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DESIGN AND TEST OF PRECISION MECHANICS FOR HIGH ENERGY RESOLUTION MONOCHROMATOR AT THE HEPS

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Abstract

A monochromator stands as a typical representative of optical component within synchrotron radiation light sources. High resolution monochromators (HRMs), which incorporate precision positioning, stability control, and various other technologies, are a crucial subclass within this category. The next generation of photon sources imposes higher performance standards upon these HRMs. In this new design framework, the primary focus is on innovating precision motion components. Rigorous analysis and experimentation have confirmed the effectiveness of this design. This structural model provides valuable reference for developing other precision adjustment mechanisms within the realm of synchrotron radiation.

INTRODUCTION

The Nuclear Resonance Scattering (NRS) spectroscopy at High Energy Photon Source (HEPS) demands extremely high energy-resolving power better than 10^{-7}. As an optical element upstream of focusing mirror, the HRM shall maintain a high stability in terms of positioning, which could influence the energy precision as well as the beam stability at sample position, at fourth generation sources like HEPS. In the proposed monochromator configuration [1, 2], the range for fine pitch adjustment mechanism is relatively small. There also lacks an integrated angular sensing measurement device, thus real time precise tracking of fine pitch position is not possible. These factors impose constraints on the operation and performance of the monochromator. By referring to the previous design from APS and PETRA III [3-6], we have designed a new compact HRM mechanism with an *in-situ* metrology framework. This newly designed flexure mechanism is promising in increasing the stroke while minimizing errors of measurement system through highly rigid metrology devices. The developed mechanism successfully balances requirements between large travel range and high stability. In this paper, we will present the concept, simulation and offline measurements of the new HRM.

MECHANICAL DESIGN

According to the optical design, the HRM comprises two pairs of pseudo channel-cut crystals, with each pair being secured and adjusted by a pose adjustment mechanism. Consequently, the HRM is equipped with two pose adjustment mechanisms for each pair of pseudo channel-cut crystals.

As shown in Fig. 1, in response to the crystal pose adjustment requirements, each set of pose adjustment mechanisms comprises of six motion axes. These include x-axis coarse adjustment, z-axis coarse adjustment, Bragg axis adjustment, lattice matching axis tilting adjustment, and precision adjustment for crystal pitch angle and roll angle. While the first four motion axes are directly actuated by precision stages from KOHZU, the design of the last two precision adjustment mechanism is intricately linked to the ultimate performance of the monochromator and forms the core of the monochromator's structural design.

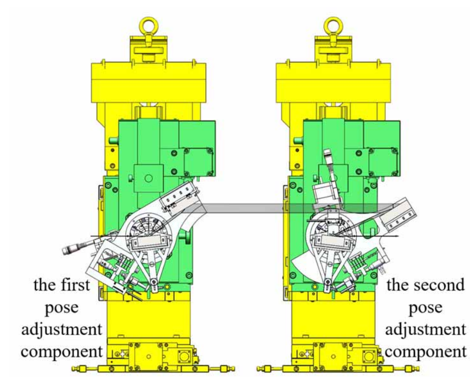

Figure 1: Mechanical design of the HRM.

In Fig. 2, we present the design of the first pose adjustment component. Due to the relatively lower resolution requirement for roll angle adjustment compared to pitch, we have directly employed a Newport 8321 picomotor as the actuator and an industrial flexible pivot as the rotational bearing. This configuration allows for the precise adjustment of the crystal's roll angle. In the design process, we carefully considered the impact of the driver's travel distance on the final angular resolution. As a result, we maximized the driver's travel distance while ensured high stability.

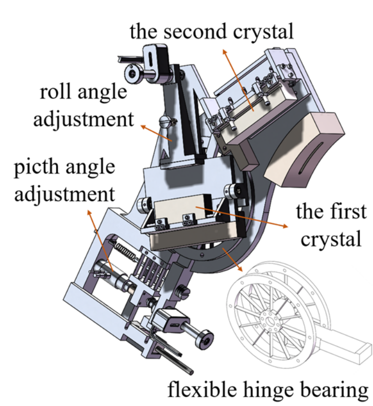

Figure 2: The first pose adjustment component.

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Given the stringent requirements for pitch angle adjustment precision and the need for a broad adjustment range, the mechanism necessitates a delicate balance between high flexibility to ensure a large range of motion up to 2 degrees and high stiffness to guarantee resolution of 25 nrad and stability of 50 nrad in motion. The original designs found in the literature struggled to meet these criteria, prompting the redesign of the core precision rotating component – the flexible hinge bearing.

