Propagation-based x-ray phase-contrast imaging with broad focus conventional x-ray sources

M. G. Hönnicke¹, E. M. Kakuno², J. Manica³ and C. Cusatis¹

February 2, 2008

¹Departamento de Física, Universidade Federal do Paraná, Caixa Postal 19091, 81531-990, Curitiba-PR, Brazil
²Universidade Federal do Pampa, 96412-420 Bagé-RS, Brazil
³Departamento de Engenharia Mecânica, Universidade Federal do Paraná, Caixa Postal 19011, 81531-980 Curitiba-PR, Brazil

Abstract
A propagation-based x-ray phase-contrast imaging (PBI) setup using a conventional x-ray source (LFF Cu target) is presented. A virtual x-ray source of 40 x 50 µm² was created by using, horizontally, a 6° take-off angle (with the x-ray tube working in the line focus geometry) and, vertically, a 50 µm slit. The sample was set 12 m from the source. Propagation-based x-ray phase-contrast (PB) image and conventional radiography (CR) of a polypropylene tube were acquired. Edge enhanced effects and a crack, not detected in CR, were clearly seen in the PB image. Contrast, visibility of the object edges and signal to noise ratio of the acquired images were exploited. The results show that PB images can be acquired by using normal focus (macro focus) conventional x-ray sources. This apparatus can be used as a standard phase-contrast imaging setup to analyze different kind of samples with large field of view (75 x 75 mm²), discarding the use of translators for sample and detector.

Keywords: x-ray imaging, phase-contrast imaging, x-ray optics
PACS: 07.85.Qe, 87.59.Bh, 87.59.-e

1 Introduction
Conventional x-ray radiography is based on the detection of differences in x-ray attenuation by different details in an object (sample). Thus, details with similar attenuation coefficient gives low contrast images. Enhanced contrast x-ray imaging can be achieved by using attenuation contrast agents. Alternatively, it can be achieved by exploiting the real part of the refraction index, which is responsible for the phase shifts, in addition to the imaginary part, which is responsible for the absorption. Such exploitation is done by the well-established x-ray phase-contrast imaging techniques.

Several ways are reported in the literature to acquire phase-contrast images:
a) propagation-based x-ray phase-contrast imaging (PBI), that uses a monochromatic \cite{1,2} or polychromatic \cite{3} partially coherent x-ray source; b) x-ray phase-contrast imaging based on x-ray interferometry \cite{4,5} and; c) analyzer-based x-ray phase-contrast imaging (ABI) \cite{6,7,8,9,10}, that uses diffraction by perfect single crystals.

PBI is well known by its simplicity, once that, it does not require any sophisticated optics. The unique requirement is a high quality small source with high brilliance provided by micro focus x-ray sources \cite{5,11,12} or, by the high brilliance and low emittance third generation synchrotron radiation sources \cite{1,2}. This technique can be developed in the edge detection geometry or in the holographic geometry \cite{2}, depending on the quality of the source and the distance from the sample to the detector. Such technique has been successfully applied severally in biology \cite{13}, medicine \cite{14,15} material sciences \cite{2,16} and archeology \cite{17}.

In the present work, a PBI setup using normal focus conventional x-ray source is proposed and realized. The idea is to get a reasonably transverse coherence length by creating a virtual micro source and by placing the sample far away from the source. To characterize such a setup attenuation contrast images (conventional radiography, CR) and propagation-based (PB) x-ray phase-contrast images of a polypropylene tube (low density material) were acquired. The images were also analyzed in terms of exposure time, contrast and signal to noise ratio.

A description of the experiment followed by quantitative results and conclusions will be presented.

2 Experiment

The experimental setup (fig. 1) was mounted using a normal focus conventional x-ray source (Cu LFF target) set in the line focus geometry with a take off angle of 6°. Such take off angle provides a virtual horizontal x-ray source size of 40 \(\mu\text{m}\). To have an x-ray source with similar vertical dimension, a 50 \(\mu\text{m}\) slit was set horizontally, just after the beryllium window of the x-ray tube resulting in a virtual source size of 40 x 50 \(\mu\text{m}^2\). A vacuum path, 12 \text{m} long, was used along the x-rays path until the sample. Such vacuum path was made employing PVC tubes with 25 \(\mu\text{m}\) thick kapton windows and a pressure of 1 mbar. The field of view at the sample position was 75 x 75 \(\text{mm}^2\). The measured divergence of the beam on the sample was \(6 \times 10^{-3} \text{ rad}\) in the horizontal and vertical scattering planes.

