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Precision goniometer equipped with a 22-bit absolute rotary encoder

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The calibration of a compact precision goniometer equipped with a 22-bit absolute rotary encoder is presented. The goniometer is a modified Huber 410 goniometer: the diffraction angles can be coarsely generated by a stepping-motor-driven worm gear and precisely interpolated by a piezoactuator-driven tangent arm. The angular accuracy of the precision rotary stage was evaluated with an autocollimator. It was shown that the deviation from circularity of the rolling bearing utilized in the precision rotary stage restricts the angular positioning accuracy of the goniometer, and results in an angular accuracy ten times larger than the angular resolution of 0.01 arcsec. The 22-bit encoder was calibrated by an incremental rotary encoder. It became evident that the accuracy of the absolute encoder is approximately 18 bit due to systematic errors.

Keywords: absolute encoder; angular resolution; angular accuracy; reproducibility; lost motion.

1. Introduction

When an X-ray diffraction experiment is carried out in a synchrotron radiation facility, a quick experimental set-up is required as the experimental time is limited. For almost all X-ray diffraction experiments, it is very convenient to use a goniometer that can be quickly completely rotated to any position within an angular resolution of 0.005°, and can also be precisely rotated down to sub-arcseconds for a range of a hundred arcseconds. Furthermore, it is preferable that the goniometer is equipped with a rotary encoder. The encoder guarantees the positioning of the goniometer with an angular accuracy of a few arcseconds at all angles. However, the mechanism of such a goniometer is complex and heavy, and the cost is high. Here, we report on the performance of a compact low-cost precision goniometer equipped with a 22-bit absolute rotary encoder.

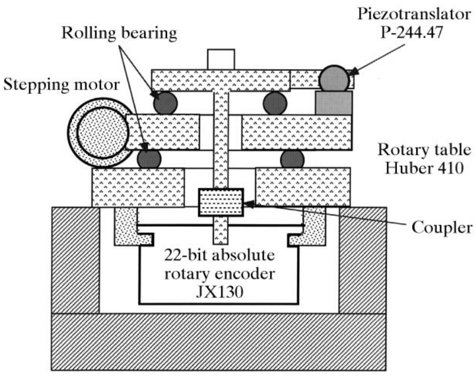

Figure 1
Schematic diagram of a goniometer equipped with an absolute rotary encoder. The coarse rotation of the instrument utilizes a Huber 410 goniometer. A precision rotary stage driven by a piezotranslator is stacked on the Huber goniometer, to which the rotary centre of the encoder shaft is coupled.

2. Construction and performance

A schematic diagram of the instrument is shown in Fig. 1. A commercial rotary table (Huber 410) is utilized as the base stage. On top of the Huber 410 table, a precision rotary stage is stacked, which is rotated by a piezotranslator-driven tangent bar. The rotary encoder is coupled to the rotational shaft of the precision rotary stage. The instrument has two rotational axes: this structure is simpler than the design of a common axis with a stage-selectable electromagnetic clutch, although it is not easy to completely tune one axis that lies on another.

Usually, the use of an absolute encoder is superior to that of an incremental one, except for its cost and resolution. The resolution of almost all commercial absolute encoders is larger than 18 bit ($360°/2^{18}$ = 0.00137°), which is quite poor for X-ray diffraction experiments. In X-ray diffraction experiments, the angular positioning is required to be better than 1 arcsec. High-resolution

