Multi-Lateral Shearing Interferometry: Principle and Application on X-ray Laboratory Sources

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Abstract

Phase contrast imaging techniques are more sensitive to soft material detection as compared to classical absorption, in the hard X-ray region (10-100 keV). One possible technique to exploit phase information is multi-lateral shearing interferometry. It is a phase sensitive technique in development for the past 20 years using a single 2D grating. The grating generate multiple identical but tilted replicas of the initial wave leading to individual maxima and minima intensity pattern, called interferogram. As an adaptation of previous work on synchrotron source in the X-ray domain, we are currently working on a single grating interferometry set-up using a laboratory X-ray source. This set-up gives an appropriate response to industrial demands for non destructive controls of soft materials like polymer or composite. Quality of the interferogram enables an optimization of the phase retrieval process in order to generate quantitative phase contrast imaging. Therefore, we present in this paper the influence of experimental parameters such as the cone-beam propagation, magnification and source spectrum on the interferogram generation. This study is performed within the framework of our simulation tool based on Kirchoff-Fresnel formalism and ray tracing.

Keywords: Radiographic Testing (RT), Image processing, Phase contrast, Modelling

1. Introduction

X-ray imaging is widely used in non-destructive testing (NDT) dedicated to security domain or industrial control. As most of the radiographic techniques, the image is produced due to the attenuation of the sample. This attenuation, which is related to the variation of the X-wave front amplitude, produce contrast on the final image especially if the sample has a high atomic number Z. For low-Z material, attenuation brings poor contrast but the phase information of the X-wave front can be exploited. Indeed, in the hard X-ray region (10-100 keV), the phase signal is more sensitive compared to the attenuation signal. However, while the attenuation imaging is quite straightforward to produce (especially for radiographic image), phase imaging demands additional material and/or elaborate phase retrieval treatment. Multiple phase contrast techniques have been developed and a complete review of the developments in this field has been proposed by Momose [1]. Most of the existing technique are using synchrotron radiation but since 20 years, applications on X-ray tube have been established [2–4] and arouse interest among NDT field due to their convenient aspect. In this framework we are developing an X-ray phase contrast set-up using a single phase grating interferometer on laboratory X-ray source.

In order to understand the main parameters influencing the image formation and the phase retrieval process for our set-up configuration, we have developed a simulation tool. In this article, we are going to describe our simulation tool and validations, then we will present first results of parameters optimisation.
2. Context

2.1. Multi-lateral shearing interferometry

Our approach is based on multi-lateral shearing interferometry technique [5]. This technique consists in measuring the phase gradient in at least 2 orthogonal directions with a single phase grating (we consider here a 2-D phase grating made of square pattern). The impinging wave front to be analysed is divided into multiple identical but tilted replicas, by a dedicated two-dimensional grating (see Fig. 1). During the propagation, this selected order interferes and leads to a grid of individual spots, called interferogram.

![Figure 1](image_url)

*Figure 1.* A single grating replicates the incoming wave front in multiple identical and tilted waves. The grating design generates a phase modulation to the replicas.

The spatial distribution of the spots is directly linked to the incident wave front and the grating design. For a perfect plane wave illumination without any sample, spots are placed on a regular Cartesian grid called reference interferogram. When we place a sample, the translation of each spot versus the reference interferogram is directly proportional to a local optical path modification of the analyzed wave front. This optical path variation is related to a phase variation. In addition to the selected order, residual diffracted orders will introduce variations in the spot diagram along the propagation axis. These variations will vary periodically at discrete distances $Z_{Tm}$, according to classical Talbot rules [6], with:

$$Z_{Tm} = \frac{m a^2}{\lambda}$$

for a plane wave propagation, where $\lambda$ is the wavelength, $a$ the grating period and $m \in \mathbb{N}$.

The phase gradient can be recovered by Fourier deconvolution of the interferogram pattern. The interferogram is interpreted as sinusoidal modulation leading to harmonique generation $\sum_{i=1}^{n} H_i$ in the Fourier space (with $n \in \mathbb{N}$). Treatment of at least two harmoniques leads to the phase gradient $\nabla_i \phi$, which is then integrated.

$$H_i = \frac{2\pi}{a} D \nabla_i \phi$$

where $D$ is the grating-detector distance.

