Software X-ray Beam Hardening Correction of Cylindrical Specimens

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ABSTRACT

X-ray beam-hardening (BH) produces artefacts in tomography that cause the reconstructed image to have incorrect attenuation values that makes the job of segmentation difficult. The amount of BH varies depending on the material composition of the specimen and the X-ray spectrum. BH can be corrected for each material provided a BH curve is known. In this paper we consider specimens composed of concentric cylinders, *e.g.*, a rock core within a container. By assuming a uniform material for each cylinder we can generate BH curves directly from the projection data in a manner similar to that obtained by imaging wedge phantoms. Here we show 1) how to determine the center and radius of the cylinders, 2) how to generate BH curves, and 3) by fitting a power law model to the BH curves, how to linearise the projection data. The BH artefacts are significantly reduced in the tomographic reconstructions resulting from these corrected projections.

1. INTRODUCTION

Micrometre-scale computed tomography (micro-CT) systems in the laboratory use a microfocus X-ray source that emits polychromatic (bremsstrahlung) radiation. The spectrum of the X-ray source spans many wavelengths and unfortunately the objective function, attenuation coefficient, is a function of X-ray energy. Soft or low-energy radiation is absorbed more readily when passing through the specimen causing the X-ray beam to have a higher proportion of hard or high-energy X-rays, *i.e.*, X-ray beam-hardening (BH). Standard tomographic reconstruction algorithms assume monochromatic radiation. Ignoring the polychromatic nature of the radiation in reconstruction produces incorrect attenuation coefficient values in the tomogram which is identifiable in the form of *cupping* or *streaking* artefacts. These artefacts make subsequent tomogram segmentation and analysis difficult.

BH can be reduced by physically filtering the beam (effectively pre-hardening the beam). However, sometimes sufficient filtering is not utilised or may not be feasible due to reduced X-ray flux. In these cases some form software correction method is required. Several correction methods have been developed that apply a linearization curve (*e.g.*, Herman 1979). The inverse of the BH curve is applied to remap the measured attenuation in the projection data. The BH curve is the non-linear relationship between object thickness and recorded attenuation. It can be measured (wedge phantom) or estimated by some BH model, (typically a polynomial). Methods to estimate the curve without imaging phantom are typically iterative and computationally intensive – something we wish to avoid.

In this work we consider specimens composed of concentric cylinders, *e.g.*, a rock core within a container. This assumption covers a significant fraction (>50%) of the specimens currently imaged at our facility. By assuming a uniform material for each cylinder we can generate BH curves directly from the projection data in a manner similar to that obtained by imaging wedge phantoms. Here we demonstrate the principle for single cylinders and concentric multi-component cylinders. The work presented here is entirely complementary to the BH correction method previous developed by our group that minimises reprojection distance (Kingston 2011). The reprojection distance method enforces self-consistency in the data but does not work for objects where attenuation is a function of radius.

We have measured the BH curve of several materials at our micro-CT facility. Figure 1 shows the “linearised” attenuation versus material thickness for two materials (Aluminium, glass) as an example. Here “linearised” attenuation is defined as logarithm of intensity divided by clear field intensity. The linear nature of these log-log plots shows that a simple power law behaviour can serve as an appropriate BH model and is demonstrated in this paper.

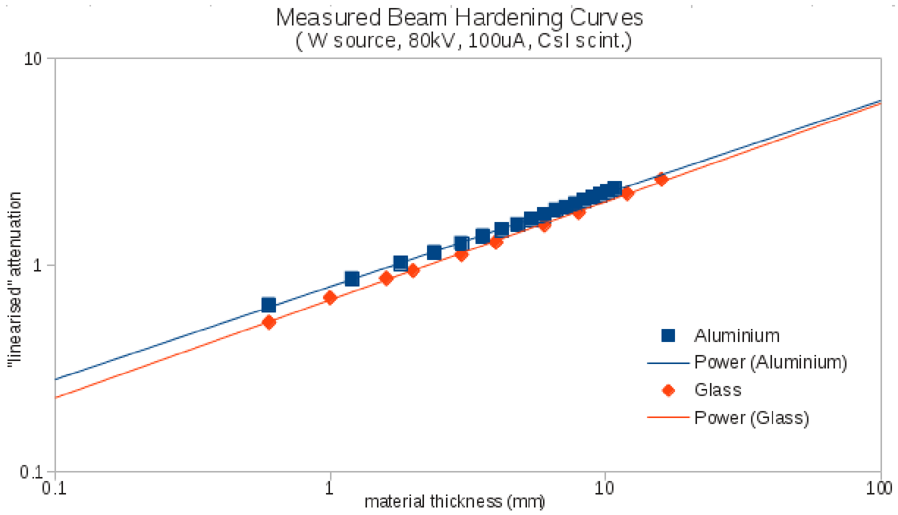


Figure 1: *Measured X-ray beam-hardening curves at our facility*

2. FITTING CYLINDERS (OR CIRCLES)

Here we consider specimens consisting of concentric cylinders. This could, for example, simply be a single cylindrical rock core, or a three cylinder system such as a rock core encased in a cylindrical container filled with high contrast fluid. The proposed modelling method requires the accurate determination of the cylinder boundaries. To discover the centres $\boldsymbol{c}_i$ and radii r_i defining the boundaries, a minimization problem is solved, where the cost function is defined as the sum of the dot products of the reconstructed-image gradient with the circle normals divided by distance to the circle perimeter (Eq. 1).

