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THERMAL-DEFORMATION-BASED X-RAY ACTIVE OPTICS DEVELOPMENT IN IHEP*

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Abstract

Active optics is a key technology for maintaining wavefront preservation during X-ray beam transport in fourth-generation light sources. In this paper, we propose a concept for surface thermal-driven active optics. In this scheme, the overlap between the position of driving source and the x-ray footprint can give strong modulation performance, including spatial resolution and modulation efficiency. Finite element analysis has experimentally verified the high modulation performance of this approach. To give the feedback of the modulation, we have established a vacuum in-situ surface profile measurement system. Preliminary experiments show that the measurement accuracy of the system's flat mirror can reach 80 nrad rms. The development of these technologies will provide new, low-cost solutions for fully exploiting the performance of fourth-generation light sources.

INTRODUCTION

The High Energy Photon Source (HEPS) currently under construction will be China's first fourth-generation X-ray light source with high energy and high brightness. Like other similar facilities, the quality of various optical instruments and equipment on the beamline seriously affects the X-ray beam transport performance of the beamline. On the one hand, it is important to choose high-quality optical components, such as ultra-precision X-ray mirrors and crystals. On the other hand, it is also necessary to consider the deformation errors of optical optics caused by clamping and thermal loads in the working environment. To solve these problems, the synchrotron radiation field has developed various active optics technologies over the past few decades, including bimorph mirrors [1, 2], bent mirrors [3, 4], phase plates [5-7], and REAL [8, 9] technology. To reduce the engineering risk of HEPS and the difficulties of budgeting, we propose and study a low-cost, low-technical-difficulty active optics technology scheme. By integrating the mirror surface with the driving element, the overlap between the footprint of x-ray beam and the driving modulation unit can be achieved, which is also conducive to improving the spatial frequency and driving efficiency of modulation. In conjunction with the surface shape modulation device, high-precision surface shape detection equipment is an important link in achieving feedback adjustment. To achieve in-situ measurement, extensive research has been done on various light sources, including measurement schemes using interferometers [10, 11] and long trace profilers [12-15]. However, due to the influence of scanning window errors, the measurement error of the system is relatively large. In this project, we have developed a vacuum-based surface profiler metrology system. Finally, a closed-loop active optics modulation system is formed.

DEFORMABLE MIRROR AND PERFORMANCE ANALYSIS

Surface Modulation Scheme

Thermal deformation has always been one of the challenges faced by synchrotron radiation beamlines. Studies have shown that thermal deformation can be effectively suppressed through various means, including notch structure design, advanced cooling schemes, and balanced design of cooling and heating areas. These methods have been developed to ensure that the optical instruments and equipment on the beamline maintain their shape and performance under heating load conditions.

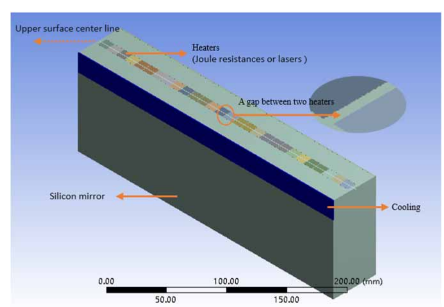

Figure 1: Multi-units surface heating-based shape modulation model.

In response to the demand for high spatial frequency modulation [16], a thermal-driven active optics mirror based on thermal deformation effects has been proposed, as shown in Fig. 1. The typical feature of this system is the overlap between the X-ray footprint and the heating driving area. Unlike traditional schemes, the fact that the position of the driving source is so close to the light-use area means that the transmission path is shorter, which is conducive to high spatial resolution. Each unit in the system is individually current-controlled, and the substrate material can be chosen as single crystal silicon, quartz, metal, etc., depending on the monochromatic and white light

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conditions. The former has good thermal conductivity and can work under thermal load conditions. Quartz has a relatively high thermal expansion coefficient and can produce significant deformation under relatively low power drive in monochromatic light, reducing the demand for heat dissipation. The metal substrate is also attractive and suitable for thermal load conditions and extremely high thermal deformation capabilities. However, the processing technology of the metal substrate, especially the maintenance of roughness, is a major technical challenge. There are two methods for implementing the heating device: (1) forming a heating resistance channel on the substrate through modification or coating, and (2) laser irradiation of the mirror surface, which is absorbed and converted into heat. Both of these technologies have relatively mature processes. The size of the modulation unit is basically not limited by the process and can reach the millimetres level. The specific size depends on the performance requirements of the spatial resolution and the cost control of the entire system.

