Simulated X-Ray Phase Contrast Tomography

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Introduction

Phase contrast imaging (PCI) offers a promising alternative to traditional absorption imaging techniques.

PCI is a method of imaging an object by analysing how the phase of a penetrating x-ray varies as it traverses the object.

The behaviour of such an x-ray can be described by the object's complex refractive index, n, where,

$$\boldsymbol{n = 1 - \delta + i\beta}.$$

β is the extinction coefficient, proportional to the absorption cross section.

δ is the real refractive index decrement, proportional to the phase shift cross section [1].

PCI techniques can be up to **three orders of magnitude** more sensitive than absorption techniques [2].

Edge enhancement interference effects are present in PCI:

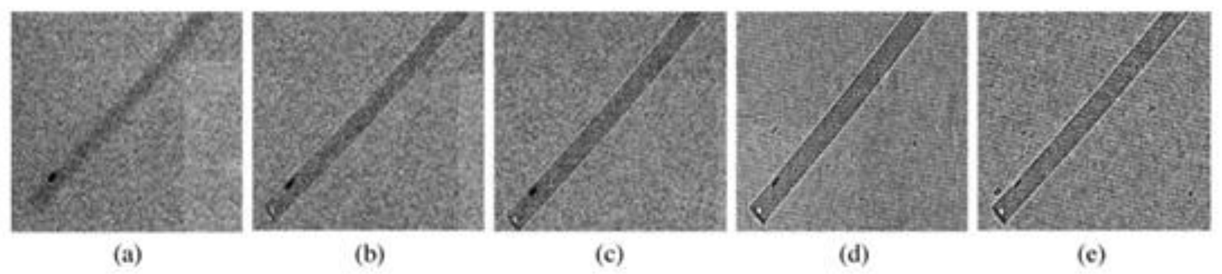

Figure 2. Propagation-based phase contrast images of a 0.4mm nylon fibre at varying sample to detector distances: **(a)** 0.008m, **(b)** 0.6m, **(c)** 0.9m, **(d)** 4.3m, **(e)** 6.5m. [3]

Computed tomography (CT) is a method of imaging a 3D object with the use of a penetrating wave, such as an x-ray.

Two-dimensional images are taken of thin segments of the object before reconstructing a three-dimensional representation of the entire body.

Tomography finds its most prominent use in medical imaging.

Understanding PCI effects and the tomographic techniques that harness them is key to producing more informative imaging for medical staff.

Project Aims

- Simulate absorption and phase contrast imaging.
- Investigate tomographic techniques.
- Combine these to produce a simulation of 3D phase contrast tomography.
- Generate a 3D reconstruction of an organic sample from experimental data.

X-Ray Simulation Methods

Absorption – Ray Trace Simulation

- Rays were generated in a random radial distribution.
- The source was modelled to be at infinity and entirely coherent.
- Absorption was measured through a copper sphere and through a PMMA cylinder to model an optical fibre (Fig. 2).

Phase Effects – Fresnel Diffraction Simulation

- Fourier optics methods based on an initial field $U_1(x, y)$, and a "Fresnel propagator" $H(f_x, f_y)$ were employed [4]:

$$U_2(x, y) = \boldsymbol{\mathcal{F}^{-1}}\left[\boldsymbol{\mathcal{F}}\{U_1(x, y)\} * \boldsymbol{\mathcal{F}}\left\{H\left(f_x, f_y\right)\right\}\right].$$

