FACTORS AFFECTING IN-LINE PHASE CONTRAST IMAGING WITH A LABORATORY MICROFOCUS X-RAY SOURCE

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ABSTRACT

An in-line method of phase contrast imaging is investigated using a polychromatic laboratory-based microfocus X-ray source. The effect of source size is considered, and by introducing water into the imaging path the influence of water on the phase contrast is determined. The results confirm that good phase contrast images can be achieved using a polychromatic laboratory-based X-ray source, and demonstrate the importance of transverse coherence length. Phase contrast images are achieved with samples containing water, however beam hardening has a detrimental effect on phase contrast.

INTRODUCTION

Conventional X-ray imaging relies on absorption contrast, which is excellent for many applications but has shortcomings when attempting to image materials of low or similar density [1]. Here, phase contrast imaging comes into its own because it relies not on the complex term of the material refractive index (the absorption component) but the real term representing phase [2]. The phase of an X-ray beam is altered on passing through a material according to the following:

\[
\phi = -\int_0^z \left( \frac{2\pi}{\lambda} \delta(z) \right) dz \quad (1)
\]

where \( z \) is the sample thickness and \( \delta \) is the complex component of the refractive index, by

\[
n = 1 - \alpha + i\beta \quad (2)
\]

Much of the X-ray phase contrast imaging work published to date has been performed using monochromatic synchrotron radiation. Due to the high intensities available across a wide range of wavelengths, monochromated synchrotron radiation is commonly used for phase contrast imaging [5]. Realistically, however, synchrotron radiation cannot be used for the majority of potential commercial applications of phase contrast imaging. Thus further development of phase contrast imaging techniques for practical application ultimately depends on the suitability of laboratory X-ray sources. In practice, low dispersion monochromatic X-ray radiation such as that obtained at synchrotron sources is not achievable by laboratory-based microfocus X-ray sources. Wilkins et al have already determined that a laboratory X-ray source can provide good phase contrast images with its natural polychromatic spectrum [6]. Another example of polychromatic X-ray phase contrast imaging uses a scorpion sting, shown in Figure 1. While an absorption image of the scorpion sting shows up minimal detail, the phase contrast image retains far more information. This includes a crisp outline of the sting, clear edge detail within the poison sac and tail joint, and the narrow shaft through which poison is injected into the scorpion’s prey. This
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demonstrates the advantage of phase contrast images over absorption images using a laboratory based microfocus X-ray source.

**Figure 1:** Images of scorpion sting attained via (a) absorption contrast, (b) phase contrast

Phase contrast imaging requires a spatially coherent source, i.e. one whose transverse coherence length is long. The transverse coherence length \( d \) is determined by the following relation:

\[
    d = \frac{\lambda l}{\sigma} \quad (3)
\]

where \( \lambda \) is the wavelength, \( l \) the source-sample distance and \( \sigma \) the source size. Thus the transverse coherence length increases with decreasing X-ray energy, decreasing source size and increasing source-sample distance [7].

When investigating the effect of water on the phase contrast, it is necessary to consider the detrimental effect of X-ray absorption on the intensity of the beam via the relation:

\[
    I = I_o \exp(-\mu z) \quad (4)
\]

where \( I_o \) and \( I \) are the intensities before and after absorption respectively, \( \mu \) the absorption coefficient and \( z \) the material thickness. Consider the rhodium target: with water path-lengths of 3mm, 5mm, 7mm, 10mm and 12.5mm the respective changes in the spectrum are modelled (Figure 2). It is seen that the water reduces the intensity of the Bremsstrahlung radiation significantly: with a water path length of 10mm or more the \( K_\alpha \) line is reduced to less than half the original intensity. While uniform absorption across the spectrum will not affect the quantifiable phase contrast, the drastic reductions in intensity will make it more difficult to detect.

**EXPERIMENTAL DETAILS AND ANALYSIS TECHNIQUE**

We have studied experimentally the variation of phase contrast in a simple in-line set-up, shown in Figure 3(a), with the transverse coherence of equation 3. A model test object, approximating to a Heaviside Function, was created by layering two similar sheets of acetate to form an abrupt boundary between two areas of different thickness, \( t_1 \) & \( t_2 \), as shown in Figure 3(b). A polychromatic X-ray beam was obtained directly from a Bede Microsource® microfocus X-ray tube [9,10], using rhodium and copper targets. Apart from the Be window on the X-ray tube, no
additional optical elements were included in the beam path. A real-time digital method of image acquisition was employed, allowing images to be acquired directly to a computer. This was done using a Photonic Science X-ray Eye i2i CCD camera which provided a useful field of view 10 mm in diameter, with pixel size 11 μm. Images were averaged over 256 frames, requiring 40 second exposures. Images were acquired with a gamma setting of unity, hue & saturation settings of 50, and brightness & contrast settings of 255. Using Media Cybernetics Image-Pro Plus software, images were adjusted to offset the dark background, the sample images normalised against a background image, and an intensity map of the sample boundary viewed via a thick line profile.

