At-wavelength metrology using the X-ray speckle tracking technique: case study of a X-ray compound refractive lens

S Berujon1,2, H Wang1 and K J S Sawhney1

1Diamond Light Source, Harwell Campus, Didcot, Oxon, OX11 0DE, UK
2European Synchrotron Radiation Facility, BP-220, F-38043 Grenoble, France

E-mail: sebastien.berujon@diamond.ac.uk

Abstract. The X-ray speckle tracking technique has been established on the Test beamline B16 at Diamond and is being used as a valuable tool for at-wavelength metrology. We show here the possibilities and the achievable performances of the X-ray Speckle Tracking technique for optics characterization: the description is illustrated with the case study of the characterization of a compound refractive lens. This optical element was characterized online using the speckle tracking method with nanoradian accuracy and micrometer spatial resolution. For discussion purpose, the results are compared to the ones obtained under similar conditions using a grating interferometer.

1. Introduction

The requirements on the quality of X-ray optics employed on synchrotron beamlines are becoming increasingly stringent, and it has become more than ever necessary to qualify them with high accuracy and reliability. The best way to monitor the quality of the optical elements under working conditions is to perform online metrology in which in situ characterization is performed on the beamline: this type of analysis uses the X-rays to measure the distortions introduced into the wavefront by the optical element. Only a few techniques are available in the X-ray regime for optics characterization [1-3]. Among them, the X-ray Speckle Tracking technique (XST) is a new concept that allows measurement of deflection angle with a high sensitivity and with low requirements on longitudinal and transverse coherence, in addition to several other advantages [4-5]. The technique, which is sensitive to the first derivative of the wavefront, uses a dephasing membrane to create a random intensity pattern in combination with digital correlation algorithms that allows wavefront characterization through the calculation of the speckle pattern distortion. The technique has been implemented at the Diamond Light Source Test beamline B16 to characterize different types of optical elements. We present here the practical aspects of the method and demonstrate the suitability of the technique for at-wavelength metrology. The online characterization of a compound refractive lens (CRL) is described to illustrate the quality of the technique. For discussion purposes, the results are then compared with the metrology data obtained using the more established Grating Interferometry (GI) technique.
2. Method

Like several other devices such as the Hartman sensors [4], the coded apertures or, to some extent the Grating Interferometry, the XST technique is a deflection angle technique. The principle of the technique relies on the measurement of the local wavefront gradient $\nabla W$ or phase $\nabla \varphi$ through the deflection angle $\alpha$ [4]:

$$|\alpha| = \frac{\partial W}{\partial r} = \frac{1}{k} \frac{\partial \varphi}{\partial r} = \frac{|\vec{v}|}{\Delta l} \tag{1}$$

In this equation, $k$ is the wavevector, $\vec{v}$ is a measured displacement vector and $\Delta l$ the propagation distance.

In the XST technique, the calculation of the displacement vector $\vec{v}$ and then $\alpha$ uses digital speckle image correlation algorithms [4]. As shown in figure 1, a speckle generator membrane, usually a biological filtering membrane is placed into the beam to produce a static statistically uncorrelated pattern (speckle). Then, a two dimensional detector capable of resolving the grains features of the pattern records two images: one with and one without the object under investigation inserted into the beam. Digital image correlation algorithms are employed to calculate, for each subset of pixels, the displacement between the images. The displacement vector $\vec{v}$ is retrieved with this procedure for each pixel and $\alpha$ is then calculated using equation (1) where $\Delta l$ is the distance between the membrane and the detector. Processing in this way, one can map the two dimensional wavefront gradient induced by the sample on the X-ray beam from only two recorded images. Using an integration algorithm, it is then possible to reconstruct the total wavefront: the calculation of its distortion from the expected ideal surface permits to recover the optics aberrations.

![Figure 1. XST setup. A sample induces distortion on the beam wavefront. To recover it, a speckle pattern is created and projected on the detector and its distortion from the reference pattern allow the calculation of the wavefront deflection angle $\alpha$.](image)

In addition of having a simple experimental setup, two important advantages of the XST technique for at-wavelength metrology are the high sensitivity and spatial sampling resolution that it provides. Indeed, the large propagation distance $\Delta l$ available and the subpixel accuracy of the cross-correlation algorithm used to calculate $\vec{v}$ permit to achieve nanoradians sensitivity. In parallel, choosing subsets centered on every pixel provides a resolution to be obtained, which is limited almost solely by the small grain size.