It is important to note that correcting the overall surface shape may not always be efficient. From the perspective of the entire beamline, high-order errors can be eliminated using thermal deformation mirrors, and the overall spherical curvature can be fine-tuned and compensated using pressure bending devices or tilted mirrors, as shown in Fig. 2.

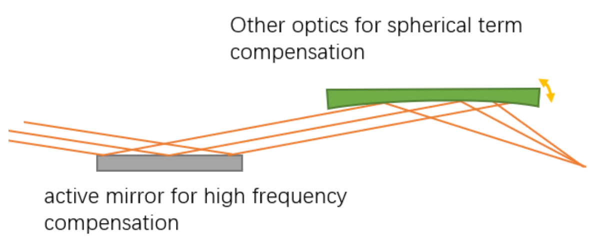

Figure 2: Beamline compensation strategy by combining with other optics devices.

Modulation Performance and Analysis

Due to the difficulty of solving thermal deformation using traditional analytical methods, we use the widely used finite element method (FEA) to simulate the thermal deformation of the mirror to verify the performance of the entire system, as shown in Fig. 1. In FEA, the thermal-structural coupling simulation scheme is designed as follows: the geometry dimension of mirror is 300 mm (L)*50 mm (W)*100 mm (H), single crystal silicon as substrate of the mirror. In the steady-state heat transfer module, the initial temperature of the mirror is 22 ℃. As shown in Fig. 3(a), assuming that the cooling surfaces on both sides of the mirror are ideal and maintained at a constant temperature of 20 ℃, a 10 mm×10 mm area on the mirror's reflective surface is taken as a driving unit, with a gap of 0.5 mm between the units covering the entire mirror length. The constraint conditions in the steady-state structural module only suppress the rigid motion of the mirror, simulating the process of its free thermal expansion.

Considering the linear superposition characteristics of thermal deformation [17] and referring to the resolution analysis of optical imaging systems, we can use the single-point thermal deformation curve to characterize the spatial resolution of the system. Figure 3 shows the thermal deformation response curve of a single unit. To highlight the efficiency of surface excitation, the simulation results of lateral thermal excitation are also given, with the same unit size. The results show that the modulation half-width is increased by a factor of 5. At the same time, to achieve the same thermal deformation, the surface excitation method can reduce the power demand by a factor of 9.

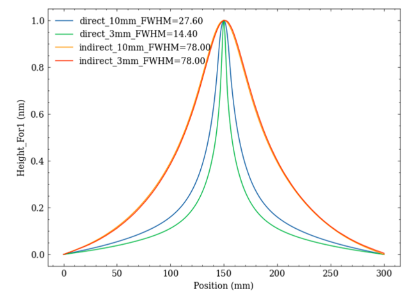

Figure 3: Deformation response for single driving unit.

Furthermore, we conducted simulation experiments to study the surface shape modulation performance of the deformation mirror. With 28 units covering the entire mirror length under the condition of equal thermal power loading, the response functions obtained for each unit are shown in Fig. 4(a). Taking the blue line shown in Fig. 4(b) as an example, the target function of surface shape modulation is a sine function with a period of 100 mm and an amplitude of 5 nm. The green line represents the surface shape obtained by least-squares optimization based on the theory of thermal deformation superposition effects, as well as the corresponding thermal power of each unit is calculated. By directly loading the corresponding thermal power in FEA, the mirror temperature field obtained is shown in Fig. 4(c), with a maximum/minimum value within a range of 1 degree Celsius. Within this temperature range, the thermal expansion coefficient of single crystal silicon is basically maintained at 2.46×10-6 C-1. The deformation result of the central line is shown as the red line in Fig. 4(b). It can be seen that the theoretical modulation residual curve is basically consistent with the residual curve obtained from finite element simulation (0.03 nm rms), which indicates that thermal deformation is a linear response under certain material properties. In the subsequent analysis and calculation, the theoretical value can be directly used for actual surface shape modulation.

