Application-Oriented X-ray Grating Interferometer

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Abstract. Grating-based Differential Phase Contrast X-ray imaging (DPCi) provides, in one measurement, unique information about the absorption coefficient, the index of refraction and the microscopic structure of a sample at hard X-ray frequencies¹¹⁻¹⁷. For this reason, DPCi can potentially overcome the limitations of classical absorption-based radiography, notably for weakly absorbing materials. However, the implementation of the technology in industrial applications is still restricted due to the limited field of view and the insufficient contrast at high X-ray energies. Here, we report on a new experimental setup with field of view $5 \times 7 \text{ cm}^2$ that acquires single projections as well as Computerized Tomographic (CT) measurements of the sample. New micro-fabrication processes were developed to manufacture X-ray gratings with few defects. This allows the instrument to deliver images of industrial quality when operated with a conventional x-ray tube at 40kV. The complementarity of DPCi with conventional absorption-based radiography was experimentally demonstrated.

Keywords: X-ray Phase Contrast Imaging, Phase Stepping Interferometry.

PACS: 41.50.+h, 07.85.-m

INTRODUCTION

Conventional Absorption based Radiography (AR), as used in most x-ray facilities, relies on a simple principle. The object under study is placed between an x-ray source and a detector. The acquired image thus reflects the attenuation of the radiation induced by the object. Such AR systems have found widespread applications in areas as diverse as medicine, luggage screening at the airports or quality control of manufactured products.

However, AR shows shortcomings for weakly absorbing materials embedded in dense media. The absorption contrast is indeed inherently poor for such features since the absorption coefficient depends strongly on the atomic number¹.

To overcome this problem, methods based on the phase shift of the x-rays in the object have been proposed in the last decades²⁻⁹ and promising results were demonstrated in situations where the contrast in AR was too weak to provide useful information. Despite of these high expectations, most of these technologies could not find their way to commercial products either because the technical requirements were too high (synchrotron radiation) or because the improvements compared to AR were too small.

Grating-based Differential Phase Contrast X-ray imaging (DPCi)¹⁰⁻¹³ is a recently developed method which fulfills the requirements to be a serious candidate for industrial applications. DPCi can indeed be used with conventional x-ray tubes with a large focal spot, benefits from a high sensitivity and a good spatial resolution and can be combined with scanning¹⁴ and computerized tomography¹⁵⁻¹⁷ approaches.

We present here our new experimental setup which tackles the issues mentioned above and provides three different images: the classical transmission image, the differential phase contrast image¹² (based on the phase shift of the wave front in the object) and the dark field image which reflects the loss of spatial coherence of the x-ray beam due to small angle scattering¹⁸.

EXPERIMENTAL SETUP

Talbot-Lau Interferometer

FIGURE 1. (a) Schematic setup of the Talbot-Lau X-ray interferometer. The distances between G_0 and G_1 and between G_1 and G_2 are $L=131\text{cm}$ and $d=6.9\text{cm}$, respectively. On the bottom, cross sections of the gratings (b) G_0 of periodicity $57\mu\text{m}$ and depth $60\mu\text{m}$, (c) G_1 of periodicity $2.85\mu\text{m}$ and depth $12.7\mu\text{m}$ and (d) G_2 of periodicity $3\mu\text{m}$ and depth $30\mu\text{m}$ obtained by Scanning Electron Microscopy (SEM).

Differential Phase Contrast imaging (DPCi) has been documented in details in the literature¹¹⁻¹⁵ and is only described shortly in the following paragraph. The setup (see Figure 1) consists of a conventional x-ray tube from COMET (MXR-160HP 20) with a focal spot size of $1 \times 1 \text{ mm}^2$, a scintillation-based x-ray detector from Radicon (Shad-o-Box 2048 with a scintillator Min-R 2190) with 2048×1024 pixels of size $48 \times 48 \mu\text{m}^2$ and three gratings G_0 , G_1 and G_2 .

The phase sensitive part of the instrument is composed by G_1 and G_2 , which form an array of collimated slits. Thus, any change in the beam propagation due to the object will induce a change in the interference pattern I_{fr} created by G_1 (see Figure 1). Such changes in I_{fr} , like for example the lateral deviation of the fringes due to the refraction of the beam in the object, will finally reflect in the intensity $I(m,n)$ of the corresponding pixel.