3. Experiment

At-wavelength metrology using XST has been established and is now regularly operated at the Diamond Light Source Test beamline B16. We describe here the characterization of a two dimensional focusing single lens of a CRL. The characterization was performed by both the XST and the GI techniques in equivalent configurations and the results then compared.
The CRL was made of Beryllium and had a parabolic shape with a design radius of curvature \( R = 200 \mu m \) at the apex. The CRL, the metrology components (grating or membrane) and the detector were mounted on three different motorized stations of a versatile table, allowing for each one, six degrees of freedom. The detector used was a CCD camera with indirect illumination from a scintillator imaged with a microscope objective. Because the measurement of \( \vec{v} \) depends directly on the detector sampling grid, the effective pixel size was accurately measured and was of \( P_{eff} = 0.9 \mu m \). The membrane used was made of cellulose nitrate with pore size about \( \sim 5 \mu m \) size. The distance between the membrane and the detector was chosen to \( \Delta l = 455 mm \). The beam energy was set to 15 keV using the Si 111 double crystal monochromator of the beamline. It was possible to remove the CRL out of the beam so that we measure and isolate only the influence of the CRL on the wavefront.

![Figure 2](image)

**Figure 2.** (a) Reference image with a zoom of a small area of speckle pattern. (b) Sample image. (c) Displacement vector field plot.

The XST technique was applied recording two images: one with the CRL in the beam, the second one after the lens removal (see figure 2 (a) and (b)). A sub-pixel accuracy zero normalized cross-correlation algorithm was then employed to calculate the displacement vector for each pixel from the two images of size 1200x1200 (see figure 2 (c)). The wavefront gradient was calculated using eq.1 and finally the wavefront distortion was reconstructed using an inversion matrix algorithm [6]. This wavefront reconstruction is shown in figure 3 (a) and the vertical central line of the wavefront gradient is displayed in figure 3 (b).

For comparison, the wavefront distortion was also measured using a 1D grating interferometer. The methodology employed for the CRL characterization is similar to the one described in [7-8]. In this experiment, two sequential phase stepping scans to measure the gradient in the two transverse directions of the beam were performed in exactly the same equivalent configuration as when performing the XST technique. The integrating distance was set to the 7\(^{th}\) Talbot order of a \( \pi \) phase shift grating with 4 \( \mu m \) pitch. The measured wavefront gradient of the vertical central line derived by the GI technique is also displayed in figure 3 (b) for comparison.

![Figure 3](image)

**Figure 3.** (a) Wavefront reconstruction from XST data. (b) Wavefront gradient measured with
The results from GI and XST techniques agree well to each other. The calculated radius of curvature of the lens at the apex was 195 µm using linear fitting from XST data, which is close to the theoretical value of 200 µm.

Using the above experimental parameters, the angular sensitivity of the XST method is expected to be:

\[ S_\alpha = \epsilon_{CC} P_\xi / \Delta l = 60 \text{ nrad} \]

when taking the cross-correlation algorithm accuracy ε_{CC} as equal to 0.03 pixel, which is more than reasonable. This sensitivity is corroborated by the standard deviation value of the wavefront gradient in an area of known constant phase which was below 45 nrad. Considering the micrometer size spatial resolution, this corresponds to wavefront accuracy better than \( \lambda / 100 \).

Because of the experimental constraints, the distance \( \Delta l \) was chosen as equal to 455 mm, but an increase of this distance would further improve the angular sensitivity.

The sharpness of the features of the XST measurements compared to the GI data is due to the higher spatial resolution of the method; working at the 7th Talbot order with the GI, the spatial resolution is of ≈14 µm, while the sampling rate of the XST technique is in the order of few microns.

4. Conclusion

It has been demonstrated that the newly introduced XST tracking technique is well suited for the online characterization of optical components. The two-dimensional information obtained with the technique in a dual image process allows rapid wavefront reconstruction, with very high sensitivity and micrometer spatial resolution. Its applicability to the characterization of a compound refractive lens has been presented as a case study. Another example of application of this technique at Diamond in the optimization and characterization of a superpolished bimorph mirror is presented elsewhere in these proceedings [9]. However for reflective optics, the characterization is done usually using the absolute mode described in [4] that measures the effective phase of the beam. The method is therefore well established at Diamond B16 where at-wavelength performance study of a wide range of X-ray optics is now routinely performed.

References

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