The x-ray generator was set at 25 \text{kV} in order to have lower energy photons therefore, large transverse coherence length, once that, the transverse coherence length \((l_t)\) is:

\[
    l_t = \frac{\lambda D}{2 \sigma_x}
\]

where \(\lambda\) is the wavelength of the incoming x-ray beam, \(D\) is the distance from the source to the sample and \(\sigma_x\) is the source size.

The images were acquired using low-resolution commercial x-ray films (Kodak INSIGHT dental film). The PB images were obtained with the x-ray film set 2 \text{m} from the sample. Another vacuum path was also employed between the
Figure 1: Propagation-based x-ray phase-contrast imaging (PBI) setup. A normal focus conventional x-ray source (Cu LFF target) was used in the line focus geometry. The take-off angle of 6° and a horizontal slit of 50 µm create a "virtual" x-ray micro source of 40 x 50 µm². The sample was set 12 m from the source. Conventional radiographies (CRs) were acquired with the film in contact with the sample. Propagation-based (PB) x-ray phase-contrast images (edge detection images) were acquired with the sample and film 2 m apart.

To characterize the present PBI setup, a polypropylene tube, with an external diameter of 6 mm and internal diameter of 3.8 mm (tube wall 1.1 mm thick) was used as sample. This tube was fixed on an one-layer paper (about 50 µm thick). The CR and PB images of the polypropylene tube are shown in figs. 2a and 3a, respectively. The cross-sections are shown in figs. 2b and 3b, respectively. The cross-sections simulations were done considering an incoming x-rays monochromatic (14.4 keV) plane wave beam being attenuated by the sample. A theoretical pixel size of 25 x 25 µm² was considered. This is far of the real experiment, however it worked fairly well for the CR, as can be seen in fig. 2b. This means that, even using a white beam, the energies around 14 keV are the major contributors for the contrast in CR. This is reasonable, once that the simulation for a conventional x-ray Cu target at 25 kV shows a maximum of the Bremsstrahlung spectra at 15.5 keV [18].

A disagreement between the measured and simulated cross section profile can be seen for the PB image because the phase effects and the divergence of the beam were not considered in the simulations. However, it is worth noticing that phase effects could be seen in the measured cross-section profiles (indicated by arrows, in fig. 3b). Moreover, the edges and details of the tube are better defined in the PB image (fig. 3a) than in the CR (fig. 2a): for instance, a crack, not visible in the CR, is clearly seen in the PB image. Also, a background structure can be noted in the fig. 3a. Such structures can be attributed to the phase-contrast effects due to the one layer paper behind the tube. The edge enhanced effect can be attributed to the rapid variations in the refractive index (boundary effect) that produces strong phase-contrast, even using a polychromatic beam.

3 Results

To characterize the present PBI setup, a polypropylene tube, with an external diameter of 6 mm and internal diameter of 3.8 mm (tube wall 1.1 mm thick) was used as sample. This tube was fixed on an one-layer paper (about 50 µm thick). The CR and PB images of the polypropylene tube are shown in figs. 2a and 3a, respectively. The cross-sections are shown in figs. 2b and 3b, respectively. The cross-sections simulations were done considering an incoming x-rays monochromatic (14.4 keV) plane wave beam being attenuated by the sample. A theoretical pixel size of 25 x 25 µm² was considered. This is far of the real experiment, however it worked fairly well for the CR, as can be seen in fig. 2b. This means that, even using a white beam, the energies around 14 keV are the major contributors for the contrast in CR. This is reasonable, once that the simulation for a conventional x-ray Cu target at 25 kV shows a maximum of the Bremsstrahlung spectra at 15.5 keV [18].

A disagreement between the measured and simulated cross section profile can be seen for the PB image because the phase effects and the divergence of the beam were not considered in the simulations. However, it is worth noticing that phase effects could be seen in the measured cross-section profiles (indicated by arrows, in fig. 3b). Moreover, the edges and details of the tube are better defined in the PB image (fig. 3a) than in the CR (fig. 2a): for instance, a crack, not visible in the CR, is clearly seen in the PB image. Also, a background structure can be noted in the fig. 3a. Such structures can be attributed to the phase-contrast effects due to the one layer paper behind the tube. The edge enhanced effect can be attributed to the rapid variations in the refractive index (boundary effect) that produces strong phase-contrast, even using a polychromatic beam.

3 Results

To characterize the present PBI setup, a polypropylene tube, with an external diameter of 6 mm and internal diameter of 3.8 mm (tube wall 1.1 mm thick) was used as sample. This tube was fixed on an one-layer paper (about 50 µm thick). The CR and PB images of the polypropylene tube are shown in figs. 2a and 3a, respectively. The cross-sections are shown in figs. 2b and 3b, respectively. The cross-sections simulations were done considering an incoming x-rays monochromatic (14.4 keV) plane wave beam being attenuated by the sample. A theoretical pixel size of 25 x 25 µm² was considered. This is far of the real experiment, however it worked fairly well for the CR, as can be seen in fig. 2b. This means that, even using a white beam, the energies around 14 keV are the major contributors for the contrast in CR. This is reasonable, once that the simulation for a conventional x-ray Cu target at 25 kV shows a maximum of the Bremsstrahlung spectra at 15.5 keV [18].

