Nuclear Instruments and Methods in Physics Research A 701 (2013) 201–207

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Use of oversampling to quantify phase effects in X-ray images of straight fibers

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ARTICLE INFO

Article history:
Received 4 July 2012
Received in revised form
27 October 2012
Accepted 27 October 2012
Available online 16 November 2012

Keywords:
X-rays
Phase effects
Phase contrast
Oversampling
Straight edge

ABSTRACT

We use oversampling techniques, similar to those applied to obtain detector MTF from slanted edges, to generate profiles of X-ray magnification images of straight fibers. We have applied this semi-automatic technique to the analysis of 0.5–0.8 mm diameter nylon fiber images acquired on a 48 μm pixel pitch flat panel detector with 30 and 40 kV Mo/Mo, Mo/Nb and W/Al X-rays from a 35 μm nominal focal spot size microfocus tube, under in-line magnification geometry. The oversampled profiles permit to visualize details in the image beyond what could be observed with traditional methods or visually. The edge enhancement observed in the profiles is an indication of phase effects in the interaction between radiation field and the object. Not only the interference maximum at the profile edge, but also indications of a first minimum in the fiber attenuation region, can be observed. Features of the profile agree with those predicted by Fresnel-based simulations which take into account the radiation spectral shape and the detector MTF. The inverse dependence of edge enhancement on X-ray effective energy is observed (2.8% for 30 kV Mo/Nb and 1.1% for 40 kV W/Al, at magnification 3 and source-to-detector distance 1.0 m). The systematics of the edge enhancement studied for magnifications up to 4 and source-to-detector distances up to 1 m agree with those previously reported by independent methods. This technique, that produces sampling distances many times smaller than the detector pitch, might improve the analysis of measurements designed to evaluate phase effects from fiber profiles.

1. Introduction

X-ray imaging of weakly absorbing objects and visualization of substances having similar elemental composition may be a difficult task if only based on attenuation [1]. Since X-ray interactions involve a change in the electromagnetic wave amplitude and phase, in addition to conventional beam attenuation contrast due to phase effects can be observed [2]. Wave phase shifts induce interference and generate bright and dark stripes around object edges, leading to a better border definition (edge-enhancement) and provide additional information that may improve the diagnostic value of radiological images [3–12]. This phase contrast is complementary to absorption contrast produced solely by attenuation [13]. If X-rays are produced by a tube with an extended focal spot, sufficient source-to-object distance is required to attain at least partial beam coherence required for interference. Also, the detector spatial resolution must be sufficient to resolve the interference fringes.

For the analysis and measurement of phase effects in X-ray images of objects having straight edges authors have used intensity profiles in regions-of-interest ROI [1,4,8,9,13–36]. The edge-enhancement of phase-contrast radiography can be quantified by different methods based on visibility and contrast [4,33,13]. Since the manifestation of edge-enhancement is generally weak, its quantification requires data with high statistical value as well as high spatial resolution at the object edge region. Oversampling techniques, such as those used to quantify the spatial resolution of an imaging system, digitization of compact discs, and signal processing, among others, offer an option to improve data resolution as well as statistics [37–39].

This work presents a formalism to obtain oversampled intensity profiles across objects that present two parallel edges. As an application, we have processed magnification X-ray images of cylindrical plastic fibers acquired under common laboratory conditions and used the oversampled profiles to quantify edge enhancement due to phase effects. A Matlab modular code has been created to run on a PC or laptop.

2. Materials and methods

2.1. X-ray source, object and detector

The system layout consisted of the X-ray source, the object (a custom-designed plastic fiber phantom) and the digital detector,

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http://dx.doi.org/10.1016/j.nima.2012.10.082

all arranged in-line [40]. Transmission images were obtained in Fresnel diffraction mode under magnification conditions [3]. The setup is shown in Fig. 1.

We used Oxford Instruments Apogee 5000 series microfocus X-ray tubes with 35 μm nominal focal spot size and molybdenum (Mo) or tungsten (W) anodes. We employed 25 μm thick Mo, 25 μm thick niobium (Nb) and 1 mm thick aluminium (Al) filters. Anode/filter combinations were Mo/Mo, Mo/Nb and W/Al at 30, 30 and 40 kV operating voltage, respectively. The Mo/Nb beam is quasi-monoenergetic due to the Nb absorption K-edge at 19.0 keV that strongly attenuates the K_β characteristic line of Mo (see Fig. 2b in [41]). The objects were 0.5, 0.6 and 0.8 mm nominal diameter straight nylon ($C_6NH_{11}O$) fibers placed in a custom-designed phantom (see Fig. 1). Fibers were tilted by 3–5° with respect to the rectangular phantom frame. Transmission images of the phantom in air were recorded by a Rad-icon, Shad-o-Snap flat panel detector (48 μm pitch size, 2000 × 2048 pixels, eight CMOS panels, 16-bits raw integer file) [42], under magnification conditions obtained varying the source-to-object (R_1), object-to-detector (R_2) and source-to-detector ($d_{sd} = R_1 + R_2$) distances. Values of d_{sd} were 0.30, 0.50 and 1.0 m. Geometrical magnification was defined as $Mag = d_{sd}/R_1$. The horizontal border of the detector was aligned with the horizontal direction in the laboratory and thus the fiber images were tilted by 3–5° with respect to the detector pixel matrix.

