Radiation Physics and Chemistry 95 (2014) 280–283

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

A generalized reverse projection method for fan beam geometry under partially coherent illumination

Z. Wu [a], Z.L. Wang [a,*], K. Gao [a], K. Zhang [b], X. Ge [a], D.J. Wang [a], S.H. Wang [a], J. Chen [a], Z.Y. Pan [a], P.P. Zhu [a,b], Z.Y. Wu [a,b,**]

[a] National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China
[b] Institute of High-Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Fan beam geometry with geometrical magnification is used with the modified RP method.
- In the calculation of conjugate projection images, unitary ray is taken into account for fan beam geometry.
- We have considered the influence of the spatial coherence on the extracted information.
- The measurement range of the generalized RP method is enlarged by moving the sample close to the light source.

ARTICLE INFO

Article history:
Received 19 October 2012
Accepted 6 January 2013
Available online 16 January 2013

Keywords:
Spatial coherence
Phase contrast imaging
RP method
Fan beam geometry

ABSTRACT

In this paper, a generalized reverse projection (RP) method for grating-based fan beam phase contrast imaging is presented. Compared to the original RP method, rays rather than projection images are taken into account during the information extraction process. We also discuss the influence of partial coherence on the extracted information. Theoretical derivations and numerical simulations are performed to confirm the validity of the method.

1. Introduction

Conventional X-ray absorption imaging is a power tool in medical diagnosis, industrial non-destructive testing and security inspection. However, its poor contrast to low-Z elements limits its applications in soft tissue imaging. If we write the complex refractive index of an object as $n=1-\delta-i\beta$, its real part determines the phase shift of the wave front while its imaginary part is associated to the linear attenuation coefficient. In the hard X-ray regime and for low-Z elements, δ is about 1000 times greater than β. Therefore, the phase shift is about three orders of magnitude of the absorption. As a consequence different phase contrast imaging methods have been proposed (Bravin et al., 2013; Chen et al., 2010; Davis et al., 1995a; Ge et al., 2011; Momose, 2005; Wang et al., 2010a, 2010b; Zhou and Brahme, 2008), such as, interferometric methods (Momose et al., 1995), crystal analyzer-based methods (Davis et al., 1995b; Yuan et al., 2006), propagation-based methods (Gureyev et al., 2009; Wilkins et al., 1996; Snigirev et al., 1995) and grating-based methods (David et al., 2002; Momose et al., 2003; Pfeiffer et al., 2006, 2008; Weitkamp et al., 2005). Grating-based methods are considered the most promising phase contrast imaging methods, thanks to their less stringent requirements regarding the light source. In the phase contrast imaging, phase and absorption information are collected together thus information separation is inevitable. So far, three primary phase extraction methods have been introduced: the Fourier harmonic method (Wen et al., 2008), the phase stepping (PS) method (Weitkamp et al., 2005) and the reverse projection (RP) method (Zhu et al., 2010). The first one is the earliest method and quite fast due to only one required projection image at each projection position. Compared with the Fourier harmonic method, the PS method collects several images at each projection angle but provides higher quality results. It is widely adopted in the laboratory. Nevertheless, because of the long exposure time, the large radiation dose is unacceptable for practical applications, especially for medical imaging. On the contrary, the RP method requires lower dose and is a simpler and faster phase extraction method. It takes advantage of the anti-symmetry (i.e., with a rotation of 180°, you can collect an image with the same absorption

* Corresponding author. Tel.: +86 551 6360 2017.
** Corresponding author at: National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China. Tel.: +86 551 6360 2077; fax: +86 551 6514 1078.
E-mail addresses: wangnsrl@ustc.edu.cn (Z.L. Wang), wuzy@ustc.edu.cn (Z.Y. Wu).

0969-806X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.radphyschem.2013.01.006

but opposite differential phase information), thus reduces the number of the required images by extending the scanning angle range from 180° to 360°. However, the RP method has been mainly introduced to run experiments with parallel beam geometrical configurations.

In this contribution, we present a generalized RP method for fan beam geometry. We also discuss the effects of partially coherent illumination on the extraction information.

2. The RP method in fan beam geometry

Based on the setup shown in Fig. 1 and the scale factor of fan beam geometry (Donath et al., 2009; Engelhardt et al., 2007), the intensity recorded by a virtual detector at the rotation axis in the paraxial approximation can be written as:

$$I(x_r,\phi,z) = I_0 \exp\left[-\int_{-\infty}^{\infty}\mu(x,y,z)dr\right] S\left(\frac{x_g}{R_2}+\kappa\theta_r\right),$$
$$\kappa = \begin{cases} R_0/R_1 & 0<R_0<R_1 \\ (R_1+R_2\text{-}R_0)/R_2 & R_1<R_0<R_1+R_2 \end{cases} \quad (1)$$

where ϕ is the projection angle and I_0 is the intensity at the position of phase grating G_1 without the sample. μ denotes the linear attenuation coefficient of the sample and the function S is the shifting curve. R_0, R_1 and R_2 are the distances respectively from the source to the rotation axis of the sample, between the source and the phase grating G_1 and from G_1 to the analyzer grating G_2. x_g refers to the displacement of G_2 along the direction perpendicular to the groove of grating. θ_r is the refraction angle. (x_r,y_r,z) is a stationary coordinate system while (x,y,z) is a rotational one fixed on the sample shown in Fig. 1. Their origins of coordinates are set at the intersection of the rotation axis and the optical axis.