A disagreement between the measured and simulated cross section profile can be seen for the PB image because the phase effects and the divergence of the beam were not considered in the simulations. However, it is worth noticing that phase effects could be seen in the measured cross-section profiles (indicated by arrows, in fig. 3b). Moreover, the edges and details of the tube are better defined in the PB image (fig. 3a) than in the CR (fig. 2a): for instance, a crack, not visible in the CR, is clearly seen in the PB image. Also, a background structure can be noted in the fig. 3a. Such structures can be attributed to the phase-contrast effects due to the one layer paper behind the tube. The edge enhanced effect can be attributed to the rapid variations in the refractive index (boundary effect) that produces strong phase-contrast, even using a polychromatic beam,
Figure 2: (a) Conventional radiography (CR) of a polypropylene tube. (b) Measured (o) and simulated (−) cross-section profiles of the image.
as previously described by Wilkins [3].

For quantitative reasons the images, shown in figs. 2a and 3a, were compared with each other by measuring the area contrast \( C \), the signal to noise ratio in the area case \( SNR_{area} \), the visibility of the object edges \( V \) and the signal-to-noise ratio for the edge case \( SNR_{edge} \). These quantities are defined according to Pagot [19] and references therein in the following way:

\[
C = \frac{<I_{obj}> - <I_{backg}>}{<I_{backg}>} \tag{2}
\]

\[
SNR_{area} = \frac{<I_{obj}> - <I_{backg}>}{\sqrt{\sigma_{obj}^2 + \sigma_{backg}^2}} \tag{3}
\]

\[
V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{4}
\]

\[
SNR_{edge} = \frac{I_{max} - I_{min}}{\sqrt{2}\sigma_{backg}} \tag{5}
\]

where \(<I_{obj}>\) and \(<I_{backg}>\) are the mean intensity values of a given area in the object and in the background, respectively; \(\sigma_{obj}\) and \(\sigma_{backg}\) are the standard deviations of the distributions of \(I_{obj}\) and \(I_{backg}\); and finally, \(I_{max}\) and \(I_{min}\) are the maximum and minimum of the mean intensity profile across the edge.

In general, the different PB and CR images were acquired with different beam intensities, but the exposure time for the object and for the background were the same.

The results are shown in tab. 1. The contrast \( C \) and the visibility of the object edges \( V \) for PB images are really higher than for CR. However, the good values of \( V \) show that the ABI is highly sensitive to the sample borders (jump of the phase in these regions). The low values for the signal to noise ratio are mainly due to the low intensity found in our measurements. This means, in equations (3) and (5), high values of \(\sigma_{obj}\) and \(\sigma_{backg}\). Such values could be improved by increasing the exposure times (typically 30 minutes, in our experiment). Also, \(SNR_{area}\) and \(SNR_{edge}\) have worse (small) values for the PB images than for the CRs. A reason for that is because the background was taken with the paper, which produces phase effects. Therefore, higher values for \(\sigma_{obj}\) and \(\sigma_{backg}\) are found. The present results show that such setup can be used for phase-contrast x-ray imaging and can be applied for studies of different kind of samples with large field of view (in the present work, 75 x 75 mm²). However, this setup can be improved by using a rotating anode tube (in order to get, at least, 10 times more intensity), increasing the distance from the source to the sample and employing a tomography stage with a high spatial resolution CCD detector.

| Technique | Contrast \( C \) | \( SNR_{area} \) | Visibility \( V \) | \( SNR_{edge} \) |
|-----------|-----------------|-----------------|-----------------|-----------------|
| CR        | -0.19           | -2.66           | 0.31            | 7.52            |
| PBI       | -0.25           | -1.43           | 0.57            | 5.17            |

Table 1: Contrast \( C \), signal-to-noise ratio in the area case \( SNR_{area} \), visibility of the object edges \( V \) and signal to noise ratio for the edge case \( SNR_{edge} \) for PB image and CR. The visibility \( V \) and the \( SNR_{edge} \) were obtained at the top edges of the tube (across the tube wall).
Figure 3: (a) Propagation-based (PB) x-ray phase-contrast image (edge detection image) of the same polypropylene tube shown in fig. 2. Edge enhancement and a crack (i), not seen in the fig. 2a, are clearly seen here. (b) Measured (o) and simulated (−) cross-section profile of the image.
4 Conclusions

A propagation-based x-ray phase-contrast imaging setup (PBI) was mounted using a conventional x-ray source. A virtual micro focus source was demonstrated by using a 6° take-off angle and a horizontal slit (50 μm). The sample was set 12 m from the source. The propagation-based (PB) x-ray phase-contrast images were acquired with the film and the sample set 2 m apart. Edge detection effects (that improve the contrast in the images) and details, such as a crack, not detected in the attenuation radiography (conventional radiography, CR) show that a PBI setup with a normal focus conventional x-ray source, as shown here, can be used as standard x-ray phase-contrast imaging setup for studying different kind of samples, with large field of view.