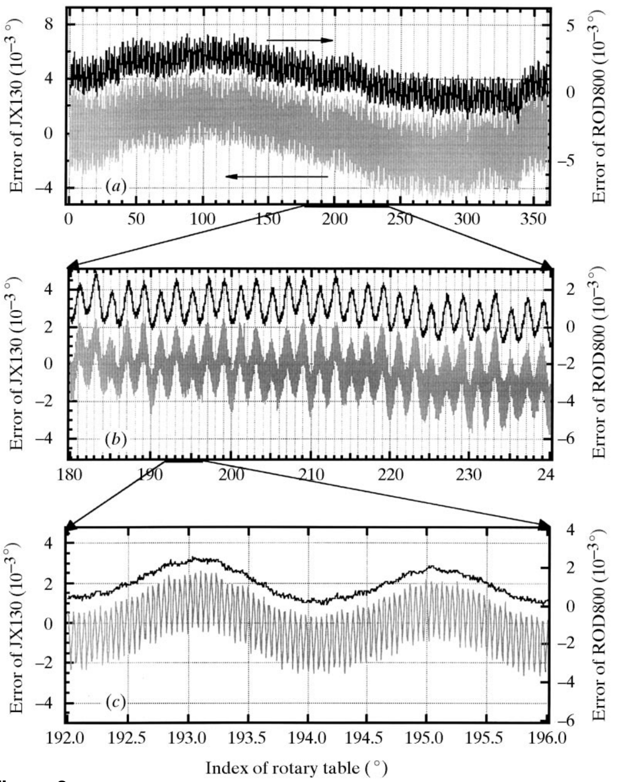

Figure 2
Comparison between the 22-bit (resolution $360°/2^{22}$) absolute rotary encoder (JX130) and the precision incremental rotary encoder (ROD800, resolution 0.00005°, accuracy 1 arcsec). (*a*) All measurement points from 0 to 360° with an angular interval of 0.006°. Data concerning the ROD800 and the JX130 encoders are plotted using the right and left *Y* axes, respectively. (*b*) Enlarged view of the part from 180 to 240° in (*a*). The oscillation with a period of 2° is due to the pitch variation of the worm gear in the RA20-02 goniometer. (*c*) Enlarged view of 192 to 196° in (*a*). The ripples with dots are characteristic systematic errors of the JX130.

absolute encoders (22 bit, 24 bit) were supplied commercially by the Changchun Institute of Optics and Fine Mechanics. The size of the 22-bit encoder (JX130) is $\varnothing$ 130 $\times$ 90 mm, which is more compact than of the Huber 410 goniometer, and can be satisfactorily assembled into the Huber goniometer.

The characteristics of the JX130 encoder were calibrated with a rotary table made by Kohzu (RA20-02), equipped with an ROD800 incremental precision encoder (Heindenhain, 0.36 arcsec resolution and 1 arcsec accuracy). The measured results are shown in Figs. 2(*a*), 2(*b*) and 2(*c*). We define the error here as meaning the difference between the angular position read from the encoder and that from the stepping-motor index. The inaccuracies of both the rotary table and the encoders are included in the errors. We can compare them with each other and deduce the error source. In Fig. 2(*a*), 60 001 measurement points for 360° are shown. The curvature with a period of 360° in the figure is due to the eccentricity of the worm wheel in the rotary table. Fig. 2(*b*) is a partially enlarged view of Fig. 2(*a*); the oscillation, having a period of 2°, is due to the pitch variation of the worm gear of the rotary table. Fig. 2(*c*) is a partially enlarged view of Fig. 2(*b*); ripples with an amplitude of 0.001° and a period of 0.04° are characteristic errors of the JX130 encoder. These results mean that although the angular resolution of the absolute encoder is 22 bit, its accuracy is only 18 bit.

The Fourier-transform power spectra of the JX130 (upper) and the ROD800 (lower) errors are shown in Fig. 3. In the upper spectrum, the sharp peaks located at 22.7592, 45.5239, 68.2887 and 91.0534 deg^{-1} correspond to an inaccuracy with a period of 0.044° (shown in Fig. 2*c*); other peaks are the harmonics. A sharp peak means that the error appears regularly; thus, the inaccuracy with a period of 0.044° and its harmonics are systematic characteristic errors of the JX130 encoder. We tested the encoder a few tens of times, and found that although the accuracy of the encoder is not very high, its reproducibility is good. Therefore, when a position-correction table was used, a higher accuracy could be realized. The correction table was tabulated based on the angular position difference between the JX130 and the ROD800 encoders. A corrected result is shown in Fig. 4 for comparison; the original position data of the JX130 and those of the ROD800 are also shown.

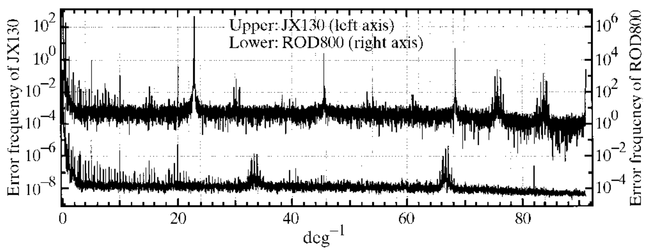

Figure 3
Fourier-transform power spectra of the JX130 (left *Y* axis) and the ROD800 (right *Y* axis) errors shown in Fig. 2. The sharp peaks in the spectrum of the JX130 located at 22.7592, 45.5239, 68.2887 and 91.0534 deg^{-1} correspond to the systematic characteristic error of the JX130. The sharp peaks in both spectra located at 20.0, 10.0 and 5.0 deg^{-1}, and other integer positions correspond to the characteristic error of the rotary table.

