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Ring artifact correction in gamma-ray process tomography imaging

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ABSTRACT

Ring artifacts have been studied for X–ray based Computed Tomography (CT) systems but not on γ-ray based in-situ applications. This paper discusses application of recently proposed automatic ring artifact reduction method (Yoon et al., 2016) on previously obtained experimental projection data from a γ-ray based Industrial Process Tomography (IPT) system for a prototype catalytic column. Studies include qualitative and quantitative evaluation of the method. It is observed that ring artifacts are suppressed without loss of significant information in γ-ray PT images.

1. Introduction

Industrial Process Tomography (IPT) is an imaging technique used to generate a cross-sectional image of a process column from measured data. Thus, it is basically an application of CT technology in process industries where using X-ray source as required in a CT set-up is not feasible (IAEA-TECDOC-, 1589, 2008). Typically, such installations use γ-rays from an appropriate radioisotope selected based on desired penetration power, which is generally higher than that of conventional X-rays used in laboratories. Portability of the radioisotope source is also one of the potent advantages. ^{60}Co and ^{137}Cs are preferentially used as a gamma radiation source due to their high penetration power into large and high-density objects (Boyer and Fanget, 2002). In industrial conditions it may be difficult to obtain systematic data in usual CT geometry because of restrictions in access; therefore, most of the systems prefer acquiring sparse data and using iterative reconstruction techniques (Clackdoyle and Defrise, 2010; Fessler, 1995). However, it is desired to have uniformly spread dense dataset to apply analytical method like Filtered Back Projection (FBP) to obtain similar images. This method not only requires access all around the column but also needs enough projections and samples per projection to get a decent reconstruction. An array of detectors formed using individual scintillator detectors along with a radioisotope source and mechanical manipulator system can create such dataset for obtaining steady state flow distribution across dynamic flow process columns with or without catalysts. Like the X-ray based CT systems employed in controlled conditions in laboratory environments, the in-situ γ-ray based PT systems also suffer from artifacts and require data filters to correct them.

One such commonly visible error ‘Ring artifact’ occurs in IPT due to non-uniform response of individual detector elements used in forming a linear array for data acquisition. Ring artifacts are concentric rings in the reconstructed images around the center of rotation of a tomographic setup (Prell et al., 2009). They not only degrade the appearance of a reconstructed image but also introduce errors in measurement of geometrical parameters and their quantification in terms of attenuation coefficient or approximate bulk densities. Therefore, removing or reducing such artifacts is indispensable for qualitative and quantitative analysis of the tomographic images (Abu Anas et al., 2010) especially for the characterization of porosity and liquid retention through process column. Porosity and liquid retention are two important parameters to evaluate since they provide data for two-dimensional hydrodynamic models (Abdolkarimi, 2013; Bittante et al., 2014).

Techniques to reduce ring artifacts can be broadly classified into two approaches: image-domain post-processing approach and sinogram-domain pre-processing approach (Rashid et al., 2012). There are also approaches, which differ from sinogram pre-processing and image post-processing techniques (Paleo and Mirone, 2015). In the image-domain post-processing approach, different image processing algorithms are applied on reconstructed image corrupted with ring

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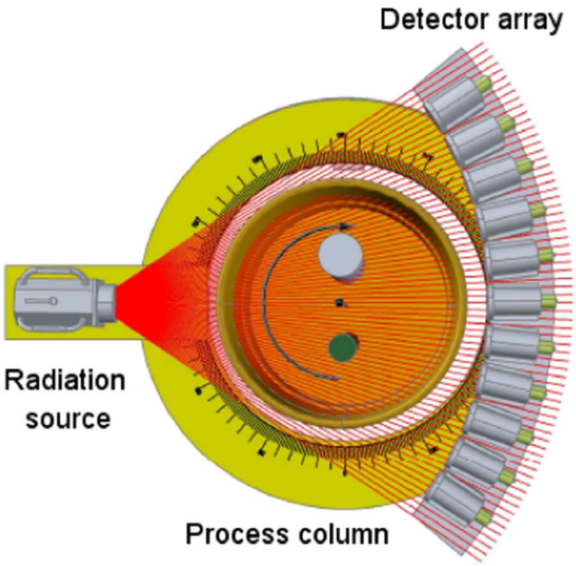

Fig. 1. Schematic representation of equiangular fan-beam geometry used for the experiment.

artifacts. On the other hand, sinogram-domain pre-processing approach modifies acquired sinogram by processing using various filters and algorithms before reconstruction (Ashrafuzzaman et al., 2011; Brun et al., 2011, 2013; Hasan et al., 2012). Sinogram pre-processing approach includes wavelet-fourier filtering (Munch et al., 2009); line-ratio based correction method (Kim et al., 2014), automatic ring artifact reduction method (Yoon et al., 2016), and 1D filter for ring artifact suppression (Titarenko et al., 2016). An Automatic Ring Artifact Reduction (ARAR) method aims at estimation of non-uniformity of detector elements in the sinogram space. Literature survey however reveals that not much work has been reported involving studies on ring artifact and its correction in γ-ray tomographic imaging.

