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Angular sensitivity and spatial resolution in edge illumination X-ray phase-contrast imaging

P.C. Diemoz*, M. Endrizzi, C.K. Hagen, T.P. Millard, F.A. Vittoria, A. Olivo

Department of Medical Physics and Bioengineering, UCL, WC1E 6BT London, UK

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ABSTRACT

Edge illumination (EI) is an X-ray phase-contrast imaging (XPCi) technique which bears high potential for applications in several fields, thanks to its simple experimental setup and to its applicability with conventional X-ray sources. In this context, the estimation of the phase sensitivity and spatial resolution achievable with EI is of particular importance, as it will enable assessing and quantifying the full potential of the technique. We present in this article a simple theoretical model that allows the analysis of these two quantities and of their dependence upon the different acquisition parameters. We believe that the obtained results will prove very useful for the design and optimization of future setups. Besides, we demonstrate experimentally that the simplicity of the EI setup does not come at the expense of the sensitivity; on the contrary, EI allows achieving very high angular resolutions.

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1. Introduction

X-ray phase-contrast imaging (XPCi) has been the subject of intensive research over recent years, due its potential to provide greatly enhanced image contrast compared to conventional attenuation-based X-ray methods [1–8]. The improvement achievable with XPCi is particularly important when materials characterized by very similar attenuation properties are considered (e.g. biological soft tissues at high X-ray energies). In fact, phase effects can still be significant even when the attenuation signal is very low and falls below the detectability threshold (i.e. below the noise level).

Among the several XPCi techniques that have been proposed and applied so far, edge illumination (EI), currently under development at University College London (UCL), appears as one of the most promising [5,9,10]. The EI setup is schematically presented in Fig. 1(a). The beam is split into several micrometric beamlets by an absorbing mask placed in front of the sample (the so-called 'sample' mask). A corresponding absorbing mask (the 'detector' mask) is placed in contact with the detector and misaligned with respect to the first, so that a fraction of each beamlet is intercepted and stopped, while the remaining part is transmitted through the detector (Fig. 1(a)). Each beam, upon traversing the object, can undergo both a decrease in its amplitude due to sample attenuation and a deviation in its direction due to the sample-induced refraction. The latter effect typically arises at the sample interfaces, the refraction angle being proportional to the gradient of the X-ray phase shift. Due to refraction, the beamlet is spatially shifted: as a result, the fraction of photons passing through the second mask can be either decreased or increased, and so will do the intensity measured by the detector (Fig. 1(a)) [11,12]. The image of the sample obtained with EI will therefore be characterized by a mixture of attenuation and refraction signals, the latter visible as black or white fringes running along the sample interfaces, where the gradient of the phase shift is largest.

The realization of the EI principle does not require the use of a coherent beam: the method is in fact intrinsically incoherent and non-interferometric, and can be described from a purely geometrical perspective (i.e. by considering X-rays as particles propagating along straight lines and neglecting any interference effects). Since it does not require temporal or spatial coherence, EI can be efficiently applied with broadly polychromatic beams and relatively large focal spots can be tolerated, as long as the projected source size is small enough to prevent the different beamlets from mixing at the detector plane [9,10]. Therefore, the method is readily applicable to state-of-the art X-ray tubes in normal laboratories and, thus, it has very high potential for applications in several different fields including biomedical research, materials science, culture heritage, non-destructive industrial testing, etc.

It is therefore extremely important to quantitatively characterize the performance of an EI setup, in terms of the achievable image quality and of the sample features that can be potentially detected. In this context, two essential quantities describing the image quality need to be estimated: the spatial resolution and the angular resolution. The first quantity determines the size of the smallest features that can be detected, while the second determines the smallest refraction angle that can be measured (i.e. the image contrast and the 'sensitivity' of the technique to very weak signals).

* Corresponding author.
E-mail address: p.diemoz@ucl.ac.uk (P.C. Diemoz).

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2. Sensitivity and spatial resolution under geometrical approximation

As already mentioned, in EI image contrast originates from a mixture of attenuation and refraction signals. We recently developed a method to disentangle and quantify these two quantities, by combining two images acquired at different misalignments of the sample and detector masks [10–12]. A typical choice is represented by $\pm 50\%$ mask misalignments, i.e. configurations where one of the edges of the detector aperture is aligned with the center of the sample aperture, so that either the lower ('plus' image) or the upper ('minus' image) half of the beam are stopped by the mask (Fig. 1(a)). If the sample is not in the beam, the signal measured by each detector pixel is the integral of the beam intensity $I_{ref}(y)$ falling within the corresponding detector mask aperture, and can thus be expressed as

$$S(y_{e,\pm}) = \int_{y_{e,\pm}}^{y_{e,\pm}+d} dy I_{ref}(y) = S_0 C(y_{e,\pm}) \quad (1)$$