X-Ray Simulation Results

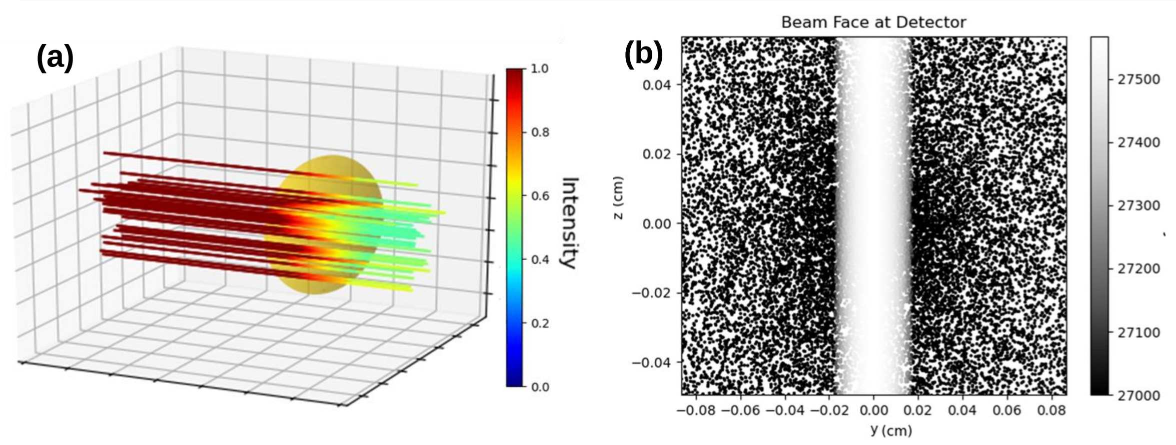

Figure 2: **(a) -** Ray-trace visualisation of the absorption of x-rays through a r=1cm copper sphere. **(b) -** Ray-trace simulation of a r=0.175mm PMMA fibre. The fibre is modelled to be a purely absorption object (no phase effects).

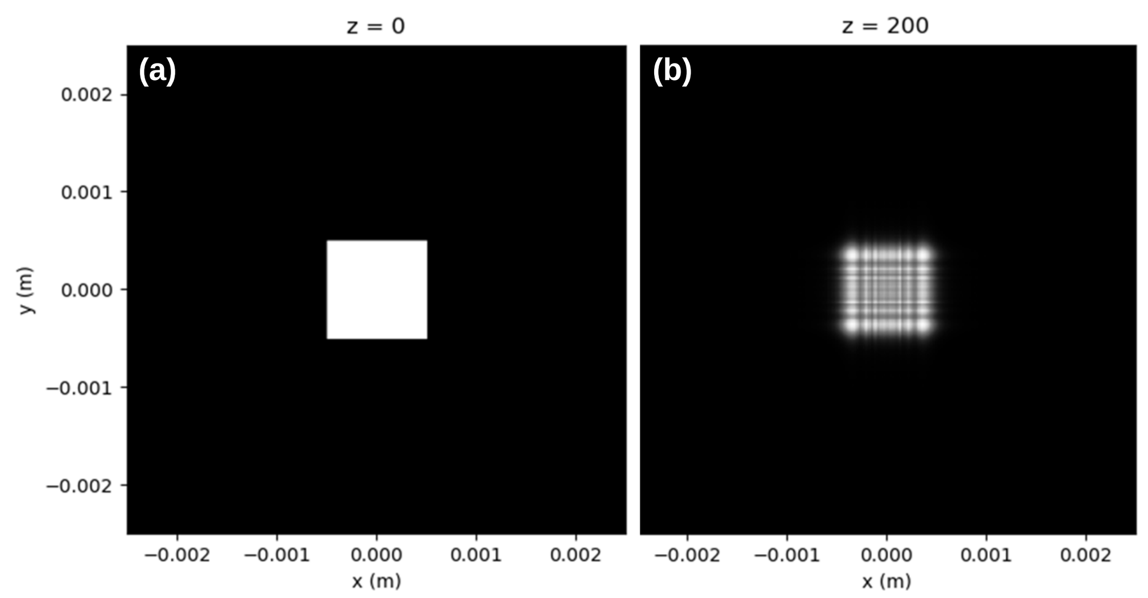

Figure 4: Simulation of the Fresnel diffraction through a d=1mm square aperture, over a propagation distance of 200m in free space. **(a)** no propagation, **(b)** 200m propagation.