The authors are grateful to PRONEX/CNPq/Fundacao Araucaria and CNPq for the financial support. M.G. Hönnicke is grateful to CNPq/PDJ for the fellowship. The authors also acknowledge Douglas S.D. da Silva, Hilton C. Guimaraes and Rubens C. da Silva for the workshop assistance.

References

[1] A. Snigirev, I. Snigireva, V. Kohn, S. Kuznetsov, I. Schelokov: Rev. Sci. Instrum. 66 (1995) 5486.
[2] P. Cloetens, M. Pateyron-Salome, J. Y. Buffiere, G. Peix, J. Baruchel, F. Peyrin, M. Schlenker: J. Appl. Phys. 81 (1997) 5878.
[3] S. W. Wilkins, T. E. Gureyev, D. Gao, A. Pogany, A. W. Stevenson: Nature 384 (1996) 335.
[4] M. Ando and S. Hosoya: Proc. 6th International Conference on X-ray optics and Microanalysis ed G. Shinoda et al (Tokyo): University of Tokio Press, Tokio (1972) p. 63.
[5] F. Pfeiffer, T. Weitkamp, O. Bunk, C. David: Nature Physics 2 (2006) 258.
[6] E. Förster, K. Goetz, P. Zaumseil: Krist. Tech. 15 (1980) 937.
[7] K. M. Podurets, V. A. Somenkov, S. Sh. Shilshtein: Sov. Phys. Tech. Phys. 34 (6) (1989) 654.
[8] V. N. Ingal, E. A. Beliaevskaya: J. Phys. D 28 (1995) 2314.
[9] T. J. Davis, D. Gao, T. E, Gureyev, A. W. Stevenson, S. W. Wilkins: Nature 373 (1995) 595.
[10] D. Chapman, W. Thomlinson, R. E. Johnston, D. Washburn, E. Pisano, N. Gmr, Z. Zhong, R. Menk, F. Arfelli, D. Sayers Phys. Med. Biol. 42 (1997) 2015.
[11] J. Jakubek, C. Granja, J. Dammer, R. Hanus, T. Holy, S. Pospisil, R. Tykva, J. Uher, Z. Vykydal: Nucl. Instrum. Meth. A 571 (1-2) (2007) 69.
[12] T. Tanaka, C. Honda, S. Matsuo, K. Noma, H. Ohara, N. Nitta, S. Ota, K. Tsuchiya, Y. Sakashita, A. Yamada, M. Yamasaki, A. Furukawa, M. Takahashi, K. Murata: Invest. Radiology 40 (7) (2005) 385.

[13] M. W. Westneat, O. Betz, R. W. Blob, K. Fezzaa, W. J. Cooper, W. -K. Lee: Science 299 (2003) 558.

[14] R. E. Johnston, D. Washburn, E. Pisano, C. Burns, W. C. Thomlinson, L. D. Chapman, F. Arfelli, N. F. Gmur, Z. Zhong, D. Sayers: Radiology 200 (3) (1996) 659.

[15] J. Li, Z. Zhong, R. Lidtke, K. E. Kuettner, C. Peterfy, E. Aliyeva, C. Muehleman: Journal of Anatomy 202 (5) (2003) 463.

[16] J. Baruchel, J. Y. Buffiere, P. Cloetens, M. Di Michiel, E. Ferrie, W. Ludwig, E. W. Maire, L. Salvo: Scripta Materialia 55 (1) (2006) 41.

[17] Y. Chaimanee, D. Jolly, M. Benammi, P. Tafforeau, D. Duzer, I. Moussa, J. J. Jaeger: Nature 422 (2003) 61.

[18] R. Jenkins, R. L. Snyder: Introduction to X-ray Powder Diffractometry (Chemical Analysis, vol.138) ed J. D. Winefordner (John Wiley and Sons) (1996) p. 4.

[19] E. Pagot, S. Fiedler, P. Cloetens, A. Bravin, P. Coan, K. Fezzaa, J. Baruchel, J. Härtwig: Phys. Med. Biol. 50 (2005) 709.