The Application of Beam Hardening Correction for Industrial X-ray Computed Tomography

Joseph J. Lifton\textsuperscript{1}, Andrew A. Malcolm\textsuperscript{2}, John W. McBride\textsuperscript{3}

\textsuperscript{1}The University of Southampton, United Kingdom; Email: J.J.Lifton@soton.ac.uk.
\textsuperscript{2}Singapore Institute of Manufacturing Technology, Singapore; Email: Andy@SIMTech.a-star.edu.sg.
\textsuperscript{3}The University of Southampton Malaysia Campus, Malaysia; Email: J.W.Mcbride@soton.ac.uk.

Abstract

X-ray computed tomography (CT) is a non-destructive, radiographic scanning technique that enables the visualisation of both the internal geometry and the composition of a workpiece; X-ray CT is therefore well suited for non-destructive inspection tasks. Several physical processes reduce the quality of CT images, and therefore influence both qualitative and quantitative analyses made from CT data-sets; one such physical process is beam hardening. In this work a simulation-based method is presented for correcting beam hardening, this method is applied to industrial X-ray CT measurement tasks and demonstrated to improve CT image quality.

Keywords: Computed tomography, Beam hardening, Artefact correction, Linearisation, Spectrum estimation.

1. Introduction

X-ray computed tomography (CT) is a radiographic scanning technique for imaging cross-sections of a workpiece, and is therefore well suited for non-destructive material inspection and characterisation tasks; one example of such an inspection task is the characterisation of metal foams, whereby pore shape, and size may influence the foams functional properties [1]. The first step to these types of quantitative inspection tasks is often segmentation of the CT data-set; with good segmentation, accurate pore information can be evaluated, followed by reliable characterisation. Beam hardening is a physical process that degrades the quality of CT images, introducing artefacts that are detrimental to visual inspection and automated segmentation algorithms. Beam hardening typically manifests itself as false density gradients in CT images of homogenous materials, termed cupping, and as streaks between highly attenuating structures, termed streaking [2].

The term beam hardening originates form the following consideration: as a beam of polychromatic X-rays propagate through a material, low energy photons are preferentially attenuated, the effective energy of the beam increases, and the probability of photon interaction decreases, \textit{i.e.} the beam becomes more penetrating and is said to become ‘harder’; as a consequence, the attenuation caused by a particular volume element becomes dependent on the projection angle and X-ray path length. The inverse Radon transform, on which most reconstruction algorithms are based, requires attenuation to be a linear function of material thickness; this is only the case for monochromatic X-rays. The physical process of beam hardening results in polychromatic attenuation being a non-linear function of material thickness; hence the combination of polychromatic attenuation and reconstructing via the inverse Radon transform leads to artefacts in the resulting CT images.
Numerous beam hardening correction methods have been developed, they include: pre-filtering the X-ray spectrum, linearisation [3], dual energy [4] and iterative post-reconstruction [5]; each method is described briefly by Krumm et al. [6]. Recent work has focused on developing beam hardening correction methods that require no prior knowledge of the workpiece composition, X-ray spectrum, and detector response [6, 7, 8]; however, the composition of the workpiece is often known, and it is possible to estimate the X-ray spectrum via deterministic models [9], Monte Carlo simulations, or via transmission measurements [10, 11], hence this prior information can be made good use of to correct beam hardening artefacts.

In this work a method for simulating polychromatic attenuation is developed, the method requires prior knowledge concerning the workpiece composition, X-ray spectrum, and detector response; all of which are readily available from online databases and simple measurements. The ability to simulate polychromatic attenuation enables polychromatic projections to be corrected to monochromatic projections prior to reconstruction using the linearisation method. To demonstrate the value of this method for industrial X-ray CT, a comparison of image statistics is made between CT images reconstructed from uncorrected projections and projections corrected using the proposed method.

2. Methodology

2.1 Workpieces

To demonstrate the proposed beam hardening correction method an aluminium heat exchanger and a piece of aluminium foam are CT scanned, see Figure 1; these workpieces are chosen based on their complex geometries, which induce strong streaking artefacts.