$$C(r, \boldsymbol{c}) = -\sum_{\boldsymbol{i}} \frac{\boldsymbol{G}(\boldsymbol{i}) \cdot (\boldsymbol{i} - \boldsymbol{c})}{\|\boldsymbol{i} - \boldsymbol{c}\|(\|\boldsymbol{i} - \boldsymbol{c}\| - r)^2} \qquad (1)$$

Here $\boldsymbol{G}(\boldsymbol{i})$ is the reconstructed-image gradient vector at pixel $\boldsymbol{i}=(i_0, i_1)$. Powell minimization was used to discover local minima of this cost function, employing multiple starts, where the starting radii were varied from 10% of the image width to 50% of the image width in 2% increments. The starting centre coordinate for the Powell optimisations was the centre coordinate of the reconstructed-image. From the multiple local minima, the best *n* circles are chosen as those that have the lowest associated cost values and which are non-coincident, (*i.e.*, radius and centre coordinate differ by more than 1 pixel).

3. FITTING MATERIAL ATTENUATION

The projection of *n* concentric cylinders is modelled by *2n-1* solid cylinders. A hollow cylinder can be modelled as the projection of a cylinder with its outer radius and attenuation μ along with the projection of a cylinder with its inner radius and attenuation $-\mu$.

An initial estimate for μ_i can be considered as the mean attenuation value in the reconstructed image of the i^{th} cylinder region. An improved estimate of the attenuations can be obtained by optimizing the match between the true-specimen projections and the concentric cylinder projections. One could potentially use the same minimization approach to additionally fit the circle parameters and avoid the need for the reconstructed image (gradient) in the *C* cost function. However, true-sample non-uniformity (particularly at the inner true-sample boundary) tend to bias the solution and result in poor circle fits for porous samples.

4. FITTING BEAM HARDENING CORRECTION MODELS

As outlined in the introduction, the BH curve is modelled as a linear combination of n power laws for n cylinders as in (Eqn. 2).

$$p_{bh} = a_0 {p_0}^{k_0} + a_1 {p_1}^{k_1} + \cdots \quad (2)$$

Where p_i are the true (or estimated linear) projection data per-cylinder/material and p_{bh} is the beam-hardened projection produced by the curve. The (a_i,k_i) parameters are fit by minimising the least square error of measured projections and the uniform-attenuation concentric-cylinder model beam hardened projections.

4.1. Single Cylinder

For a single cylinder, the beam-hardened-corrected estimated linear projections are calculated as the inverse of the BH curve (Eqn. 2)

Figure 2 shows the cupping and streaking artefacts for two single cylinder examples. Despite the objects showing non-uniform texture, the BH correction curves produced assuming an average attenuation coefficient over the cylinders has significantly reduced the artefacts in both example images. Note that by correcting for BH, image contrast has also been improved.