We know that the RP method for parallel beam geometry is based on the anti-symmetric characteristic. However, under fan beam illumination, we can see from Fig. 2(a) that the anti-symmetry between the mutually reverse projection images is no longer fulfilled. In the following, a modified approach considering unitary ray (see Fig. 2(b)) is introduced to find the conjugate projection images.

It can be seen from Fig. 2 that the anti-symmetry between mutually reverse rays still exists in fan beam geometry. If we consider a single ray $I(x_r,\phi_1,z)$ and its reverse ray $I(-x_r,\phi_2,z)$, from the geometrical relationship exhibited in Fig. 2(b), we can obtain:

$$\phi_2 = \phi_1 + \pi + 2\arctan\left(\frac{x_r}{R_0}\right) \quad (2)$$

When the refraction angle $\theta_r < d_2/4\kappa R_2$, with d_2 the period of G_2, the shifting curve can be linearly approximated at its half slope by its first order Taylor term. Consequently formulae for information retrieval can be given as follows:

$$\int_{-\infty}^{\infty}\mu(x,y,z)dr = \ln\left(\frac{2S(x_g/R_2)I_0}{I(x_r,\phi,z)+I(-x_r,\phi+\pi+2\alpha,z)}\right)$$
$$\theta_r(x_r,\phi,z) = \frac{1}{\kappa C}\frac{I(x_r,\phi,z)-I(-x_r,\phi+\pi+2\alpha,z)}{I(x_r,\phi,z)+I(-x_r,\phi+\pi+2\alpha,z)} \quad (3)$$

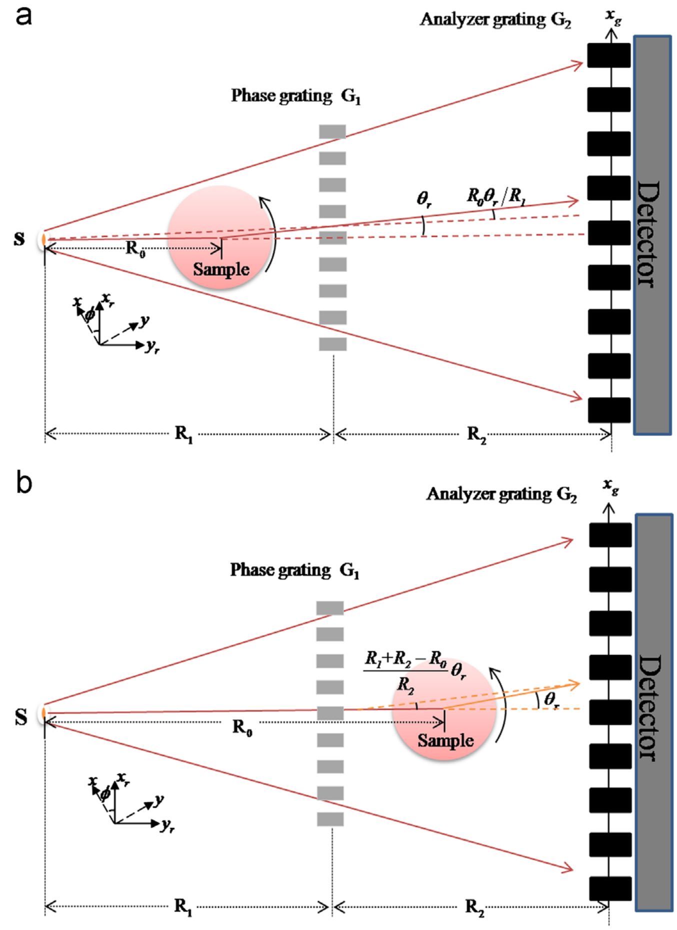

Fig. 1. Schematic diagram of the grating-based interferometer in fan beam geometry: the sample is located (a) before the phase grating ($0<R_0<R_1$) and (b) after the phase grating ($R_1<R_0<R_1+R_2$).

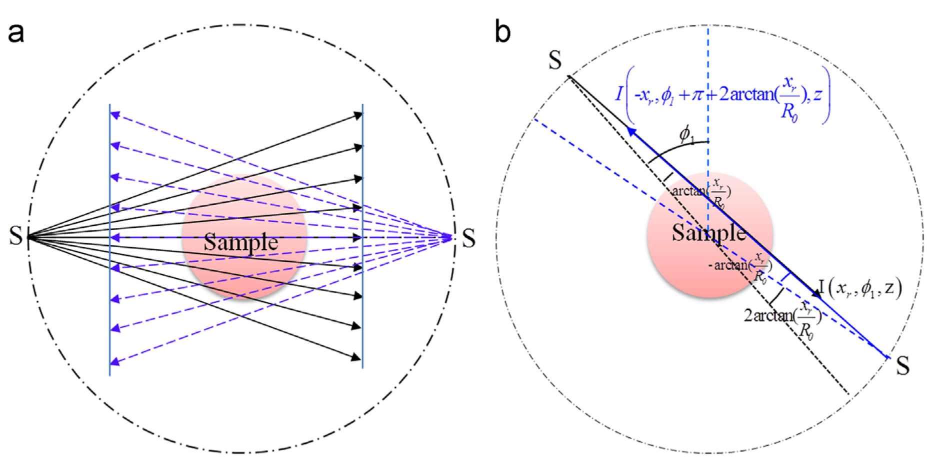

Fig. 2. The realization of the RP method in fan beam geometry: (a) mutually reverse projections and (b) single ray is considered as unit.