ESRF	**Experiment title:** Potential advantages of phase contrast in X-ray diagnostic medical imaging	**Experiment number**: MD-2
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Report:

The aim of the experiments was to utilize the coherence properties of a third generation synchrotron source to study the properties of the in-line holographic technique in terms of sensitivity, geometrical requirements and energy. Images of nylon, aluminum and copper cylindrical wires from 50 µm to 240 µm in diameter were recorded onto a FRELON camera developed at ESRF using an optical resolution of 1.8 µm. An analytical model based on geometrical optics was developped which gives a good prediction of the contrast enhancement effects and allowed the estimation of the fringes' frequency, the phase contrast amplitude and the measure of the refraction index from the wires images. A comparison of the images with the Fresnel diffraction theory proved the adequacy of the analytical model with experimental data. A nylon fiber was investigated in air, water and oil to study the effect of the relative electronic density on the edge enhancement effects. In order to demonstrate the potential of phase-contrast effects on biological tissue samples, phase contrast images of a pork kidney have also been produced at various distances between the object to be imaged and the detector.

Results

The phase contrast image of a wire can be simulated by means of the Fresnel-Kirchhoff integral. The interaction between a cylindrical wire and a spherical monochromatic wave E_0 is given by the following equation :

$$\frac{E(x,z)}{E_0(x,z)} = 1 + \sqrt{\frac{z}{i\lambda R_0 R}} \int_{-r}^{r} \exp\left[i \frac{\pi z}{\lambda R_0 R} \left(\xi - \frac{R_0}{z} x \right)^2 \right] \left(F(\xi) - 1 \right) d\xi \quad (1)$$

where : λ is the wavelength of the radiation. R and R_0 are the object to detector and the source to object distances. $z = R+R_0$ is in the direction of the propagation of the x-rays. (x,y) and (ξ,η) are the lateral coordinates in the planes on the detector and on the wire of radius r

The transmission function of a homogeneous cylindrical object is : $F(\xi) = \exp\left[-\frac{4\pi}{\lambda} (\delta + i\beta) \sqrt{r^2 - \xi^2} \right]$ (2)

where δ and β are respectively the real and imaginary parts of the complex refractive index.

The theoretical intensity was normalized by the image background. It was convoluted with the frequency response of the camera and the projected source distribution modelised by a Gaussian function. A sharp edge of 200 µm thick of tungsten placed perpendicularly to the beam was utilized to determine the frequency response (MTF) of the camera for each energy utilized. Figure 1 shows the agreement between numerical simulations of the wire and the experimental results (black: numerical simulations from Fresnel theory / red: experimental results). A model developed on the basis of geometrical optics allowed to analyze the interference fringes comportment and the associated phase contrast. The analytical image intensity was found equal to :

$$I(x) = \begin{cases} \left[1 + \frac{\lambda R}{\pi}\frac{d^2\varphi}{dx^2}\right]^{-1} \exp(-\mu h) & \text{if } x < r \\ 1 + \left[1 + \frac{\lambda R}{\pi}\frac{d^2\varphi}{dx^2}\right]^{-1} \exp(-\mu h) + 2\left[1 + \frac{\lambda R}{\pi}\frac{d^2\varphi}{dx^2}\right]^{-1/2} \exp(-\mu h/2)\cos\left[\pi + \frac{\lambda R}{4\pi}\left|\frac{d\varphi}{dx}\right|^2\right] & \text{if } x > r \end{cases} \quad (3)$$

where φ is the x-ray phase difference in the object.

A comparison with the Fresnel diffraction theory proved the validity of the analytical model in the edge fringes region (fig. 2). According to this model, the fringes frequency at the cylinder edges was found to be:

$$D(x(\varphi)) = \frac{2\pi}{d\varphi/d\varphi} = \frac{\varphi}{2\pi}\sqrt{\left[1 + \left(a^2/2\right)^{1/3}\right]^2 - 1} \qquad \text{where } a = \frac{2\pi R}{r} \quad (4)$$

The measured fringe spacing at the wire edges gave an estimation of the refractive index for the nylon wire (fig. 3). The results for 5 defocalising distances between 0.2 to 1.8 m gave the mean values $\delta = 1.05 \cdot 10^{-6}$ and $\delta = 1.07 \cdot 10^{-6}$ respectively for the nylon fibers with the diameters of 74 and 240 µm. The theoretical value for nylon at 15 keV is $\delta = 1.15 \cdot 10^{-6}$.

