X-ray microscopy using two phase contrast imaging techniques: two dimensional grating interferometry and speckle tracking

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Abstract. Two phase contrast imaging techniques, namely two dimensional grating interferometry and X-ray speckle tracking (XST), have been combined with the use of a Fresnel Zone Plate (FZP) for application to X-ray microscopy. Both techniques allow the phase shift introduced by a sample on a hard X-ray beam in two dimensions, to be recovered with a high sensitivity and low requirements on transverse and longitudinal coherence. Sub-micron phase imaging of carbon fibres was achieved using the two methods thanks to the high magnification ratio of the FZP. Advantages, drawbacks and differences between these two techniques for X-ray microscopy are discussed.

1. Introduction

In the last decade, X-Ray phase contrast imaging using grating interferometry (GI), has been well developed and is widely used[1, 2, 3]. The X-ray source has been extended from high brilliant synchrotron sources to low brilliance, lab-based X-ray sources by adding a source mask grating [4]. In addition to the phase stepping method, Moiré fringe analysis has also been used since only a single exposure is required [5, 6]. Furthermore, this device is largely achromatic[3], and can be used with broad energy bandwidth X-rays [7]. Based on a different concept, the X-ray speckle tracking (XST) technique has recently been extended into the hard X-ray domain [8, 9]. The principle of this technique is to follow the propagation direction of near field-speckle produced by a random object inserted into the beam, and then reconstruct the wavefront from the calculated trajectory of the X-rays. Although, both techniques are compact and robust with sub-microradian angular sensitivity, the spatial resolution is limited either by lateral shear for GI, or the detector pixel size for XST [3, 10, 11]. In this paper, we demonstrate that the spatial resolution for the two techniques can be further enhanced by combining with a Fresnel Zone Plate (FZP) [10, 12]. Two dimensional (2D) GI has been employed to simultaneously recover beam phase in both the horizontal and vertical directions [6, 13], and the results were compared with those obtained from XST.

2. Experiment

All measurements were performed at B16, the Test beamline on a bending magnet (BM) source at Diamond Light Source[5]. As presented in the sketch in Fig. 1a, the FZP and an order sorting aperture
(OSA) were mounted on dedicated motorized towers. The aperture of the FZP was 200µm, and its outermost zone width was 100nm. The energy of the X-ray beam was 8.2 keV for grating interferometry, selected using a silicon double-crystal monochromator. The 2D grating shearing interferometer and 2D CCD X-ray detector with an effective pixel size of $S_p=6.4 \, \mu m$ were mounted on three different motorized towers of a versatile optics test bench, and the distance ($d_{in}$) between the phase grating ($G_1$) and the absorption grating ($G_2$) was set to the fifth order Talbot distance of 61mm. The pitch of the first grating $p_1=3.576 \, \mu m$ was less than twice the pitch of the second grating $p_2=2 \, \mu m$ in order to match the beam’s divergence. The specimen was composed of a bunch of carbon fibres and placed about 10mm upstream of the FZP. The focal length of FZP is 132mm at 8.2keV, and the distance between $G_1$ and FZP is 945mm. Hence, the corresponding magnification ratio $M$ is 7.2. The setup of x-ray speckle tracking technique is illustrated in Fig. 1b, wherein a filter membrane with pore size of 3µm was mounted downstream of focal plane. In this case, the photon energy was set to $E=11$ keV, and the focal length of FZP is 178mm. Here, the carbon fibres were placed $L_1=29mm$ downstream of the focal plane, and the distance between the specimen and membrane is $L_2=826mm$. The CCD was installed on a separated tower with $L_3=3310mm$, and the magnification ratio $M=(L_1+L_2+L_3)/L_1$ was 143.7.