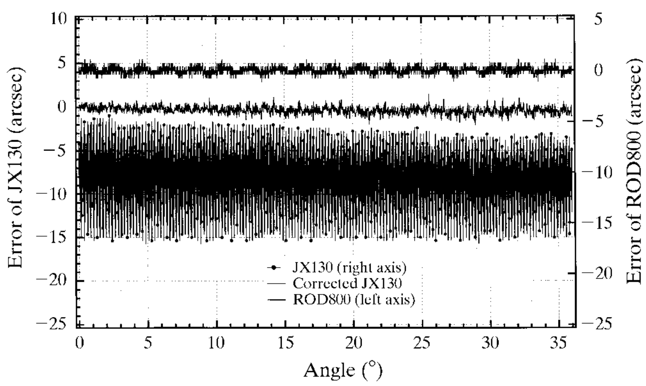

Figure 4
Errors of the JX130 encoder before (line with dots) and after being corrected (solid line). For a comparison, the error recorded by the ROD800 encoder (solid line left *Y* axis) is shown.

The precision rotation stage is driven by a hysteresis compensating piezotranslator (Physik Instrument, P-244.47 translator, E-107 HV unit, E-108 sensor unit, E-255 D/A converter). The maximum expansion of the piezotranslator is 60 μm, and the factor of the expansion conversion to the rotation is 1.5 arcsec/1.0 μm. The piezotranslator could respond to a 1 mV reference voltage and realize an expansion of 6 nm, which corresponds to a stage rotation of 0.01 arcsec. In other words, the angular resolution of the rotary stage is 0.01 arcsec. However, we utilize a rolling bearing as a rotational axis; the deviation of this bearing from circularity limits the angular accuracy realized by the stage. For converting a piezotranslator expansion of 6 nm into an accurate stage rotation, the rotational centre should be fixed within a circular area of 6 nm diameter.

The accuracy of the rotary stage was evaluated with an autocollimator (Rank Taylor Hobson, DA200) as follows. A target mirror was mounted on the rotary stage and the autocollimator was set in an optimized situation. Thus, when the stage is rotated by the piezotranslator, the value displayed in the *X* direction of the autocollimator varies, and that in the *Y* direction, which is parallel to the rotational axis, almost does not. For measuring an angle at sub-arcsecond accuracy, one should estimate the atmospheric disturbance and instrumental resolution. Since the accuracy of the autocollimator is considered to be equivalent in the *X* and *Y* directions, the atmospheric fluctuation and the instrumental resolution can be estimated from the values displayed in the *Y* direction.

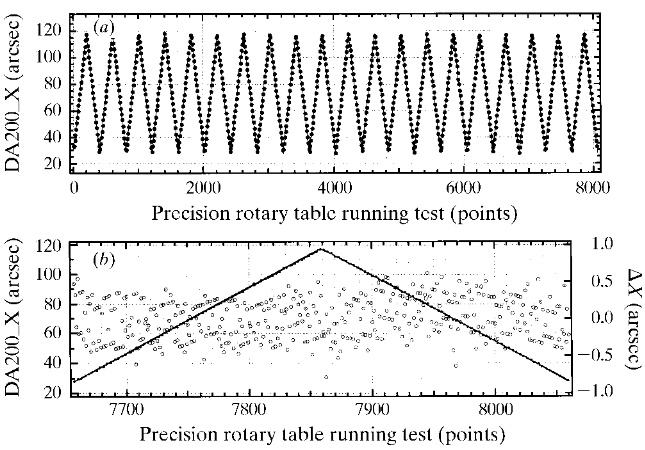

Figure 5
(*a*) 20-turn direction-alternated measurements of the precision rotary stage. The maximum expansion of the piezotranslator is 60 μm; the expansion conversion to the rotation factor is 1.5 arcsec/1.0 μm. (*b*) Data for the 20th measurement and their line fitting (dots and line, left *Y* axis) and angular positioning error (open circles, right *Y* axis).