This paper studies ring artifact correction in γ-ray based process tomography images by ARAR algorithm keeping FBP filter unchanged. The assessment of the effectiveness of the ARAR method was carried out using experimental simulation data acquired on a custom built Process Tomography (PT) system. Qualitative comparison of PT slices by visual inspection and quantitative comparison performed using image quality indices are also presented. The data presented here was acquired four years back on the system installed at R & D center of Indian Oil Corporation Ltd, Faridabad, India.

The paper is organized as follows; Section 2 explains the geometry of data acquisition for the experiment and Section 3 elaborates the FBP filtering and ARAR method for correcting ring artifacts. Section 4 contains method employed for image reconstruction and Section 5 has the description of evaluation metrics. Section 6 describes the experimental PT system used for data acquisition. Experimental results and discussion are presented in Section 7. Finally, conclusions are given in Section 8.

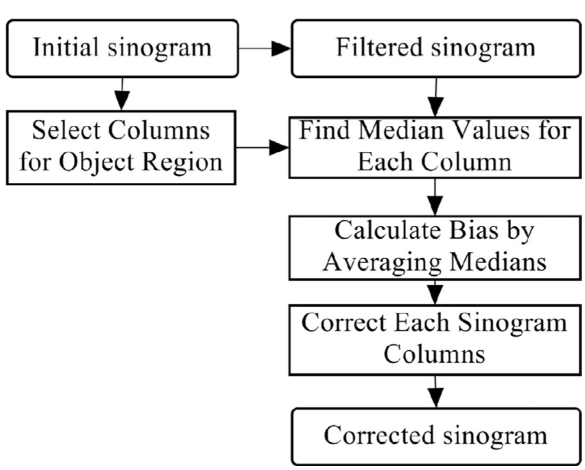

Fig. 2. Flow diagram of ring artifact reduction procedure.

2. Projection data acquisition

Acquisition of γ-ray projection data is based on equiangular fan-beam geometry (Fig. 1). Fan-beam projection, P_{raw} (β_i,θ_n), can be expressed as shown in Eq. (1) (Kak and Slaney, 2001):

$$P_{raw}(\beta_i, \theta_n) = \ln\left[\frac{(I_0 - D)}{(I - D)}\right];\quad i = 1, 2, \ldots, N_p \text{ and } n = 1, 2, \ldots, N_s \tag{1}$$

Where, I and I_0 respectively represent detected intensities with and without specimen at n-th detector element for projection angle β_i, θ_n is the angle of the n-th detector element in the fan-beam, D is the intensity of background radiation when there is no gamma source, N_p is the total number of projections, N_s is the total number of samples per projection, i and n are indices for projection angle and detector element, respectively.

An averaged I_0 has been observed to be giving 33,000 photon counts while the background, D, has been observed 300 photon counts which is small value relative to I_0. The set of projection data over N_p projections with N_s rays per projection forms a ‘sinogram’. The columns in the sinogram represent detector elements and rows represent projection angles. Thus, any detector irregularities or inhomogeneities manifest as vertical lines in unfiltered sinogram.

3. Data processing

Data processing consists of two steps: filtering to reduce noise and ring artifact reduction.

3.1. Filtering to reduce noise

Standard FBP reconstruction filter have been used to reduce noise in the experimental projection data. It is a combination of Ram-Lak filter and a low-pass (window) filter. Filtering operation can be accomplished by a multiplication in Fourier space. The Fourier transform operator, F, of i-th row of filtered sinogram P_{corr} is given by:

$$F[P_{corr}(\beta_i, \theta)] = F[P_{raw}(\beta_i, \theta)] \otimes w_s(\theta) \otimes h_r(\theta) \tag{2}$$

Where $\otimes$ is the convolution operator, $w_s(\theta)$ is the low-pass filter and $h_r(\theta)$ is the Ram-Lak filter.

Using inverse Fourier transform operator, F^{-1}, on Eq. (2), the i-th row of filtered sinogram can be expressed as

$$P_{corr}(\beta_i, \theta) = F^{-1}[F[P_{raw}(\beta_i, \theta)] \bullet W_s(q) \bullet H_r(q)] \tag{3}$$

Where ‘•’ is the multiplication operator, $W_s(q) = F[w_s(\theta)]$ and $H_r(q) = F[h_r(\theta)]$. This means that W and H are in Fourier space while w, h, P_{raw} and P_{corr} are in real space.

In this study, specifically, four widely employed filters (Shepp-Logan, Hamming, Hann and cosine) have been used for filtering γ-ray experimental projection data to suppress the noise. The filters are characterized by one tuning parameter referred to as cutoff frequency, also known as roll-off frequency or critical frequency. The amplitude of the filter at cutoff frequency is dependent on the type of filter. The cutoff frequency (f_c) is a function of cutoff value and Nyquist frequency (N_q) according to the formula (Bian et al., 2013; Lyra and Ploussi, 2011):

$$\textit{Cutoff frequency} = \textit{Cutoff value} \bullet \textit{Nyquist frequency} \tag{4}$$

$$N_q = \textit{Nyquist frequency} = \frac{1}{2\Delta} \tag{5}$$

Where Δ is the sampling interval.