WAVEFRONT DISTORTION MEASUREMENT OF A SR EXTRACTION MIRROR FOR THE BEAM PROFILE MONITOR USING SHACK-HARTMANN METHOD

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Abstract

The wavefront measurement technique using the Shack - Hartmann wavefront sensor has been developed for measurement of wavefront distortion of a SR extraction mirror for the beam profile monitor at Photon Factory. The instrument consists of a multi-lens array (8x8 array, 250 μm pitch and focal length of 4.5 mm), a beam expander (20:1), an image relay lens system (1:1), a He-Ne laser (633 nm) and a digital CCD camera. To analyze positions of focal spot on the CCD in 1/10 of the pixel size, the wave front sensor can measured to be λ/30. A dynamic range of the wavefront sensor was designed 12.6 μm max. Performance of the wavefront sensor was tested with an optical flat. With this wavefront sensor, a wavefront error caused by surface deformation of the SR extraction mirror was measured at Beamline 27 of Photon Factory. The correction of the measured wavefront distortion is also described.

1 INTRODUCTION

The beam profile monitor based on an imaging of the synchrotron radiation (SR) will give a visible beam profile, which greatly improves the efficiency of the operation of the accelerators. In this monitor , the visible SR beam is extracted from the accelerator ring by a mirror, then the SR beam guided into a focusing system to making an image of stored electron beam in the accelerator ring. We use a water-cooling mirror made of beryllium as a extraction mirror [1]. The mirror will be deformed by not only a mechanical stress but also a thermal expansion caused by absorption of X-rays in the spectrum. The deformation of the Be-mirror introduce a wavefront error (often more than few λ(λ=633 nm) and it makes a blurred beam image. To correct the blurred image, it is necessary to measure the wave front error caused by the deformation of the Be-mirror. The measured wavefront error is used to calculate the point spread function (PSF). The PSF is the intensity distribution that would result from imaging a point source. The beam profile is then estimated from the correlation of images and PSF by a deconvolution process. We have several methods to measure the wavefront error such as interferometer technique. The interferometer is generally very sensitive to grand vibrations. The Be-mirror is fixed in the accelerator and is not insulated from the grand vibration. In this time, we apply the Shack-Hartmann wavefront sensor [2] because of this sensor can measure a mean wavefront error under having a grand vibration.

In this time, a Shack-Hartmann wavefront sensor was designed and constructed for a measurement of wave front error caused by a deformation of the Be-mirror. We corrected the blurred beam image by the use of deconvolution technique. This investigation was performed at beamline-27 in Photon Factory, High Energy Accelerator Research Organization.

2 WAVEFRONT SENSOR

To measure the wavefront distortion of Be-mirror, we designed and constructed the Shack-Hartmann wavefront sensor. The sensor consists a multi-lens array (a number of lenses distributed in matrix) and a detector (like a CCD camera) and is based on geometrical optics. The principle of the Shack-Hartmann wavefront sensor is shown in Fig. 1.

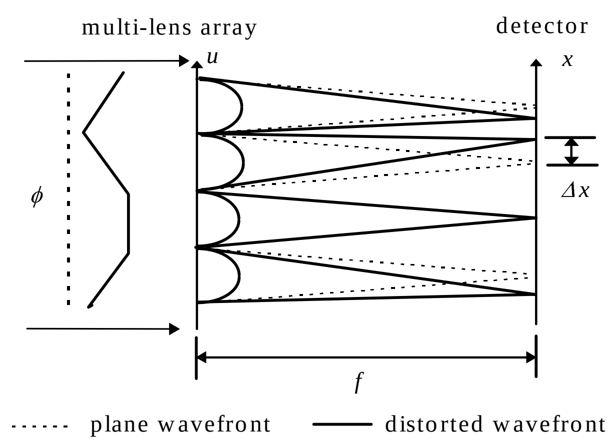


Fig. 1 principle of Shack-Hartmann wavefront sensor

The wavefront comes into a multi-lens array and it is divided by each lenslet. In the multi-lens array's focal plane, the image spot of each lenslet is shifted by a quantity proportional to the local slope of the wavefront. When a wavefront ϕ comes into a lenslet, if we measure a spot displacement in the focal plane as Δx, the corresponding slope measurement is

$$\frac{\partial\phi}{\partial\phi} = \frac{2\pi\Delta x}{\lambda f} \qquad (3)$$

where f is the focal length of the each lenslet and λ is the wavelength of detected light. The spot image is recorded by the detector in the multi-lens array's focal plane. The position of the each spot image is calculated by a centroiding algorithm. This measurement determines the mean slope of the wavefront on subaperture of lenslet, in perpendicular directions. To integrate the gradient in perpendicular direction we reconstruct the phase ϕ from its gradients using the least-square fitting algorithm.