The phase contrast image of this boundary (Figure 4(a)) displays the intensity profile shown in figure 4(b). The intensity remains fairly constant where the X-rays have passed through sections of material of uniform thickness. The peak and trough represent refraction of X-rays from one side of the boundary to the other, thus phase contrast is present in the image. By making use of a Heaviside Function sample, phase contrast may be quantified by substituting the maximum and minimum intensities in Figure 4(b) into the following visibility formula:

\[
Contrast = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad (4)
\]

For samples providing significant absorption, the maximum and minimum intensities are determined by averaging the two flat sections as shown in Figure 4(c). Again, by applying Equation (4) the absorption contrast may be quantified and the two contrast values are compared.
RESULTS

The above set-up was used to investigate the effects of individual factors on phase contrast. As discussed in the theory section, the source size is expected to influence the phase contrast due to its effect on transverse coherence length. In order to verify this relationship, the source, sample and detector remained in fixed positions while the source size was gradually increased via beam defocusing. The copper source size ranged from 14μm width x 17μm height to 62.5μm width x 125μm height. The sample was imaged with the boundary positioned vertically, and the experiment was repeated with the boundary horizontal. The phase contrast was calculated for all vertical and horizontal images and plotted separately against beam width and height (Figure 5).

Figure 4: (a) Typical phase contrast image of a sample approximating to a Heaviside Function. (b) Intensity profile across image (c) Intensity profile across image with significant absorption contrast

Figure 5: Change in phase contrast with copper target beam size: (a) plotted against beam width, (b) plotted against beam height
The correlations of the copper results (Figure 5) were calculated: the phase contrast of the vertical boundary shows better correlation with beam width than beam height, while the phase contrast of the horizontal boundary shows better correlation with beam height than with beam width. Results using the rhodium target show the same relationships. From these results it is deduced that for a given boundary of a sample, the phase contrast recorded is dominated by the transverse coherence length in the direction perpendicular to that in which the boundary lies.

With phase contrast imaging moving toward in vivo medical diagnostic applications [12,13], the effect on polychromatic laboratory phase contrast imaging with the introduction of water becomes an important issue. In order to investigate this, a water container was required which had no significant effect on phase contrast when introduced to the system. The design comprised an aluminium frame supporting a latex sheath which was stretched taut. Five containers were made, holding water path lengths of 3mm, 5mm, 7mm, 10mm and 12.5mm. By comparing the phase contrast of images of the Heaviside sample taken with and without each (empty) container in place, it was verified that the containers had no appreciable effect on the phase contrast. By filling one container with water and comparing the phase contrast of images of the Heaviside sample taken with the water in various positions along the optic axis, it was also verified that the position of the water in the set-up was not critical.

The sample was first imaged without water in the system, and while the sample remained fixed, each container of water in turn was placed between the source and sample planes and further images were taken. The phase and absorption contrast of these images are shown in figure 6(a).

![Graph](image)

**Figure 6:** (a) Change in phase and absorption contrast with water path length, determined experimentally. (b) Theoretical change in absorption contrast due to beam hardening.
The results of this experiment show the dramatic reduction in phase contrast caused by water in the system. Not only is the phase contrast reduced but the absorption contrast also decreases as water is added to the system, and it is this aspect of the results which hints at the reason for the significant loss of phase contrast. When introduced to a polychromatic X-ray beam, the low-energy absorption of X-rays by water causes beam hardening, i.e. a shift in the dominant X-ray energy range to higher energy. The absorption contrast of a given sample boundary decreases at higher energy. This is demonstrated by taking a weighted mean of the X-ray spectrum with each path-length of water to find the dominant X-ray energy, then applying it to the relevant sample boundary. The absorption contrast expected using this approach is shown in Figure 6(b) and it is seen to follow the same trend as the experimental absorption contrast.

This result is positive in that it is seen that water does not destroy the phase contrast. Clearly, however, beam hardening will be a problem for any polychromatic laboratory source used for in vivo phase contrast imaging. In order to combat this issue, it is necessary to use either a very high intensity polychromatic source, or to initially monochromate the source while retaining a high intensity beam.

CONCLUSIONS

From the experimental work detailed here, it is seen that good phase contrast imaging can be achieved using a polychromatic microfocus X-ray source at both low and high energies. It is demonstrated that the source size must be as small as possible, in line with the spatial coherence requirement, and that for any given boundary in the sample, its phase contrast is dominated by the perpendicular spatial coherence. It is seen that the presence of water in a sample has a significant detrimental effect on the phase contrast due to beam hardening resulting from absorption by water. However, the phase contrast is not destroyed, which is a positive result towards development of phase contrast imaging techniques for medical diagnostic applications.

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REFERENCES