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Characterisation of speckle-based X-ray phase-contrast imaging

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Abstract. We present a study on the influence of different scan and reconstruction parameters on the image quality of the differential phase signals obtained from speckle-based X-ray phase-contrast imaging measurements in single-shot as well as 2D and 1D speckle-stepping modes. In particular, the effects of the analysis window size and the number of diffuser steps on the spatial resolution and signal sensitivity of images of a phantom sample are investigated and discussed. It is shown that the trade-off between spatial resolution, scan time and simplicity of the setup has to carefully be addressed for each specific experiment.

1. Introduction

In the last decades X-ray phase-contrast imaging has shown vast potential in the fields of biomedical imaging, material science and metrology. Among the different techniques speckle-based X-ray phase-contrast imaging [1, 2, 3], has recently seen increased interest due to its simple setup and its compatibility with polychromatic X-rays [4, 5].The sample-induced modulations of an X-ray near-field speckle pattern created by a random phase modulator are analysed to retrieve the differential phase signal, the transmission and the small-angle scattering signal. X-ray speckle imaging is typically performed in two different operational modes, speckle tracking [1, 2] and speckle scanning [3]. While single-shot speckle tracking is fast and dose efficient, it suffers from low spatial resolution. The speckle-scanning mode can achieve significantly higher resolution, but requires several hundreds of projections, an extremely stable setup and high-precision scanning motors. Recently, also a one-dimensional stepping approach has been proposed [6], and other operational modes are currently being explored aiming to further reduce the number of steps and simplify the stepping scheme [7]. Here, we characterise the different existing operational modes of X-ray speckle-based imaging on a phantom sample exploring the effects of different scan and reconstruction parameters, in particular the analysis window size and the number of diffuser steps.

2. Experimental setup and signal reconstruction

Measurements were performed at the I13-2 Diamond-Manchester Imaging Beamline at Diamond Light Source, UK using a monochromatic X-ray beam of energy 19 keV with the setup shown in Fig. 1(a). The sample - silicon spheres (diameter 0.48 mm) and quartz spheres (diameter 0.35 mm) in a polypropylene pipette tip filled with water - was mounted on a hanging rotation

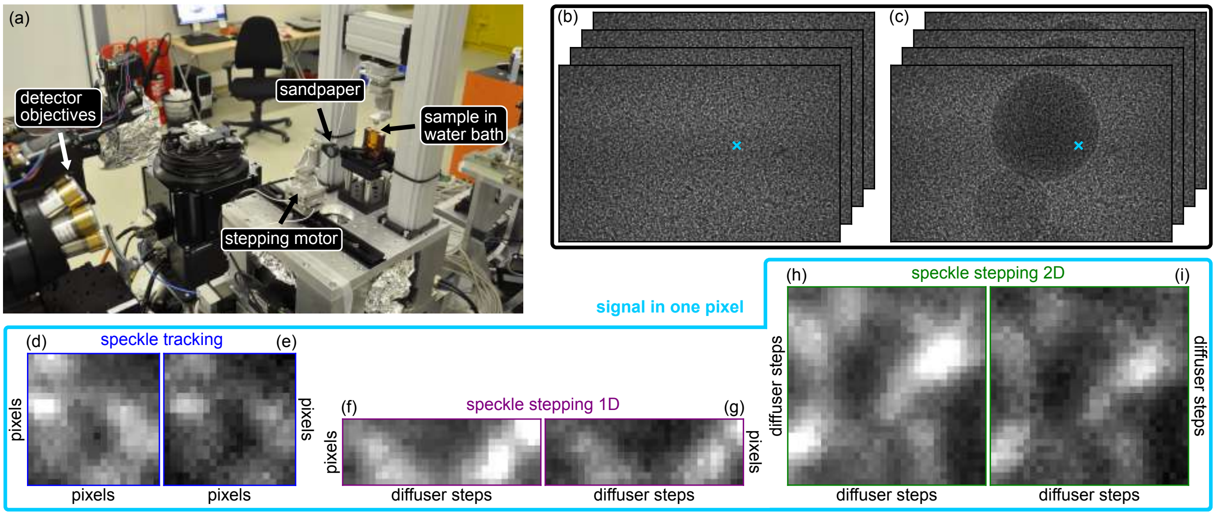

Figure 1. Experimental setup (a). Reference images (b) and sample images (c) are collected for different diffuser steps. The visibility[1] of the pattern averaged over the whole field of view is 42%. The signal in one pixel (cyan cross) is shown for single-shot tracking analysis (d, e), for 1D speckle-stepping mode (f, g) and for 2D speckle-stepping mode (h, i).

stage and immersed in a water tank. The diffuser, here a piece of P800 sandpaper, was placed on a piezo xy-translation stage at a distance of approximately 10 cm downstream of the specimen. The detector system (150 μm-thick CdWO4 scintillation screen, optical microscope with 20× magnification, pco.4000 CCD camera with 9 μm pixel size) giving an effective pixel size of $p_{\mathrm{eff}} = 0.45\,\mu$m was positioned 20 cm downstream of the diffuser.
Reference and sample images were acquired for 30×30 translational steps of the diffuser (step size: $d_{\mathrm{step}} = 0.45\,\mu$m) with an exposure time of 2.0 s per projection.