The layout of the Shack-Hartmann wavefront sensor is shown in Fig. 2. The instrument consist of a multi-lens array (8x8 array, 250 μm pitch and focal length of 4.5 mm), a image relay lens system (20:1), an image relay lens system (1:1), a He-Ne laser (λ=633 nm) having a collimator system and a digital CCD camera (Electrim, EDC-1000M, 324x242 pixels, 10x10 μm each pixel). The image of Be-mirror is transfer on the multi-lens array by the use of the image relay lens system (20:1). Because of the focusing length of the lenslet is only 4.5 mm, the focal plane image of the multi-lens array is again transferred on the CCD by the use of the image relay lens system. This image on CCD is captured by a computer and analyzed. In this system, we can measure the root mean square spot displacement by 1/10 of the pixel, then the corresponding sensitivity is λ/30 (λ=633 nm).

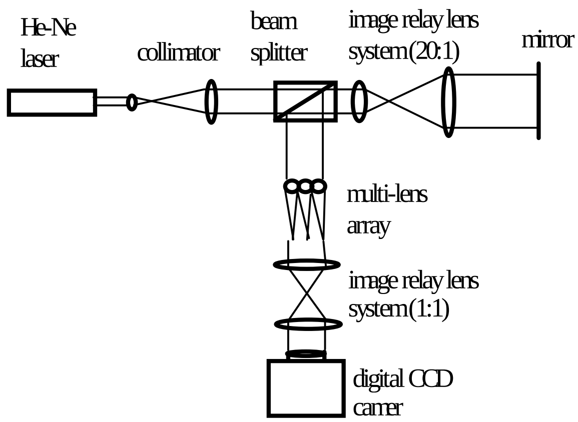


Fig. 2 the system of the Shack-Hartmann wavefront sensor

3 PERFORMANCE OF SHACK-HARTMANN WAVEFRONT SENSOR

We tested the performance of the Shack-Hartmann wavefront sensor using an optical flat (surface quality λ/20) and a gimbal mirror holder having a micrometer. We tilt the optical flat and measure the tilt of wavefront. A result of measured wavefront is shown in Fig.3. The flatness of wavefront from Fig.3 is λ/20. Result of angular response of the sensor is shown in Fig.4. The scattering from the linear line is 0.03 mrad in maximum. The precision of the ginbal holder is about 0.04 mrad, so small scattering from linear line is mainly due to this precision. A dynamic range of the Shack-Hartmann wavefront sensor is 12.6 μm max.

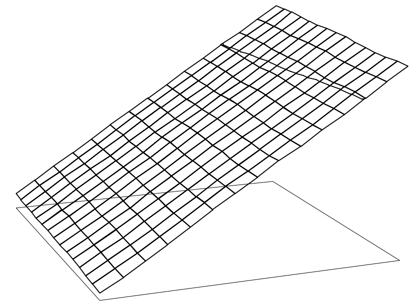


Fig. 3 A result of wavefront by the Shack-Hartmann wavefront sensor. Flatness of the wavefront is less than λ/20. The side length of the 3-dimensional plot is 35 mm.

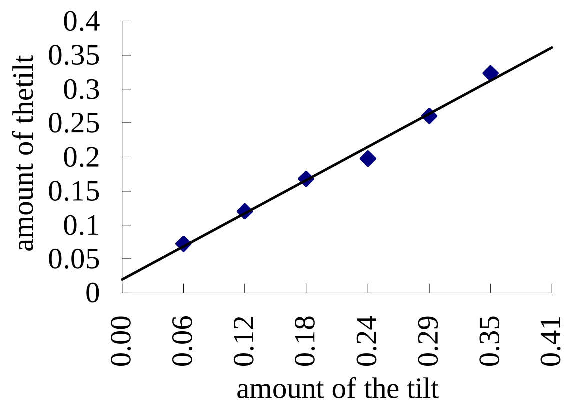


Fig. 4 Angular response of the Shack-Hartmann wavefront sensor

4 MEASUREMENT OF THE WAVEFRONT ERROR

We measured a wavefront error caused by surface deformation of the Be-mirror using Shack-Hartmann wavefront sensor. A result of the measurement is shown in Fig. 5.

