State of the Art and Recent Advances in X-Ray Speckle-Based Phase-Contrast Imaging

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ABSTRACT

X-ray speckle-based imaging (SBI), one of them most recent phase-contrast imaging methods, has received growing interest in the last years. Its simplicity, cost-effectiveness and robustness combined with the high phase sensitivity and compatibility with laboratory X-ray sources make it an attractive method for visualising even minute density differences in samples. Since its first demonstration, SBI has seen rapid development and a range of applications have been identified. Among the various ways to perform SBI, the unified modulated pattern analysis (UMPA) offers a number of advantages. Here, we present an overview of the state of the art of SBI, including some of our work using UMPA in the recent years. We demonstrate the potential of UMPA for applications such as optics characterisation, biomedical and geological imaging and discuss its translation from large-scale synchrotron facilities to the laboratory.

Keywords: X-ray speckle-based imaging, X-ray phase-contrast imaging, Computed tomography, Biomedical imaging, X-ray optics characterisation

1. INTRODUCTION

X-ray phase-contrast imaging has become an established method for the investigation of samples with small density differences, for which it can reach superior contrast than conventional absorption imaging.¹ Different methods have been developed in the last two decades to convert the X-ray phase shift induced by a sample into intensity variations that can be recorded by a detector and analysed computationally.² Among these, X-ray speckle-based imaging (SBI)^{3–5} has attracted increasing attention in the last years. Thanks to its high phase sensitivity and quantitative character, the simplicity and robustness of the experimental setup⁶ and its compatibility with polychromatic and divergent X-ray beams,^{7,8} SBI is expected to become a widespread imaging method.

SBI makes use of a random speckled intensity pattern, which is used as a wavefront marker. These X-ray near-field speckles are created by a diffuser, such as a piece of sandpaper, comprised of small randomly distributed particles, which lead to scattering and interference of the illuminating X-rays. When a sample is inserted into the beam path, the reference speckle pattern is modulated locally in position, intensity and visibility (i.e. speckle contrast), which encodes information on the sample's refraction, absorption and small-angle scattering properties. Commonly, reference images with only the diffuser in the beam and sample images with both the diffuser and the sample in the beam are acquired. The various speckle modulations are then extracted computationally from the data set to obtain the differential phase, transmission and dark-field images of the sample simultaneously.

Here, we give a short overview of the state of the art of SBI, focusing on the phase-contrast signal, and summarise some of our recent achievements and ongoing work. These include the optimisation of data acquisition and analysis routines, applications of SBI in various fields and our efforts of implementing SBI with a laboratory X-ray source.

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2. DATA ACQUISITION AND ANALYSIS METHODS

Various methods for data acquisition with SBI have been proposed based on either single-shot measurement (only one reference image without and one sample image with the specimen in the beam) or moving the diffuser to several different transverse positions.⁶ While the single-shot speckle-tracking mode^{3,4} allows for short scan times and a simple setup, it is limited in spatial resolution and signal sensitivity. The speckle-scanning methods,^{5,9} on the other hand, can achieve a spatial resolution down to the resolution of the detector system and nanoradian angular sensitivity. However, this comes at the cost of a large number of diffuser steps leading to long scan times and the need for precise, accurate scanning stages. To tackle these limitations and combine the benefits of both approaches, advanced stepping schemes have been proposed.^{10–12} Among these, the unified modulated pattern analysis (UMPA)¹² has shown potential for applications in various fields.^{13–15} Importantly, UMPA is a promising candidate for widespread implementation at laboratory sources,¹⁶ which will facilitate its uptake by a large user community.

UMPA encompasses both the single-shot and the speckle-scanning approaches. It can be operated with a single sample and reference image as well as speckle-scanning data consisting of hundreds of equidistant steps. However, it also covers the cases between these two extremes in terms of the number of steps, sensitivity and spatial resolution. Compared to the previous 2D⁵ and 1D⁹ scanning modes, UMPA greatly relaxes the conditions on the number of steps and the step size, allowing large and irregular steps and omitting the need for high-precision scanning stages.¹⁷ The main advantage of UMPA lies in its flexibility and tunable character making it possible to adapt the scan and reconstruction parameters to the desired spatial resolution and sensitivity of the results.^{12,17}

From the single-shot or stepping SBI data, the multi-modal images of the sample can be extracted using various methods based on cross-correlation,^{3,5,11} least-squares minimisation,^{7,12} the transport-of-intensity equation^{18,19} and other principles.^{20,21} UMPA makes use of a cross-correlation approach, which was shown to give accurate and precise results and is robust to instabilities.¹² Some of our recent efforts are focused on the acceleration, optimisation and extension of the UMPA algorithm.²² Our latest version of the code is implemented as a Python module written in C.¹⁶ Further ongoing work includes the combination with other phase-retrieval approaches and the optimisation of the dark-field signal. New scanning routines are also being investigated with the potential of reducing image artefacts and extending the field of view.