The reconstruction of the image signals in single-shot mode as well as in 2D and 1D stepping modes is based on cross-correlation in real space [4] delivering the displacement s of the speckle pattern caused by the refraction of X-rays in the sample, which can be converted into a refraction angle $\alpha = s\zeta/z$, where z is the diffuser-detector distance, $\zeta = p_{\mathrm{eff}}$ for the single-shot mode and $\zeta = d_{\mathrm{step}}$ for the speckle-stepping mode. In case of 1D stepping, $\zeta = d_{\mathrm{step}}$ for the refraction in the scan direction and $\zeta = p_{\mathrm{eff}}$ for the signal perpendicular to the scan direction. For the single-shot analysis a windowed cross-correlation is applied to a single reference and sample image, see Figs. 1(d)-(e), while the analysis of the 2D speckle-stepping scan is performed pixel-wise in the diffuser plane over the sample and reference signals at the different diffuser steps, see Figs. 1(h)-(i). A 1D stepping analysis was conducted considering only one row of 30 steps in the horizontal and a few pixels in the vertical direction for cross-correlation (see Figs. 1(f)-(g)). From the two differential phase signals the phase shift can be obtained, e.g. via 2D Fourier integration [8].

3. Effects of different scan and reconstruction parameters

The different parameters used for reconstruction in single-shot speckle-tracking, in conventional 2D speckle-stepping and in 1D horizontal speckle-stepping modes are summarised in Tab. 1.

For the speckle-tracking analysis the window size was varied from 5 × 5 pixels to 30 × 30 pixels. Figures 2(a)-(d) show the reconstructed refraction angle signals in the horizontal direction.

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[1] We define the visibility of the speckle pattern as $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$, where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensities of the pattern in a 100 × 100 pixels region of interest in the background area.

tracking	**5×5 px**	**10×10 px**	**20×20 px**	**30×30 px**
$\sigma_x \mid \sigma_y$ [nrad]	1982 | 1824	1309 | 1157	352 | 270	153 | 144
2D stepping	**5×5 steps**	**10×10 steps**	**20×20 steps**	**30×30 steps**
$\sigma_x \mid \sigma_y$ [nrad]	1979 | 1875	1346 | 1219	399 | 312	180 | 150
1D stepping	**30 steps, 5 px**	**30 steps, 10 px**	**30 steps, 20 px**	**30 steps, 30 px**
$\sigma_x \mid \sigma_y$ [nrad]	764 | 675	435 | 331	241 | 184	188 | 139

Table 1. Different reconstruction and scan parameters and respective angular sensitivities.

