High-Precision Positioning Mechanism Development at the Advanced Photon Source

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Abstract

There are many challenging tasks in the design of the beamline instrumentation that relate to high precision positioning mechanism for users at a third-generation synchrotron radiation source, such as the 7 GeV Advanced Photon Source (APS). Over the last few years, progress has been made in the development of novel mechanisms with high positioning resolution and high stability at the APS. Applications include: a high-energy-resolution monochromator, x-ray nanoprobe scanning stages, and a sample-exchange automation system for x-ray cryo-biocrystallography.
In this paper, the particular design upgrades, as well as the new mechanism design specifications, are summarized.

Keywords: precision positioning, monochromator, scanning stage, mechanism design

1. Introduction

With the availability of third-generation hard x-ray synchrotron radiation sources, such as the Advanced Photon Source (APS) at Argonne National Laboratory, new high-precision positioning techniques present a significant opportunity to support the instrumentation development for state-of-the-art synchrotron radiation research, such as:

- A hard x-ray monochromator with resolution and stability in the nanoradian scale for high-energy-resolution x-ray inelastic scattering and x-ray nuclear resonant scattering.
- A ultraprecision scanning stage system for a x-ray microscope with pixel repeatability in the nanometer scale.
- A robot-based sample-exchange automation system with high positioning repeatability for x-ray cryo-biocrystallography.

Over the last few years, progress has been made in the development of novel mechanisms with high positioning resolution and high stability at the APS. In this paper, the particular design upgrades, as well as the new mechanism design specifications, are summarized.

2. High-Stiffness Weak-Link Mechanism for High-Energy-Resolution Hard X-ray Monochromator

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" [1]. 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. This new technique provides a significant support for the high-resolution hard x-ray monochromator with meV energy resolution at the SRICAT beamline 3-ID at the APS.

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 a thin metal sheet [2]. By stacking these thin metal weak-link sheets with align-pins, we can construct a solid complex weak-link structure for a reasonable cost. Figure 1 shows a finite element simulation for a wheel-shaped weak-link machanism with angular displacement on its central portion under a 0.89 Nm torsion load.

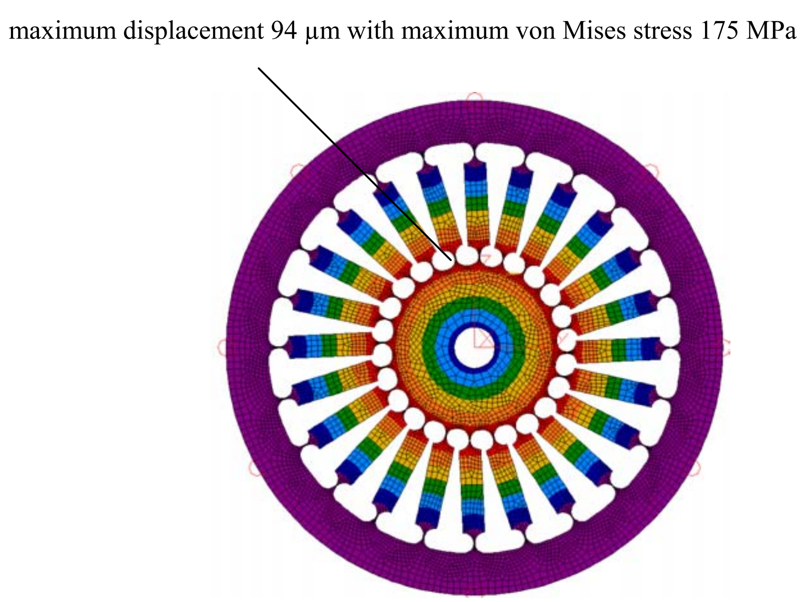


Fig. 1: A finite element simulation for the wheel-shaped weak-link displacement under a 0.89 Nm torsion load.

Figure 2 shows the first version of the motion mechanism for an artificial channel-cut crystal. The structure consists of three subassemblies: one base weak-link mechanism and two crystal holders. 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 mounted on each side of the base plate. A sine-bar is installed on the center of the planar rotary shaft for the pitch alignment between the two (4 4 0) single crystals. Two linear drivers are mounted on the base plate serially to drive the sine-bar. The rough adjustment is performed by a Picomotor™ [3] with a 20 nm to 30 nm step size. A closed-loop controlled PZT with capacitance sensor provides 1 nm resolution for the pitch fine alignment. A pair of commercial flexure bearings is mounted on one of the crystal holders, and a Picomotor™ -driven structure provides the roll alignment for the crystal.

