of ROM, (5) the self-accuracy calibration technology of the angle sensor by itself, and (6) the high-resolution angle calibration system technology for 0.001 seconds and self-accuracy calibrating reproducibility for 0.005 seconds. These engineered components achieved a high-resolution of 30 bits and a high accuracy angle sensor. Furthermore, a new technology that generates multi-rotation signal, speed, and angular-acceleration data within the sensor was developed and high speed bi-directional serial bus communication with a control system was achieved. An angle of 1 ms is equivalent to a resolution of one billion and a 10^9 nano-resolution. This angle is equivalent to that of the observation of the height of a person located on the moon. This high-resolution of 1 ms is equal to the length of 0.5 nm on a circle of 100 mm. A ball screw with a 10 mm pitch is equivalent to the resolution length of 0.01 nm. Thus the nanotechnology control system becomes achievable.

In order to pursue the construction of an ideal angle sensor, high-precision compositions were developed along with an evaluation measuring instrument, accuracy compensation technology, signal dividing technology for high-resolution, and less wire high-speed signal communication technology.

This paper describes high-precision angle measurement technology focusing on the high-precision (1) angle evaluation measurement system, (2) self-accuracy calibrating angle sensor, and (3) 2-dimensional length measurement technology for disks. The high-precision technology for the nanotechnology control system and the advanced features were obtained by this study.

2. Technical outline of angle measurement

2.1. Application and features and principle of angle sensors

There are two types of angle sensors, one is an optical encoder and others are electromagnetic-induction type resolver. A high-precision angle sensor has been expected for nanotechnology systems for several years. Nanotechnology systems can be applied in several areas such as the semiconductor field and scientific-optical apparatus, space observation, etc. In field applications, higher precision is expected. An encoder is an angle sensor in which high-precision can be realized. A 30-bit encoder out line is shown in Fig. 1.

2.2. Types and accuracy of angle calibration system

When developing a high-precision angle sensor, precise evaluation of accuracy is of great importance. Generally, an accuracy of 100 times is required for the resolution and that of 10 times is essential for the measured angle sensor. In order to measure the angle sensor with an accuracy of 0.1 seconds, it is necessary for the measuring device to have an accuracy of 0.01 seconds and a resolution of 0.001 seconds.

Although there are several measuring instruments such as the autocollimator, the circular dividing table, etc., the angle sensor with an accuracy of 0.1 seconds could not be evaluated because of lengthy measuring time, limited measurement points, and the error of the criteria angle sensor being included in the measurement. Further, an angle measuring device that can evaluate the angle sensor with an accuracy of 0.01 seconds has been developed by this study.

It became possible to develop a high-precision disk, high-precision coupling, and high-precision angle sensor using this measuring instrument.

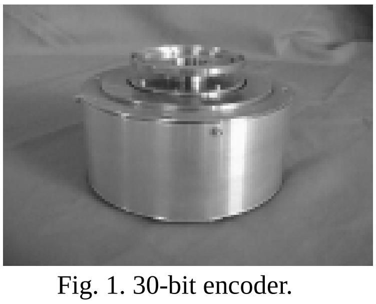


Fig. 1. 30-bit encoder.

3. High-precision angle calibration system

3.1. Principle of time conversion method and equal-dividing and averaging method

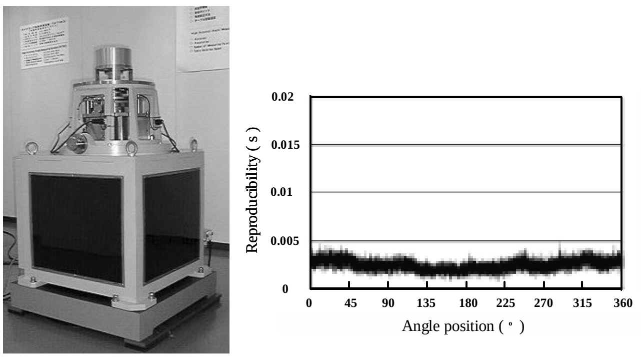
This is an angle measuring technology method. The theory is a time-conversion method, which operates on the principle of high-precision angle measurement. The measured angle sensor is rotated at uniform velocity, and a clock is positioned between the pulses of the criteria angle sensor and the measured angle sensor, and rotated at fixed speed. High-precision measurement can be achieved by rotation at a speed with low variability, and at high clock frequency.

This time-conversion method can measure the angle sensor with a resolution of 0.001 seconds. However, the error of the criteria sensor will be included and the accuracy of an angle sensor and measured instrument could not be separated from the measurement result.

