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Modular Overconstrained Weak-Link Mechanism for Ultraprecision Motion Control

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Abstract. We have designed and constructed a novel miniature overconstrained weak-link mechanism that will allow positioning of two crystals with better than 50nrad angular resolution and nanometer linear driving sensitivity. The precision and stability of this structure allow the user 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."

Unlike the traditional kinematic linear spring mechanisms, the overconstrained weak-link mechanism provides much higher structure stiffness and stability. Using a laminar structure configured and manufactured by chemical etching and lithography techniques, we are able to design and build a planar-shape, high stiffness, high precision weak-link mechanism.

In this paper, we present recent developments for the overconstrained weak-link mechanism. Applications of this new technique to synchrotron radiation instrumentation are also discussed.

Keywords: ultraprecision mechanism, motion control, x-ray instrumentation.

1. Introduction

The SRI-CAT 3-ID beamline at the Advanced Photon Source (APS) 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. For x-ray inelastic scattering experiments, the beamline optical system includes a 4-crystal in-line high-resolution monochromator using a nested channel-cut crystal geometry to deliver a x-ray beam with meV bandpass [2,3].

There are design restrictions to the nested channel-cut geometry:

- The lack of availability of large crystals with good long-range crystallinity restricts the size of the outer channel-cut crystal;
- The input beam power absorbed by the first optical surface on the outer channel-cut crystal can cause local temperature and strain variations in the crystal.

In certain high-energy-resolution applications, these effects become major restrictions to the optical design.

Since 1998, to overcome these obstacles, we have been developing of a novel high-stiffness weak-link mechanism. The precision and stability of this mechanism should 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.

In 1999, a high-stiffness weak-link mechanism with stacked thin metal sheets was developed at the APS (shown in fig. 1)[4]. We have tested the first prototype artificial channel-cut crystal using this new technique at the APS 3-ID-B experiment station. During the test, the artificial channel-cut crystal performed as an outer crystal for a 4-crystal in-line high-resolution monochromator with nested configuration as shown in fig. 2. A less than 25 nrad per hour

angular drift of two crystals was demonstrated in a two hours stability test with a 1-meV bandwidth monochromatic beam [5].

In this paper, we present recent developments in the overconstrained weak-link mechanism. Applications of this new technique to synchrotron radiation instrumentation are also discussed.

2. Modular Weak-link Mechanism

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 were used to provide more flexibility for the optical design.

Fig. 3 shows the new design of the artificial channel-cut crystal. The structure 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.

The novelty of this new structure is combining the closed-loop-controlled piezoelectric transducer (PZT) technology with a modularly designed high-stiffness weak-link mechanism. To optimize the system stiffness, we have chosen overconstrained mechanisms in this design. The precision of modern photochemical machining processes using lithography techniques makes it possible to construct a strain-free (or strain-limited) overconstrained mechanism on the thin metal sheets. By stacking these thin-metal weak-link sheets with alignment-pins, we can construct a solid complex weak-link structure for a reasonable cost.

3. Sensitivity and Stability Test

We have tested the sensitivity of the weak-link sine-bar structure with a laser Doppler angular encoder with nanoradian sensitivity [8]. During the test, a series of 5 nm incremental steps is applied to the sine-bar by the 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 for the weak-link mechanism.

We have tested the second prototype artificial channel-cut crystal as an outer crystal for a 4-crystal in-line 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 tunable between 21.5 - 21.7 keV. Fig. 4 shows a sixty-minute intensity stability test result with an 1meV 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.

4. Discussion

We have built a compact positioning mechanism with better than 50nrad angular resolution and stability for a high-resolution hard x-ray monochromator at the APS. The new modularly designed high-stiffness weak-link mechanism provides more flexibility for the optical design. Compared with the first prototype, the new structure has a more compact size and is lighter as can be seen from the dimensions given in table 1.

We hope that the successful application of this new technique to an artificial channel-cut crystal assembly for inelastic x-ray scattering studies will be followed by other innovative applications. Combining this new high-stiffness weak-link mechanism with a laser Doppler encoder for a closed-loop feedback control [8], we were able to design a linear actuator with near-Angstrom resolution and 50 mm travel range, which will be useful for other synchrotron radiation instrumentation and industrial applications.

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Figure Captions:

Fig. 1. Photograph of the overconstrained weak-link mechanism for an artificial channel-cut crystal. This "integral" version combines the linear motion and rotary motion on the same template.