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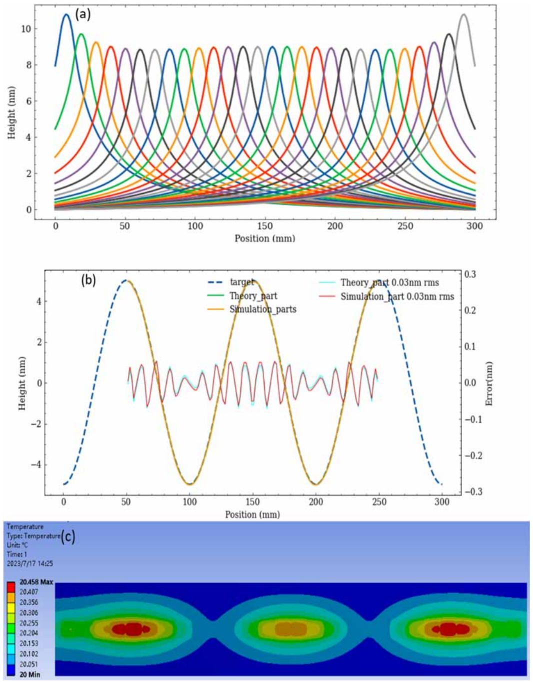

Figure 4: The response functions when each unit is loaded with 1 W heating power (a). Theoretical calculation results and their residuals for a spatial period of 100 mm target function Finite element simulation results and their residuals (b). Temperature distribution on the reflective mirror surface (c).

Compensation for Real Mirrors

Low- and medium- frequency errors are the challenges in mirror manufacturing. The use of active optical devices to compensate for these errors can significantly reduce the precision requirements and costs of the process. To verify the system's ability to correct various real surface shape errors, we calculated the correction for the mirrors in DABAM (Database for the Analysis of metrology of Beamline Mirrors) surface shape database. The response of each unit calculated in the previous section is used for modulating and compensating for these errors. For example, in Fig. 5, the surface shape modulation of a 200 mm length of one of the mirrors is performed, and its negative height value is taken as the modulation target function (blue dashed line). As can be seen, through this surface modulation method, theoretically, a relatively rough reflection mirror (26.51 nm rms, 86.21 nm pv) can be corrected to a surface with low residual error (0.23 nm rms, 1.23 nm pv), where the rms and pv values are reduced to 0.87% and 1.4% of the original values, respectively. The compensation results of the 28 mirrors in the database are shown in Fig. 6, which provides the compensation residuals and the required driving capabilities. The surface compensation accuracy can generally reach the sub-nanometer level, and the driving power depends on the choice of substrate material. Single crystal silicon requires higher power due to its low thermal expansion coefficient. From the perspective of the beamline, materials with a large thermal expansion coefficient can be chosen as the base of the active deformation mirror.

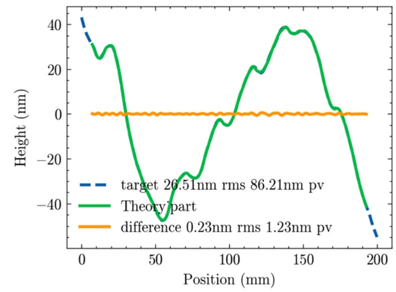

Figure 5: Shape compensation by the deformable mirror for No. 16 mirror in DABAM.

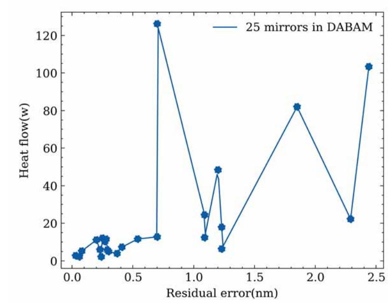

Figure 6: Power consumption in shape compensation by the deformable mirror for mirrors in DABAM.