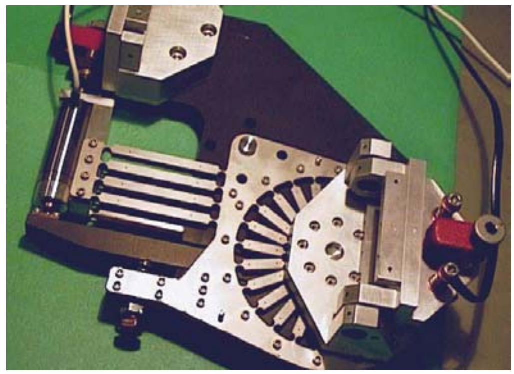
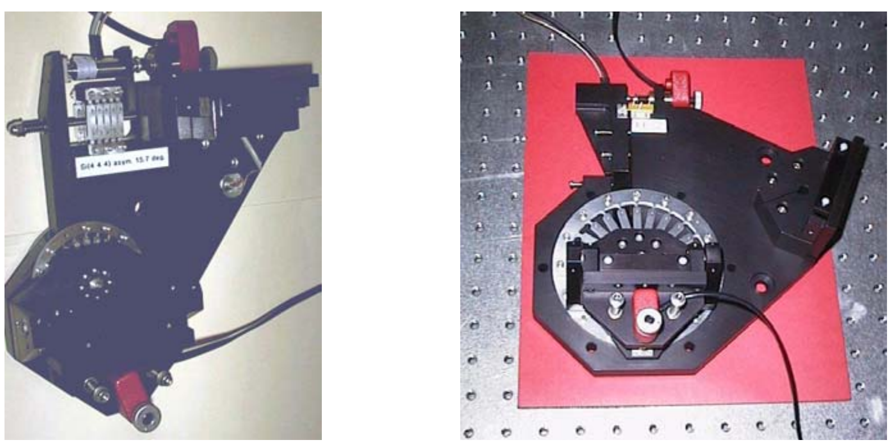


Fig. 2: Photograph of the first version of the weak-link structure mounted on the base plate.

Based on the experience we got designing, building, and testing the first artificial channel-cut crystal, we have designed a second prototype. In this new version, two sets of modularly designed overconstrained weak-link mechanisms, one for angular motion and one for linear motion, were used to provide more flexibility for the optical design.



(a) (b)

Fig. 3: (a) Photograph of the modularly designed weak-link structures, one for angular motion and one for linear motion, mounted on the base plate. (b) Photographs of the modularly designed weak-link structure mounted on the base plate. Since this mechanism only uses a Picomotor™ linear driver for angular adjusment, the linear motion weak-link module is not needed.

As shown in Fig. 3a, the new modularly designed artificial channel-cut crystal mechanism consists of three subassemblies: one base structure and two crystal holders. The base structure includes a compact sine-bar driving mechanism for the crystal pitch alignment, which is the key component of the structure. Figure 3b shows an artificial channel-cut crystal mechanism that only uses a Picomotor™ linear driver for angular adjusment.

We have tested the sensitivity of the weak-link sine-bar structure with a laser Doppler angular encoder. During the 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. 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 test results show 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 [1].

3. A Linear Actuator System with 1 Angstrom Closed-Loop Control Resolution and 50 Millimeter Travel Range

We have designed and tested a novel linear actuator system with 1 angstrom closed-loop control resolution and 50 mm travel range. There are two major ultraprecision motion control techniques that have been applied to this actuator:

- A novel laser Doppler encoder system with multiple-reflection optics having sub-Angstrom measuring resolution.
- A specially designed high-stiffness weak-link mechanism with stacked thin metal sheets having sub-Angstrom driving sensitivity with excellent stability.

3.1 Laser Doppler Encoder

Since 1997 a prototype laser Doppler linear encoder (LDLE) with multiple reflections has been developed at the APS [4,5]. With a customized commercial laser Doppler displacement meter (LDDM) [6], this novel linear encoder achieved sub-angstrom sensitivity in a 300 mm measuring range. The LDDM is based on the principles of radar, the Doppler effect, and optical heterodyning. 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.