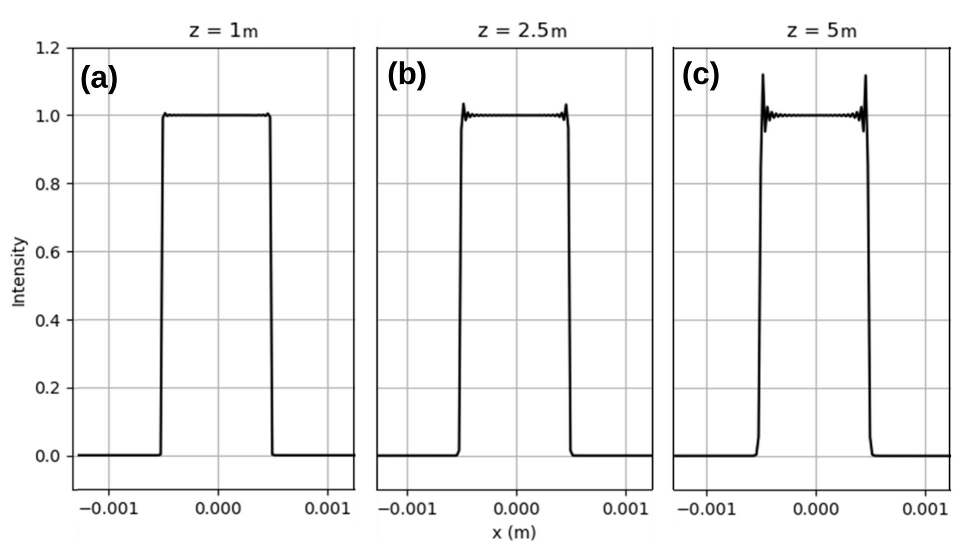

Figure 5: A demonstration of the development of edge enhancement effects as the propagation distance is increased. Propagation distances of **(a)** z=1m, **(b)** 2.5m, and **(c)** 5m. The aperture size is d=1mm.

Tomography Methods

In this project, due to the intensity of tomographic calculations, high performance code was required. For that reason, the parallisable reconstruction algorithms of the Tomopy package were used.

- A 3D Shepp-Logan phantom was generated from the Tomopy phantom bank as a subject for slicing [5].
- An coaxial x-rays were projected through the object for each of a batch of heights up the phantom (Fig. 6a).
- For each of these heights, the 1D slices were merged to form a sinogram (Fig. 6b).
- From this stack of sinograms, a deck of radiographs was reconstructed using the analytic filtered back-projection algorithm (Fig. 6d).

