Optik 127 (2016) 3286–3291

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The influence of spectrum and imaging geometry on propagation-based phase-contrast imaging for micro-focus source

Jinming Cheng*, Yudong Cao, Qingguo Yang, Shuangxi Qi, Yan Ye, Weixin Qian, Dongbing Liu, Limin Meng, Pengfei Zhu, Jun Li

Institute of Fluid Physics, CAEP, Mianyang 621900, Sichuan, PR China

ARTICLE INFO

Article history:
Received 3 May 2015
Accepted 16 November 2015

Keywords:
Phase-contrast imaging
Geometry
Polychromatic
Micro-focus

ABSTRACT

In addition to the widely used monochromatic X-ray source, the polychromatic X-ray source may also be used in many cases of propagation-based phase-contrast imaging (PB-PCI). It is not sufficient to investigate the optimization procedure only for the monochromatic applications. The focus of this paper is to investigate the effects of spectrum and imaging geometry on the image quality of PB-PCI, for applications involving propagation in vacuum and air. The quality of phase contrast image has been quantitatively characterized by using contrast and SNR as quality metrics in this paper. The optimal geometry has been investigated in three situations, where four cases are considered. Based on the numerical simulation, it is observed that the contrast and SNR in the case of polychromatic X-ray are lower than the monochromatic X-ray. Therefore, the influence of the X-ray spectrum on the contrast and SNR must not be neglected. The contrast in the case of polychromatic X-ray, and the SNR in both polychromatic and monochromatic X-ray, is lower for propagation in air compared to the propagation in vacuum. Evidently, the air absorption is an important factor in the propagation-based phase-contrast imaging. The experimental and numerical results for all three situations are presented to verify the effect of the geometry on the image quality in the air condition. It is found that the experimental results confirm the validity of numerical results for both the quality metrics. The object specification and the X-ray scattering have obvious influence on the image quality, as seen in the experimental results.

1. Introduction

In recent years, the Propagation-Based X-ray Phase-Contrast Imaging (PB-PCI) has become a common method for the characterization of the internal structure of weakly absorbing objects using synchrotron radiation [1–3], laboratory micro-focus sources [4–7], and laser plasma X-ray sources [8–11]. The PB-PCI does not require monochromatic radiation and additional optical component except, an X-ray source, object stage, and X-ray detector.

The theoretical analysis of the problem of PB-PCI was performed by Pogany et al. using the weak object approximation with Fourier optic method [12]. One of the most important observation is the role of wavelength λ, that acts as a separable factor in the near-field regime. Therefore, the broadband polychromatic X-ray source may be used for the wavelength independence on the geometric specifications of the contrast. Afterwards, the problem of X-ray PB-PCI geometry optimization in monochromatic case was investigated by Nesterets et al. for three practically feasible models of the object, including two- and one-dimensional Gaussian, and blurred edge [13]. In order to quantitatively characterize the quality of a phase-contrast image, three quality metrics were considered; including contrast, Signal-to-Noise Ratio (SNR), and resolution. Additionally, the optimization procedure involved in the phase contrast imaging for all of the three models in monochromatic case were presented in the study.

However, the polychromatic X-ray source may also be used for PB-PCI in many cases, such as in phase-contrast mammography using micro-focus X-ray source [14,15]. Therefore it is not sufficient to investigate the optimization procedure only for the monochromatic case. The focus of this paper is to investigate the effect of the spectrum and the imaging geometry on the quality of PB-PCI, both for propagation in vacuum and air. In order to simplify the analysis, only the contrast and SNR have been used to evaluate the image quality in this paper.

2. Theory

The geometry of the imaging system for PB-PCI analysis is shown in Fig. 1. The object is placed between the X-ray source and the detector.

* Corresponding author. Tel.: +86 816 2494142; fax: +86 816 2485139.
E-mail address: cjinm1979@163.com (J. Cheng).

http://dx.doi.org/10.1016/j.ijleo.2015.11.192

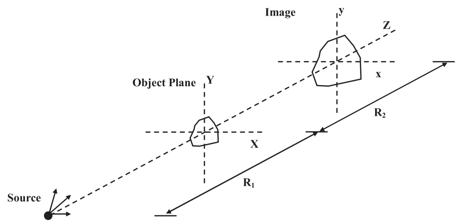

Fig. 1. Schematic diagram of the PB-PCI.