It is possible to carry out the separation of the accuracy of a measured angle sensor and measuring instrument by using the principle of the equal-dividing and averaging method [2]. The system can remove the error of the criteria sensor. This system arranges a criteria angle sensor and a measured angle sensor on the same axis. The relative angular position of the criteria encoder and the measured sensor change the position by about five division points of one turn. It is measured each time and the result is averaged. It can, thus, ensure the complete separation of the accuracy of the two angle sensors. The high-precision angle calibration system [3] is shown in Fig. 2 (a) and the specification is shown in Table 1.

3.2. Uniform low rotation speed motor and fixed brake

When this equal-dividing and averaging method is employed, the variability in the rotation of the speed of the main shaft motor appears in the accuracy; therefore, it is necessary that the variability in rotation should be minimal.



(a) Calibration system (b) Reproducibility error

Fig. 2. High-precision angle calibration system.

Table 1 Angle calibration system specification

Item	Specification
Resolution	0.001 s
Accuracy	0.01 s
Measurement uncertainty	(0.06 s (k = 2))
Rotation speed	0.01 ~ 60 min^{-1}
Starting torque	0.3 N m Max (sample)
Weight	50 Kg Max (sample)

In this study, a motor with a low variability in rotation was developed using the CAE analysis technology. The actual rotation variability data are 0.1 ratios. Moreover, it is necessary to alter the relative position of the two angle sensors arbitrarily in the equal-dividing averaging method, and once the position is decided, the precise fixation with an accuracy of 0.001 seconds was necessary. High-precision has been achieved by using an air disk brake in this study.

3.3. Measurement reproducibility and trace-ability

The method of evaluating the performance of an angle calibration apparatus consists of two parts, one is the definition of the self-accuracy function, and the other is the trace-ability to the accuracy of the angle standard. Reproducibility is shown in Fig. 2 (b). The specifications (shown in Table 1) of resolution, accuracy, reproducibility, stability, and a self-calibrating function, etc., are used to measure the performance of a measuring instrument. Moreover, the numbers that indicate these performances are required, and they should be traceable in an angle standard system. Now, a Japanese angle standard has been enacted and trace-ability is being developed. Further worldwide deployment of the angle standards is expected in the future.

4. Angle sensor with self-accuracy calibrating function

It was required to measure the accuracy of an angle sensor with high-precision, and to evaluate it when guaranteeing data. Further improvements in high-precision were realized by ROM accuracy compensation using the data. To calibrate an angle sensor in an environment where the angle calibration system cannot be used or where it cannot be removed from the equipment, it is expected to calibrate by it-self. This will be achieved by building an internal self-accuracy calibrating function [4] in the angle sensor in this study.

4.1. Basic principle of self-accuracy calibrating

The basic principle of the self-accuracy calibrating method is stated below. Two or more signal detection heads are arranged inside an angle sensor, the position data and the error component is derived from their operation, and the error of an angle sensor is automatically detected. A circuit block diagram is shown in Fig. 3. Furthermore, the secondary error separation extraction principle is shown in equation (1).

4.2. Example of error separation

Figure 4 shows the principle followed when extracting the secondary error components from the heads at 0 and 90

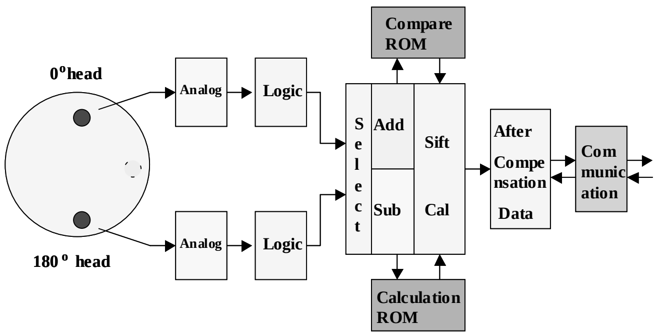


Fig. 3. Self-calibrating angle sensor block chart.

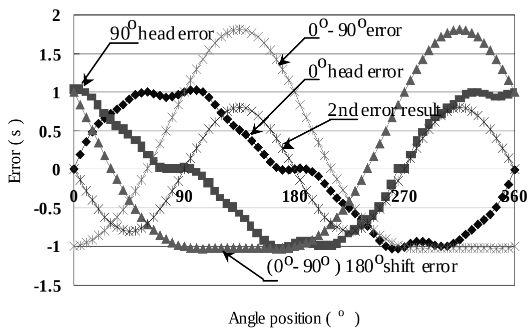


Fig. 4. Theory of secondary error separation method.

degrees. Shift 180° means to shift the error curve at 180°.

$$2^{nd}\text{error} = [(0°\text{error}-90°\text{error})-(\text{sift}180°(0°\text{error}-90°\text{error}))]/4 \quad (1)$$

The secondary error can be separated from the most of the error components using the two head signal. It is necessary to decrease the difference in each head error.

