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Ultraprecision Motion Control Technique for High-Resolution X-ray Instrumentation

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Abstract
With the availability of third-generation hard x-ray synchrotron radiation sources, such as the Advanced Photon Source (APS) at Argonne National Laboratory, x-ray inelastic scattering and x-ray nuclear resonant scattering provide powerful means for investigating the vibrational dynamics of a variety of materials and condensed matter systems. Novel high-resolution hard x-ray optics with meV energy resolution requires a compact positioning mechanism with 20 - 50-nrad angular resolution and stability. In this paper, our technical approach to this design challenge is presented. Sensitivity and stability test results are also discussed.

Keywords: ultraprecision, motion control, x-ray instrumentation

1. Introduction

The APS SRI-CAT 3-ID beamline is dedicated to high-energy-resolution x-ray scattering studies in the energy range of 6-30 keV [1]. A special 2.7-cm-period undulator, optimized for peak brilliance is installed. The beamline's basic components include filters, white-beam slits, integral shutters, and a Kohzu double-crystal monochromator with water-cooled diamond crystals as a pre-monochromator. The beamline special components, such as custom-built high-resolution monochromators and a dual-function (collimating or focusing) x-ray mirror system, provide high flexibility for the optical system, so that users can optimize the beamline configuration for various applications. In particular, a 4-bounce high-resolution monochromator using a nested channel-cut crystal approach is used to deliver a x-ray beam with meV bandpass for x-ray inelastic scattering experiments [2,3].

Since 1997 two major ultraprecision motion control techniques have been developed at the APS, Argonne National Laboratory:

- A novel laser Doppler encoder system; a valuable measuring tool in the study of a crystal's vibrational behavior because it has nanoradian sensitivity [4,5].
- A specially designed high-stiffness weak-link mechanism with stacked thin metal sheets having excellent angular stability for an artificial channel-cut crystal monochromator [6,7].

These new techniques present a significant opportunity to support the instrumentation development for a high-resolution hard x-ray monochromator with meV energy resolution. In this paper, these two technical approaches to a compact positioning mechanism for a high-resolution monochromator are presented. Future development and applications of these techniques are discussed.

2. Laser Doppler Encoder with Sub-Angstrom Sensitivity

2.1. Multiple-reflection Optics for the laser Doppler displacement meter (LDDM)

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The LDDM is based on the principles of radar, the Doppler effect, and optical heterodyning [6]. We have chosen a LDDM as our basic system, not only because of its high resolution (2 nm typically) and high measuring speed (2 m/s) but also because of its unique performance independent of polarization, which provides the convenience to create a novel multiple-reflection-based optical design to attain sub-Angstrom linear resolution extension.

A commercial LDDM system includes four components: a laser head, a processor module, a display module, and a target reflector. The laser head houses a frequency-stabilized HeNe laser, an electro-optic assembly and a photodetector, which functions as a receiver. The laser light reflected by the target is frequency-shifted by the motion of the target. The photodetector measures the phase variation caused by the frequency-shift, which corresponds to the displacement of the target. Making the laser light reflect back and forth twenty-four times between the fixed base and the target before it finally reaches the photodetector indicates that the multiple-reflection optics provides 24 times resolution extension power for the system. The limit of the maximum reflection times is determined by the optical reflectivity of the reflecting element to be used and the sensitivity of the LDDM laser detector electronics. Special coatings could be used on the surfaces of the reflecting elements to optimize the results.

2.2. Test of a Laser Doppler Linear Encoder (LDLE)

As shown in Figure 1, a precision stepping-motor-driven stage has been used to test the LDLE over a 300-mm measuring range. To trace the system resolution extension power, a second regular commercial LDDM system has been applied. A 100 mm/sec stage motion speed was tested for the prototype LDLE system without any encoder miscounting. A 0.166 nm resolution (0.083 nm LSB) was reached by the prototype LDLE system with a 24-times resolution extension optics.

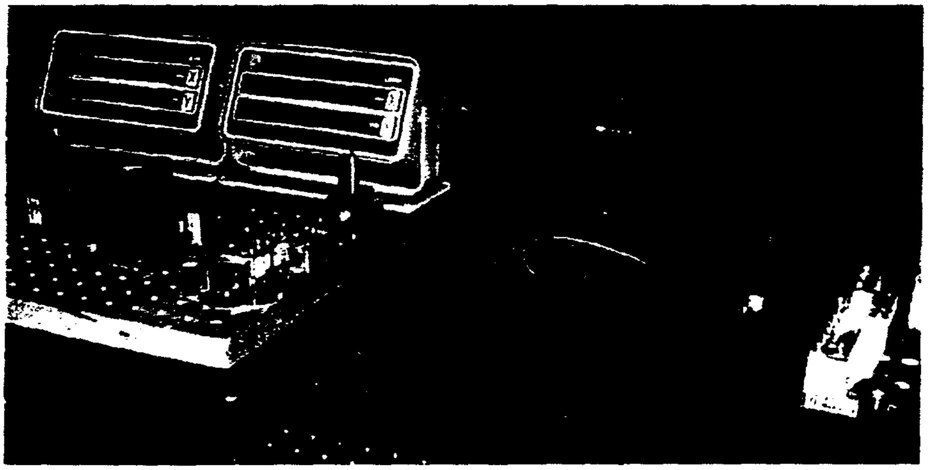

Fig.1 Photograph of the test setup of a LDLE system.