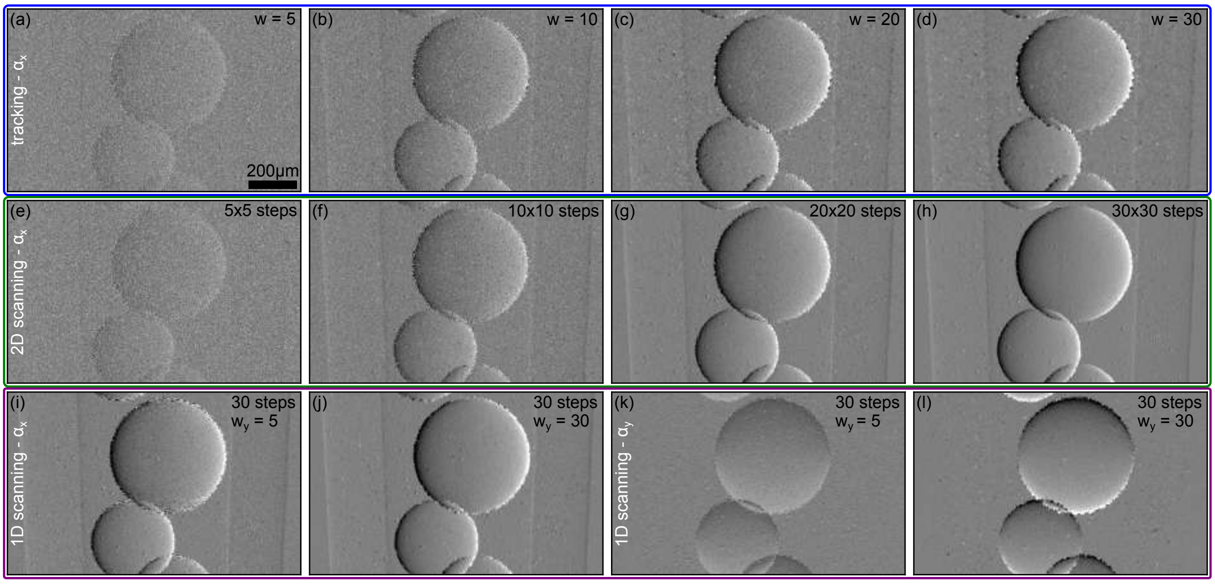

Figure 2. Refraction α_x in the horizontal reconstructed in single-shot mode with different window sizes (a-d), in 2D speckle-stepping mode with different numbers of steps (e-h) and in 1D stepping mode with 30 steps in the horizontal and different numbers of pixels in the vertical (i,j). Refraction α_y in the vertical for 1D scanning (k, l). Intensity windows: -6 μrad to 6 μrad.

A clear improvement in image quality with increasing window size can be observed. This is confirmed by the increase in angular sensitivity defined as the standard deviation of the refraction angle in a region of 100 × 100 pixels in the background area without sample, which can be found in Tab. 1. However, a larger window results in a loss in resolution as visible in Figs. 2(a)-(d). The trade-off between spatial resolution limited by the window size and image quality has to carefully be considered for the desired results.

A significant increase in spatial resolution can be achieved with the speckle-stepping mode by performing a 2D scan of the diffuser in steps smaller than the speckle size. However, this comes at the cost of a large number of acquisition frames and the need for very accurate stepping motors to ensure equidistant step sizes. The refraction angle signals in the two directions were reconstructed for different numbers of steps keeping the step size constant at 0.45 μm, see Figs. 2(e)-(h). The image quality significantly improves with more steps (see Tab. 1), however the immense increase in scan time and hence dose to the sample needs to be considered for practical implementation.

As a third operational mode providing some trade-off between the two previous methods, the diffuser can be scanned in only one direction, which significantly reduces the number of acquired projections. However, for a 2D analysis of the speckle shift, we have to take several pixels in the direction perpendicular to the scan direction. Commonly several tens of scan positions are

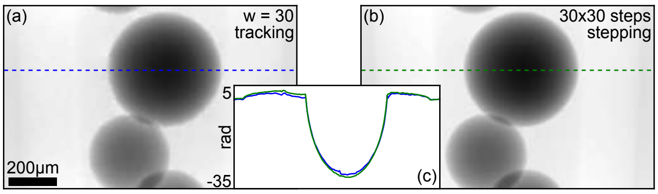

Figure 3. Integrated phase shift for the single-shot (a) and the 2D stepping case (b). Intensity window: -33 rad to 4 rad. Horizontal line profiles through the centre of the silicon sphere (c).

used for this mode to allow a small window size of only several pixels [6]. Here, a scan of 30 steps along the horizontal direction was considered and w_y pixels in the vertical direction were taken for analysis. The reconstructed refraction angle signals in the horizontal and the vertical directions in Figs. 2(i)-(j) and 2(k)-(l), respectively, demonstrate that taking a larger number of pixels in the vertical direction for analysis improves the image quality at the cost of a reduced resolution in the vertical direction.

The observations from the differential phase signals translate to the integrated phase shift (see Figs. 3(a) and (b) for single-shot imaging with a window size of 30×30 pixels and 2D speckle scanning with 30×30 steps, respectively). The resolution of the speckle-stepping scan is superior to the single-shot case. Moreover, artefacts at the edges of the spheres can be observed in single-shot mode, which are not present for the stepping case.

4. Conclusion and outlook

We have presented a study on the effects of scan and reconstruction parameters on the image quality of the differential phase signal obtained from speckle-based single-shot tracking, 2D scanning and 1D scanning measurements.

For single-shot speckle imaging the size of the analysis window needs to be in the order of 20×20 pixels for an acceptable angular sensitivity, which, however, leads to a loss in spatial resolution of $20\times$ the pixel size. A comparable angular sensitivity at much higher resolution can be achieved with 2D stepping over at least 20×20 steps, which also yields accurate results at the edges of features where the single-shot analysis fails. 1D scanning requires less projections, but leads to a reduced resolution in the direction perpendicular to the scan direction.

When choosing the preferred operational mode for a speckle imaging experiment, there is an inevitable trade-off between spatial resolution, scan time and simplicity of the setup. To overcome this and combine the advantages of the techniques, investigations of a mixed approach are currently being undertaken and are expected to yield high-resolution, high-sensitivity results with a simple setup and only few required projections.

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