Fig. 2. Schematic of a 4-crystal in-line high-resolution monochromator with nested configuration.

Fig. 3. The design of the artificial channel-cut crystal with the modularly designed overconstrained weak-link mechanism. There are two sets of stacked thin-metal weak-link modules used in the driving mechanism: one is a planar-shaped, high-stiffness, high-stability weak-link mechanism acting as a planar rotary shaft (1), and the other one is a weak-link mechanism acting as a linear stage to support a PZT translator. Both weak-link mechanisms have two modules 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™ [6] (6) with a 20-30nm step size. A Physik Instrumente™ [7] closed-loop controlled PZT (7) with strain sensor provides 1nm resolution for the pitch fine alignment. A pair of commercial flexure bearing (8) is mounted on one of the crystal holders (9), and a Picomotortm driven structure (10) provides the roll alignment for the crystal.

Fig. 4. A sixty-minute stability test result with a 1MeV bandwidth monochromatic beam.

TABLE (1). Design specifications for a (4 4 0) artificial channel-cut crystal

	Integral Version	Modular Version
Maximum Overall Dimension	216 mm x 212 mm x 92 mm	180 mm x 175 mm x 92 mm
Main Shaft Diameter	10 mm	10 mm
Maximum Thickness in Nested Area	30 mm	30 mm
Single Crystal Size	25 mm x 25 mm x 50 mm	25 mm x 25 mm x 50 mm
Number of Angular Alignment Axes	2	2
Angular Alignment Resolution (Pitch)	50 nrad	50 nrad
Angular Alignment Resolution (Roll)	600 nrad	600 nrad
Angular Alignment Stability (Pitch)	Drift less than 25 nrad per hour	Drift less than 25 nrad per hour
Angular Alignment Stability (Roll)	Drift less than 100 nrad per hour	Drift less than 100 nrad per hour
Angular Alignment Range (Pitch)	0.6 degree	1.2 degree
Angular Alignment Range (Roll)	2 degrees	2 degrees