The flexible hinge bearing is, illustrated in Fig. 2, composed of twelve sets of leaf spring hinges radially connected. The outer ring remains fixed, while the inner ring serves to drive the upper roll angle adjustment mechanism and facilitate precise angle rotation for the crystal within the series drive system. Flexible bearings built on leaf spring hinges can achieve substantial motion strokes within compact dimensions while upholding axial and radial stiffness, thus ensuring the mechanism's reliable load-bearing capacity.

The series drive system incorporates a picomotor and a piezoelectric actuator. The coarse motion is enabled by picomotor which can travel by tens of millimeters with position resolutions in the tens of nanometers., Fine tuning with sub-nanometer resolution can be attained with the piezoelectric actuator. However, the latter is limited to a stroke in the micrometer range. To effectively meet both stroke and resolution requirements, these two types can be connected in series. The connection between the piezoelectric actuator and the inner ring of the flexible hinge bearing is established via a straight rod. Simultaneously, the piezoelectric actuator and the outer ring of the flexible hinge bearing are affixed to the same flat plate, and a flexible guide mechanism is integrated between them. The leaf spring hinges are arranged in parallel, with one end anchored while the other consistently delivers precise displacement with outstanding linearity, powered by the force generated by the piezoelectric actuator. This arrangement guarantees the high-quality input displacement for the monochromator mechanism.

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) of the designed mechanism was conducted to validate the design.

As illustrated in Fig. 3, the analysis of the flexible hinge bearing revealed that with the utilization of aluminum alloy materials, the optimized configuration provides a ±2° stroke with a stress value of 196 MPa. Additionally, the radial stiffness is 26802 N/mm, while the axial stiffness reaches 886 N/mm. In the free state with an arm, the natural frequency achieves 58 Hz.

Similarly, the simulation analysis results for the flexible guide mechanism, as depicted in Fig. 4, demonstrate a significantly larger total stroke compared to the piezoelectric actuator, excellent output linearity across its stroke range, a maximum stress of 21 MPa, and a natural frequency of 414 Hz.

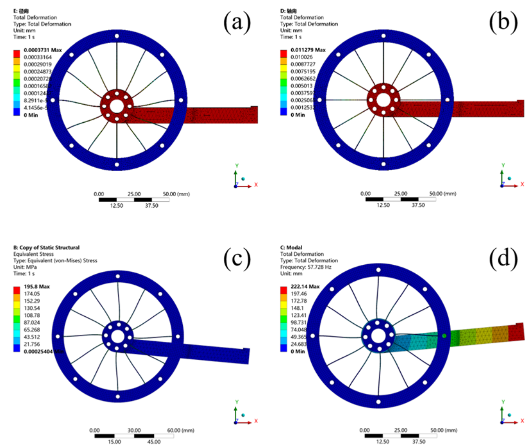

Figure 3: FEA of the flexible hinge bearing. (a) Radial stiffness, (b) axial stiffness, (c) stress and (d) modal FEA.

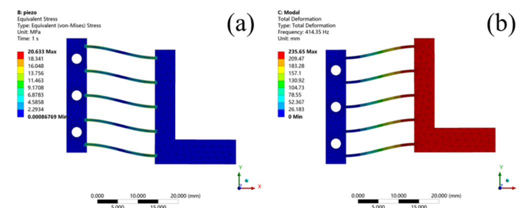

Figure 4: FEA of the flexible guide mechanism. (a) Stress and (b) modal FEA.

The precision pose adjustment mechanism incorporates a grating ruler measurement device, enabling real-time detection. In the structural design, the emphasis lies on maximizing the solid structure while ensuring that the sensor can be adjusted with multiple degrees of freedom. The representative simulation analysis results in Fig. 5 indicate a mode with a frequency of 331 Hz and a stable foundation for measurement.

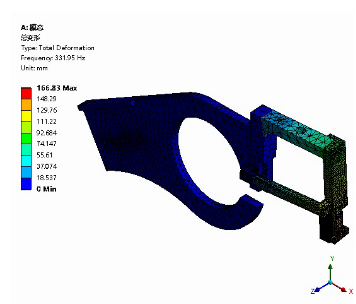

Figure 5: Modal FEA of the measurement structure.