VACUUM IN-SITU SURFACE PROFILE

Over the past two to three decades, various detection technologies have been developed, including long-range profilometers [18, 19], Hartmann screen lattice measurement methods [20] and stitching interferometers. To achieve surface shape detection of thermal load mirrors such as white light mirrors in a vacuum environment, measurement schemes based on long-range profilometers are the mainstream direction. In this project, a scanning pentaprism-based long-trace profiler (pp-LTP) was established.

The surface shape scanning device mainly includes a high-precision angle measurement device - optical head, pentaprism, and a low-motion error scanning device. When the collimated beam scanning the mirror, the slope of a certain point on the SUT surface is θ, the reflected light beam through this point will produce a 2θ angle change and will be detected by the optical head. To reduce the impact of the vacuum window, the optical head is placed outside the cavity, and the guide rail and pentaprism are inside the vacuum cavity. The maximum scanning length of the entire system is 500 mm.

The results of the angle calibration measurement of the optical head are shown in Fig. 7. By conducting a rotation test with a commercial autocollimator, within a range of 40 μrad, the angular measurement error is below 100 nrad, and the root mean square (rms) is below 10 nrad. In order to assess the practical measurement performance of PP-LTP, we conducted surface profile measurements on the same standard flat mirror using both PP-LTP and a clean-room-based FSP (Flag-type Surface Profiler). The comparative test is presented in Fig. 8. The blue curve represents

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the measurement results obtained with the FSP in the cleanroom, while the black curve represents the results obtained with the PP-LTP. After correcting for linear errors, the two instruments exhibited a similar trend in the change of their measured slopes. The root mean square (RMS) measurement error of the difference was 87 nrad rms.

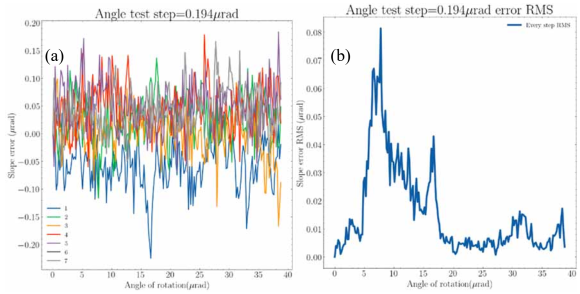

Figure 7: Performance of the optical head within 40 μrad.

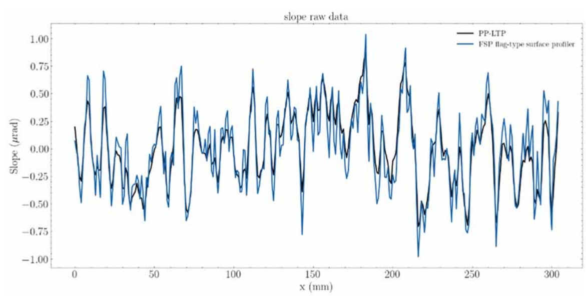

Figure 8: Performance of PP-LTP.

CONCLUSION

This paper reports on the development of a thermally-driven active optics mirror system. Analysis of the mirror's characteristics shows that surface heating-based modulation has the advantages of high spatial resolution, high precision, and high efficiency. Finite element analysis results show that using a high thermal expansion coefficient substrate can achieve high-precision deformation compensation at lower power, especially in the case of monochromatic light, which can alleviate the challenges of high-precision mirror fabrication. In terms of engineering, a vacuum in-situ surface shape detection device has been established, and comparison tests with FSP show that the measurement accuracy of the system can reach sub-100 nrad. To improve the measurement accuracy of the entire system, we plan to integrate the optical head into the vacuum chamber to eliminate the influence of window errors. Additionally, we plan to fabricate high-precision windows, considering the small size and low engineering difficulty of the pp-LTP scheme.

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