2.3. Test of the Modification for Angular Encoder Application

To apply the above multiple-reflection design for a laser Doppler angular encoder (LDAE), the moving target is mounted on the end of a sine bar to measure the shaft-rotation angular displacement. To extend the angular measuring range, prisms with different sizes are used.

A prototype LDAE has been developed for high-energy-resolution x-ray scattering applications at the Advanced Photon Source undulator beamline 3-ID. We have modified the monochromator (AAG-100, manufactured by Kohzu Seiki Co., Japan [8]) sine bar and related structure for the LDAE assembly. Figure 2 shows the configuration of an actual LDAE system with twenty-four multiple-reflections on the one end of the sine bar, which rotates the shaft on which the asymmetrically cut crystals are mounted. The LDAE system components can be identified as follows. A commercial laser Doppler displacement meter (LDDM) with a heterodyne detector inside is mounted on the invar fixed base, which is attached to the monochromator base, and the moving sine-bar arm is attached to the monochromator rotary shaft. A set of right-angle reflective prisms is mounted on the fixed base, and another set of prisms is mounted on the moving arm.

Figure 3 is a plot of the test results that correlates the performance of our LDAE with a Heidenhain ROD-800 optical encoder with a 2-arcsec accuracy and 175-nanoradian resolution [9]. The slope of the correlation data in Fig. 3 shows that our LDAE has a 0.276 nanoradian per count readout sensitivity. A 100 mrad/sec rotation speed was tested for a laboratory setup in the 8-degree measuring range without any encoder miscounting.

