Nuclear Instruments and Methods in Physics Research A 747 (2014) 13–18

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Contrast transfer function in grating-based x-ray phase-contrast imaging

Jianheng Huang [a], Yang Du [a,b], Danying Lin [a], Xin Liu [a], Hanben Niu [a,*]

[a] Key Laboratory of Optoelectronics Devices and Systems of Ministry of Education and Guangdong Province, Shenzhen University, Shenzhen 518060, China
[b] Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China

ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form
16 January 2014
Accepted 18 January 2014
Available online 27 January 2014

Keywords:
x-Ray phase contrast imaging
Grating interferometry
Contrast transfer function
Resolution

ABSTRACT

x-Ray grating interferometry is a method for x-ray wave front sensing and phase-contrast imaging that has been developed over past few years. Contrast and resolution are the criteria used to specify the quality of an image. In characterizing the performance of this interferometer, the contrast transfer function is considered in this paper. The oscillatory nature of the contrast transfer function (*CTF*) is derived and quantified for this interferometer. The illumination source and digital detector are both considered as significant factors controlling image quality, and it can be noted that contrast and resolution in turn depends primarily on the projected intensity profile of the array source and the pixel size of the detector. Furthermore, a test pattern phantom with a well-controlled range of spatial frequencies was designed and imaging of this phantom was simulated by a computer. Contrast transfer function behavior observed in the simulated image is consistent with our theoretical *CTF*. This might be beneficial for the evaluation and optimization of a grating-based x-ray phase contrast imaging system.

1. Introduction

x-Ray imaging is widely used in medical diagnostics, for example mammography, and chest x-ray. Conventional radiography utilizes the absorption-contrast imaging technique, which records the intensity attenuation due to absorption. This method is not very applicable for a low absorption material, such as soft tissue or polymers. Consequently, various phase contrast techniques have been developed [1,2]. Phase contrast imaging makes use of the contrast from the phase shift in an x-ray wavefield passing through objects. There are basically four different types of phase-sensitive methods: crystal interferometry [3,4], the propagation-based method [5–7], diffraction enhanced imaging [8–10] and the grating-based method [11,12].

The grating-based method can be efficiently used to retrieve quantitative phase images with a low brilliance polychromatic x-ray source in a conventional laboratory [13,14]. This method utilizes the Talbot effect and uses a grating interferometer to produce a series of images by the phase stepping scan process. Three different images, i.e., standard absorption image, differential phase image and dark-field image, can be constructed from those detected images. The principles of the grating-based method has been explained and confirmed by experiments in the previous literature [15]. In recent years, the researchers mainly concentrate on the performance evaluation and optimization of the grating-based method, for instance noise analysis [16] and field of view [17]. Contrast and resolution are the criteria used to specify the quality of an image. The optical transfer function in propagation-based imaging with a micro-focus x-ray source was considered by Pogany in 1997, and it had been shown that image resolution depends mainly on lateral coherence, with longitudinal coherence being of lesser importance [18]. Subsequently, similar work was reported by Salditt in 2009 [19]. And spatial resolution characterization of differential phase contrast CT systems via modulation transfer function (*MTF*) measurements is discussed in 2013 [20]. However, studies on the contrast transfer function (*CTF*) in grating-based phase imaging have not been reported.

In this paper a simple theoretical framework is presented to treat the grating-based phase imaging by x-rays. The theory is based mainly on the approximate Kirchhoff–Fresnel theory, treating the imaging process in terms of contrast transfer function (*CTF*). Existing literatures have not measured the oscillatory nature of the *CTF* for phase image yet, so the oscillatory nature of the *CTF* for phase image will be quantified here. And the projection of the array source and the pixel sampling of the digital detector are considered as two significant factors controlling image quality. We further use a simulated test pattern to quantitatively verify that the *CTF* shows the predicted oscillatory behavior.