Figure 1. Two aluminium workpieces; their complex internal structures induce strong streaking artefacts. A) An aluminium heat exchanger. B) A piece of aluminium foam.
2.2 Monochromatic and polychromatic attenuation

Linearisation is one method for correcting beam hardening artefacts [3]; the method estimates monochromatic attenuation from polychromatic attenuation, thus satisfying the requirements to reconstruct via the inverse Radon transform. The ability to accurately simulate polychromatic attenuation allows the required correction function to be derived without additional material-specific attenuation measurements; this is often considered a major drawback of the linearisation method. Monochromatic attenuation is written according to the Beer-Lambert law of attenuation, see equation (1), where $I_0$ is the intensity of X-rays that fall incident on a homogenous attenuator, with a linear attenuation coefficient of $\mu(E)$, and thickness $t$, and $I$ is the intensity of X-rays emerging without having undergone an interaction:

$$-\ln(I/I_0) = \mu(E)t$$  \hspace{1cm} (1)

Polychromatic attenuation is written as per equation (2); the function $W(E)$ describes the relative contribution of each photon energy to the total polychromatic attenuation: $W(E)$ is dependent on the X-ray spectrum emitted by an X-ray source, alongside the energy dependent response of the detector [6, 12, 13].

$$-\ln(I/I_0) = -\ln \left\{ \int_0^{E_{max}} S(E) e^{-\mu(E)t} dE \right\}$$  \hspace{1cm} (2)

To evaluate equation (2) knowledge of each term is required: values of $\mu(E)$ for elements, mixtures and compounds are available from the NIST XCOM database [14]. $W(E)$ can be estimated via a deterministic model of X-ray spectra generation [9], alternatively a Monte Carlo simulation of X-ray generation and detection can be used [15], or the X-ray spectrum and detector response can be estimated via X-ray transmission measurements, see for example Sidky et al. [10]; in this work the latter is used, and the methodology adopted is described in the next section.
2.3 Estimating X-ray spectrum and detector response from transmission measurements

Rearranging equation (2) allows X-ray transmission $I/I_0$ to be written as a system of linear equations in the form $Ax = b$, where:

$$A = e^{\mu(E)t}$$

$$x = W(E)$$

$$b = I/I_0$$

For a set of $m$ X-ray transmission measurements of attenuators with known $t$ and $\mu(E)$, it is possible to solve for $W(E)$ composed of $n$ discrete energies. Equation (2) is thus rearranged and discretised:

$$
\begin{bmatrix}
\exp(-\mu_1 t_1) & \cdots & \exp(-\mu_n t_1) \\
\vdots & \ddots & \vdots \\
\exp(-\mu_1 t_m) & \cdots & \exp(-\mu_n t_m)
\end{bmatrix}
\begin{bmatrix}
W_1 \\
\vdots \\
W_n
\end{bmatrix}
= 
\begin{bmatrix}
I_1/I_0 \\
\vdots \\
I_m/I_0
\end{bmatrix}
$$

The $A$ matrix in equation (6) is typically ill-conditioned; it is therefore solved iteratively and with a positivity constraint. Sidky et al. proposed the use of a multiplicative update function; initial estimates therefore remain positive or zero upon iteration. With an estimate of $W(E)$, equation (2) can be evaluated for the purpose of deriving a beam hardening correction.

To evaluate equation (6), X-ray transmission is measured for varying thicknesses of titanium using an X-ray source voltage of 130 keV and current of 8 µA. Ten titanium foils of 0.1 mm thickness, and ten foils of 0.5 mm thickness are stacked such that the thickness varies from 0.1 mm to 6 mm. The titanium foils are assumed pure, and values of $\mu(E)$ are obtained from the NIST XCOM database. Using the X-ray transmission measurements, values of $\mu(E)$, and knowledge of the material thickness, $W(E)$ is estimated using the aforementioned iterative method, the initial estimate is half a sine wave. The initial and final estimate of $W(E)$ are shown in Figure 2A, whilst Figure 2B shows the measured and simulated X-ray attenuation, the latter is calculated using the estimate of $W(E)$. 
2.4 Beam hardening correction

With an estimate of $W(E)$, knowledge of the workpiece’s composition and thickness, it is possible to calculate polychromatic attenuation by evaluating equation (2): both the workpieces shown in Figure 1 are composed of an aluminium alloy with a the maximum thickness not exceeding 2.5 cm; again, values of $\mu(E)$ are obtained from the NIST XCOM database. Figure 3A shows polychromatic attenuation plotted against material thickness, notice the non-linear relationship. A sixth order polynomial fits the simulated data with a coefficient of determination ($R^2$) of 1. Evaluating the gradient of the polynomial for $x = 0$ gives the gradient of the monochromatic line plotted in Figure 3A [16]. Finally, plotting polychromatic attenuation versus monochromatic attenuation, as per Figure 3B, gives the function required to correct polychromatic to monochromatic attenuation, this function is approximated again with a sixth order polynomial: the polynomial fits the data with an $R^2$ value of 1.
2.5 CT scan and subsequent data processing

