An experimental method for ripple minimization in transmission data for industrial X-ray computed tomography imaging system

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Abstract. Industrial Computed Tomographic (ICT) imaging systems based on X-rays require a high stability source. This emanates from the fact that in a computed tomographic imaging system, statistical variation inherent in the penetrating radiation used to probe the specimen, electronic noise generated in the detection system and reconstruction errors play an important role in the overall quality of the image. A conventional industrial X-ray machine used for routine radiography work is not suitable for tomographic imaging applications because of its output dose variations. In this paper, an experiment is described to utilise a general-purpose 160 kV constant potential industrial X-ray machine with significant ripple in its output beam, in an experimental Computed Industrial Tomographic Imaging System (CITIS) developed at Isotope Applications Division of Bhabha Atomic Research Centre. Studies carried out include the analysis of temporal profile of X-ray beam intensity and online averaging of detected signals for the minimization of periodic ripple, which mainly showed up, at the power line frequency. A tomographic image of a typical specimen, reconstructed with the processed projection data is analysed. It was observed that the mean value of reconstructed linear absorption coefficients and standard deviation computed over a window within a constant density region of the object were stable.

Keywords. Tomography imaging; reconstruction software; X-ray imaging; signal averaging.

1. Introduction

The first prototype Computed Industrial Tomographic Imaging System (CITIS) based on monochromatic gamma rays, designed and developed at Isotope Applications Division, Bhabha Atomic Research Centre to present an approximation of density or linear attenuation coefficient map across a slice through a specimen, has been useful to visualise many types of structures, flaws, voids, inclusions, porosity and relative density distribution (Umesh Kumar

et al 2000). This system has since been used to examine many simulated objects as well as real industrial specimen. The system has provided solutions to many problems, which are not possible with conventional radiography. However, due to low dose rate of the radioisotope source and single detector used, system was slow. Hence a modified X-ray based tomographic imaging system in multi-detector configuration has been planned. Due to high beam intensity and variable energy range, X-ray equipment specifically manufactured for tomographic imaging purposes is preferred to gamma sources. Polychromatic nature of the X-ray emission from constant potential industrial tubes and different other factors which affect projection data, design and development of such tomographic imaging systems demand various studies to be carried out. The continuous spectrum from such sources and misalignment of the system causes different artifacts in the tomographic image. Due to preferential absorption of low energy components in the X-ray beam as it passes through a material gives rise to beam hardening effect in the reconstructed image (Kak & Slaney 1988). An experimental system with five CsI(Tl)-PIN photodiode detector assembly and a computerised mechanical manipulator was used for initial studies carried out for design parameter optimisation of a 160 kV constant potential X-ray based computed tomographic imaging system. In this paper, an experiment is described to utilize a general-purpose 160 kV constant potential industrial X-ray machine with significant ripple in its output beam, which adversely affect transmission data for use with a computed industrial tomographic imaging system. The instrumentation used, corrected transmission data pattern recorded and tomographic data profiles after image reconstruction are discussed. Statistical calculation over the uniform density region of the reconstructed data grid has been carried out to observe the variations in the mean value as well as associated standard deviation.

2. Principle

Attenuation of a mono-energetic collimated beam of X-ray or gamma rays through a homogeneous material of thickness x is given by

$$I = I_0 e^{-\mu x}, \quad (1)$$

where, I is the intensity after passing thickness x of the material, I_0 is the initial intensity of the beam without material, μ is the linear attenuation coefficient of the material for radiation energy used and x is the path length of the material.