5. High-resolution and high-precision angle sensor

(1) The high-precision manufacturing technology with an accuracy of 0.3 seconds accuracy disk, (2) CAE analysis technology and high-precision coupling technology, and (3) signal dividing R/D technology were applied, (4) angle measurement technology and accuracy compensation technology was possible by efficient use of ROM. This section describes the fundamentals of high-precision angle sensor technology.

5.1. High-precision disk

In an optical encoder, the disk is an important part influencing its accuracy. The slit width of a high-precision disk is about 10 μm. But it is necessary for a high-precision disk an accuracy of less than 0.5 μm and 1 second. In order to achieve accuracy that is equivalent to that of 10 times of a conventionally disk, the measurement of the disk accuracy was evaluated by the length and angle. Therefore, the high-precision disk was achieved by eliminating the reproducibility error of the drawing equipment.

A. Error evaluation by 2-dimensional length measurement of disk

In order to evaluate the error of a disk, it is necessary to measure the disk in term of angle and length precisely. Although the accuracy of a disk is finally estimated by the angle, the length of 0.1 μm can be converted into an angle error of approximately 0.2 seconds, and it can be evaluated. In an area of 150 mm square, the length was measured with an accuracy of 0.1 μm. The recently devised high-precision 2-dimensional length measurement technology [5] can separate the error of a measuring instrument and the error of a measured disk. This principle is explained in Table 2. Similar to equation (2), the angle error $\Delta\theta$ is expressed in x-y rectangular coordinates.

$$\Delta\theta = \theta - \tan^{-1}[(G \times x) / (K \times y)] \quad (2)$$

G and K are the absolute error ratios as opposed that by the length along the x-axis and the direction of the y-axis.

Table 2 Equations of theoretical length : (La - Ld)

La = DeaA − Oea − MeA	Ld = DedA − Oed − MeA
Lb = DebB − Oeb − MeB	La = DeaB − Oea − MeB
Lc = DecC − Oec − MeC	Lb = DebC − Oeb − MeC
Ld = DedD − Oed − MeD	Lc = DecD − Oec − MeD
Lc = DecA − Oec − MeA	Lb = DebA − Oeb − MeA
Ld = DedB − Oed − MeB	Lc = DecB − Oec − MeB
La = DeaC − Oea − MeC	Ld = DedC − Oed − MeC
Lb = DebD − Oeb − MeD	La = DeaD − Oea − MeD

In addition, the scale ratio error of each axial direction and the error of the perpendicular to each axis are equivalent to the error of the measuring instrument. The measurement error of the measuring instrument of approximately 1 μm will be included. The measured encoder disk is rotated to the four directions of 0 degree, 90 degrees, 180 degrees, and 270 degrees, and measurement is carried out each time. The error of a measured encoder disk is separated from each measured value. The theoretical values of La-Ld which were solved using 16 equations are shown in Table 2, since DeaA, DebB, DecC, and DedD (error for which DeaA measured a sides of measured object using the measuring instrument A section) become constant, and it sorts eight variables Oea, Oeb, Oec, Oed, MeA (Oea is the error of a side of the measured object), and MeB, MeC, and MeD (error on measuring MeA using the A section of a measur-
ing instrument)).

$$\Delta\theta = G_1 \times \sin^{-1}(\theta) + G_2 \times \sin^{-1}(2\theta + \delta_2) + G_3 \times \sin^{-1}(3\theta + \delta_3) + \dots \quad (3)$$

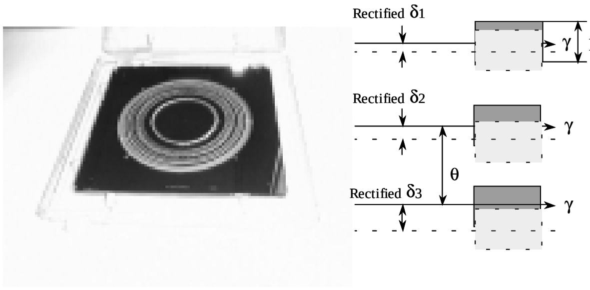
$$\theta = \theta + \Delta\theta \quad (4)$$

For G_1 - G_3, the error gain and θ are an angle measurement position. The error of an angle is $\Delta\theta$ and the error of a relative angle is δ_i; thus, equations (3), and (4) can be generated. The errors of the measuring instrument and the encoder disk were separated using this measurement principle. The error of the measurement tool is 1 μm and the error of the disk is 0.4 μm.

B. Disk accuracy measurement and accuracy compensation by angle

The accuracy of the disk is measured by angle using calibration system shown in session 3. These data are used as values for accuracy correction and the compensation disk is manufactured using a CAD-CAM system again. The accuracy is verified before and after the manufacture of the compensation disk, if the effect of compensation achieves the target value, the manufacture of the disk is considered completed. Figure 5 (b) shows the disk slit image figure that achieves the angle compensation (correction value $\delta 1$, $\delta 2$, and $\delta 3$) of the slit arrangement angular position.

