Curved optics for x-ray phase contrast imaging by synchrotron radiation

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Abstract
Conventional radiographic techniques have strong limitations when low-absorption contrast samples are imaged. Phase contrast radiography has been shown to produce high-quality images of soft tissues. In this technique the recorded intensity patterns are related to gradients in the refractive index of the sample. A critical point of this new technique is the need to employ crystal analysers, which results in an appreciable reduction in the beam intensity and consequently in rather long exposure times. In this paper the use of focused beams is suggested to overcome this aspect. Biological samples with small structures and low absorption variations were imaged using both flat and curved monochromator crystals, demonstrating that the use of curved optics leads to a decrease in the exposure time with only a limited degradation of the spatial resolution. This opens up the possibility of using the phase contrast technique with laboratory sources.

1. Introduction
In conventional radiography x-rays emerging from an object give information about the absorption occurring along different paths within the sample (Wilkins \textit{et al} 1996). This classical radiography technique has great limitations when imaging low-density materials. Recently, phase contrast imaging has been used to produce high-quality images of soft tissue (Davis \textit{et al} 1995, Ingel and Believskaya 1996, Buijbéve \textit{et al} 1996, Snigirev \textit{et al} 1995, Cloetens \textit{et al} 1996, 1997, Nugent \textit{et al} 1996, Artelli \textit{et al} 1998) and in structural non-destructive analysis of composite materials (Buffière \textit{et al} 1999). This technique records variations in intensity due to gradients of the refractive index inside the sample. By using synchrotron radiation a considerable improvement of contrast over standard imaging has been shown by Chapman \textit{et al} (1997) on a mammographic phantom and more recently by Pisano \textit{et al} (2000) on breast cancer.
photographic film

diffactometer

second mirror

channel-cut Si(111) crystal

second Si(311) crystal

first mirror

first Si(311) crystal

beam line monochromator

X-ray beam

source

46.6

31.6

28.1

24.8

0 (m)

Figure 1. Side view of the experimental set-up. The beam coming from the bending magnet source is monochromatized by two Si(311) crystals. The two mirrors and the monochromator constitute the standard beam line optics. The monochromatic beam hits a channel-cut Si(111) crystal. The first reflection produces an almost plane wavefront which then passes through the sample. The second crystal surface diffracts waves undeflected by the sample and directs them into a high-resolution film where the image is recorded. The inset shows the beam line monochromator scheme.

specimens. Beliaevskaya et al (1998) showed, on a synthetic mammographic structure used as a dummy test object, that phase contrast images can reveal features which are invisible using the conventional radiographic technique due to their negligible absorption contrast (less than 1%). Interest in the phase contrast technique is not restricted to the biomedical field but also extends to several industrial applications, including food technology and materials science (Gilboy 1995).

Several methods have been implemented to detect the phase variation of an x-ray beam traversing the sample (Busheev et al 1998, Fitzgerald 2000), like the use of an interferometer, the spatial coherence of the x-ray beam and the use of an analyser crystal (diffraction enhanced mode).

When laboratory sources are employed, a critical point of the phase contrast technique is the long exposure time which ranges from a few minutes to 2 h (Pisano et al 2000, Beliaevskaya et al 1998, Wilkins et al 1996). This originates from the need to use diffracting crystals. Recently it has been demonstrated that the use of synchrotron radiation overcomes this drawback. However, widespread use of phase contrast requires laboratory sources to be used and it is therefore worthwhile to find ways of increasing the flux on the sample.

In this paper we describe phase contrast imaging experiments in diffraction enhanced mode where the use of focusing x-ray optics was tested in order to increase the photon flux available on the sample. Images obtained with this new experimental set-up were compared with those taken with non-focusing optics and a standard mammographic unit.

