Validation Process for Electrical Charge Tomography System Using Digital Imaging Technique

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Abstract
Electrical charge tomography (EChT) is a non-invasive imaging technique that is aimed to reconstruct the image of material being conveyed based on data measured by electrodynamics sensor installed around the pipe. The method to ensure the stability and accuracy of the image reconstruction should be applied to obtain a meaningful image reconstruction results. In this paper, Least square with regularization (LSR) method was introduced to reconstruct the cross-section image of material in gravity mode conveyor pipeline. Numerical analysis result based on data measured by sensor indicates that the algorithm is efficient to overcome the numerical instability. Instead of image reconstruction process, validation of the images is very important. It would be parts of verification process to the new image reconstruction method. In this system, digital imaging technique was used to interrogate the flow in pipeline around sensing area using CCD camera. It was found out that there is a good match between LSR method of image reconstruction and image capture by CCD camera due to the similarity of both images. This study implies that LSR method produced images that are stable and accurate as well as applicable for industrial use. It is suggested that another validation process should be conducted using duty ratio, signal to noise ration and structure correlation to validate the quality of image produced by LSR method.

Keywords: Tomography, Digital imaging technique, Least square, Validation, Regularization method

1. Introduction
Electrical charge tomography (EChT) is a non-invasive imaging technique that is aimed to reconstruct the image of material being conveyed in pipeline. Electrical tomography has many advantages over other tomography modes due to
its high-speed, low-cost, non-intrusive sensors, no radiation, rapid response and robust as well as suitable for industrial applications (Yang & Liu, 2000).

Many image reconstruction techniques have been extensively developed over the last two decades as reliable tools for electrical tomography. Examples are system linear back projection (Dyakowski, et. al., 1997), filter back projection (Isa et. al, 2008), singular value decomposition (SVD) (Hua, et. al. 2004), Tikhonov regularization (Jinchuang et. al. 2002), simultaneous algebraic reconstruction technique (Jiang et. al. (2003), landweber iteration (Yang et. al. 2003) and etc.

In electrical charge tomography, although there are numbers of work been done applying electrostatic charge carried by particles in solid/powder conveyor pipeline to tomographic imaging, only three methods were introduced - namely linear back projection (LBP), filter back projection (FBP) and least square method (Bidin et. al., 1995; Machida et. al. 2000; Green et. al.,1997).

In this paper, novel algorithm for electrical charge tomography is presented. Basically, the previous method will be discussed and the advantages of the new method will be highlighted. All discussion will be based on similarity of the image being reconstructed by these methods as compared to image captured by CCD camera that has been processed using digital imaging technique.

2. Methods & materials

2.1 Background to EChT image reconstruction

EChT image reconstruction process involves two problems which have to be solved i.e. forward modeling problem solution and inverse problem solution. In electrical charge tomography, imaging forward modeling is pre-described as the theoretical of the system in sensing area. It is related to sensor’s sensitivity to the three-dimensional charge which contains a uniformly distributed charge in coulomb per square meter (C/m²). Process tomography system by electrical charge is given one measurement from each of the sensors; the amount of information available is equal to the number of the sensors (Green et. al., 1997). Therefore, forward modeling of the pipe and the sensing area are mapped equally to the number of the sensor i.e sixteen by sixteen rectangular arrays consisting of 256 pixels or elements. The length between sensors is divided equally and located around the pipe at respective coordinates. The sensitivity map, S derived from the modeling and the summation of complete sensitivity map for sixteen sensors in two and three-dimensional is shown in Figure 2.

Inverse problem is the solution to provide an image of the charge concentration distribution within the sensing area. The data captured by 16 sensors is used to generate an image concentration. This image concentration is generated using analytical and statistical approaches such as linear back projection (LBP), filter back projection (FBP), and least square with regularization (LSR) methods.

2.2 Linear Back Projection (LBP)

Linear back projection is a straight forward solution which refers to the relationship between the distribution of charge, q and the detection of voltage by the detector as in equation (1).

\[ V = S \cdot q \]  

(1)

S is the sensitivity map or sensitivity matrix with a dimension of 16 X 16 (as discussed in section 2.0). The measurement data, V and the charge distribution q are unknown.

To reconstruct the images in this system, the inverse problem has to be solved using equation (1). However, there are some difficulties in calculating the inverse matrix of the sensitivity matrix S. The concept of general inverse has to be introduced. Moore proposed the concept of general inverse matrix, and Penrose gave the definition of Moore general inverse matrix in a definition form (Yong et. al., 2007). Thus, the equation (1) becomes \[ q = S^{-1} \cdot V \], known as back projection. In practice, the concept of pseudo-inversion is used by assuming that \[ S^{-1} = S^T \] (Dyakowski et. al., 2000). In the reality, S is a symmetry value, so this is formulated as equation (2).

\[ q_{LBP} = S \cdot V \]  

(2)

2.3 Filter Back Projection (FBP)

The major limitation of linear back projection method arises due to the non-linear sensing mechanism of the electrostatic charge transducer. Filter can be determined by combining with the back projection method to provide filtered back projection. This filter provides weighting to individual pixels to provide a uniform concentration profile when the sensor has equal outputs (Green et. al.,1997).