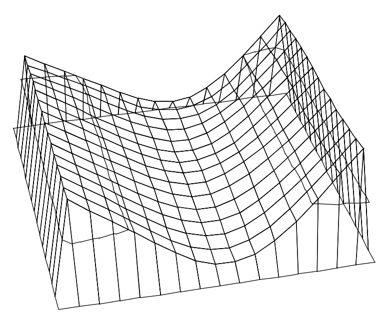


Fig. 5 The surface deformation of the Be-mirror. The side length of the 3-dimensional plot is 35 mm.

The Be-mirror was deformed to cylindrical way in the horizontal about 2 μm peak to valley (this deformation was caused by baking process). The side length of the 3-dimensional plot is 35 mm.

5 OBSERVATION OF THE BEAM IMAGE

The optical image of the beam is produced by a diffraction limited focusing system [1]. To obtain the PSF caused by the deformation of the Be-mirror and finite aperture of the entrance pupil of the focusing system at the balanced astigmatism point, the propagation of the wavefront error is calculated by a computer code ZEMAX. A result of the PSF is shown in Fig. 6.

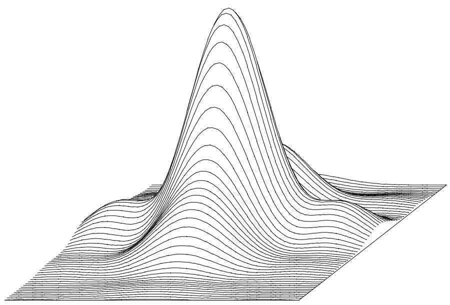


Fig. 6 The PSF at the balanced astigmatism point. The side length of the 3-dimensional plot is 96 μm.

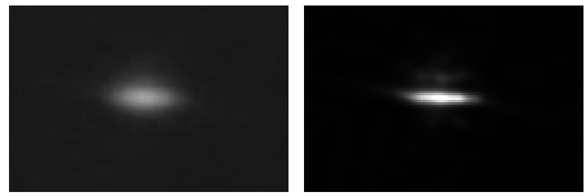
The rms width of the central peak of the PSF are 13 μm in vertical and 15 μm in horizontal. The image of the beam is given by a convolution of the PSF and geometrical image. The observed image of the beam as shown in Fig. 7 (a) is given by a convolution of the PSF (Fig. 6) and the geometrical image. The rms beam size from the beam image are 96.5 μm in the vertical and 280 μm in horizontal. Considering the conjugation ratio of 0.148, the rms width of PSF is almost same size as in the beam size. Therefore, to observe the original beam size, it is necessary to deconvolute the raw image by the PSF. In the present time, Wiener inverse filter [3] was applied. In the spatial frequency domain, the convolution integral is represented by

$$G(u,v) = H(u,v)F(u,v) + N(u,v) \qquad (2)$$

where G denotes a two dimensional Fourier transform of blurred image, H is thought of as inverse filter (two dimensional Fourier transform of PSF), F is a two dimensional Fourier transform of original image, and N is as a two dimensional Fourier transform of noise term in the image. The Wiener inverse filter H_w in equation (2) is given by

$$H_w(u,v) = \frac{H^*(u,v)}{\left|H(u,v)\right|^2 + \dfrac{\phi_n(u,v)}{\phi_f(u,v)}} \qquad (3)$$

where the asterisk indicates the complex conjugate of H. ϕ_n is the power spectra of the noise and ϕ_f is the power spectra of the signal. In the present time, the observed image was taken at the balances astigmatism point, we neglect asymmetric components of the obtained PSF as shown in Fig. 6, and use a Gaussian approximation as the PSF. To perform the deconvolution process, we use the computer code Hidden Image which has the maximum entropy deconvolution method. A result of the deconvolution is shown in Fig. 7 (b). The rms beam size from this beam profile are 59.4 μm in the vertical and 231 μm in the horizontal.



(a) (b)

Fig. 7 A beam image of the Photon Factory. The ring energy is 1 GeV and the beam current is 1 mA. (a), The observed image of the beam; (b), the beam image after deconvolution process.

6 CONCLUSION

The Shack-Hartmann wavefront sensor for the measurement of wavefront error was designed and constructed. The deformation of the Be-mirror was measured within λ/30. We have analyzed aberration of the focusing system including the deformation of the Be-mirror in the Fourier optical manner, and obtained PSF at the balanced astigmatism point of the focusing system. By the use of obtained PSF and beam profile image, we applied the image restoration method. After the image restoration process, we obtained a beam size 59.4 μm in vertical and 231 μm in horizontal. The performance of the Shack-Hartmann wavefront sensor is enough to measure the wavefront error of SR beam.

7 ACKNOWLEDGMENTS

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