### 3. 2D grating interferometer

For the 2D GI measurement, a raster scan of 8×8 points of the first grating $G_1$ was made over one period of the grating in each direction using a piezo motors [10]. The phase stepping scan was performed with and without sample in the beam such that the flat field could be removed. From a Fourier analysis of the signal in each pixel, the horizontal and vertical phase gradient image, absorption and dark-field images of the sample can be recovered simultaneously. Fig. 2 shows the results of a bunch of carbon fibres using the 2D GI. It can be seen that visibility of the vertical features is low in the horizontal phase gradient image (Fig. 2a) and vice versa. The conventional x-ray absorption image is shown in Fig. 2d, whereas Fig. 2e contains the dark-field image. Once the two transverse phase gradients have been calculated, the wavefront phase (Fig. 2c) induced by the carbon fibres can be reconstructed by solving a Poisson equation with a pseudo inversion matrix algorithm[14]. As expected, only the edges of carbon fibres are clearly visible in the conventional absorption image. The corresponding phase image shown in Fig. 2c reveals complementary details of the inside parts of carbon fibres. The expected phase shift for the carbon fibre at 8.2 keV with a diameter of 11µm is 1.5 radian, which is very close to the values calculated in the reconstruction and demonstrates the quantitative accuracy of this method [10]. Here, the spatial resolution is limited by the detector pixel size rather than the shear of the first grating [10]. Hence, the effective spatial resolution is defined as $S_p/M=0.84\mu m$, where $M$ is the magnification ratio.
4. X-ray Speckle Tracking Technique
X-ray phase microscopy using speckle tracking was performed in a differential configuration [9]. The speckle image without and with carbon fibres present in the X-beam are shown in Fig. 3a and Fig. 3b, respectively. Movement of the speckles can be tracked with accuracy better than 0.05 pixel using a digital image correlation algorithm [9, 11]. Displacement vectors, calculated from the speckle image, give the two directional phase gradients (Fig. 3c and 3d) induced by the carbon fibres. Using the same reconstruction method [14], the phase calculated from the horizontal and vertical phase gradient is shown in Fig.3e. The imaginary part of refractive index of the carbon fibre is $3.77 \times 10^{-6}$ at 11 keV, and the expected phase shift for the above carbon fibre is 1.7 rad. It shows that the reconstructed phase agrees well with the theoretical calculation. Moreover, the spatial resolution for the XST technique can reach 45nm due to the large magnification ratio achieved by placing the sample close to the focal plane, as illustrated in Fig. 1b.

5. Summary
The 2D grating interferometer and X-ray speckle tracking technique have been established and further developed. The 2D x-ray sub-micrometer phase contrast imaging was performed by combining the FZP with the two techniques. Compared with XST technique, the two grating pitches are required to
match the beam divergence and the experimental setup is relatively complicated. In addition, the total transmission of the 2D GI is several times lower than the membrane used in XST technique. XST technique only requires collecting two images for phase imaging, but at least dozens of images are required for GI technique to perform the phase stepping scan. However, it is also possible to perform a single shot for GI technique using the Fourier analysis of moiré fringe.[6] Furthermore, the dark-field image can be retrieved simultaneous with phase gradient image for GI technique. Both the XST and GI are compact and robust, and they are thereby complementary to other phase retrieval methods for x-ray phase microscopy.

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References

[1] David C, Nöhammer B, Solak H, Ziegler E 2002 Differential x-ray phase contrast imaging using a shearing interferometer. Appl. Phys. Lett. 81 3287
[2] Momose A 2003 Phase-sensitive imaging and phase tomography using X-ray interferometers. Opt. Express 11 2303
[3] Weitkamp T, Diaz A, David C, Pfeiffer F, Stampanoni M, Cloetens P 2005 X-ray phase imaging with a grating interferometer Opt. Express 13 6296
[4] Pfeiffer F, Weitkamp T, Bunk O, David C 2006 Phase retrieval and differential phase-contrast imaging with low-brilliance X-ray sources. Nat. Phys. 2 258
[5] Wang H, Sawhney K, Berujon S, Ziegler E, Rutishauser S, David C 2011 X-ray wavefront characterization using a rotating shearing interferometer technique Opt. Express 19 16550
[6] Itoh H, Nagai K, Sato G, Yamaguchi K, Nakamura T, Kondoh T 2011 Two-dimensional grating-based X-ray phase-contrast imaging using Fourier transform phase retrieval Opt. Express 19 3339
[7] Momose A, Yashiro W, Maikusa H, Takeda Y 2009 High-speed X-ray phase imaging and X-ray phase tomography with Talbot interferometer and white synchrotron radiation Opt. Express 17 12540
[8] Morgan K, Paganin D, Siu K 2012 X-ray phase imaging with a paper analyzer. Appl. Phys. Lett. 100 124102
[9] Berujon S, Ziegler E, Cerbino R, Peverini L 2012 Two-Dimensional X-Ray Beam Phase Sensing Phys. Rev. Lett. 108 158102
[10] Berujon S, Wang H, Pape I, Sawhney K, Rutishauser S, David C 2012 X-ray submicrometer phase contrast imaging with a Fresnel zone plate and a two dimensional grating interferometer. Opt. Lett. 37 1622
[11] Berujon S, Wang H, Pape I, Sawhney K 2012 X-Ray phase microscopy using the Speckle Tracking technique paper in submission.
[12] Atsushi M 2009 X-ray phase tomography with a Talbot interferometer in combination with an X-ray imaging microscope. Journal of Physics: Conference Series 186 012044
[13] Zanette I, Weitkamp T, Donath T, Rutishauser S, David C 2010 Two-dimensional x-ray grating interferometer Phys. Rev. Lett. 105 248102.
[14] T. Simchony RC, M. Shao 1990 Direct Analytical Methods for Solving Poisson Equations in Computer Vision Problems. IEEE Transactions on Pattern Analysis and Machine Intelligence 12 435