Multi-harmoniques generation $H_i$ in the Fourier space allows a robustness of the deconvolution process and also a direct evaluation of the noise by the phase derivative closure map [7].

Multi-lateral shearing interferometry was developed in visible and infrared domain [8, 9], adapting to quantitative microscopy [10] and more recently in the X-ray region [11, 12] at SOLEIL synchrotron source.
2.2. Application on X-ray tube

For more convenient and accessible use of the phase contrast imaging we are focusing on X-ray tube source. Adaptation to this configuration brings modification of the previous assumptions. X-ray tubes produce a non coherent illumination, in particular with a non negligible spectral bandwidth. In this specific case, Talbot effect presents a particular behaviour, characterized by an achromatic and continuously self-imaging regime [13] defined at a distance $Z_P$. This distance, called panchromatic distance, is give as follows for the plane wave configuration:

$$Z_P = \frac{2a}{\Delta\lambda}$$

(3)

where $\Delta\lambda$ is the spectral bandwidth.

For a cone-beam configuration, fractional Talbot distances $Z_{T_m}$ from equation (1) and panchromatic distance $Z_P$ from equation (3) are respectively rescaled to: [14]

$$Z_{T_m}^c = \frac{d}{d - Z_{T_m}} \times Z_{T_m}$$

(4)

$$Z_P^c = \frac{d}{d - Z_P} \times Z_P$$

(5)

where $d$ is the source-grating distance.

Therefore, in our configuration, it is important to understand experimental parameters such as magnification, spectrum or grating quality and shape, in order to predict and optimize the interferogram generation.

3. Phase imaging simulator

3.1. Theory

We have developed a simulation tool based on the Krichoff-Fresnel formalism. For the $z$-propagation direction and $(x,y)$ the plan perpendicular to the propagation, the impinging amplitude wave $U_{in}$ interacts with an object, in our case, a grating leading to an output amplitude $U_{out}$ defined as:

$$U_{out}(x,y) = U_{in}(x,y) \times T(x,y)$$

(6)

where $T(x,y)$ is the grating transfer function:

$$T(x,y) = A(x,y) \times e^{i\phi(x,y)}$$

(7)

with

$$A(x,y) = \exp \left[ -\frac{1}{2} \int \mu(x,y,z)dz \right]$$

(8)
and \( \phi(x,y) \) the phase, related to the real part of the complex refractive index by

\[
\phi(x,y) = \frac{2\pi}{\lambda} \int (1 - \delta(x,y,z)) \, dz
\]  

(9)

At the detector plan the amplitude \( U_{det}(x,y) \) is equal to:

\[
U_{det}(x,y) = U_{out}(x,y) \circ P(x,y)
\]  

(10)

where \( \circ \) denote the convolution product and \( P(x,y) \) is the propagator defined by

\[
P(x,y) = \frac{1}{i\lambda D} \exp \left[ i\frac{\pi}{\lambda D} (x^2 + y^2) \right]
\]  

(11)

then the incident detector intensity \( I(x,y) \) is defined as \( ||U_{det}^2(x,y)|| \).

### 3.2. Numerical approach

Our simulator is based on a deterministic computation using ray tracing on facetized objects. First, in order to simulate amplitude and phase variations due to the object, as described in equations (8) and (9), we built a projector based on z-buffer algorithm [15,16]. This projector modify pixels detector values of only projected facets and allow us to collect distances intercepted by the ray tracing. The object can be grating and/or sample. Then we simulate the propagator as described in equation (11). In order to filter high frequencies which do not contribute to image formation, we sampled the propagator in the Fourier space. Also, we assume that there is no propagation inside the object (i.e. thin sample) and that the image is generated by a point source.

