



Monte Carlo simulation of grating-based neutron phase contrast imaging at CPHS

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ABSTRACT

Since the launching of the Compact Pulsed Hadron Source (CPHS) project of Tsinghua University in 2009, works have begun on the design and engineering of an imaging/radiography instrument for the neutron source provided by CPHS. The instrument will perform basic tasks such as transmission imaging and computerized tomography. Additionally, we include in the design the utilization of coded-aperture and grating-based phase contrast methodology, as well as the options of prompt gamma-ray analysis and neutron-energy selective imaging. Previously, we had implemented the hardware and data-analysis software for grating-based X-ray phase contrast imaging. Here, we investigate Geant4-based Monte Carlo simulations of neutron refraction phenomena and then model the grating-based neutron phase contrast imaging system according to the classic-optics-based method. The simulated experimental results of the retrieving phase shift gradient information by five-step phase-stepping approach indicate the feasibility of grating-based neutron phase contrast imaging as an option for the cold neutron imaging instrument at the CPHS.

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1. Introduction

In general, for neutron imaging, an object is characterized by the complex neutron refractive index distribution $n = 1 - \delta - i\beta$, where the decrement δ determines the phase shift of the neutron beam passing through the object and β is related to the linear attenuation coefficient of the neutron beam. The conventional neutron imaging is based on the detection of the attenuation distribution of an object [1]. This method can give direct information on the imaginary part of the refractive index distribution in the object. However, some materials have very small β values and thus little contrast can be observed in conventional attenuation images [2]. On the other hand, neutron phase contrast imaging methods utilize the phase shift related to the real part of the refractive index distribution in the object, which possibly to a great extent enhances delicate features of the weakly attenuating object. Currently, there are several methods for measuring the phase shift of neutrons. The crystal interferometer-based method is the most direct method, where a coherent reference beam interferes with a beam that has been passed through the object [3]. Propagation-based methods utilize Fresnel diffraction to provide contrast related to the Laplacian of the phase shift [4]. Analyzer-based methods generate a differential phase shift using a perfect

crystal according to Bragg diffraction [5]. However, the above methods require strict conditions such that the neutron sources have sufficient coherence and brilliance. In 2006, Pfeiffer et al. [6] reported a Talbot–Lau-interferometric grating-based neutron phase contrast imaging technique which permits the use of a large beam with lax coherence. Grating-based neutron phase contrast imaging has recently been demonstrated at the SINQ and BENS facilities [6,7]. In 2009, Huang et al. [8] described a classic-optics-based grating-based imaging method to obtain differential phase contrast images, with incoherent X-ray sources, that can also be extended to the neutron field. Both the methods require less spatial and chromatic coherence of the neutron sources. We believe that the grating-based phase contrast imaging is a promising option for neutron radiography and tomography instrument at the Compact Pulsed Hadron Source (CPHS), which is currently under design and construction at Tsinghua University, Beijing, China [12,13]. In this paper, Monte Carlo simulation is used to validate the design of the classic-optics-based grating-based imaging system at the CPHS and some preliminary results are also demonstrated.

2. Method

2.1. The layout of the grating-based neutron imaging at the CPHS

The cold neutron radiography/tomography instrument at the CPHS uses simple pinhole geometry, as well as additional coded-aperture technology to improve the utilization efficiency of

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neutron flux. For more details about the instrument, please see Ref. [14] this issue.

We plan to adopt the classic-optics-based method [8] using absorption gratings to implement grating-based phase contrast imaging. The source grating G0 is put close to the aperture and the last two absorption gratings G1 and G2 are put behind the tested object. The layout of the grating-based imaging at the CPHS is shown in Fig. 1.

In the classic-optics-based method, the relationship of three gratings can be listed as follows [8]:

$$p_1 = p_2 \frac{l}{l+d} \quad (1)$$

$$p_0 = p_2 \frac{l}{d} \quad (2)$$

$$l_{coh} \equiv \frac{l}{s} \lambda < p_1 \quad (3)$$

where p_0 , p_1 and p_2 are the periods of G0, G1 and G2, respectively, l is the distance between G0 and G1, d is the distance between G1 and G2, l_{coh} is the transverse coherence length, s is the opening of G0 and λ is the wavelength of neutrons.