In the case of monochromatic plane incident wave, the Fourier transform of the intensity distribution in the image $I_p(u\,;z)$ acts as a function of phase shift and attenuation induced by the object, and it can be written as [13]

$$I_p(u;z) = I_0\left[\delta(u) - 2m(u)\cos\left(\pi\lambda z u^2\right) - 2\Phi(u)\sin\left(\pi\lambda z u^2\right)\right] \tag{1}$$

where I_0 is the intensity distribution of the incident wave in the object plane, and $m(u)$ is the Fourier transform of $\mu(z)$, which is given as:

$$\mu(z) = \int dz \cdot 4\pi\beta/\lambda \tag{2}$$

$\Phi(u)$ is the Fourier transform of $\phi(z)$, given as:

$$\phi(z) = \int dz \cdot 2\pi\delta/\lambda \tag{3}$$

Furthermore, in the case of monochromatic spherical incident wave, where the X-ray source is considered as a point-like monochromatic source, and the detector is assumed to have a delta-function-like spatial resolution, the Fourier transform of the intensity distribution in the image $I_s(u\,;R_1,R_2)$ can be expressed in the form as [13]:

$$I_s(u;R_1,R_2) = I_p(Mu;z_{\text{eff}}) \tag{4}$$

where $M \equiv (R_1+R_2)/R_1$ is the magnification, and z_{eff} is the effective propagation distance.

$$z_{eff} \equiv \frac{R_1R_2}{R_1+R_2} = \frac{R(M-1)}{M^2} = \frac{R_1(M-1)}{M} = \frac{R_2}{M} \tag{5}$$

In the case of the X-ray source to have a finite size, and the detector to have a finite spatial resolution, the Fourier transform of the intensity distribution in the image $I(u\,;R_1,R_2)$ can be given as:

$$I(u;R_1,R_2) = P(u;M)\,I_s(u;R_1,R_2) \tag{6}$$

where $P(u;M)$ is the modulation transfer function of the system written as:

$$P(u;M) = S[-(M-1)u]D(u) \tag{7}$$

The term $S[-(M-1)u]$ acts as the Fourier transform of the source intensity distribution, and $D(u)$ is the Fourier transform of the detector resolution function. To simplify the analysis, it is assumed that both the source intensity distribution and the detector resolution function are symmetrical Gaussians and normalized to unity; therefore, these can be written as:

$$S[-(M-1)u] = \exp[-\pi^2(M-1)^2\sigma_s^2u^2] \tag{8}$$

$$D(u) = \exp(-\pi^2\sigma_d^2u^2) \tag{9}$$

where σ_s characterizes the source size and σ_d characterizes the detector resolution.

Considering the spectrum effect, $I(u\,;R_1,R_2)$ can be expressed in the form as:

$$\begin{aligned} I(u;R_1,R_2) &= p_s t\sigma_d^2 D(u)S[-(M-1)u] \\ &\times \int d\lambda\left[\delta(u) - 2m(Mu,\lambda)\cos\left(\pi\lambda z_{\text{eff}}M^2u^2\right) - 2\Phi(Mu,\lambda)\sin\left(\pi\lambda z_{\text{eff}}M^2u^2\right)\right]w_d(\lambda)w_s(\lambda) \end{aligned} \tag{10}$$

where t is the exposure time, and p_s is the photon flux (i.e., the number of photons passing through unit area per second) of the incident wave in the object plane, propagating in air. The photon flux p_s is described as:

$$p_s = \frac{p_\Sigma}{\Omega R_1^2\exp(-\mu_{\text{air}}\rho_{\text{air}}R_1)} \tag{11}$$

where p_Σ act as the total photon flux of the X-ray source, i.e., the number of photons emitted by the source per second into the solid angle Ω. μ_{air} is the X-ray mass attenuation coefficient of dry air. ρ_{air} is the density of dry air.

$w_d(\lambda)$ is the spectrum response function of the detector, i.e. the gray value response per X-ray photon.

$$w_d(\lambda) = \kappa\eta w_{ab}(\lambda)\cdot 1.24/\lambda \tag{12}$$

where κ is the energy transformation coefficient of attenuation dose per unit mass of the detector. η is the gray value of the detector response to unit attenuation dose. $w_{ab}(\lambda)$ is the X-ray absorption of the detector.

$w_s(\lambda)$ is the normalized spectral density of the source radiation, where

$$\int w_s(\lambda)d\lambda = 1 \tag{13}$$

It is more convenient for further analysis to work with an image projected back onto the object plane, as described in following.

$$\begin{aligned} I_{BP}(u;R_1,R_2) &= I\left(\frac{u}{M;R_1,R_2}\right) \\ &= p_s t\sigma_d^2\exp\left[-\pi^2\left(1-\frac{1}{M}\right)^2\sigma_s^2u^2 - \frac{\pi^2\sigma_d^2u^2}{M^2}\right] \\ &\times \int d\lambda\left[\delta(u) - 2m(u,\lambda)\cos\left(\pi\lambda z_{\text{eff}}u^2\right) - 2\Phi(u,\lambda)\sin\left(\pi\lambda z_{\text{eff}}u^2\right)\right]\cdot w_d(\lambda)w_s(\lambda) \end{aligned} \tag{14}$$

Additionally, the image intensity distribution projected back onto the object plane is given as:

$$I_{\text{BP}}(\rho;R_1,R_2) = \text{FT}^{-1}I_{\text{BP}}(u;R_1,R_2) \tag{15}$$

3. Materials and methods

3.1. Evaluation of a phase contrast image

In order to quantitatively characterize the quality of the phase contrast image in numerical simulation and experiment, two quality parameters, the contrast and SNR [13] are used in this study. The contrast is defined as the ratio of the signal to the intensity of the