In the self-aligning multiple-reflection optical design for the LDDM system resolution extension, the heterodyning detector is housed coaxially inside the frequency-stabilized laser source. Instead of a typical single reflection on the moving target, the laser beam is reflected back and forth twelve times between the fixed base and the moving target. The laser beam, which is reflected back to the heterodyning detector, is frequency-shifted by the movement of the moving target relative to the fixed base. With same LDDM laser source and detector electronics, this optical path provides twelve times resolution extension power for the linear displacement measurement and encoding. A 0.3 angstrom resolution was reached by the prototype LDLE system recently [7].

3.2 High-Stiffness Weak-Link Mechanism

We have developed a novel stage using a high-stiffness weak-link mechanism to perform linear motion closed-loop control at the 1 angstrom level. The precision and stability of this mechanism allow us to control the stage with 0.3 angstrom driving sensitivity. The structure consists of four groups of overconstrained weak-link parallelogram mechanisms made with lithography techniques (Fig. 4).

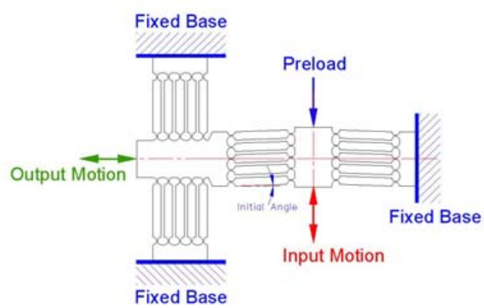


Fig. 4: Design of the high-stiffness weak-link linear motion reduction mechanism.

We have tested the sensitivity of the weak-link linear motion reduction mechanism with a laser Doppler linear encoder. During this test, a Physik Instrumente PI-841 PZT actuator with E-501.10 amplifier [8] was used for input motion control. A 0.3 angstrom driving sensitivity was demonstrated with this weak-link linear motion reduction mechanism [7].

3.3 Test of the One-Dimensional Laser Doppler Linear Actuator System

A one-dimensional linear actuator system based on the above high-stiffness weak-link technique and LDDM with multiple reflection optics has been tested. Figure 5 shows a schematic diagram of the one-dimensional laser Doppler linear actuator (LDLA) system. In this closed-loop control setup, a PZT-driven motion-reduction mechanism (1) was mounted on the top of a DC-motor-driven stage (2) to drive the motion object (for instance, a sample holder for atomic force microscope). A laser Doppler displacement meter (3) with an optical resolution extension assembly (4) is used to measure the sample holder motion in a 50 mm range with sub-angstrom resolution. The LDDM position signal is fed back through a system control computer to control the PZT (5). The PZT drives the motion-reduction mechanism with sub-angstrom resolution to stabilize the motion. The system control computer also synchronizes the stage position and PZT feedback lock-in point with the LDDM position signal.

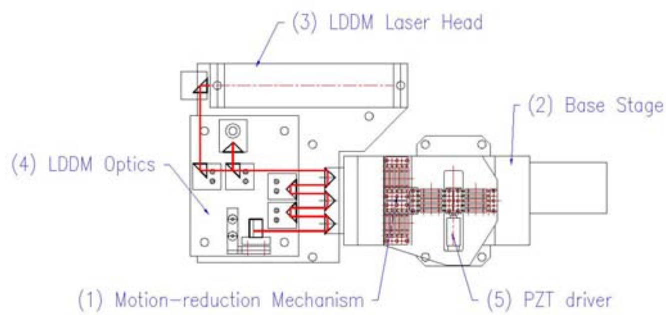


Fig. 5: Schematic of the one-dimensional laser Doppler linear actuator (LDLA) system.

We have tested the closed-loop control resolution for a one-dimensional laser Doppler linear actuator system. A series of 1 angstrom, 2 angstrom, and 3 angstrom steps have been demonstrated as shown in Fig. 6.