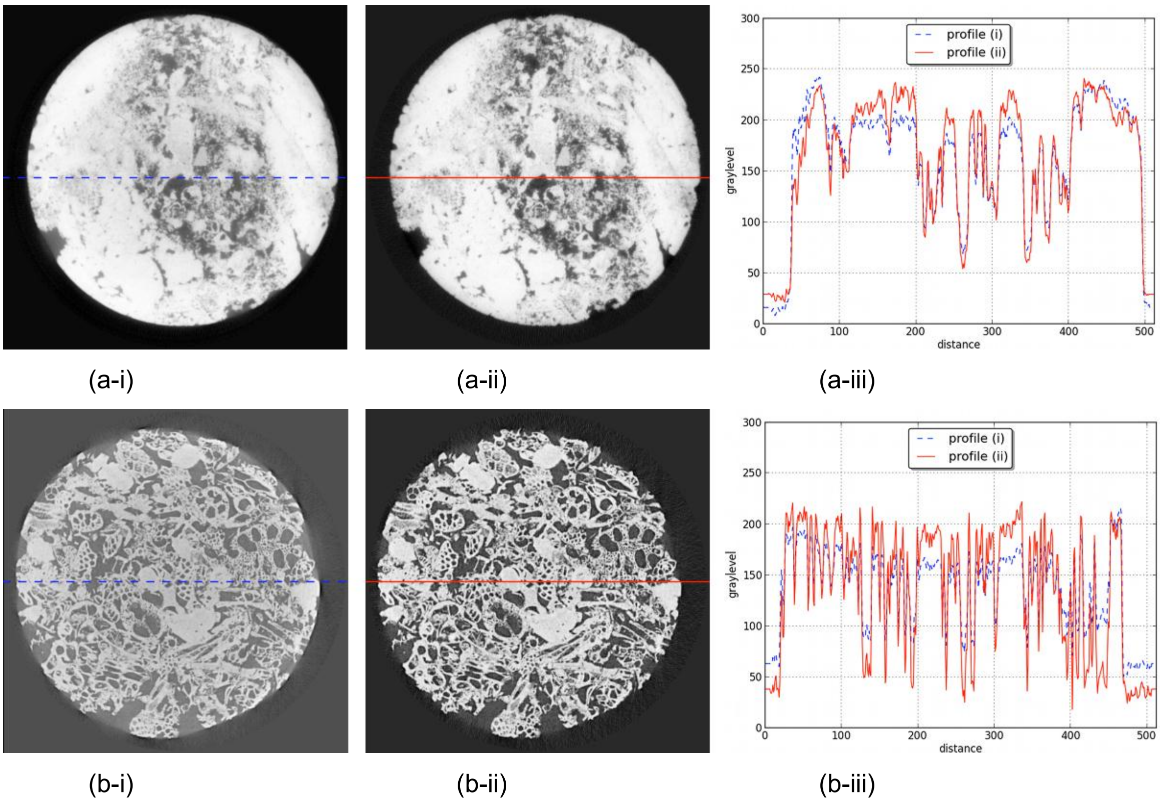
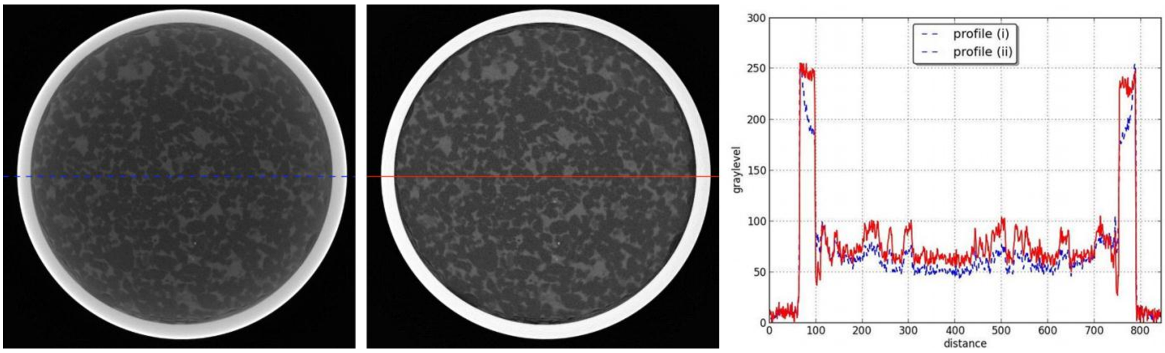


Figure 2: *Horizontal slices through two single cylinder specimens (a) and (b). (i) reconstructions with beam-hardening artefacts, (ii) reconstructions after correction, and (iii) profile through the centre of images as indicated by dashed lines*

4.2. Concentric Cylinders

For multiple materials, the inversion of the power law is performed per-cylinder/material with the corrected projection calculated as the sum of per-material corrected projections. The per-material inversion requires the calculation of the per-material contributions to the measured projections. These contributions are estimated from simulated-projections (Radon transform) of the per-material (per-annulus) masked reconstructed image, (*i.e.*, the image reconstructed from the measured projections).



(i) (ii) (iii)

Figure 3: *A horizontal slice through a two cylinder specimen. (i) reconstructed using measured attenuation, (ii) reconstructed using corrected attenuation, and (iii) profile through the centre of images as indicated by dashed lines*

Figure 3 shows the cupping artefacts around holder and around the edge of the rock core specimen have been reduced for the 2 cylinder system using the assume BH model (Eqn. 2) and the proposed correction.

5. CONCLUSIONS

A simple beam-hardening correction method has been demonstrated for single and multiple concentric cylinder specimens. The method essentially turns the projection of cylinders into the image of a wedge phantom to directly measure the beam-hardening curve. Several examples have been included to demonstrate that the method does indeed reduce cupping and streaking artefacts. Future work could include developing an automatic method to determine the execution of cylindrical and non-cylindrical beam hardening correction code and exploring more sophisticated/appropriate models for beam-hardening curves (e.g., Van de Casteele 2002).

6. REFERENCES

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