where $y_{e,\pm}$ indicates the position of the lower edge of the aperture in the two configurations, d is the aperture size, $S_0 = \int_{-\infty}^{+\infty} dy I_{ref}(y)$ is the total signal that would be measured without the detector mask, and $C(y_e) \equiv \int_{y_e}^{y_e+d} dy I_{ref}(y)/S_0$ is the so-called illumination curve, which represents the fraction of photons that are transmitted through the aperture. The illumination curve is a function comprised between a minimum value close to 0 (when the two masks are completely misaligned) and a maximum close to 1 (when they are perfectly aligned). An example of curve C is reported in Fig. 1(b), where the experimental parameters of one of the setups installed at UCL have been considered: $z_1 = 1.6$ m, $z_2 = 0.4$ m, focal spot of the X-ray tube = 70 μm, sample aperture $a = 12$ μm, detector aperture $d = 20$ μm, detector mask period = 85 μm. Masks, however, are here assumed to be fully absorbing (unlike in the experimental setup, where transmission through the masks is present). The intensity profile $I_{ref}(y)$ of the beam incident on the detector mask is the result of the wave propagation between the two masks and its estimation requires, in the general case, the calculation of Fresnel diffraction integrals. However, in the case of a laboratory EI setup making use of an extended focal spot, the blurring due to the source effectively washes out all diffraction ripples. As a result, as shown in [12,13], the geometrical optics (or 'ray tracing') approach can be safely used to describe the beam propagation and therefore the intensity incident on the detector mask. Under these conditions, the beam profile can thus be calculated simply as the convolution of the magnified sample aperture and of the projected source size distribution [12,14,15].

Under the assumption that the sample attenuation and refraction functions are almost constant on the length scale of the sample aperture, the signals recorded in the 'plus' and 'minus' images when the sample is inserted in the beam can be expressed as

$$\begin{aligned} S_{obj}(p\Delta y; y_{e,\pm}) &= T(p\Delta y) \int_{y_{e,\pm}}^{y_{e,\pm}+d} dy I_{ref}(y - z_2 \Delta\theta_y(p\Delta y)) \\ &= S_0 T(p\Delta y) C(y_{e,\pm} - z_2 \Delta\theta_y(p\Delta y)) \end{aligned} \quad (2)$$

where T is the sample attenuation, $\Delta\theta_y$ is the refraction angle in the direction y orthogonal to the aperture, p is an index representing the considered aperture and Δy the sample mask period, z_2 is the sample-detector mask distance and $z_2\Delta\theta_y$ represents the displacement of the beam along y due to refraction. Therefore, the attenuation simply reduces the beam intensity by a constant factor, while the refraction rigidly deviates the beam, effectively shifting the position on the illumination curve. Eq. (2) can be combined to analytically retrieve the refraction angle [12]

$$\Delta\theta_y = \frac{1}{z_2} R^{-1}\left(\frac{S_{obj,+}}{S_{obj,-}}\right) \quad (3)$$

where the function R is defined as

$$R(z_2\Delta\theta_y) \equiv \frac{C(y_{e,+} - z_2\Delta\theta_y)}{C(y_{e,-} - z_2\Delta\theta_y)} \quad (4)$$

and can be calculated from an experimental measure of the illumination curve C without the object. Eq. (3) also enables the uncertainty on the calculated values of the refraction angle to be analytically estimated. In fact, if we assume the input images $S_{obj}(p\,\Delta y; y_{e,\pm})$ to be only affected by statistical noise and we use error propagation, we obtain, for symmetric positions $y_{e,+}$ and $y_{e,-}$

$$\alpha = \sigma(\Delta\theta_y) \simeq \frac{\sqrt{C(y_{e,+})}}{z_2\sqrt{2TS_0}\,[I_{ref}(y_{e,+}) - I_{ref}(y_{e,+}+d)]} \quad (5)$$

The value of α represents a measure of the angular resolution (or angular sensitivity) of the setup, as it defines a detectability threshold for the refraction angle. Refraction angles larger than the noise level will create, in fact, detectable features in the image, while angles smaller than this level are likely to be undetectable. Eq. (5) is extremely useful, as it allows a simple and fast estimation of the sensitivity of a given EI setup, without the need of time-consuming wave optics simulations. It can be used to analyze the dependence of the sensitivity from the various experimental parameters, to compare different setups, or in the design of new setups, in order to optimize the parameters for maximized sensitivity.

Alongside sensitivity, spatial resolution is another crucial parameter for image quality, defining the size of the smallest detectable features. In a single EI image acquired with the setup in Fig. 1(a), the spatial resolution is determined by the spacing (i.e. the period) of the apertures in the first mask. However, a procedure called 'dithering' is often used to improve the spatial resolution. Under this

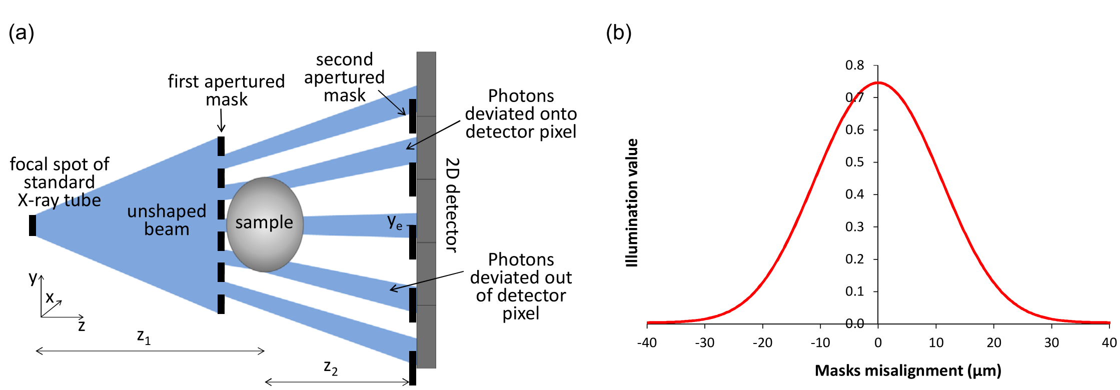

Fig. 1. (a) Schematic diagram of the edge illumination setup (not to scale). (b) Illumination curve, for a set of parameters partially matching those of one of the experimental setups available at UCL (see text for details).

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