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Mechanical design and finite element analyses of surface bending mechanism for X-ray optics

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ABSTRACT

A new surface diffraction beamline is designed at the Shanghai Synchrotron Radiation Facility (SSRF). The purpose is to provide a high-performance instrument for measurements of the surface interfaces of structures constructed using different materials for researchers from different countries. There are many technical difficulties associated with the construction of the beamline. One of them is the achievement of a high-focusing quality so as to reduce stray lights from substrates because of the small grazing incident angles. Two perpendicular focusing mirrors are adopted to focus the beam. In order to obtain an excellent light spot, the two mirrors are bent to obtain the expected curvature radii and surface errors. In this study, a new X-ray optics bending mechanism is designed for the mirrors, and its principle of operation is described. The mechanical state, the bending resolving power, and the suppression methods for surface errors are studied using finite element analyses. The mirror's minimum bending radius and bending resolving power are 1002 m and 24.2 m, respectively, and its suppression ability for surface error is better than 0.78 μrad. These characteristics are better than the predictions, and further improve the performance of the beamline.

1. Introduction

The synchrotron radiation light source is a revolutionary light source. The first synchrotron was built by Goward & Barnes in 1946, but the synchrotron light was not observable [1]. It was first observed by General Electric (GE) in 1947 as the phenomenon whereby an electron emits electromagnetic radiation when it rotates in a circle in a synchrotron, and was subsequently developed within a time period that spanned more than three generations. The first generation was a dual-purpose light source, "parasitically" running in synchrotrons. The second generation was a special light source whose purpose was to provide a powerful experimental tool for basic researchers in chemistry, biology, material science, and medicine. Owing to the promotion of the second generation light source to science and technology, major worldwide economic powers constructed the third generation light source in succession, achieving smaller beam divergence than the first and the second generation light sources that generally ranged between 5–12 nm·rad,thereby resulting in a higher spectral brilliancy [2]. Shanghai's Synchrotron Radiation Facility (SSRF) is equipped with a third generation light source, whereby dozens of beamlines have been established within it. High-brightness light beams from SSRF need to be deflected, collimated, monochromatized, and focused, by a series of high-performance optical devices.

The small beam divergence of the third generation light source results in a small grazing incidence angle (whereby for hard X-ray wavelengths, the grazing incidence angle is less than 5mrad), which gives rise to a long reflector length in the beam propagation direction, sometimes resulting in a length that exceeds 1m. With the current improvements in optical processing technologies, a highly accurate plane, or a highly accurate sagittal surface, can be manufactured on the surface of the mirror. However, it is difficult to manufacture a highly accurate cylindrical shape, or an elliptic cylinder shape whose radius is several kilometers along the meridional direction. Therefore, mechanical bending methods are usually adopted in the case of a large mirror to generate a deformation in the meridional direction to obtain a meridional shape. Through the use of the mechanical bending method, in addition to forming a highly accurate surface, the radius of the surface can be adjusted by controlling the bending force to adapt to different focal lengths and grazing incident angles. Dominating mechanical bending methods include three-point bending, four-point bending, two-arm bending, and flexible hinge bending [3–8]. Piezoelectric bending has emerged in recent years, which achieves a mirror bent by controlling numerous bimorphs between the mirror and its base in a segment-by-segment manner. This method is of high precision and high stability. It is usually applied to bend short-length mirrors [9].

In view of the characteristics of high-precision and high-economy of

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mechanical bending, researchers in synchrotron radiation facilities and beamline equipment suppliers all over the world have been studying in-depth different mechanical bending methods for large reflectors in order to develop superior performance mechanical bending equipment.

Depending on the surface diffraction beamline at SSRF, this study assesses a four-roller mechanical bending method using numerical simulations, and presents the development of a beamline bending equipment. This paper will elaborate the design process of the bending equipment, the mechanical state of the bending process, and the causes and suppression methods for surface errors, and will explain the relationship of the push-rod displacement, the mechanical state, the stress state, and the bending radius. The research outcomes presented herein are expected to provide detailed data and technical guidance for the future development of bending equipment with higher performance.