3. APPLICATIONS OF X-RAY SPECKLE-BASED IMAGING

Although SBI is a relatively young imaging method, it has already found a number of applications. SBI has become an established tool for metrology and optics characterisation at synchrotron and free-electron-laser sources.^{6,23} Other applications for which UMPA has proven promising include biomedical imaging, materials characterisation and analysis of geological samples.^{6,15} Here, we outline some applications of UMPA speckle-based phase-contrast imaging that were demonstrated in the last years.

3.1 X-Ray Optics Characterisation

Figure 1. Deviations from the expected focusing behaviour (refraction angle deviation $\Delta\alpha$) of a polymer point-focus refractive lens. (a) Horizontal, (b) vertical deviation, (c) absolute deviation vector. The strong deviations were caused by prior beam damage of the lens when used as a focusing element at a synchrotron beamline. Figure adapted from Ref.,¹³ licensed under CC BY 4.0.

We have previously reported on the precise and accurate characterisation of two X-ray refractive lenses made from SU-8 photoresist polymer.¹³ The deviations from the design focusing behaviour of a point-focus refractive lens, caused by previous radiation damage, were determined using UMPA phase-contrast imaging, see Fig. 1. The results were validated and agree well with measurements of the same sample using conventional X-ray grating interferometry with the additional advantage of UMPA to provide 2D information on the focusing behaviour. For a line-focus refractive lens that had not experienced previous damage, deviations in the focusing behaviour over the height of the lens were identified, which could be attributed to shape errors. Our results suggest that UMPA is suitable for the precise and accurate characterisation of X-ray optics. This could be exploited for in-situ optics alignment and correction at synchrotron beamlines, but in the future also for routine quality control performed at laboratory X-ray sources to assess and improve the fabrication of optical elements.

3.2 3D Virtual Histology and Biomedical Imaging

X-ray phase-contrast imaging has also shown to be a promising method for biomedical imaging to visualise human and animal soft tissue. In particular, phase tomography has great potential for non-destructive 3D virtual histology, extending and complementing the 2D information from conventional histology. First results on biomedical specimens obtained at the synchrotron have confirmed the high image quality and information content accessible with UMPA without the need for tissue staining.¹⁴ An example is presented in Fig. 2, which shows the phase tomogram of a mouse testis. The high contrast allows for the visualisation of the detailed inner structure of the testis, which is comprised of numerous seminiferous tubules, see Fig. 2(b),(c), and the identification of features such as blood vessels, see Fig. 2(a),(d). Further analysis includes the segmentation and quantification of components in the sample.¹⁴ While all demonstrations of UMPA for biomedical imaging to date have been performed on healthy tissue to assess and confirm the promising potential of the technique, pre-clinical studies on pathological tissue will be performed in the future.

Figure 2 also demonstrates that UMPA can achieve high image quality even with a small number of diffuser steps (with constant exposure time and hence dose per step). Although the image in Fig. 2(b), which was reconstructed with 20 diffuser steps, shows superior image quality to the image in Fig. 2(c) taken with 5 diffuser steps and at 1/4 of the dose, all the main features of the sample are still visible in the latter. The small number of required steps allows reducing the imaging time and dose to the sample significantly, which is important particularly for biomedical samples that can be radiation-sensitive. It should be noted that the image sensitivity

Figure 2. (a),(d) Slices through the phase tomogram of a mouse testis obtained with UMPA. (b),(c) Regions of interest showing details of the inner structure comprised of seminiferous tubules at high contrast, reconstructed with 20 diffuser steps (b) and with 5 steps and 1/4 of the dose (c). It can be seen that even the lower-dose data obtained with 5 steps still delivers sufficient image contrast albeit at the loss of spatial resolution due to the larger analysis window used in the UMPA reconstruction. Data acquired at beamline I13-2 at Diamond Light Source (UK) at a mean X-ray energy of 22.7 keV, 1201 projections of the tomography scan, effective pixel size: 2.26 μm. Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature “3D Virtual Histology Using X-ray Speckle with the Unified Modulated Pattern Analysis” in Ref. ¹⁵ by Marie-Christine Zdora © The Author(s), under exclusive license to Springer Nature Switzerland AG (2021).

and contrast depend on both the number of diffuser positions and the size of the analysis window used in the UMPA reconstruction process, as described in more detail in Ref. ¹² A smaller number of diffuser steps can be compensated for by choosing a larger analysis window to achieve comparable image contrast at the cost of spatial resolution, as observed in Fig. 2(c).