Moiré fringes are generated by the combination of the absorption grating (G1)'s projection-image and the absorption grating G2. A phase-stepping approach is adopted to measure the phase shift gradients according to Moiré methodology [6,8,9]. When compared with the Talbot–Lau-interferometric method, the classic-optics-based method has more relaxed conditions and does not require the Talbot effect; hence the design of the imaging system is more flexible and can employ all polychrome X-rays.

2.2. Monte Carlo simulation with Geant4

Geant4 [10] can be used to model the neutron system and simulate neutron interactions with matter. In our simulation program, several neutron physics processes have been registered to neutron—including neutron elastic scattering, neutron inelastic scattering and neutron capture. Neutron cross-section data are acquired from the ‘Geant4 Neutron Data Library’ which includes several evaluated neutron libraries. However, the physics required for simulating neutron phase contrast phenomena are not provided in the current version of Geant4. A similar problem existed in the case of simulating X-ray phase contrast imaging with Geant4 before our group developed a tool that added the capability of simulating X-ray refraction to Geant4 and then successfully applied it to model the X-ray grating-based imaging system [11]. A similar idea is extended to implement the Monte Carlo simulation on the neutron phase contrast imaging with Geant4 now.

As we know, the spatial varying of phase shift induced by an object causes refraction of the neutron beam. The basic idea of the additional tool is to implement the refraction of neutrons governed by Snell's law. In our program, the refractive index of a certain material is added manually to the material properties table. When a neutron hits the boundary of two different materials, the incident angle of the neutron can be acquired to calculate the departure angle according to Snell's law. Note that

our Monte Carlo simulation program using the principle of the classic-optics-based method, is well in accordance with the particle transport theory of the conventional Monte Carlo method in some sense.

3. Experiment

3.1. Simulation of Moiré effect

The fundamental phenomenon of grating-based neutron phase contrast imaging is the Moiré effect. A Monte Carlo simulation of the Moiré fringes is shown in Fig. 2. Parallel monochromatic neutrons with an energy of 50 meV are generated; the two absorbing gratings G1 and G2 with the same period of 8 μm are separated by a distance of 5 cm. The angle between the lines of two gratings is 2°. 10 million neutrons were used in the simulation. The image is 10 $\times$ 10 cm with a pixel size of 500 μm .

3.2. Simulation of phase-stepping process

A five-step phase-stepping process is simulated. Suppose cone beam monochromatic neutrons with an energy of 50 meV are generated in the program, the angle of the cone beam is 1.03°. As shown in Fig. 1, the source grating G0 made of absorbing gadolinium lines is placed close to the source, the grating G1 made of gadolinium is placed 360 cm away from the source ($l=360$ cm), and the grating G2 is placed 3 cm behind the first one ($d=3$ cm). The period p_1 of the grating G1 is set to 4 μm and the period p_2 of the grating G2 can be calculated from (1), to be 4.033 μm . The period p_0 of the source grating can be calculated from (2) to be 484 μm . The thickness of the gadolinium lines of the gratings is set to 20 μm , resulting absorption of 99.9% according to the Geant4 simulation. A detector with a pixel size of 500 μm is placed closely behind the grating G2 to record transmitted neutrons. The objects used in the simulation are two balls with $\delta=2.0 \times 10^{-6}$, whose diameters are 4 cm (left) and 2 cm (right), respectively. The refraction angle information (or the phase gradient information) is retrieved from the phase-stepping

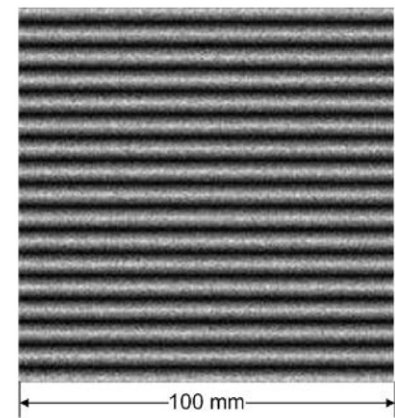


Fig. 2. Monte Carlo simulation of Moiré fringe effect.

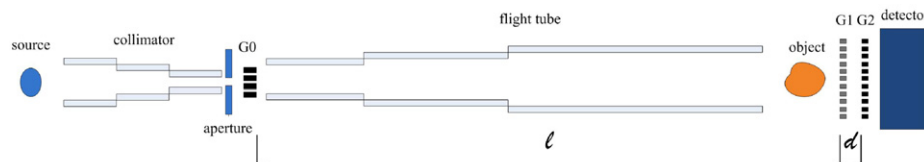


Fig. 1. Layout of grating-based imaging at CPHS.

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