2.2. Image processing

Images acquired by the flat panel detector were preprocessed to free them from artifacts, and averaged to reduce the noise. Preprocessing included two common systematic adjustments for these detectors, namely anomalous pixel and X-ray field non-uniformity corrections [43]. All image processing was done using custom-made codes written in Matlab.

For each set of geometrical and radiation conditions, three types of images were acquired keeping the detector integration time (the time interval when data are recorded [44]) constant; they are referred to as Dark, Flat and Object images. Dark images have no object or radiation field and are generated by the detector electronic noise or dark current. Flat images are acquired with the X-rays but without the object and they are used to correct for systematic radiation field and pixel-to-pixel detector imperfections. Object images are acquired with X-rays and the object of interest [43].

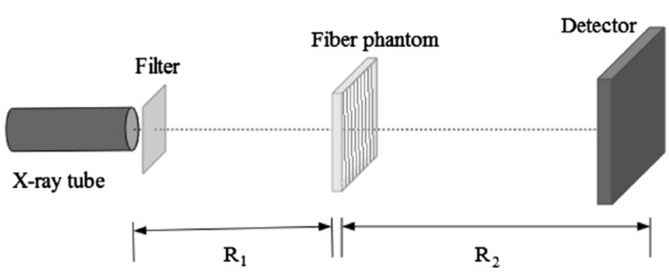

Fig. 1. Experimental setup. Microfocus X-ray tube, object (custom-designed plastic phantom) and flat panel detector.

Anomalous pixels were detected in the Flat image, their position was registered and the (defective) values were replaced by the average of the eight neighboring pixels. If the anomalous pixels were grouped together, their corrected value was chosen randomly from any non-anomalous pixel in the image. The radiation field non-uniformity correction was applied to averages of Flat and Object images in order to increase statistics and reduce noise. Pixel-by-pixel correction (at coordinates x and y, where these correspond to the detector matrix coordinates) followed Kwan [43], according to the following equation:

$$I_c(x,y) = \langle I_f - I_d \rangle \left(\frac{I_o(x,y) - I_d(x,y)}{I_f(x,y) - I_d(x,y)} \right) \quad (1)$$

where I_c is the resulting image corrected by non-uniformities, I_o is the average Object image, I_d is the average Dark, and I_f is the average Flat image. $\langle I_f - I_d \rangle$ is the average pixel value for the complete subtracted image of I_f minus I_d. The standard deviation of the pixel values in background ROIs (near the fiber) from the three images was statistically propagated according to the operations in Eq. (1), and the resulting value was referred to as the combined noise. The combined noise divided by the average of I_c pixel values in the background ROI constitutes a relative combined noise for image I_c. The optimum number of images for the averages was determined by minimizing the relative combined noise. Averages of Flat and Object images had statistical noise that decreased (relative to the signal) with an increased number of images, while the noise in a Dark image was constant (pixel by pixel) for a given integration time. Test acquisitions indicated the convenience of using one Dark, the average of 7–10 Flat, and the average of 7–10 Object images. More images would not improve substantially the relative combined noise while representing an increased tube load.

2.3. Oversampling method to obtain intensity profiles

The oversampling technique was based on the formalism commonly employed to obtain the presampling MTF from a slanted edge image [45]. The two-edge object (fiber) was placed at a small angle with respect to the detector matrix in order to measure the profile at a sampling interval much finer than the pixel-to-pixel distance. The mathematical algorithm had been previously used [46] to measure MTF from a border image in agreement with the IEC protocol [47]. We now describe the main steps in the method.

First task was to identify both edges and determine the fiber central axis. A ROI was selected and edges were detected using a 2D gradient convolution with a Sobel filter [−1 0 1] for one edge, and its inverse [1 0 −1] for the other. Each border was determined finding the maximum pixel value along a row for each Sobel filter direction. Distances (in integer pixel units) between the edges were stored in a matrix, and the reference straight line

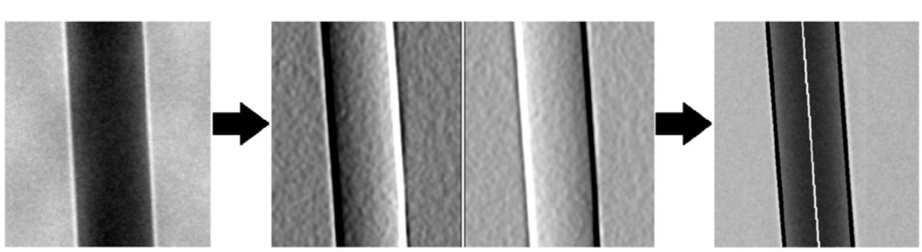

Fig. 2. Determination of a reference straight line between the edges of a cylindrical fiber image. From left to right, the preprocessed image, the application of the filters to both edges, the straight fits to the edges and the reference central line. Geometrical and radiological conditions were 30 kV Mo/Mo X-rays at $Mag = 4$, $d_{sd} = 1.0$ m.