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A single-image retrieval method for edge illumination X-ray phase-contrast imaging: Application and noise analysis

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ABSTRACT

Purpose: Edge illumination (EI) X-ray phase-contrast imaging (XPCI) has been under development at University College London in recent years, and has shown great potential for both laboratory and synchrotron applications. In this work, we propose a new acquisition and processing scheme. Contrary to existing retrieval methods for EI, which require as input two images acquired in different setup configurations, the proposed approach can retrieve an approximate map of the X-ray phase from a single image, thus significantly simplifying the acquisition procedure and reducing data collection times.
Methods: The retrieval method is analytically derived, based on the assumption of a quasi-homogeneous object, i.e. an object featuring a constant ratio between refractive index and absorption coefficient. The noise properties of the input and retrieved images are also theoretically analyzed under the developed formalism. The method is applied to experimental synchrotron images of a biological object.
Results: The experimental results show that the method can provide high-quality images, where the "edge" signal typical of XPCI images is transformed to an "area" contrast that enables an easier interpretation of the sample geometry. Moreover, the retrieved images confirm that the method is highly stable against noise.
Conclusions: We anticipate that the developed approach will become the method of choice for a variety of applications of EI XPCI, thanks to its ability to simplify the acquisition procedure and reduce acquisitions time and dose to the sample. Future work will focus on the adaptation of the method to computed tomography and to polychromatic radiation from X-ray tubes.

1. Introduction

Edge illumination (EI) is an X-ray phase-contrast imaging (XPCI) technique that is currently being developed at University College London [1,2]. As opposed to conventional imaging techniques, in XPCI the contrast does not only rely on the absorption of the sample, but is also produced by the phase shift that X-rays experience when passing through different regions of the sample [3,4]. This new mechanism for generating contrast can provide images with considerably improved detail visualization, especially in the case of materials with similar attenuation properties, such as biological soft tissues. The phase shift undergone by the beam, in fact, can be significant even when its absorption counterpart is very small and insufficient to create adequate image contrast.

EI has been extensively applied using both monochromatic synchrotron radiation [1,5–8] and polychromatic and divergent beams generated by X-ray tubes [2,9–13]. In particular, the applicability to X-ray tubes in table-top laboratory setups is possible thanks to the low coherence requirements of the technique, both in terms of beam polychromaticity and focal spot size [2,10,14,15]. This feature of EI has the potential to enable a widespread implementation of the technique for various applications in fields like biology, medicine, industrial testing, etc.

A schematic of the EI working principle is presented in Fig. 1. The beam is collimated before the sample by means of a slit (henceforth called "sample slit", with an aperture of a few or tens

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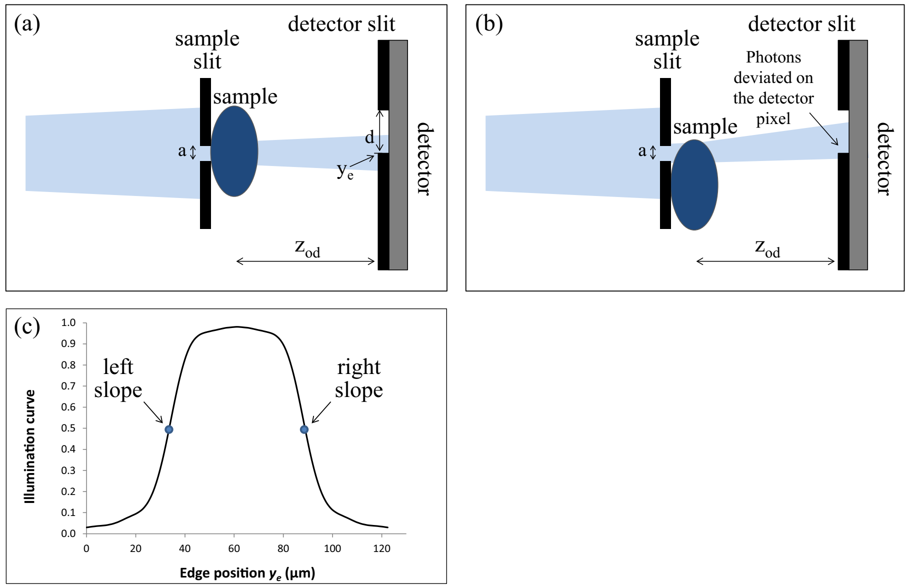