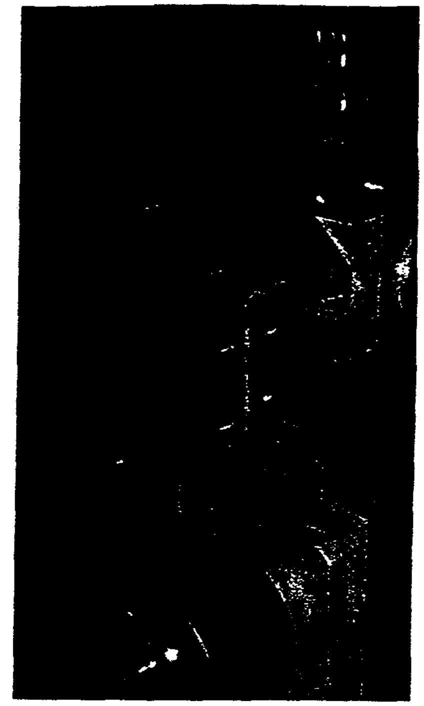

Fig.2 Photograph of the LDAE assembly

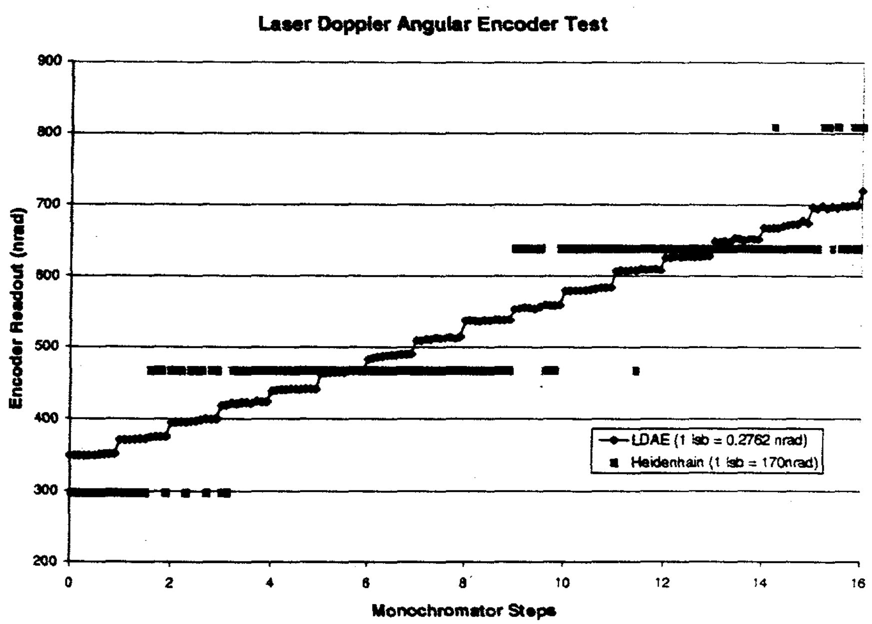

Fig. 3 Plot of a test results of the LDAE system

3. High-stiffness Weak-link Mechanism

3.1. Design Restrictions to the Nested Channel-Cut Geometry

There are design restrictions to the nested channel-cut geometry. Because these two channel-cut crystals are nested within each other, the size of the crystals becomes an important design factor. The lack of availability of large crystals with good long-range crystallinity restricts the size of the outer channel-cut crystal. On the other hand, the input beam power absorbed by the first optical surface on the outer channel-cut crystal can reach a fraction of a

Joule and can cause crystal local temperature and strain variations. In certain high-energy-resolution applications, these effects become major restrictions to the optical design.

To overcome these obstacles, we have developed a novel high-stiffness weak-link mechanism. The precision and stability of this mechanism allow us to align or adjust an assembly of crystals to achieve the same performance as does a single channel-cut crystal, so we call it an "artificial channel-cut crystal." Using this mechanism, we can make an outer channel-cut crystal large enough to optimize the nested monochromator's performance and compensate the crystal local temperature and strain variations.

3.2. Structure Design

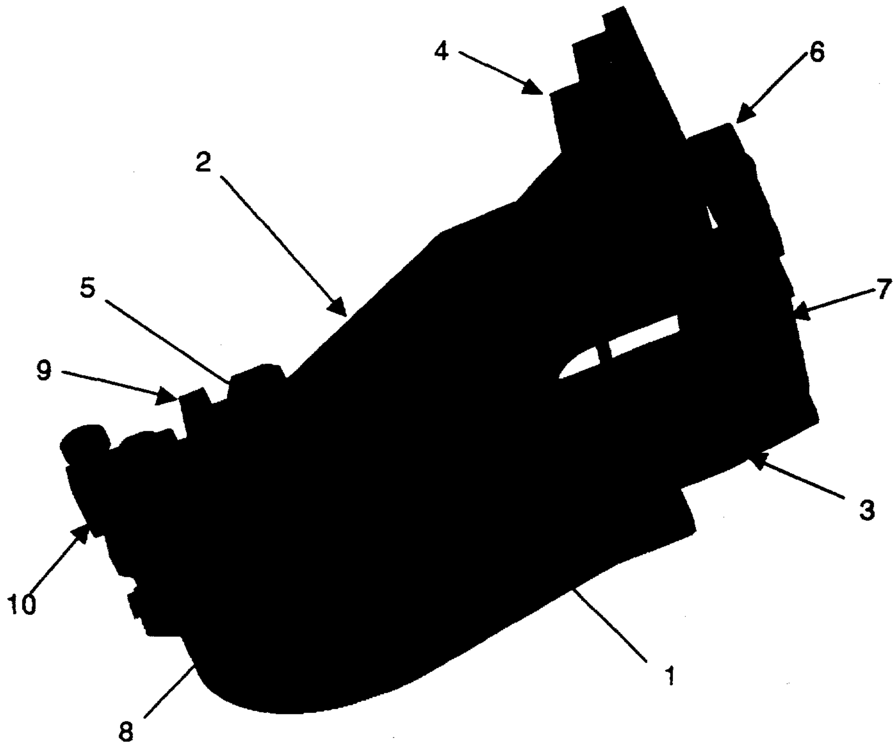

Fig. 4 The base mechanism includes a compact sine-bar driving structure for the crystal pitch alignment, which is the key component of the whole mechanism. There are two groups of stacked thin metal weak-link structures (1) mounted on each side of the base plate (2). A sine-bar (3) is installed on the center of the planar rotary shaft for the pitch alignment between the two (4 4 0) single crystals (4, 5). Two linear drivers are mounted on the base plate serially to drive the sine-bar. The rough adjustment is performed by a Picomotor™ [10] (6) with a 20-nm to 30-nm step size. A Queensgate™ [11] closed-loop controlled PZT (7) with capacitance sensor provides 1-nm resolution for the pitch fine alignment.

Figure 4 shows the design of the miniature multiaxis driving structure for an artificial channel-cut crystal. The structure consists of three subassemblies: one base weak-link mechanism and two crystal holders.