Direction-alternated measurements of the stage rotation were made for 20 turns. The results are shown in Fig. 5(*a*). The data for the 20th measurement and the positioning error are shown in Fig. 5(*b*). The error in the *X* direction is defined as the difference between the value of the autocollimator and the angular position based on the piezotranslator expansion; that in the *Y* direction is defined as the difference between the autocollimator and average *Y* values. The error distributions in the *X* and *Y* directions of a single-direction measurement are shown in Fig. 6. The standard deviation in the *Y* direction is 0.15 arcsec, which corresponds to the intrinsic uncertainty of the measurement system; however, that in the *X* direction is 0.27 arcsec. The error distribution in the *X* direction is considered to be enlarged by approximately 0.1 arcsec by the deviation from circularity of the rolling bearing utilized in the precision stage.

The rolling bearing also causes lost motion of the rotary stage. When the rotational error distributions of the stage were separately collected by their movement directions, as shown in Fig. 7, the lost motion is given by the distance between the main peaks of two distributions. In Fig. 7, the solid line with dark circles is the direction of piezotranslator expansion; the dashed line with open circles denotes the opposite direction. The main peaks of the two directions are approximately located at the ±0.3 arcsec positions, respectively, which correspond to the standard deviation of the error distribution in the *X* direction shown in Fig. 6. The peak widths in Fig. 7 are approximately equal to 0.1 arcsec; they correspond to the difference in the standard deviation between the *X* and the *Y* directions in Fig. 6, and indicate the intrinsic inaccuracy of the rotary table. The lost motion is about 0.6 arcsec, five times larger than the inaccuracy of rotation. This phenomenon is considered to be caused by the bearing internal clearance.

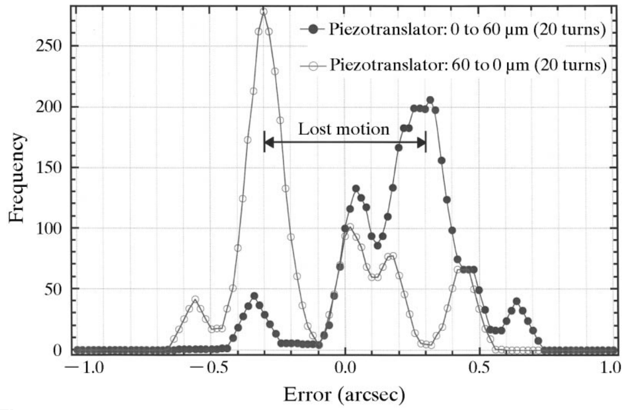

Figure 7
Rotational error distributions of the stage separately collected based on their movement directions. The lost motion of the precision rotary stage is evaluated by the position of the main peak of the distribution in each direction.

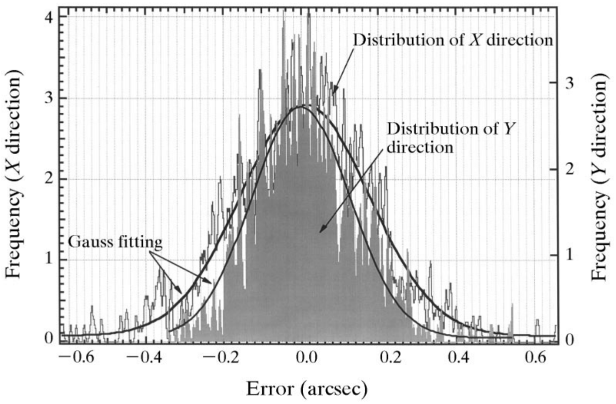

Figure 6
Distributions of the positioning error measured with an autocollimator (DA200) and their fitting by a normal distribution. The *X* and *Y* directions of the autocollimator are perpendicular and parallel to the rotary axis, respectively. The errors in the *Y* direction correspond to intrinsic uncertainties of the measurement system, which are caused by the atmospheric fluctuation and instrumental resolution of the autocollimator. The standard deviations in the *X* and *Y* directions are 0.27 and 0.15 arcsec, respectively. The error distribution in the *X* direction is considered to be enlarged by the deviation from circularity of the rolling bearing.

3. Conclusions

A 22-bit absolute rotary encoder was calibrated. Before the correction, its accuracy was approximately 18 bit, worse than its resolution; after being corrected by the calibration table, its accuracy approached its angular resolution. A goniometer equipped with this corrected encoder can produce an angular accuracy as high as the precision incremental encoder (ROD800). Although the angular resolution of the precision rotary stage is 0.01 arcsec, its accuracy is approximately equal to 0.1 arcsec, ten times worse than its angular resolution. The accuracy limitation is caused by the rolling bearing, which is used as the rotational axis in the stage. For studies of high-resolution and high-accuracy X-ray spectroscopy, the design of a goniometer without a rolling bearing spindle is required.