Rewriting (1) as

$$\ln(I_0/I) = \mu \cdot x. \quad (2)$$

If the radiation beam passes through a non-homogenous material, its path can be considered to consist of a number of elements of width w with attenuation coefficients $\mu_1, \mu_2, \mu_3, \dots, \mu_n$ then (2) becomes

$$\ln(I_0/I) = \mu_1 \cdot w + \mu_2 \cdot w + \mu_3 \cdot w + \dots + \mu_n \cdot w \quad (3)$$

In other words, the natural logarithm of the measured transmission ratio along a particular ray represents the sum of the attenuation coefficients multiplied by the corresponding path length of all the elements that the ray traverses. In transmission tomography, the quantity $\ln(I_0/I)$ is normally called *ray-sum*. A single ray-sum cannot by itself give any information about the distribution of the attenuation coefficients inside the specimen. A set of ray-sums

at different angles in the test object is needed. A mathematical algorithm is then used to reconstruct the unique distribution of the attenuation coefficients (μ) within the object. (Shepp & Logan 1974).

It has been shown (Scudder 1978) that ideally the projection p in presence of noise sources can be represented by

$$p + n_p \cong K \log I + K n_I / I, \quad \text{if } n_I \ll I, \quad (4)$$

where, p is ideal projection, I is corrupted by n_I and n_p symbolizes noise introduced by ADC quantisation and K is a constant. The term $K n_I / I$ includes noise because of variations in source intensity itself and should be minimized. For CT scanning, the X-ray tube potential should be constant potential with very low ripple. Ripple (or any other interference) that occurs in times comparable to sampling times can have a detrimental effect (McCullough & Payne, 1977). Different methods can be used to minimize the ripple effect in transmission data such as online averaging of the data recorded in various ways, use of a notch filter if profiles are corrupted by noise of a single frequency (Press *et al* 1993) or using a reference detector. The experiment reported here describes the use of simple instrumentation to carry out averaging of transmission signal to generate projection data for subsequent image reconstruction.

For parallel-beam scanning geometry, it has been shown (ASTM 2000) the noise at the centre of a reconstructed cylinder of radius R_o irradiated by X-rays of effective energy $\bar{E}$ is given, in case of Shepp & Logan (1974) convolution filter, by the formula:

$$\sigma_{S\&L} = 0.71 / (s\sqrt{V}) \sigma_d, \quad (5)$$

where, s = the spatial sampling increment, V = the number of views or orientations and σ_d = the standard deviation of the noise on the samples in the profile data.

The numerical calculation of σ_d is complicated as the profile data is natural logarithm of the ratio of intensity of the unattenuated radiation designated as n to the detected signal. However, in the approximation that photon noise dominates, the minimum possible data noise σ_d is given by the expression:

$$\sigma_d = \left[\left\{ 1/n \cdot \exp[-2\mu_0(\bar{E})R_0] \right\} + (1/n) \right]^{1/2}, \quad (6)$$

where $\mu_0(\bar{E})$ is linear attenuation coefficient of the cylinder.

Experimentally, the usual process of determining the standard deviation σ , for a homogeneous area of reconstructed image containing m pixels, each with some value μ_i , is by using the following two expressions:

$$\bar{\mu} = \frac{1}{m} \sum_{i=1}^m \mu_i, \quad (7)$$

$$\sigma = \left[\sum_{i=1}^m (\mu_i - \bar{\mu})^2 / (m - 1) \right]^{1/2}, \quad (8)$$

where $\bar{\mu}$ is the mean value of m pixels.

The noise in a reconstructed image does have a positional dependence, especially near the edges of an object.

3. Design criteria

The design is based on the concept that a slice of the specimen is intercepted with a thin beam of X-rays, which is attenuated as it passes through the specimen. The fraction of the radiation beam that is attenuated is directly related to the density and thickness of the material through which the beam has travelled and the effective energy of the beam. The reconstruction routine quantitatively determines from the set of one dimensional radiation measurements taken at different scanning angles, the point by point mapping of the approximate attenuation coefficients at the effective energy of the penetrating radiation (Brooks & di Chiro 1976).

4. Reconstruction algorithm

It is a procedure for solving a mathematical problem by a series of operations following a set procedure. In computed tomography the mathematical process is used to convert the digitized transmission measurements into cross sectional images. There are two commonly used computation methods for image reconstruction from projection data. The Fourier transform method or filtered back projection method (FBP) normally operates in spatial frequency domain whereas a simplified version called Convolution Back Projection method (CBP) operates in spatial domain and is easy to implement (Scudder 1978; Kak 1988). In this work reported, CBP method has been employed for the development of image reconstruction software. The reconstructed image is processed by separate image processing software.