* Corresponding author. Tel.: +86 755 26538579; fax: +86 755 26538580.
E-mail addresses: xianhuangjianheng@163.com (J. Huang), wolfduyang@163.com (Y. Du), dylin@szu.edu.cn (D. Lin), sblx@szu.edu.cn (X. Liu), hbniu@szu.edu.cn (H. Niu).

0168-9002/$ - see front matter © 2014 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.nima.2014.01.029

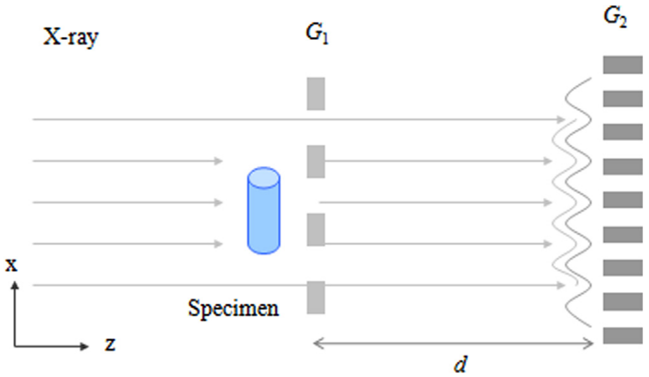

Fig. 1. Schematic diagram of grating interferometer. A phase specimen in front of the phase grating G_1 will cause the incident beam slight refraction, which results in changes of the locally transmitted intensity through the analyzer grating G_2.

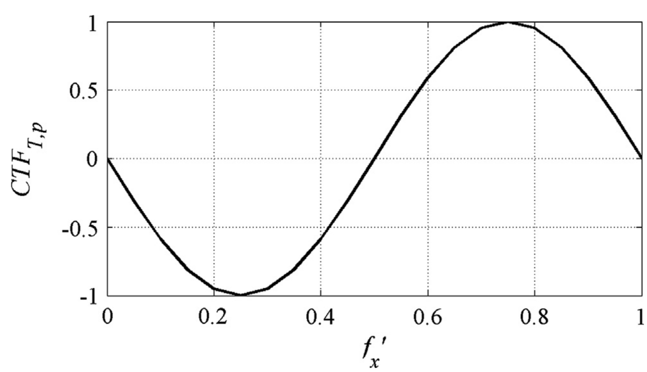

Fig. 2. The normalized $CTF_{T,p}$ for the Talbot interferometer($f_x' = sf_x$).

2. Contrast transfer function derivation

The principle of grating interferometry is based on the Talbot effect or a self-imaging phenomenon by a periodic object, for instance a transmission grating, under spatially coherent illumination. It is characteristic of the Talbot effect that one can observe the appearance and disappearance of the grating's self-image along the optical axis. This phenomenon is understood as Fresnel diffraction by the grating.

2.1. Two grating interferometer CTF

In the case of monochromatic plane wave illumination, the interferometer is shown diagrammatically in Fig. 1. It consists of two gratings, a phase grating (G_1 with a period of p_1 and a phase shift of π) and an analyzer absorption grating (G_2 with a period of p_2). Let a thin object in front of the grating G_1 be illuminated with a monochromatic plane wave. The transmission function of the object in the Cartesian coordinate is given by

$$q(x,y) = \exp[-\mu(x,y) + i\varphi(x,y)] \tag{1}$$

where $\mu(x,y)$ and $\varphi(x,y)$ are the absorption and phase-shift components of the object (μ is the z projection of half the usual linear attenuation coefficient for the intensity), respectively. For a weak absorption and weak phase object, Eq. (1) can be approximated by the Taylor series as

$$q(x,y) = 1 - \mu(x,y) + i\varphi(x,y). \tag{2}$$

Then we can have in spatial frequency domain of Eq. (2)