2. Experiment

The experiments were performed on the Italian CRG beam line ILDIA at the European Synchrotron Radiation Facility (ESRF), France. Figure 1 shows the experimental set-up.
The white beam coming from the storage ring, vertically collimated by a first mirror, is filtered by the beam line monochromator. This is composed of two independent Si(111) crystals with a vertical scattering plane. The second crystal can be flat or can be curved (sagitally focusing geometry) by two mechanical pushers (figure 1 and Pascarelli et al (1996)). The radius of curvature is 11 m at 8 keV and 3.5 m at 24 keV when focusing at 46.6 m from the source. When the curved crystal is used, radiation in a large horizontal angle of 3.6 mrad is collected and focused in the horizontal plane. The x-ray beam coming out of the monochromator is focused on the vertical plane by a second mirror, into a channel-cut Si(111) crystal with vertical scattering plane mounted on a two-axis diffractometer. The first element of the channel-cut crystal is asymmetrical cut with an angle $\alpha = 12^\circ$ providing an expansion factor of 12.5% at 8 keV (Brauer et al 1995). The second element (analyzer) is symmetrical cut. The sample is placed between the two elements of the channel-cut. The image is recorded by a photographic film located at the exit of the analyzer crystal. To record absorption contrast radiographs it is sufficient to place the film detector after the sample excluding the analyzer. The distances from the source of the different optic elements are shown in figure 1.

To illustrate how it is possible to detect the phase contrast by using the diffraction enhanced mode we consider a simplified case of an x-ray beam passing through a carbon fibre ($\rho = 2.25 \text{ g cm}^{-3}$ diameter = 200 $\mu$m) in vacuum (figure 2). Using Snell’s law at the two vacuum-fibre interfaces it is easily shown that the fibre refracts the x-ray beam like a divergent lens. The crystal analyzer (the second element of the channel-cut crystal in our experimental set-up) placed on the transmitted beam reflects only those rays which are deviated by less than its Darwin width, allowing them to reach the detector. Considering a thick perfect Si(111) crystal analyzer we have calculated the intensity variations on the detector when imaging the carbon fibre by 8 keV radiation. The calculation of the diffraction enhanced contrast has been done considering the undeflected beam in Bragg reflection condition and using the rocking curve simulated by the XOP code (Sánchez del Río and Dejus 1997). Figure 2 shows this simulation compared with the case of pure absorption imaging: the ratio between the intensity
at the centre of the fibre and that at the edge is more than a factor of 10 for phase contrast imaging and it is only 1.2 in absorption contrast.

In the present work we report phase contrast images of samples characterized by low absorption contrast (less than 10%) and/or microstructures (10–100 μm), recorded using a flat or a curved second crystal in the beam line monochromator. Because the phase contrast images were obtained using a channel-cut crystal it was not possible to change the working point of the analyser on the Darwin curve. All the images were collected with the undeflected beam at the maximum of the rocking curve. Conventional absorption contrast images were taken at the Istituto Superiore di Sanità (Italy) with a compact mammographic unit (Mammo HF, Metallurgica, Italy) equipped with a Varian (USA) x-ray source model M.147.T, incorporating a molybdenum rotating anode and a beryllium window. The tube was operated at 28 kV and the emerging radiation was filtered by a 30 μm Mo foil.

3. Results and discussion

Figure 3 shows the image of a butterfly obtained in absorption contrast mode whereas figure 4(a) shows the same sample imaged by phase contrast. Both images were collected using flat crystals in the beam line monochromator. Figure 4(b) shows a similar sample imaged by phase contrast using the sagittally focusing monochromator. These images were all obtained by 8 keV radiation. From the comparison of figures 3 and 4(a) it is confirmed that phase contrast is a powerful way to image samples with low absorption contrast and microstructures. In fact, the details in the butterfly’s legs are clearly resolved in figure 4(a) and completely lost in figure 3. Similar comparisons (phase versus absorption contrast) on insect samples can be found in literature with comparable results (Fitzgerald 2000). Figure 4(b) was obtained using a curved crystal: this radiograph exhibits several bands of beam intensity due to stiffening ribs cut on the second monochromator crystal which prevent the anticlastic curvature (Sparks et al 1982). Fortunately these bands do not prevent the interpretation of the image because the
Figure 4. Phase contrast images of a butterfly: (a) using a flat crystal monochromator (same sample as figure 3); (b) using a curved crystal monochromator (different sample).

variations in beam intensity are within the dynamic range of the photographic film. Different designs for sagittally focusing crystals yielding a homogeneous beam have been developed (Mullender et al. 1997) that can overcome this problem. Even though figures 4(a) and (b) show different specimens, these are characterized by similar absorption contrast and microstructure dimensions. Comparison of figure 4(b) with figure 3 proves that phase contrast with focusing x-ray optics can produce high-quality images with respect to pure absorption contrast.