5. Experimental details

The purpose of experimental studies described in this paper was to optimise parameters and carry out feasibility studies on using a general-purpose industrial X-ray machine in computed tomographic imaging applications.

5.1 Instrumentation

The experimental ICT system set up for visualisation of defects and structures in a wide range of specimen with a high intensity X-ray radiation source utilizes CsI(Tl)-photodiode with associated electronics as the sensing device. The system as such was operated in translate-rotate mode in this experiment. X-ray radiation is detected by the CsI(Tl)-PIN photodiode detector after passing through the test object. The detector assembly along with its associated electronics designed and developed in the laboratory, is shielded with a lead enclosure to protect from radiation damage. The detector was provided with a front-end collimator with a rectangular slit (1.0×5.0 mm). The detector resolution in the image plane is 1.0 mm and slice thickness was fixed at 5.0 mm. In the experiment reported in this paper, only the central detector out of five was used to record the transmission data. The X-ray tube was also provided with a collimator. The detector produces a current proportional to the beam intensity, which is converted to a corresponding voltage signal using a current to voltage converter stage. This is then amplified to a level (typically ten volts full scale) suitable for the analog to digital converter. Though a 16-bit ADC is preferred, here a 12-bit commercial ADC card was used. The onboard pacer was programmed to provide the trigger signal to the ADC. The ADC was programmed to operate in DMA mode for data transfer and the application software carried out averaging before transferring the data to a file. The tomographic images were reconstructed

Figure 1. Schematic block diagram of the experimental setup.

using convolution back-projection algorithm as applied to transmission tomography. Also, no beam hardening correction has been applied in the projection data through software. The X-ray machine used in this experiment was a dual-focus, 160 kV/10mA unit of Andrex make model no. CP533. Figure 1 shows the schematic block diagram of the experimental setup. Figure 2 shows the circuit diagram of a single channel of CsI(Tl)-PIN photodiode detector, preamplifier and the associated electronics used. Figure 3 shows a partial view of the experimental setup where a cylindrical Perspex block is mounted on the computerized mechanical manipulator. Left to this is shown the detector box, which houses CsI(Tl)-photodiode/preamplifier assembly. The complete software for data acquisition, machine control and MS Windows based image reconstruction and analysis was developed in this laboratory.

5.2 Description of specimen

A typical specimen was fabricated for tomographic imaging based on the proposed scheme of ripple minimisation in the detector output. Inside a hollow stainless steel (SS) cylinder, two aluminium rectangular blocks kept together were placed opposite another single aluminium block near the periphery. A solid Perspex cylindrical block was placed in between these

Figure 2. Circuit diagram of CsI(Tl)-PIN photodiode detector assembly.

aluminium blocks. A cross-section of the specimen is shown in figure 4. This assembly was scanned at a typical height in order to visualize the SS circular outline, aluminium blocks, interface between the two aluminium blocks and the third aluminium block as well as Perspex cross-section. The specimen was arbitrarily chosen to include asymmetry and non-uniformity for the purpose of tomographic imaging. The studies involved analysis of temporal profile of X-ray beam intensity and online averaging of detected signal for the minimization of periodic ripple, which mainly showed up, at the power line frequency. The specimen was then scanned in this configuration for generation of projection data and image reconstruction to visualize certain details in a cross-section.

Figure 3. Partial view of experimental X-ray tomography system.

Figure 4. Diagram showing a typical cross-section of the specimen.

6. Results and observations

Figure 5 is a plot of sampled detector output in volts by the ADC. The X-ray tube setting was 120 kV/4.7mA and the specified large focal spot of 1.5 mm was selected. Though use of smaller focal spot is always preferable for better spatial resolution, large focal spot was used in this experiment because of high detector output. Also, the detector electronics were calibrated for large focal spot setting in the X-ray tube. The sampling frequency was set at 3 kHz. Figure 6 shows frequency analysis plot of the same signal. Three peaks are observed

Figure 5. Sampled detector output.