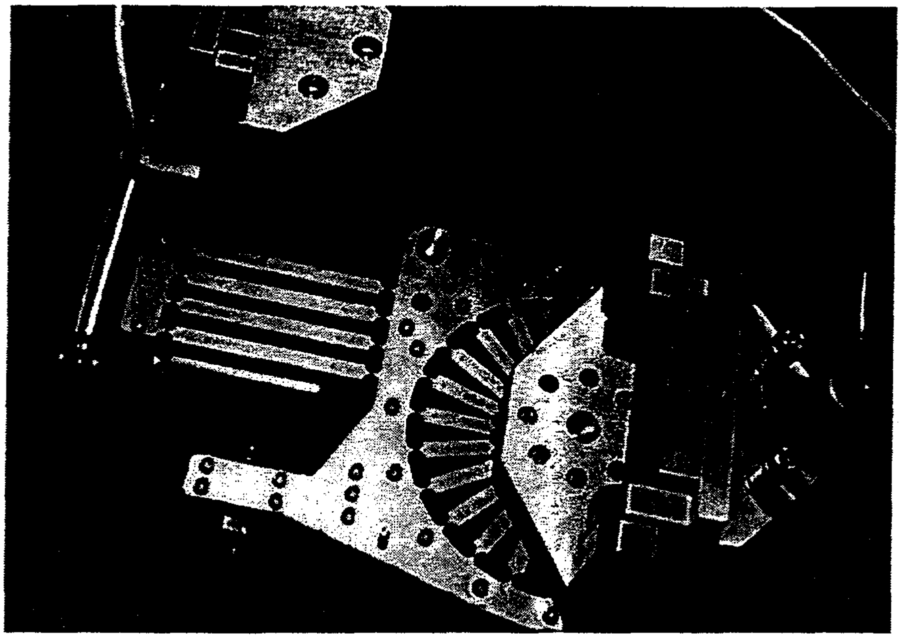

Fig. 1

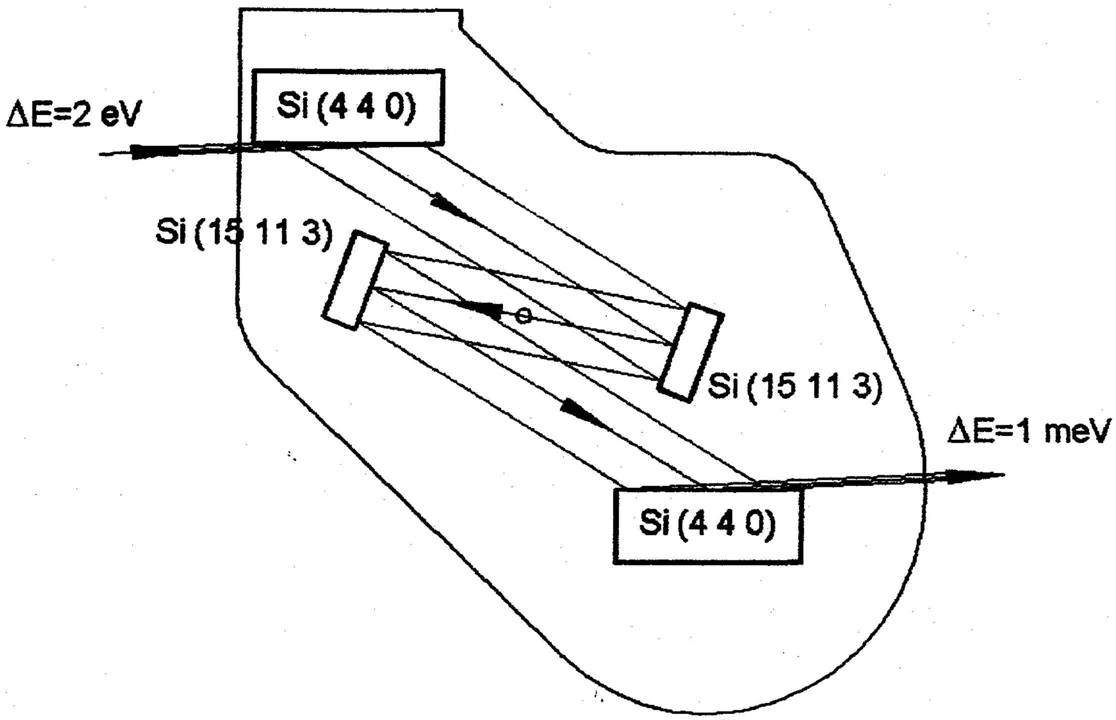

Fig. 2