A comprehensive dynamic simulation analysis was performed on the entire precision pose adjustment mechanism with crystals included. In accordance with Fig. 6, the findings reveal a first natural frequency of 155 Hz, which greatly contributes to achieving high stability. Specifically, the first-order vibration modal aligns with the roll angle direction of crystal, the second-order vibration shape corresponds to the yaw direction, and the third-order modal of 249 Hz is in pitch angle direction, all in accordance with the design expectations.

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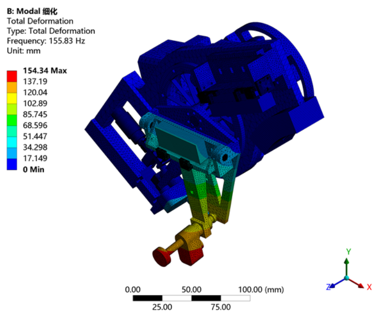

Figure 6: Modal FEA of the pose adjustment component.

OFFLINE TEST

Preliminary testing of the precision pose adjustment mechanism has been conducted. The two sets of pose adjustment mechanisms have been individually affixed to KOHZU's three-axis motorized stages, KTG and KHI. The motor's base is bolted to a granite table via an adapter. The granite table is positioned on the ground supported by 4 wedge blocks, as shown in Fig. 7.

Figure 7: Experimental device.

Regarding kinematic testing, the precision pose adjustment mechanism's stroke and resolution were measured.

As depicted in the Fig. 8, the mechanism attains a motion stroke of ±1.3°, fully aligning with the design specifications.

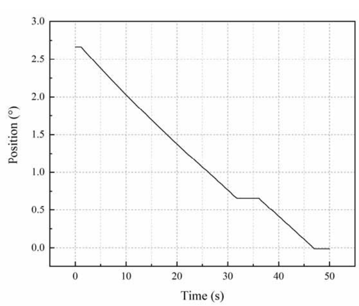

Figure 8: Stroke test of coarse pitch.

Figure 9 illustrates the coarse adjustment resolution of the picomotor and the fine adjustment resolution of the piezoelectric actuator, respectively. The experimental results were obtained using the encoder integrated into the design. With a sample rate of 2000 Hz and no filtering by an ACS controller, distinct step signals are visible at the coarse adjustment resolution of 250 nrad, and similarly, clear step signals are observed at the fine adjustment resolution of 8.3 nrad. These results not only align with the design specifications but also surpass the related test outcomes of known HRMs.

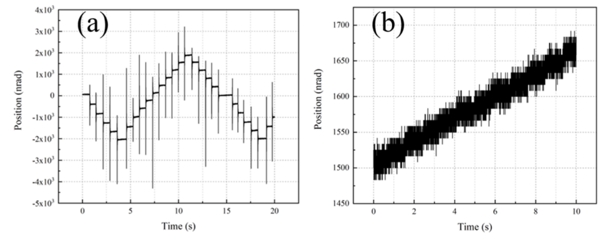

Figure 9: Resolution test. (a) Coarse adjustment resolution and (b) fine adjustment resolution.

In stability testing, evaluations were conducted for the stability between the first and second crystals, and the stability between the first and second pose adjustment mechanisms. Experimental data were collected using laser interferometers. As shown in Fig. 10, the results reveal that the stability between the first and second crystals is 12.5 nrad RMS (0.5-500Hz), while the stability between the first and second mechanisms is 55.0 nrad RMS (0.5-500Hz). The off-line angular stability is sufficient to meet the experimental requirements; however, it is still promising for further improvement through environmental control and other measures.

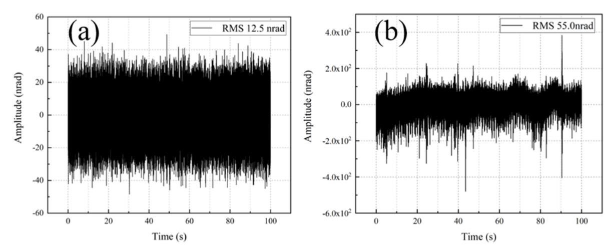

Figure 10: Stability test. (a) The stability between the first and second crystals and (b) the stability between the first and second mechanisms.

CONCLUSION

The precision adjustment mechanism incorporated within the HRM has been designed to address the demands for large stroke and high accuracy. FEA results confirm the viability of this solution, and experimental testing validates the efficiency of the design. In the future, the designed HRM will be tested under conditions more similar to its final locations. The current results demonstrate that the newly developed HRM can offer dependable optical modulation capabilities for the high energy resolution beamline of HEPS.

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