Figure 6. Frequency analysis plot of sampled output.

in this plot. The effect of the prominent one at 50 Hz is visualized in the plot of figure 5 where the pattern is repeating at that frequency. It is inferred from plot in figure 6 that in addition to 50 Hz peak, the other peaks may be harmonics generated in the rectifier section of the high voltage unit. The online averaging minimized their effects also.

Figure 7 is a plot of online time-averaged detector signal where each data point is the average value of 80 data points sampled at 2 kHz. The plot shows a total of 360 such data

Figure 7. Average detector output.

Figure 8. Average detector output through a 50 mm cylindrical Perspex block.

Figure 9. A typical projection profile.

Figure 10. Reconstructed tomographic image of the specimen.

points. The large variation in the actual detector output due to fluctuations in the X-ray tube is thus minimised. Figure 8 is a plot of averaged detector output when the X-ray beam has linearly scanned in both forward and reverse directions, a 50 mm cylindrical Perspex block mounted on the sample platform. This was done to ensure that axis of rotation matches with the central ray.

Figure 11. A typical reconstructed density profile along a horizontal line

Figure 12. A typical reconstructed density profile along a vertical line.

Figure 9 is a typical projection data profile at a given angle through this specimen. The peaks at extreme ends are because of the lesser thickness of the SS wall as compared to the broad ones due to the aluminium blocks. The Linear increment was 0.5 mm and a total of 259 points were recorded in one projection data thus giving a circle of reconstruction of 129.5 mm. The number of angular views was set to 100. This set of 25,900 data points or measured ray sums constituted the input data of the tomographic image reconstruction. The data was fed to the CITIS image reconstruction software, which is an integrated package for tomographic image reconstruction, image display, graphical profile display and data management developed by the authors. Figure 10 (259×259 pixels) is the reconstructed tomographic image, which clearly shows all the details (marked with arrows) along with reconstruction noise. Also, the interface in between the two rectangular aluminium blocks is visible. Figure 11 is the reconstructed density profile along a horizontal line ($y = 26$) through the reconstructed image while figure 12 is the reconstructed density profile along a vertical line ($x = 126$). The horizontal axes of these two plots are expanded to show the variations inside the specimen. A dip in the second broad peak from left in figure 10 is because of the resolved interface as shown in the image. All the images and diagram shown here are not to scale. The mean value of the reconstructed linear absorption coefficients were calculated within a rectangular window of 25×25 pixels and the standard deviation was found to be stable over different regions inside the Perspex cross-section. Table 1 lists the window coordinates and calculated values as described above. X and Y coordinate values are relative to the top left corner of the figure 10. We have also not observed any cupping effect within the uniform density region of the Perspex block.

Table 1. Calculated values of mean linear absorption coefficients and standard deviation. Actual image size: 259×259 pixels..

Upper left corner		Lower right corner		Mean value $\times 10^{-1} \text{ (cm}^{-1}\text{)}$	Root mean square value $\times 10^{-1} \text{ (cm}^{-1}\text{)}$	Standard deviation ($\times 10^{-3}$)
x	y	x	y			
94	109	119	134	2.482	2.487	15.70
108	104	133	129	2.472	2.474	8.235
111	85	136	110	2.477	2.479	9.516
123	100	148	125	2.461	2.462	8.526

7. Conclusion and further studies

The study demonstrated a methodology of online averaging, which may be easily adopted for pre-processing scanned data for tomographic image reconstruction for NDT applications. The experiment also shows one of the possible configurations of a tomographic imaging system designed around a general-purpose radiographic X-ray source and commonly available data acquisition systems. The experience gained with these studies will be useful in configuring and designing high-energy X-ray based industrial tomographic imaging systems. Further experiments are being carried out on beam quality and dose stability and the possible measures to minimise artifacts in computed tomographic images because of motion instability and non-uniformity in detector output in case of linear detector array based imaging systems.

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