2. Design of the surface bending mechanism

The surface bending mechanism is designed primarily for the surface diffraction beamline at SSRF, and possesses general characteristics. The primary function of the beamline is the measurement of the interfaces of structures of all types of material surfaces. Relevant work includes research studies of low-dimensional membrane material interfaces and crystalline states, atomic structures and dynamics on solid surfaces, solid–liquid and liquid–liquid interfaces, structures of biofilms, and self-assembly of soft substances. The layout of the beamline is shown in Fig. 1. It makes full use of the low-divergence angle of undulator radiation, and adopts one monochromator and one focusing system to enhance photon flux and stability. A four-blade slit located at 21.5 m from the light source defines an acceptance angle of 0.08 × 0.04 $mrad^2$ (H × V) for the optical elements downstream. A double-crystal monochromator located at 24 m from the light source defines the energy range and the energy resolution of the beamline. Two focusing mirrors located at 35 m and 37 m from the light source focus the beam in the vertical and horizontal directions, respectively. The two focusing mirrors are bent using bending equipment. This study aims to design the bending equipment of the focusing mirror that is located at 35m. The basic parameters of the focusing mirror are listed in Table 1, and the technical requirements of the bending equipment are listed in Table 2. Currently, the root-mean-square (RMS) slope error in the meridian direction can be controlled within 2–3 μrad using the mechanical bending method for a 1 m long mirror in synchrotron radiation beamlines. In some cases, fortunately, the RMS slope error can be close to 1 μrad. In this study, the requirement of the RMS slope error is 0.8 μrad.

2.1. Design principle

A four-roller bending scheme is implemented to design the bending device. There are two support rollers placed on the undersurface of the mirror, and two press rollers placed on the surface of the mirror. The distance between the support roller and the press roller is l_f. Each section of the mirror (spanning a distance l) will produce the same bending moment M when the press rollers exert the same forces F on the mirror. The surface of the mirror will generate a deformation with a radius R under the action of the bending moment M. The bending equation of the mirror is as follows,

Table 1
Basic parameters of the focusing mirror.

Item	Unit	Value
Dimensions of bending mirror	mm^3	1000′70′50
Effective area of bending mirror(L × W)	mm^2	840′40
Surface roughness	nm	≤0.3
Slope error in meridian direction	μrad	≤0.5
Base material		Monocrystal silicon

Table 2
Technical requirements of the bending device.

Item	Unit	Value
Minimum radius in meridian direction	m	≤2000
Root-mean-square (RMS) slope error of effective area of mirror after bending	mrad	≤0.8
Bending resolution	m	30(R: 2500–4500)

$$M = \frac{EI}{R} \tag{1}$$

In Eq. (1), E is the modulus of elasticity of the mirror, I is the moment of inertia of the mirror, and R is the radius of the mirror after bending. Fig. 2 shows the principle of the four-roller bending scheme. After exerting a bending moment on the mirror, the deflection (deformation) of each section of the mirror is

$$y(M) = \frac{Mlx}{6EI}\left(1 - \frac{x^2}{l^2}\right) + \frac{Ml(l-x)}{6EI}\left(1 - \frac{(l-x)^2}{l^2}\right) \tag{2}$$

The largest deflection appears in the middle of the mirror. The slope of each section of the mirror is

$$\theta(M) = \frac{Ml}{6EI}\left(1 - \frac{3x^2}{l^2}\right) + \frac{Ml}{6EI}\left(-1 + \frac{3(l-x)^2}{l^2}\right) \tag{3}$$

2.2. Design of the bending component

The bending component is a key part used to determine the deformation of mirrors directly. It includes two support rollers, two press rollers, two rocker arms, a push rod, a support frame, and a water cooling pipe. Its structure is shown in Fig. 3. The motor rotates the screw rod, which makes the push block compress the spring whose deformation will produce a certain thrust. The thrust makes the push rod drive the two rocker arms that move in the opposite directions at the same time. The two rocker arms make the press rollers press the

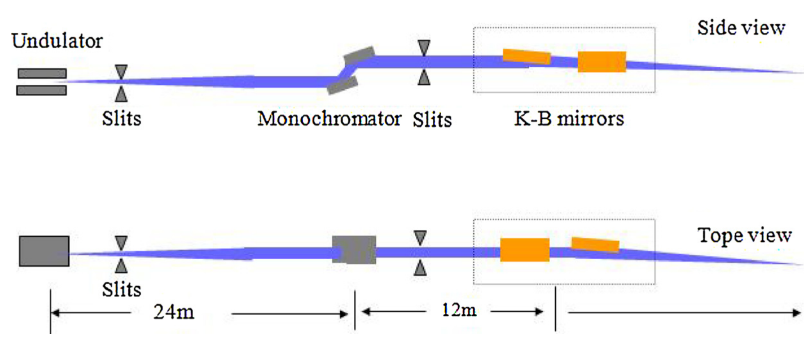

Fig. 1. Layout of the surface diffraction beamline. K-B is the abbreviation of Kirkpatrick-Baez.