$I(m,n)$ thus depends, not only on the transmission of the sample, but also on the lateral displacement and amplitude of the interference fringes I_{fr} . As a consequence, a single image is not sufficient to separate these three contributions. This problem is solved by implementing a phase stepping method¹¹.

Finally, since the x-ray beam would not interfere without a sufficient spatial coherence, G_0 forms a mask of individually coherent line sources (line width in the order of tens of microns), thus enabling the use of conventional x-ray source with a large focal spot¹².

The gratings G_0 , G_1 and G_2 (see Figure 1) were fabricated in the clean room of the CSEM in Neuchâtel by a process combining lithography, Deep Reactive Ion Etching (DRIE), wet etching and gold electroplating. The dimensions, as reported on Figure 1, have been optimized for an x-ray energy of 20keV . The field of view is limited to $5 \times 7 \text{ cm}^2$.

Experimental Procedure

G_0 is translated step-wise in the direction perpendicular to the gratings' lines over n_{per} periods and one image $I_k(m,n)$ is acquired at each step k . In our particular setup, G_0 is mounted on the x-ray tube and the latter is placed on a linear stage from Newport (UTS100PP) with mechanical uncertainty in the order of $0.3\mu m$.

Looking at a single pixel, the recorded intensity I_k forms a periodic curve as a function of the phase step k , whose shape, for a polychromatic spectrum, can be well approximated by a sine^{11,18}.

$$I_k \approx a_0 \left[1 + v \cdot \sin \left(2\pi \frac{kn_{per}}{N_{ps}} + \varphi \right) \right] \quad (1)$$

Where N_{ps} is the number of phase steps. The phase stepping curve thus comes down to the mean a_0 , the visibility v and the phase φ of the sine curve. Therefore three different images can be calculated by comparing the sample measurement (^s) (with the object in the field of view) to a reference measurement (^r) without.

The classical transmission image $T = a_0^s / a_0^r$ reflects the decrease of the beam intensity due to the absorption in the object. The dark field image $V = v^s / v^r$ reveals a decrease of the visibility of the phase stepping curve which is attributed to the local scattering power of the object¹⁸. Finally, the differential phase contrast image $DP = \varphi^s - \varphi^r$ expresses the displacement of the fringes in the direction perpendicular to the gratings' lines. The latter is linked to the angular deviation of the beam induced by a gradient in the phase shift of the x-rays after propagation through the object¹².

Note that the three images T , DP and V are also affected by beam hardening¹ which can lead to artifacts. The alignment of the gratings and their geometries also impact directly on v . Since the noise level in DP and V is directly related to the latter²⁰, it is thus critical to maximize v by a careful alignment. This is done thanks to two goniometers (Huber) with resolution of $2.5\mu m$ in translation and $9''$ in rotation, which are commanding the positions of G_1 and G_2 .

3D Reconstruction

DPCi as described above thus yields projections T , DP and V of a sample placed in the field of view. In order to go from the two-dimensional images to three-dimensional (3D) information, Computerized Tomography (CT) approaches can be combined with DPCi^{15-17,19}. For this purpose, the sample is rotated step-wise over 360° . At each step, a phase stepping series is acquired and T , DP and V are reconstructed. A filtered back projection algorithm adapted to the each contrast (T , DP and V) is finally used to build the absorption coefficient $\mu(x,y,z)$, the index of refraction $n(x,y,z)=1-\delta(x,y,z)$ and the linear diffusion coefficient $\epsilon(x,y,z)$, respectively.

For this reason, our setup is equipped with an x-z stage from Owis (LTM120) with repeatability of $15\mu m$ and travel range of $39.5cm$ in the horizontal direction and $29.5cm$ in the vertical direction. Furthermore, a precision rotation stage from Owis (DMT 65) allows the object to be rotated around the vertical axis with an angular error below 0.02° .