### 3.3. Validation

As a validation of our simulation tool, we have produced experimental and simulated images of a canonical object: an optical fiber (Multimodal fiber HCP M0600T). This fiber is composed of a silicon core of \( 600 \pm 10 \mu m \) diameter size, \( 630 \pm 5 \mu m \) of polymer cladding and \( 1040 \pm 30 \mu m \) of ETFE external cladding. The fiber is placed between the source and the detector. Images are made by free propagation over the distance \( D \) of the fiber output amplitude as described in equation (6). Fig.2 (a) presents experimental acquisition of the fiber made with a micro-focus X-ray tube (Feinfocus FXE-160.51) at 40 kV and 120 \( \mu A \) on high resolution detector (Photon-icScience VHR X-ray detector) with a pixel size of 9.7 \( \mu m \) at magnification of 10. Fig.2 (b) presents simulation image of the fiber. For this validation, we consider the Tungsten spectrum simulated with Penelope 2006 [17] and presented on Fig.3. This spectrum is filtered by the air thickness, the front window filter of the tube and the absorption of the detector scintillator. Also, we have measured the detector response and the spot size of the X-ray tube in order to convolute them with the simulation results. Finally, we add gaussian noise where the standard deviation corresponds to experimental noise value observed. Fig.2 (c) shows the plot profile of experimental and simulated fiber images. Attenuation and phase curvature are visible and the experimental curve is in good agreement with the simulated curve. Indeed the Fig.2 (d) shows the percentage of the relative correlation between simulated and experimental data. Mean correlation of the data is 97.5 % with minima value at 82.33 %. The observed misplacement of overshoots (overshoots come from the phase curvature) are due to the constructor uncertainty on the size of fiber diameter.
Figure 2. (a) Experimental and (b) simulated silicon fiber images. X-ray spot size 5 µm, spatial resolution 10 µm, 1% noise. (c) Plot profile comparison and (d) percentage of the relative correlation between simulated and experimental data.
This simulation tool will help us to dimensioning and optimise our set-up.

4. Parameters optimisation

The simulation tool that we have implemented allows us to optimize the parameters of our experimental set-up. We are presenting in this section simulation study of our laboratory configuration, which consists of:

- a micro-focus X-ray tube with two possible anode targets (Tungsten and Molybdenum) whose spectra are presented on Fig.3,
- a 2-D phase grating made of 4 µm thick gold square block with 3 µm of periodicity deposit on 100 µm of Silicon,
- a high resolution detector of 9.7 µm pixel size.

With this configuration, we are here interested in the variation of Talbot distances with Molybdenum and Tungsten spectrum at constant magnification.

4.1. Talbot distances vs spectrum

Due to the cone-beam propagation, panchromatic regime (5) is too far and can not be reached in our set-up configuration. So the key is to find fractional Talbot distances (4) in order to maximize interferogram contrast in function of our implementation and tube spectra.
In this configuration, we took a profile (red line on Fig.4) of the interferogram generated for different distances grating-detection $D$. Each profile is presented in Fig.5 for magnifications $G$ of 2, 3 and 4 and also, for Molybdenum and Tungsten spectra. The corresponding interferogram is generated every centimetre.

Images presented are normalised, therefore, the contrast is defined as the difference between the maximum and the minimum gray value of a fringe. For magnification $G = 2$ (see Fig.5 (a,b)), $G = 3$ (see Fig.5 (c,d)) and $G = 4$ (see Fig.5 (e,f)), at half of the Talbot distance, we have respectively 6%, 15% and 18% of fringes contrast for Tungsten spectrum versus 13%, 31% and 42% of fringes contrast for Molybdenum spectrum. It appears that, at constant magnification, Molybdenum spectrum gives more contrast between fringes compared with Tungsten spectrum. This is due to rays $k_\alpha$ and $k_\beta$ of the Molybdenum spectrum (Fig.3) overriding the total spectral bandwidth. Then, fringes modulation get more contrast at fractional Talbot distances. However, increasing the magnification enlarges $Z_t/2$. Therefore, in order to get a compact set-up we have to find a compromise between fringe contrast and detection placement (corresponding here, to the half of the Talbot distance $Z_t/2$).
Figure 5. Variation of the grating-detection distance at constant magnification $G$. Left column for Molybdenum target and right column for Tungsten target.
(a,b) $Z_t/2 \sim 27$ cm; (c,d) $Z_t/2 \sim 88$ cm; (e,f) $Z_t/2 \sim 213$ cm;

5. Conclusion

Multi-lateral shearing interferometry technique shows promising result on synchrotron light source. This article exposes firsts attempts to understand interferogram generation on X-ray laboratory source. For this purpose, we presented development and validation of a simulation tool. Also, first simulation study has been presented and shows the influence of the tube spectrum and magnification on the fringe contrast and fractional Talbot distances. Additional parameters are currently under simulation and experimental images are expected.

References