The curved optics in the monochromator collect quite a large horizontal divergence of the beam (3.6 mrad) and focus it on the sample. Using a flat crystal in the monochromator only a small fraction of the radiation fan reaches the sample (about 0.2 mrad for a 1 cm spot). Thus, the use of focusing optics yields a large reduction in the exposure time, and indeed the exposure times for figures 4(a) and 4(b) were 1000 s and 65 s respectively. From figure 4(b), however, we observe that the resolution of the image obtained with a curved crystal in the monochromator appears a little worse than in that obtained with a flat crystal. A quantitative comparison of these two images is not possible because these two images were taken in two different experimental runs and different samples were used in the two cases. The comparison, thus, remains at a qualitative level.

Phase contrast images recorded using a flat and a curved crystal on the same sample (snail shell) are reported in figure 5. Due to noticeable absorption of this sample these images were collected at 24 keV. In this case the (333) reflection of the channel-cut was used. The fine texture of the shell is clearly visible even if a decrease in spatial resolution is observed when using a curved monochromator. However, we emphasize that considerable detail is still visible in the images recorded with curved crystals, which shows that the resolution remains quite high.

To have a more quantitative comparison between the resolution of the two recording schemes, images of a resolution pattern were recorded in phase contrast using the flat monochromator (figure 6(a)) and using the curved monochromator (figure 6(b)), again at
24 keV. In this figure the information content of the images appears comparable. In fact, in the flat crystal image 19 line pairs per millimetre (lp mm\(^{-1}\)) are clearly resolved; in the curved crystal image the line pairs are less sharp but are still distinguishable.

In order to evaluate which level of resolution degradation is acceptable for practical applications we have compared the phase contrast image of figure 6(b), obtained with a focusing optics, with the image of the same sample obtained by using a laboratory mammograph (figure 7). Clearly the resolution in this last case is worse than in figure 6, and in fact the 19 lp mm\(^{-1}\) are not resolved. This comparison is possible because the energy range of the radiation emitted from the laboratory source in our experimental set-up is peaked around the Mo K\(_{\alpha,\beta}\) (17.479 eV, 17.374 eV respectively) fluorescence lines, as can be calculated from Boone et al (1997). The sample absorption at this energy is similar to that at 24 keV used in the synchrotron experiment.
The exposure times of the images shown in this paper vary from 1 to several minutes depending on several factors. These rather long exposure times are due to a non-optimized experimental set-up. With a suitable set-up of the beam line the exposure time can be reduced to the order of few seconds. In fact, images were recorded with a low current (10 mA instead of 200 mA) in the ESRF storage ring. Moreover, the vertical focusing of the second mirror introduced an additional flux reduction due to the low vertical acceptance of the channel-cut crystal (10 μrad); these two factors led to an overall reduction factor of about 270 compared with what should be possible with an optimized set-up.

It is worth noting that the use of a focusing crystal led to an increase in the photon flux on the sample of a factor about 12, due to the collection of a larger horizontal angle of radiation. The corresponding reduction in the exposure time is obtained at the expense of a slight decrease of the image resolution, which in fact remains quite high and appreciably higher than the resolution achievable by a conventional mammography unit. This suggests that focusing optics, like curved crystals, mirrors or crystals with a gradient in lattice spacing (Freund et al. 1972, Rustichelli 1972, Liss and Magerl 1994), can be used to reduce the exposure times in phase contrast technique. Although this reduction in exposure time alone may be not sufficient for laboratory source applications of phase contrast, the use of focusing x-ray optics combined with improvement in sources and detectors, as discussed by Pisano et al. (2000) may lead to widespread laboratory use of this technique.

4. Conclusion

This experiment demonstrates the feasibility of phase contrast imaging by using curved optics. This permits a gain in the available flux at the expense of a slight worsening in the spatial resolution that still remains better than in images taken in standard laboratory mammographic units. The use of focusing x-ray optics is shown to be an interesting implementation for laboratory applications of phase contrast techniques since it allows a considerable reduction in exposure times.
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