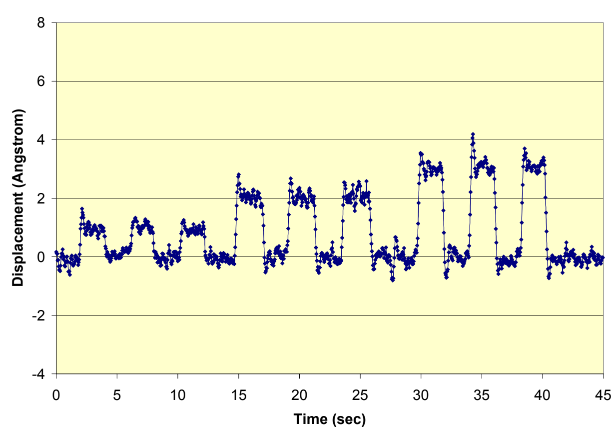


Fig. 6: Resolution test of the one-dimensional laser Doppler linear actuator closed-loop control system. A series of 1 angstrom, 2 angstrom, and 3 angstrom steps have been demonstrated.

3.4 *Design of the Two-Dimensional Laser Doppler Linear Actuator System*

A key technical challenge for a two-dimensional ultraprecision laser encoder system is to design a multiple self-aligning optical path with three-dimensional motion decoupling capability. We have designed and constructed a two-dimensional laser Doppler linear actuator system with such a multiple self-aligning optics recently [7,9].

The two-dimensional LDLA system consists of two sets of one-dimensional LDLAs. The actuator system combines four motion stages. The two base stages are commercial DC-motor-driven stages with 100 nm resolution and 50 mm travel range. The two weak-link stages, which are mounted on the top of the base stages, are high-stiffness, PZT-driven, compact motion-reduction mechanisms with 0.3 angstrom resolution. These motion-reduction mechanisms with sub-angstrom resolution and a 2 kg vertical loading capacity are key components for the motion feedback control [7].

The system is in testing and commissioning now. Preliminary testing has demonstrated its subnanometer positioning capability. This prototype will be used as part of a dynamic test station for the x-ray nanoprobe development at the APS. Figure 7 is a photograph of the two-dimensional laser Doppler linear actuator system test setup.

Fig. 7: Photograph of the two-dimensional LDLA test setup.

4. Prototype of a Robot-Based Automation System for Cryogenic Crystal Sample Mounting

One of the major bottlenecks in the data collection process for bio-cryocrystallography at synchrotron radiation beamlines is the constant need to change and realign the crystal sample. This is a very time- and manpower-consuming task. The time it takes to change and realign the sample, together with the time it takes to go in and out of the experimental station often exceeds the time of actual data taking. It is obvious that an automated sample mounting system will help to solve this bottleneck problem [10].

We have designed and developed a robot-based automation system for cryogenic crystal sample mounting. With this system, up to 96 crystal samples can be prepared at liquid nitrogen temperature. Under computer control, samples can be mounted to or retrieved from the x-ray diffractometer by a robot-arm with programmable sequences. Sample temperature has been measured at lower than 105K during the four second mounting process. Sample positioning repeatability has been tested (50 microns with conventional sample pins and 1 micron for kinematics pins). Figure 8 shows the first test setup in the APS 19-BM experimental station with a robot-based 48 sample exchanger in July 2001.

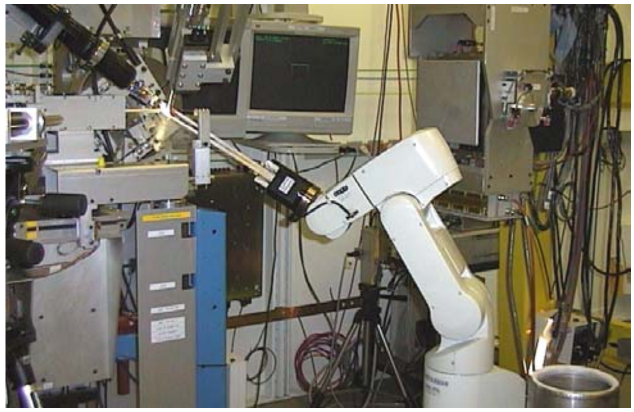


Fig. 8: Photograph of the robot-based sample mounting automation system tested at the APS 19-BM SBC experimental station with Kappa configuration and conventional mounting pins. A Mitsubishi 6-axis robot-arm was used in this test.

5. Conclusion

Over the last few years, progress has been made in the development of novel mechanisms with high positioning resolution and high stability at the APS. Applications include: a high-energy-resolution monochromator, x-ray nanoprobe scanning stages, and a sample exchange automation system for x-ray cryo-biocrystallography. Further development will be focused on the techniques of differential positioning measurement and structural dynamics optimization for ultrahigh-precision positioning devices.

6. Acknowledgments

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7. References

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