RESULTS

Radiography

As an example of DPCi, a cherry was imaged with our grating interferometer operated with an x-ray source voltage of $40kV$ and an anode current of $22.5mA$. The phase stepping series was realized with $n_{per} = 1$ and $N_{ps}=19$ and the exposure time for raw images was set to $33.5s$. The resulting T , DP and V images are shown on Figure 2. For this measurement, v^r (see "Phase Stepping Method") was around 40% . Note that a high visibility is foremost to obtain low-noise DP and V images²⁰.

¹ Beam hardening refers to the shift of the average energy of the x-ray spectrum toward the high energies due to the filtering of the low energies photons inside the object.

FIGURE 2. a) Transmission **T**, b) Differential Phase Contrast **DP** and c) Dark Field **V** images of a cherry acquired with the Talbot-Lau interferometer setup. The x-ray tube was operated with a voltage of 40kV.

The example clearly illustrates the complementarity of the information contained by **T**, **DP** and **V**. For instance, observe in **DP** the outside boundary and the fine inside structure of the stone as indicated by the black arrows in Figure 2. Furthermore, **V** shows unique features about the pulp. As pointed by the white arrow, fibers are present in the light tissue. The size of these fibers is typically below the resolution of the detector which explains that they do not appear in **T** and **DP**. However, the Ultra Small Scattering²¹ power of these fibers is sufficiently high to significantly decrease the visibility of the phase stepping curve and become visible in **V**. The dark field image **V** thus gives novel information about the (sub-) microscopic structure of the sample.

Computed Tomography

A tomographic measurement of a plastic toy (“playmobil®”) was realized by rotating the sample over 360° for a total of 721 steps. At each angular position, a phase stepping series was performed with $n_{\text{per}} = 1$, $N_{\text{ps}}=12$ and each raw image was acquired during 4 seconds. **T**, **DP** and **V** were then reconstructed at each step, as shown above for the cherry (see Figure 2).

$\mu(x,y,z)$ and $\epsilon(x,y,z)$ were reconstructed as 3D volumes using the conventional filtered back projection algorithm^{17,21} while a modified back projection algorithm¹⁵⁻¹⁷ was used to extract $\delta(x,y,z)$. Finally, the three reconstructed volumes were combined into one (as shown in Figure 3) by using the Red-Green-Blue (RGB) coding where the R, G and B channels were attributed to μ , δ and ϵ , respectively. As a result, each combination of μ , δ and ϵ corresponds to a specific color in the visible spectrum. Thus, two materials with the same attenuation coefficient (and as such cannot be separated in conventional CT) but with different indices of refraction or different linear diffusion coefficients appear as two distinct colors.

FIGURE 3. a) 3D rendering of the playmobil® done by segmentation of the index of refraction $\delta(x,y,z)$. b) Tomographic reconstructed slice of a playmobil® using RGB coding. Color channels Red, Green and Blue were attributed to the attenuation coefficient μ , the index of refraction δ and the linear diffusion coefficient ϵ , respectively. The playmobil® is made out of five different plastics, each identified by a specific color.

Figure 3-a displays the outside appearance of the playmobil® using 3D rendering. The volume was segmented from the reconstructed index of refraction $\delta(\mathbf{x}, \mathbf{y}, \mathbf{z})$. Figure 3-b shows one slice of the RGB reconstructed volume. Five different colors can be distinguished in the slice. As explained above, each color corresponds to a different plastic used in the fabrication of the playmobil®. This example clearly outlines the usefulness of the RGB coding to summarize, in one image, the information contained in the physical quantities μ , δ and ϵ .

CONCLUSION AND OUTLOOK

We have demonstrated that our x-ray grating interferometer can be used to reconstruct two new images **DP** and **V** in addition to the conventional absorption-based radiography **T**. The differential phase contrast image **DP** is sensitive to the phase shift of the x-ray beam in the sample while the dark field image **V** probes the small angle scattering power of the sample.

Our instrument possesses a field of view of $5 \times 7 \text{ cm}^2$ and can be operated with a conventional laboratory x-ray tube. In the case of a cherry, additional features could be recovered thanks to the new images which complemented absorption-based radiography.

Finally, Computerized Tomography (CT) techniques could be combined with DPCi to obtain three-dimensional information about the index of refraction and the linear diffusion coefficient. This imaging modality was illustrated for a playmobil® and helped to separate the different plastics composing it.