Following the successful results obtained at the synchrotron, efforts are currently ongoing to translate the approach to laboratory X-ray sources for wider accessibility, as outlined in Section 4.

3.3 Imaging of Geological Samples

Apart from biomedical soft tissue, we have recently studied a number of high-density samples such as volcanic rocks and cement.¹⁵ Preliminary results obtained on an ignimbrite pumice volcanic rock sample from Tenerife are shown in Fig. 3. The X-ray phase and absorption signals give complementary information on the specimen, which makes it possible to differentiate between different types of crystal inclusions. While some of the inclusions show high contrast to the bulk of the rock only in the phase but not in the absorption tomogram (red dashed circles), others can clearly be identified also in the absorption signal (turquoise circle). The two types of crystals show similar densities in the phase tomogram, see Fig. 3(a),(c), but seem to have strong differences in their X-ray absorption properties, see Fig. 3(b),(d). Only a combination of the phase and absorption information allows for both a clear separation of crystal inclusions and bulk rock and an unambiguous differentiation between the two types of crystals. This underlines the benefit of being able to extract the two complementary image modalities simultaneously from the UMPA data set.

Figure 3. Transverse slices through (a) the phase tomogram and (b) the corresponding absorption tomogram of a volcanic rock sample imaged with UMPA. (c) and (d) show the corresponding longitudinal slices. Different types of crystal inclusions can be differentiated by their contrast in both the phase and the absorption tomogram (see dashed circles). Data acquired at beamline I12 at Diamond Light Source (UK) at an X-ray energy of 53 keV, using 20 diffuser steps, 1801 projections of the tomography scan, effective pixel size: 7.59 μm . Adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature “Recent Developments and Ongoing Work in X-ray Speckle-Based Imaging” in Ref. ¹⁵ by Marie-Christine Zdora © The Author(s), under exclusive license to Springer Nature Switzerland AG (2021).

Figure 4. (a) Speckle pattern obtained at a liquid-metal-jet laboratory X-ray source using sandpaper as a diffuser and (b) region of interest from panel (a). (c) Differential phase signal in the horizontal and (d) the vertical direction of a silicon sphere (diameter: $480\text{ }\mu\text{m}$) on a wooden toothpick imaged with 19 diffuser positions. (e) Corresponding transmission signal. Effective pixel size (sample plane): $2.8\text{ }\mu\text{m}$.

4. UMPA AT LABORATORY X-RAY SOURCES

To make SBI widely accessible to users from different fields, it is essential to optimise it for use with laboratory X-ray sources. SBI does not impose very strong requirements on the spatial and temporal coherence of the X-rays and is compatible with divergent beams. It has, therefore, been implemented at laboratory sources in the single-shot and speckle-scanning modes.^{7–9,24,25}

We have recently been working towards the implementation of UMPA at a liquid-metal-jet laboratory X-ray source. An example of a speckle reference image obtained at this source is shown in Fig. 4(a),(b) revealing a fine speckle pattern of high contrast, which is suitable for SBI. This was confirmed by an UMPA scan of a test sample (silicon sphere on wooden toothpick), see Fig. 4(c)-(e). Moreover, UMPA multimodal imaging of a more complex specimen has been successfully demonstrated at this laboratory setup recently.¹⁶

Following these first demonstrations, we are working on the optimisation of the setup and analysis with the aim of making it compatible with tomography at reasonable scan times. For this purpose, the detector system, X-ray spectrum, X-ray spot and other setup parameters will be adapted to best suit SBI.

5. SUMMARY AND CONCLUSIONS

We have presented an overview of SBI and our results obtained with UMPA for various applications. The phase-contrast images obtained with UMPA show high phase sensitivity and deliver quantitative information on the phase shift and, in tomographic mode, on the electron density distribution within the sample. Its quantitative character combined with the possibility in trading off image contrast, spatial resolution and scan time/dose, make UMPA a flexible method for phase-contrast imaging. Moreover, UMPA allows for the retrieval of the complementary small-angle scattering signal, commonly called dark-field signal, which gives information on unresolved features in the sample. Although this image modality has not been discussed here, it can give valuable additional information, which can be crucial for separating different materials and investigating sub-pixel structures in large-scale samples. Finally, our recent work on implementing UMPA at laboratory sources will open up the method to a larger user community and will make it accessible for large-scale, routine investigations.

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