Tomography Results

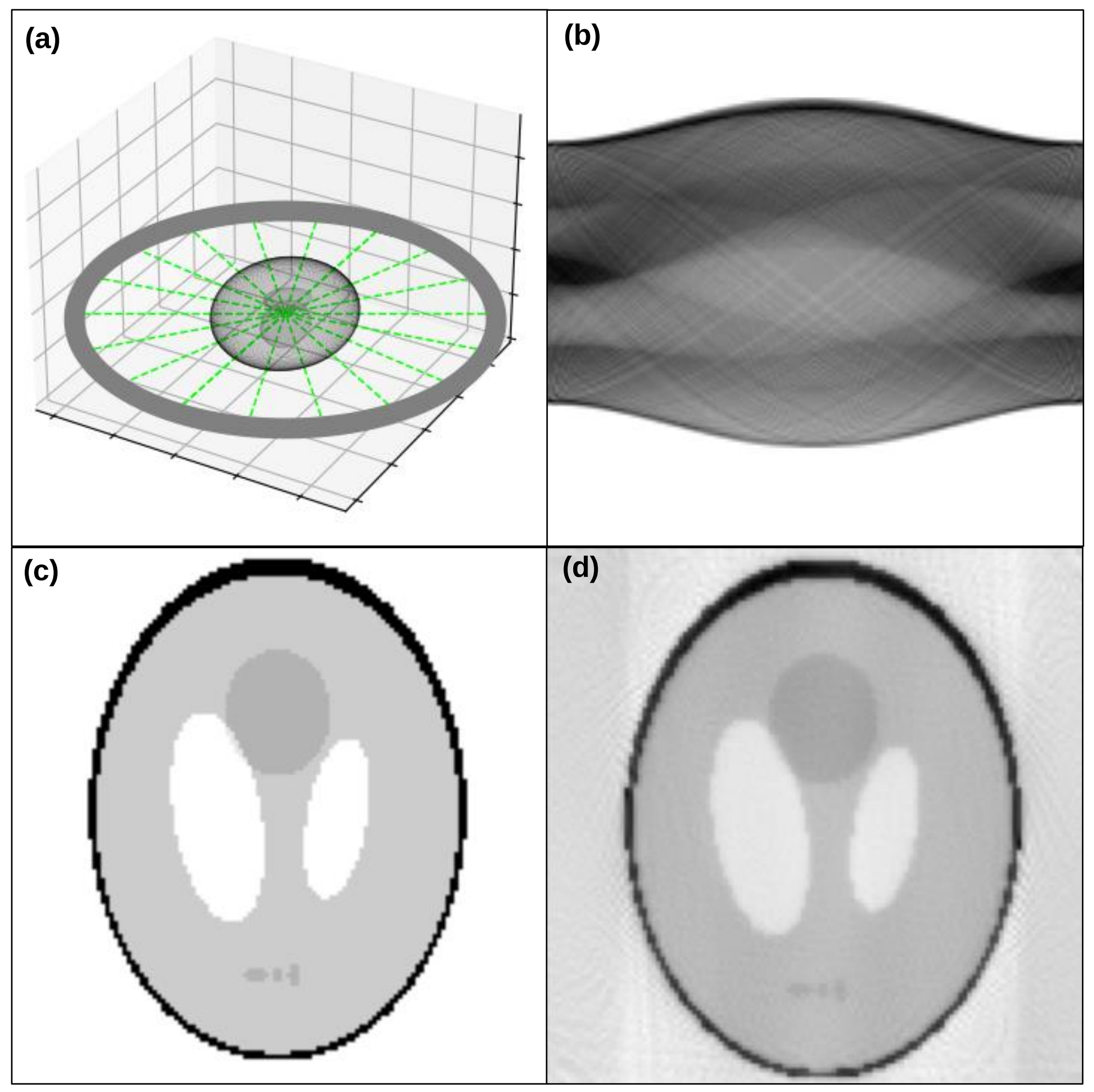

Figure 6:
(a) Visualisation of 1D slicing of the 3D phantom.
(b) The sinogram produced by stacking these 1D slices.
(c) A direct 2D slice of the phantom.
(d) A 2D slice of the phantom reconstructed from 1D slices.

Comparing the direct phantom slice (Fig. 6c) to the reconstructed slice (Fig. 6d), it can be seen that:

- Larger features are **clearly reconstructed.**
- Smaller features appear **faded** in the reconstruction.
- The radiograph suffers from **blurring** and **noise artefacts**.

Conclusions

Absorption in a PMMA optical fibre has been simulated using ray trace techniques.

In order to account for phase effects, a model based on Fourier optics was developed to simulate the Fresnel diffraction during propagation through free space.

The simulation reliably demonstrates edge enhancement effects characteristic of phase contrast imaging as propagation distance is increased.

The tomographic reconstruction produces images which capture the key features of the subject but is afflicted with blurring and noise.

Tomography is a widely used technique in medical imaging and our simulations offer insight into what future experiments might be most valuable for those attempting to design novel PCI techniques to produce more accurate CT scans.

Further Development

- Investigate the effects on phase contrast image quality when using a less ideal source (a somewhat polychromatic point source).
- Model the phase effects on the PMMA fibre.
- Compensate for the imperfections in the tomographic reconstructions.
- Reconstruct radiographs of a subject built from real images.

References

[1] Willmott, Philip. "The Interaction of X-rays with Matter." An Introduction to Synchrotron Radiation. Chichester, UK: John Wiley & Sons, 2011. 15-37. Web.

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[3] Kneip, S et al. "X-ray Phase Contrast Imaging of Biological Specimens with Femtosecond Pulses of Betatron Radiation from a Compact Laser Plasma Wakefield Accelerator." Applied Physics Letters 99.9 (2011): 093701-93701-3. Web.

[4] Begani Provinciali, G., Cedola, A., Rochefoucauld, O. de L. & Zeitoun, P. (2020) Modelling of Phase Contrast Imaging with X-ray Wavefront Sensor and Partial Coherence Beams. Sensors. [Online] 20 (22), 6469. Available from: doi:10.3390/s20226469.

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