Our next step will be to extend the domain of usable x-ray energies even further. We are currently developing a new generation of gratings that will allow images to be taken with acceleration voltages up to 100kV while keeping a high visibility of the phase stepping curve. The new setup will thus be able to acquire images of objects which are thicker and/or made of dense materials like metals compared to what has been demonstrated in this paper. Such an instrument will enable DPCi applications that were previously out of reach.

ACKNOWLEDGMENTS

We gratefully acknowledge the Division Microsystems Technology from CSEM in Neuchâtel for the gratings' fabrication.

This work was supported by the CCMX-NMMC platform (Grant Nr. 0206088).

REFERENCES

1. J. Als-Nielsen and D. McMorrow, "X-rays and their interaction with matter" in *Elements of Modern X-ray Physics*, Chichester:Wiley, (2001), pp. 17-23.
2. R. Fitzgerald, *Phys. Today*, **53**, 23 (2000).
3. U. Bonse, M. Hart, *Appl. Phys. Lett.*, **6**, 155 (1965).
4. A. Momose, T. Takeda, Y. Itai, and K. Hirano, *Nature Medicine*, **2**, 473 (1996).
5. D. Chapman, W. Thomlinson, R. Johnston, D. Washburn, E. Pisano, N. Gmur, Z. Zhong, R. Menk, F. Arfelli, and D. Sayers, *Phys. Med. Biol.*, **42**, 2015 (1997).
6. M. Wernick, O. Wirjadi, D. Chapman, Z. Zhong, N. Galatsanos, Y. Yang, J. Brankov, O. Oltulu, M. Anastasio, and C. Muehleman, *Phys. Med. Biol.*, **48**, 3875 (2003).
7. S. Wilkins, T. Gureyev, D. Gao, A. Pogany, and A. Stevenson, *Nature* **384**, 335 (1996).
8. P. Cloetens, W. Ludwig, J. Baruchel, D. van Dyck, J. van Landuyt, J.P. Guigay, M. Schlenker, *Appl. Phys. Lett.*, **75**, 2912 (1999).
9. A. Olivo and R. Speller, *Phys. Med. Biol.*, **52**, 6555 (2007).
10. A. Momose, "Phase-sensitive imaging and phase tomography using X-ray interferometers," *Opt. Express* **11**, 2303–2314 (2003).
11. T. Weitkamp, A. Diaz, C. David, F. Pfeiffer, M. Stampanoni, P. Cloetens, and E. Ziegler, *Opt. Express* **13**, 6396 (2005).
12. F. Pfeiffer, T. Weitkamp, O. Bunk, and C. David, *Nature Phys.*, **2**, 258 (2006).
13. C. David, F. Pfeiffer, and T. Weitkamp, Patent # EP0511920060530 (2006).
14. C. Kottler, F. Pfeiffer, O. Bunk, C. Grünzweig, and C. David, *Rev. Sci. Instrum.* **78**, 043710 (2007).
15. F. Pfeiffer, C. Kottler, O. Bunk, and C. David, *Phys. Rev. Lett.* **98**, 108105/1 (2007).
16. Z-T Wang, K-J Kang, Z-F Huang and Z-Q Chen, *Appl. Phys. Letters* **95**, 094105 (2009).
17. M. Bech, T. H. Jensen, O. Bunk, T. Donath, C. David, T. Weitkamp, G. LeDuc, A. Bravin, P. Cloetens, F. Pfeiffer, *Z. Med. Phys.*, **in press.**, (2010).
18. F. Pfeiffer, M. Bech, O. Bunk, P. Kraft, E. Eikenberry, C. Brönnimann, C. Grünzweig, and C. David, *Nature Materials* **7**, 134 (2008).

- 19 A. C. Kak and M. Slaney, "Algorithms for Reconstruction with Non-diffracting Sources" in *Principles of Computerized Tomographic Imaging*, edited by R. F. Cotellessa, New York: IEEE Press (1988).
- 20 V. Revol, C. Kottler, R. Kaufmann, U. Straumann and C. Urban, in preparation (2010).
- 21 O. Glatter and O. Kratky, *Small Angle X-Ray Scattering*, London: Academic Press (1982).