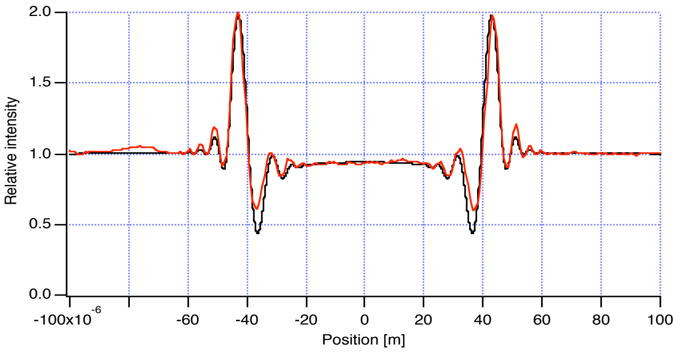

Figure 1: Nylon wire (ø 74 µm) at 15 keV and 0.9 m

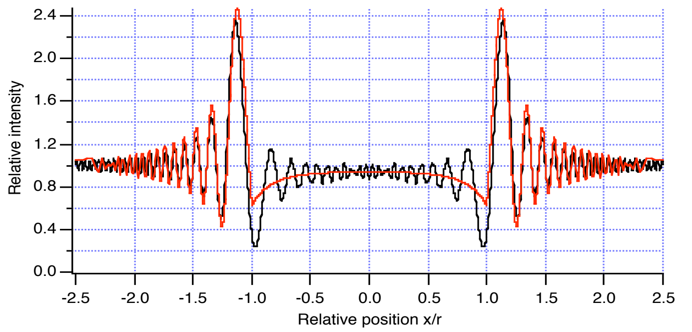

Figure 2: Comparison between the analytical model (red) and Fresnel diffraction theory (black)

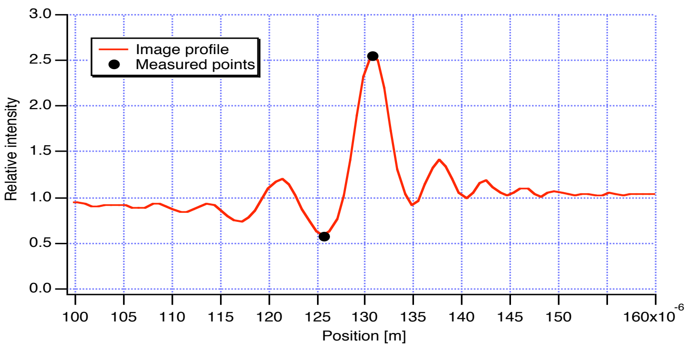

Fig. 3: Measured points on the experimental profile

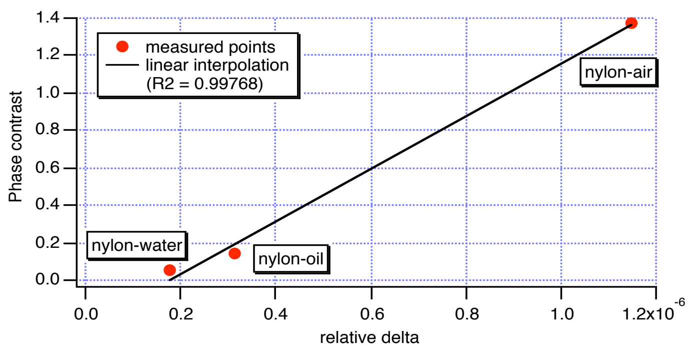

Fig. 4: Phase contrast vs refractive index

The theoretical phase contrast levels at the wire edges, given by the oscillating term of relation (3), were convoluted with the camera frequency response for the phase fringe frequency calculated with relation (4). For the materials, energies and defocalising distances used in these experiments, edge enhancement levels matched with experimental results with a relative accuracy of ± 15 %. The expected linear dependance of phase contrast level with the refractive index was investigated with images of a nylon wire in air, water and oil. Experimental results show a good linear correlation coefficient (fig. 4).

Phase contrast images of a pork kidney were recorded at 20 keV. To avoid air/tissue interfaces, the sample was immersed in a physiological liquid before acquisitions. The effects of phase modulations reveal an important improvement of small structures visibility due to edge enhancement.

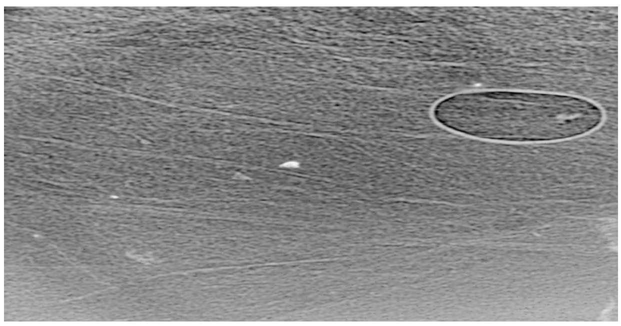

Fig. 5: Phase contrast image of a pork kidney (3.7 x 3.7 mm^2)