To optimize the system stiffness, we have chosen overconstrained mechanisms in this design. The precision of the modern photochemical machining process using lithography techniques makes it possible to construct a strain-free (or strain-limited) overconstrained mechanism on the thin metal sheet. By stacking these thin metal weak-link sheets with align-pins, we can construct a solid complex weak-link structure for a reasonable cost.

A pair of commercial flexure bearings (8) is mounted on one of the crystal holders (9), and a Picomotor™ -driven structure (10) provides the roll alignment for the crystal.

3.3. Sensitivity Test with a Laser Doppler Encoder

We have tested the sensitivity of the weak-link sine-bar structure with a laser Doppler angular encoder. A 200-mm-long aluminum arm is mounted on the center of the planar rotary shaft, perpendicular to the sine-bar. A set of prisms is mounted at the end of the arm as a multireflection displacement sensor. During this test, a series of 5-nm incremental steps is applied to the sine-bar by the Queensgate PZT. The average angular step size measured by the laser Doppler angular encoder is 33 nrad with a 7 nrad RMS deviation, which meets the design specification of the weak-link mechanism.

3.4. Stability Result from a X-ray Experiment

We have tested the first prototype artificial channel-cut crystal as an outer crystal for a 4-bounce high-resolution monochromator with nested configuration at the APS 3-ID-B experiment station. The outer crystals of the monochromator are asymmetrically cut silicon (4 4 0) and the inner channel-cut crystal is silicon (15 11 3). This combination yields a bandpass of 1 meV at 21.6 keV. The monochromator is turnable between 21.5 - 21.7 keV. As a typical case, Fig. 5 shows a forty-minute stability result with a 1-meV bandwidth monochromatic beam. The change in transmitted intensity reflects the change in beam position, thermal changes, and crystal angle variations combined. At this point we have not isolated the contribution of the artificial channel-cut crystal assembly alone. However, we infer that the contribution of the angular drift of two crystals attached to each other with the mechanism described here is less than 25 nrad per hour.

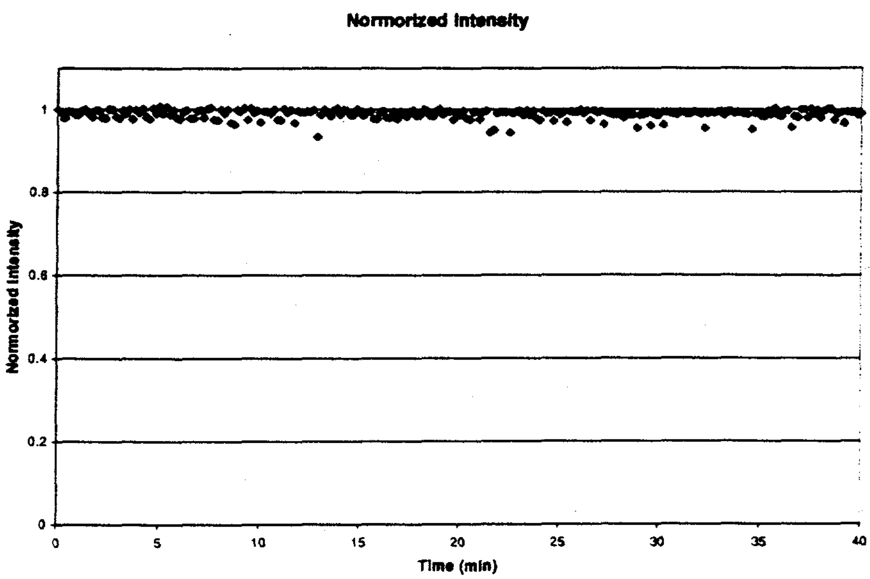

Fig.5 Plot of a forty-minute stability result with a 1-meV bandwidth monochromatic beam

4. Discussion

We have built a compact positioning mechanism with 20 - 50-nrad angular resolution and stability for high-resolution hard x-ray monochromator at the APS. Two special techniques for ultraprecision motion control were developed. A laser Doppler encoder system with multiple-reflection optics has demonstrated its near-Angstrom linear sensitivity. It became a valuable diagnostic tool for the ultraprecision motion control study. Further developments of the LDLE and LDAE system are focused on the system compactness. A Servo-system using the LDLE for closed-loop feedback is in progress.

Recently, we have developed a new high-stiffness weak-link mechanism with modular design as shown in Fig. 6 (right side). Comparing with the first prototype as shown in Fig. 6 (left side), the modular structure provides more flexibility to the users for different optics.

We hope that the immediate successful application of these new techniques to an artificial channel-cut crystal assembly for inelastic x-ray scattering studies may be followed by other innovative applications.

Fig.5 Photograph of the high-stiffness weak-link mechanisms. Left side is the first prototype of the overconstrained weak-link mechanism. Right side is a new prototype for a modular design

Acknowledgments

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