Fig. 1. Schematic diagram of the EI principle. (a) Sample and detector slits are misaligned with respect to each other, so that part of the beam is stopped by the detector slit, while the remaining part is incident on a line of detector pixels (oriented in the direction orthogonal to the plane of drawing). (b) When the sample is inserted, in addition to attenuating the beam, it can deviate the photons on (or out of) the detector, thus increasing (or decreasing) the recorded intensity. (c) Example of illumination curve.

of μm) and the beamlet exiting the object is then analyzed by means of a second slit (the "detector slit"), placed in front of the detector and aligned with a line of detector pixels. The two slits are misaligned with respect to each other, so that a fraction of the beamlet is stopped by the detector slit, while the remaining part is directly incident onto the detector (Fig. 1a). The presence of the sample in the beam can have two effects. It can attenuate the beam intensity, thus reducing the signal on the detector, and it can refract the beam, thus changing its direction of propagation (Fig. 1b). By placing the detector at a certain distance from the sample, this deviation is converted into a spatial displacement of the beam, given by $\Delta y = z_{od} \cdot \Delta\theta_y$, where z_{od} is the object-to-detector distance and $\Delta\theta_y$ is the refraction angle in the direction orthogonal to the slit aperture. This has the effect of increasing or decreasing the amount of photons hitting the detector, depending on the direction of refraction (Fig. 1b). An image of the sample can be obtained by scanning the object through the beam, and recording the detector signal at each step of the scan. When using wide beams produced by X-ray tubes, however, this scan can be avoided by replacing the two slits with two masks featuring several apertures, thus replicating the EI principle over the whole extent of the object [2,9,10].

We will consider in the following the case of a parallel and monochromatic beam (synchrotron case). If the direction x parallel to the mask lines is for the moment neglected, the signal measured on the detector at object position p can be expressed as [7,10]:

$$S(p) = N \cdot T(p) C(y_e - z_{od} \cdot \Delta\theta_y(p)) \quad (1)$$

where N is the number of photons passing through the sample slit and $T(p) = \exp(-\int dz \mu(p,z))$ is the beam transmission through the sample, with μ the linear attenuation coefficient. $C(y_e)$ is the so-called illumination curve (shown in Fig. 1c), which represents the fraction of photons passing through the detector slit, as a function of the misalignment y_e between the slits. Values of $C(y_e)$ range from about 0 (when the slits are totally misaligned) to about 1 (when the slits are perfectly aligned). In Eq. (1), the argument of the illumination curve is shifted by $-z_{od} \cdot \Delta\theta_y(y)$. This is because a displacement of the beam caused by refraction is, from the point of view of the signal, perfectly equivalent to a displacement of the detector slit in the opposite direction. The refraction angle is given by $\Delta\theta_y(p) = k^{-1}\partial\phi/\partial y(p)$, where k is the wavenumber, $\phi(p) = -k\int dz\delta(p,z)$ is the phase shift and δ is the refractive index. Due to its differential nature, the refraction signal mainly originates at the boundaries of the various object structures.

As can be seen from Eq. (1), the image signal depends on both the transmission and phase shift. Therefore, if these two object properties need to be separated and quantified, the acquisition and subsequent processing of two images, acquired in different configurations of the setup, is usually required. From a mathematical perspective, in fact, two equations are needed in order to retrieve the two unknowns T and ϕ. In practice, retrieval for EI is normally carried out by acquiring two images on the left and right slopes of the function C (Fig. 1c) [7,10]. This corresponds to taking two images with the detector slit stopping either the lower or the upper part of the beam.

This retrieval method has been demonstrated to extract accurate attenuation and phase information, both in laboratory [10,13] and synchrotron [7] EI setups. However, this procedure is not ideal if fast acquisitions are needed or in the case of computed tomography, as every image acquisition needs to be repeated twice at two different slit misalignments.

In the next section, a new acquisition and retrieval method that requires only a single input image is described, and in Section 3 this method is applied to an experimental image acquired using synchrotron radiation.

2. Theory

In the following derivation, we make the assumption that the refraction angles produced by the sample are small, so that a linear approximation can be safely adopted for the illumination curve on one of its slopes (c.f. Eq. (1) and Fig. 1c). Moreover, we exploit the fact that, in the direction parallel to the slits, the signal is equal to the free-space propagation (FSP) one, i.e. the one that would be obtained without the presence of the slits [16]. The latter can be expressed using the well-known transport-of-intensity (TIE) equation, in the approximation of near-field regime [17,18]:

$$S(x) = \left\{ T(x) - k^{-1} z_{od} \nabla_x [T(x) \nabla_x \phi(x)] \right\} * LSF_x(x) \quad (2)$$

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