The workpieces shown in Figure 1 are CT scanned with an YXLON Y. FOX (YXLON, Germany); this instrument features a 160 keV tungsten transmission target X-ray source and a Varian PaxScan detector (Varian Medical Systems, USA) with dimensions 1480 by 1848 pixels, of size 0.127 mm. The source settings are the same as those used to derive \( W(E) \) and 720 projections are acquired for both workpieces for a 360° rotation. Prior to reconstruction polychromatic projections are converted to monochromatic projections via the polynomial function derived in Figure 3B. Reconstruction is performed using the filtered backprojection algorithm, with projections ramp filtered prior to backprojection.

3. Results

CT images of the heat exchanger reconstructed from polychromatic projections and linearised projections are shown in Figures 4A and B respectively. For the uncorrected result, streaking artefacts are clearly visible between the high-aspect ratio features; looking to Figure 4B the proposed beam hardening correction successfully reduces the streaking artefacts. CT images of the aluminium foam reconstructed from polychromatic projections and linearised projections are shown in Figure 5A and B respectively. Streaking artefacts are again clearly visible in the uncorrected CT image; looking to Figure 5B, again the proposed beam hardening correction successfully reduces the streaking artefacts.

Figure 4. CT images reconstructed from A) polychromatic projections with no beam hardening correction, B) projections corrected with the polynomial function derived in figure 3B; the streaking artefacts are reduced and the contrast is increased.
Rather than present a purely qualitative inspection of the CT images, image quality is quantified by evaluating three image statistics: contrast, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). The CT images in Figures 4 and 5 are segmented based on a single grey value termed the ISO50 threshold [2]; this value is derived from the grey value histograms of each CT image and represents the grey value that lies halfway between the modal material and background grey values. The segmentation result is used as a binary mask to evaluate the mean $\bar{x}$, and standard deviation $\sigma$ of the grey values representing material and background. From these statistics, SNR is calculated as $\frac{\bar{x}_m}{\sigma_m}$, as per Casteel et al. [17], where the subscript ‘m’ denotes material; CNR is calculated as $\frac{(\bar{x}_m-\bar{x}_{bg})}{\sigma_{bg}}$, as per McKinley et al. [18], where the subscript 'bg' denotes background; and contrast is calculated as $\frac{(\bar{x}_m-\bar{x}_{bg})}{\bar{x}_{bg}}$. The image quality results are given in Figure 6A for the heat exchanger and 6B for the aluminium foam.

The results presented in Figures 6A and B show that linearisation has the desirable effect of increasing both the CNR and contrast for both workpieces; however, it has the undesirable effect of reducing SNR by almost half for the heat exchanger; this latter result is in agreement with that of Casteele et al. [17]. The application of the correction polynomial is likely to increase high spatial frequency noise in the corrected projections, the ramp filter used prior to backprojection attenuates low spatial frequencies and accentuates high spatial frequencies, thus having the unwanted effect of magnifying noise from projections; this is one drawback of this approach to beam hardening correction. It is interesting to note however that this decrease in SNR is not seen for the aluminium foam, but rather the SNR increases slightly. In summary, all image statistics are enhanced with the application of beam hardening correction bar SNR for the heat exchanger.
Figure 6. SNR, Contrast and CNR evaluated from CT images in Figures 4 and 5 respectively. A) Aluminium heat exchanger B) Aluminium foam.

4. Conclusions

In this work the energy dependent function $S(E)$ that considers the X-ray spectra and detector response has been estimated via X-ray transmission measurements; using this information and prior knowledge of the workpiece’s composition, a function that estimates monochromatic attenuation from polychromatic attenuation has been derived and shown to correct beam hardening artefacts. The beam hardening correction successfully reduced streaking artefacts for two workpieces: an aluminium heat exchanger and a piece of aluminium foam. Image statistics were evaluated and showed that the beam hardening correction had the desirable effect of increasing both image contrast and contrast-to-noise ratio.

Using the proposed methodology, the energy dependent function $S(E)$ could be estimated for multiple source settings and saved as a system specific database; with knowledge of the workpiece’s composition, a beam hardening correction could simply and easily be derived in advance, and projections corrected during the acquisition process. The method presented here is limited to the correction of single material workpieces; future work should consider extending the method for multiple materials.
References