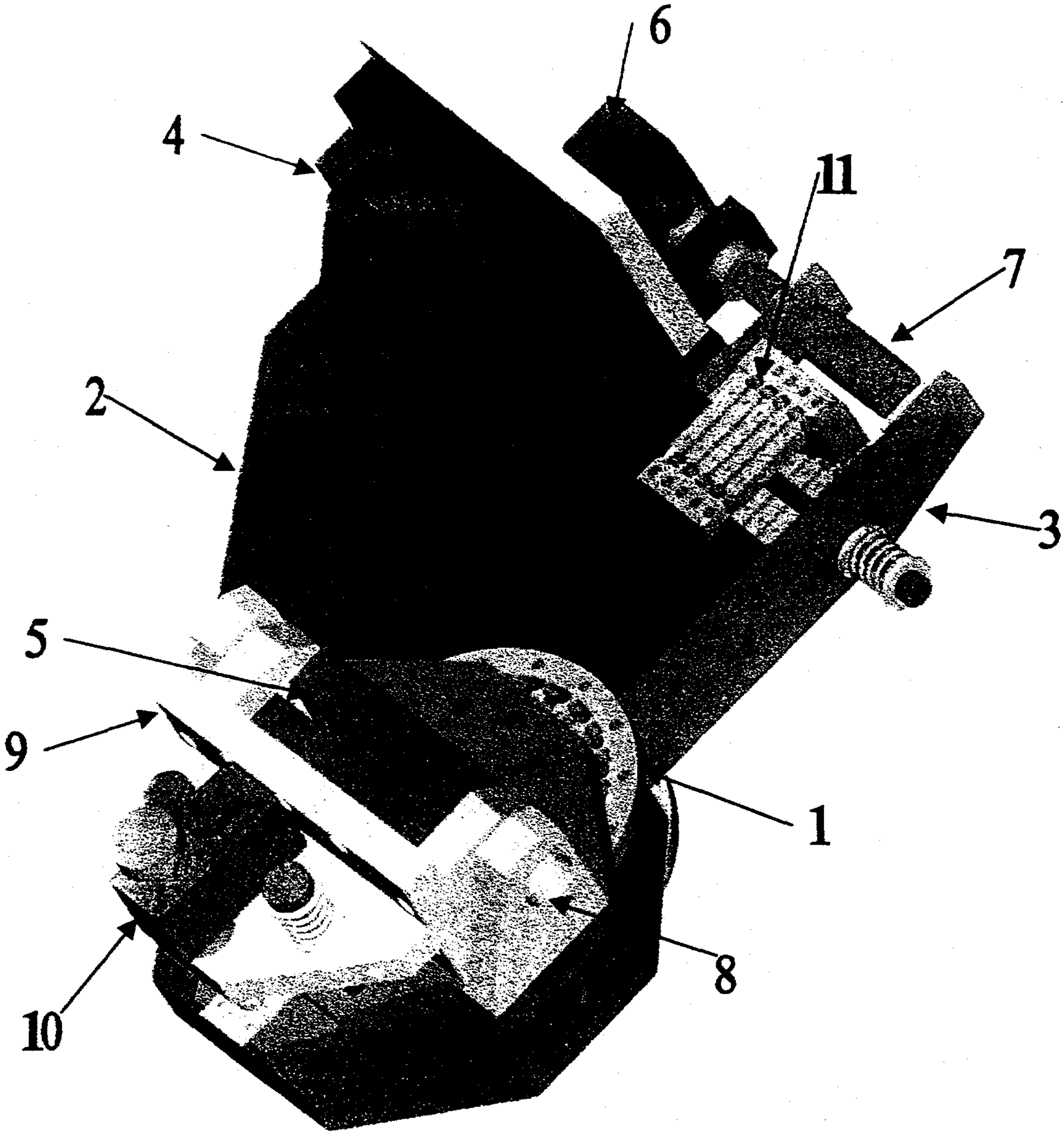

Fig. 3

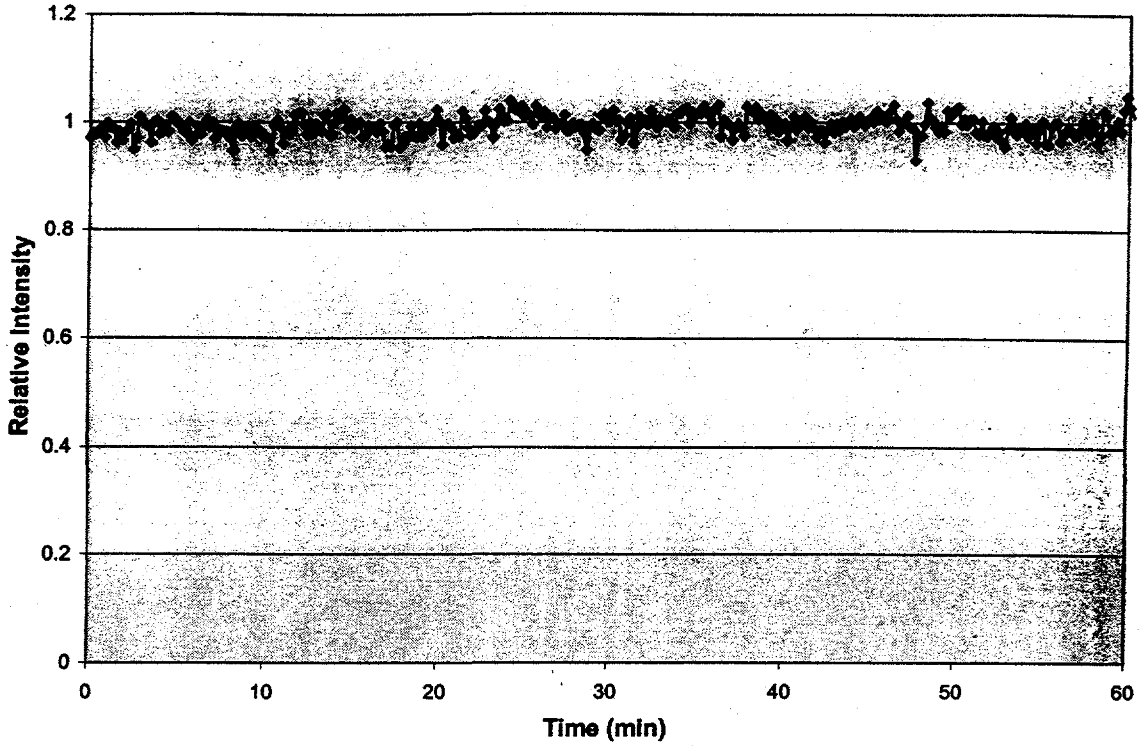

Fig. 4