$$Q(f_x,f_y) = \delta(f_x,f_y) - M(f_x,f_y) + i\Phi(f_x,f_y) \tag{3}$$

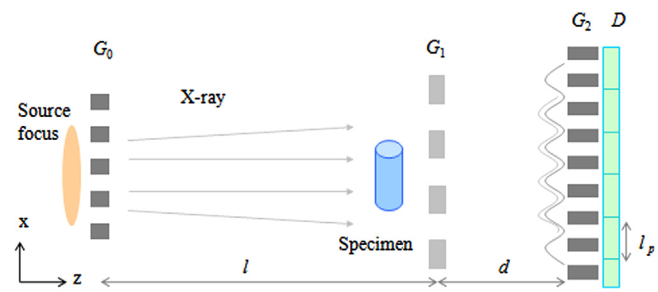

Fig. 3. Schematic diagram of the Talbot–Lau interferometer. The source grating (G_0) is just put in front of the conventional x-ray tube composing the array line source. The fringe displacements are transformed into intensity values by an absorption grating (G_2) placed at a distance from the phase grating (G_1), and this allows the use of a detector (D) with much larger pixels than the spacing of the fringes.

where Q, M and Φ are the two dimensional Fourier transformations (FTs) of q, μ and φ, respectively. f_x and f_y are the two dimensional spatial frequencies at the object or image plane.

Considering the gratings have symmetric structures and the lines are oriented parallel to each other, the intensity after the second grating G_2 can be derived approximately as (see Appendix A)

$$I(x,y;x_g) = \exp[-2\mu(x,y)]\left\{a_0 + a_1 \cos\left[\frac{2\pi x_g}{p_2} + \varphi(x-s,y) - \varphi(x+s,y)\right]\right\} \tag{4}$$

where x_g is the place where one of the gratings is scanned along the transverse direction. The transverse phase separation s in Eq. (4) between by the two main diffractive beams is given by

$$s = \frac{\lambda d}{p_1} \tag{5}$$

where λ is the wavelength of the incident wave and d is the Talbot distance.

A first-order Taylor series expansion is applied to the exponential term in Eq. (4), the cosine is expanded using the sum of angle identity and it is assumed that $\varphi(x-s,y)-\varphi(x+s,y)$ is close to zero (since the refractive index should usually not change quickly across the sample on the scale of the phase separation between beams). This means $\cos[\varphi(x-s,y)\text{-}\varphi(x+s,y)]$ is close to 1 and $\mu(x,y)$ $\sin[\varphi(x-s,y)-\varphi(x+s,y)]$ is negligible, and so we find that the intensity distribution can be written as

$$I(x,y;x_g) = \left[a_0 + a_1 \cos\left(\frac{2\pi x_g}{p_2}\right)\right] - 2\left[a_0 + a_1 \cos\left(\frac{2\pi x_g}{p_2}\right)\right]\mu(x,y) - a_1 \sin\left(\frac{2\pi x_g}{p_2}\right)[\varphi(x-s,y) - \varphi(x+s,y)]. \tag{6}$$

Following the treatment given in Ref. [18], we obtain the frequency spectrum of the intensity in Eq. (6) which is as follows:

$$F(f_x,f_y;x_g) = \left[a_0 + a_1 \cos\left(\frac{2\pi x_g}{p_2}\right)\right]\delta(f_x,f_y) - 2\left[a_0 + a_1 \cos\left(\frac{2\pi x_g}{p_2}\right)\right]M(f_x,f_y) - 2\left[a_1 \sin\left(\frac{2\pi x_g}{p_2}\right)\right] i \sin(-2\pi s f_x)\Phi(f_x,f_y). \tag{7}$$

In Eq. (7), the real and imaginary parts of the optical transfer function (*OTF*) have a simple interpretation in terms of the amplitude and phase components of the object transmission function, which can be retrieved by the phase-stepping approach from the modulated intensity signal [12]. Referring to intensity rather than amplitude, one should more correctly use the term of contrast transfer function (*CTF*) [18], and the normalized *CTF* of the