The correction value has a minimum of 0.001 seconds (0.3 nm length); high-precision compensation was attained and the manufacture of a high-precision disk was achieved. The two error results agree with the error of the length and the error from angle measurement. Both measurement results are considered appropriate. Using the error value



(a) High-precision disk (b) Compensation
Fig. 5. High-precision disk and compensation.

acquired from this result for the correction value, the drawing angular position of each slit was rectified, and a high-precision disk with accuracy exceeding that of the drawing equipment was achieved.

The high-precision disk after compensation is shown in Fig. 5 (a). A high-precision disk with an accuracy of 0.3 seconds can be achieved.

5.2. CAE technology for high-precision mechanical system

High precision is required in the mechanical parts of a disk and etc. The high-precision was optimized by using CAE technology focusing on coupling, as shown in Fig. 6

5.3. Signal dividing technology for high-resolution

The 16-bit signal dividing technology was achieved using a closed signal dividing method. Therefore, a high-resolution of 30 bits was achieved. Figure 7 (a) shows the minimum resolution bit of 30 bits pulse signal, and it implies an accuracy of 0.001 seconds.

5.4. ROM accuracy compensation principle for high-precision angle sensor

In the fundamental-wave accuracy of an angle sensor, an optical encoder is mostly determined by the disk pattern accuracy. However the component error is not zero and the assembling error increases, moreover, high-resolution divided signals also have dividing signal errors corresponding with the accuracy error of the sin and cos signal waves. The error is a reproducible error, and the high-precision error measurement system is achieved by the high-precision angle calibration system. So ROM compensation is achieved. ROM accuracy compensation is a method of storing the error value in ROM and removing the reproducible error by subtraction. This is shown in Fig. 7 (b). Wide accuracy 0.2 seconds was achieved using this principle.

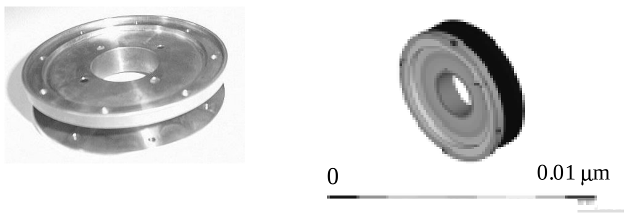
5.5. Multi-function technology of angle sensor

A. Angular-velocity and angular-acceleration data

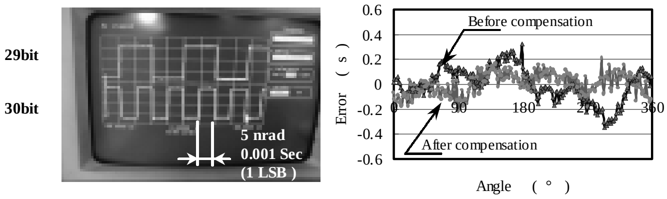
The resolution of angle sensor became high and it became possible to use the high-resolution position information data, which is operated to detect speed and acceleration signal data.

B. Bus communication

The sensor signal line numbers of the multi-axis robot are very large. Therefore less wire was expected. Despite using bi-directional serial communication, the 6-axis control system would require 12 wires; therefore, a bus communication system that can transmit all signals via two lines was developed.



(a) Outline of coupling (b) CAE analysis
Fig. 6. High-precision coupling and CAE analysis.



(a) Pulse signal of 30 bits (b) Wide accuracy
Fig. 7. Pulse signal of 30 bits and wide accuracy.

6. Conclusions

For technical realization of a high-precision angle measurement technical realization, development of a high-precision angle calibration system and a high-precision angle sensor was developed. (1) A high-precision angle calibration system (reproducibility 0.005 seconds, resolution 0.001 seconds) was developed using the angle calibration method. The accuracy of a disk was measured by angle using the angle calibration system. Then the error that was measured by 2-dimensional length measurement technology was equal to the error measured by angle. (2) The high-precision disk (accuracy of 0.3 seconds) was developed. The high-precision angle sensor was realized using this high-precision disk component. The accuracy of angle calibration system and the self-calibrating angle sensor, (3) The self-accuracy calibrating function automatically extracted the angle-accuracy error component. Using the detected error, the ROM accuracy compensation circuit technology resulted in the realization of further high-precision (0.2 seconds). An angle sensor with high-resolution was also studied and 30 bits (0.001 seconds) resolution were achieved. Thus, high-precision angle measurement technology was achieved in terms of both the technology of the angle sensor and the angle measurement instrument at 0.001 seconds high-resolution.

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