The filter matrix is obtained by taking the maximum value of pixel divided by each value of pixel within the pipe mapping as shown in equation (3).

\[ Filter = \frac{S_{max}}{S_i} \]  

(3)

Filtered back projection is a result of linear back projection multiplied by filter matrix of S, written as equation (4).

\[ q_{FBP} = S \cdot V \cdot Filter \]  

(4)
$q_{FBP} = q_{LBP} \times Filter$ (4)

2.4 Least Square with Regularization Method (LSR)

Least square (LS) method is almost the solution to the inverse problem of equation when measurement error are considered. It is meant to minimize the equation (1).

$$\text{Min} ||Sq-V||^2$$ (5)

Where, $q = (S^T S)^{-1} V$ (6)

The solution of equation (6) is not unique. This is because the matrix $(S^T S)^{-1}$ is not invertible. Therefore, the equation (6) is not a stable solution. A general principle of dealing with the instability of the problem is regularization (Yan et al., 2001), imposing additional information about the solution. A penalty term can be added to the optimization problem as in equation below.

$$E(q) = \text{argmin} ||Sq-V||^2 + \beta^2 ||R(q-q_0)||^2$$ (7)

A simple choice for the regularization penalty term is Tikhonov regularization (Jing et al. 2008). The aim of this regularization is to dampen the contribution of small singular value in solution. The matrix R is a regularization matrix which penalizes extreme changes in parameter q, removing the instability in the reconstruction. The parameter β called regularization parameter control the trade-off between the data fitting and violates the prior assumption. The solution of equation (7) would be written as a simple form of the standard Tikhonov where

$$q^L = (S^T S + \beta^2 I)^{-1} S^T V$$ (8)

For the described algorithm, the choice of regularization is important. In general, a small value of β gives a good approximation to the original problem but the influence of errors may make the solution physically unacceptable. Conversely, a large value of β suppresses the data but increases the approximation error. At present, in most cases, β is chosen empirically (Tarantola, 2004). The value of regularization parameter 0.025908 is obtained.

2.5 Singular Value Decomposition (SVD)

The SVD will reveal all the difficulties associated with the ill-conditioning of the matrix (Soleimani, 2005). Let K be the matrix of reconstructed image with M X N rectangular matrix where $M \geq N$, Then, the SVD of K is a decomposition of the form (Hansen, 2007):

$$K = \sum_{i=1}^{\text{Min}(m,n)} u_i \sigma_i v_i^T$$ (9)

Where $U_i = (u_1, \ldots, u_m)$ and $V_i = (v_1, \ldots, v_n)$ are matrices with orthonormal columns, $U_i^T U_i = V_i^T V_i = I_{n_i}$, where $\Sigma = \text{diag}(\sigma_1, \ldots, \sigma_n)$, $\sigma_i$ are the singular values of S, while $U_i$ and $V_i$ are the left and right singular vectors of S.

Discrete ill-conditionings will be considered if condition number of K is large. The condition number is equal to the ratio as equation (10).

$$\text{Cond}(S) = \sigma_1/\sigma_n$$ (10)

2.6 Digital imaging technique by CCD camera

Other than the image reconstruction process, the validation of image is also very important. It would be part of verifying process of the new image reconstruction method. In this system digital imaging technique is used to interrogate the flow in pipeline around the sensing area using CCD camera. When materials or particles flow through a pipeline, it is possible to acquire images using CCD camera with suitable illumination light source (Carter et al. 2003).

CCD camera is used to capture image of particles (Carter et al. 2003; Sugita et al. 2003; Carter et al. 2005) for various purposes such as particle size analysis, particles size distribution, mass flow rate and etc. It is quite a simple matter to focus a CCD camera on this system and acquire digital images. This general concept is illustrated in Figure 2. CCD camera will capture video of materials moving through the pipe hole as shown in Figure 2. Meanwhile, the electrodynamics sensor will be induced with charge from the material that passes through the sensors. This charge will be converted into voltage by electrical conditioning circuit attached to the sensor. The voltage will be sent to image reconstruction of computer system through Keithely STA-1800HC data acquisition card. Image reconstruction process is conducted off-line using Matlab programming language. These two types of measurements will be treated separately. Video captured by CCD camera will be processed using digital image processing and measured data from the sensor will be used to reconstruct the cross-section image of the pipe through sensing area using LBP, FBP and LSR methods. Image reconstructed by these methods will be compared to image captured by CCD camera. Validation of the image reconstruction methods will be based on similarity to the image produced by the CCD camera. The length between the point of the video captured by the CCD camera and the point of the electrodynamics sensor location is very short.
Therefore, image captured by the CCD camera and image reconstructed from the measured data by electrodynamics sensor are assumed similar.

The video captured by the CCD camera will go through several processes to produce a single image and to produce the concentration of particles in the pipeline. The processes involving algorithms for image processing are shown in Figure 3. Figure 3 shows the schematic flow of the algorithm for image processing. Materials being moved through the pipe are captured by a CCD camera. This is continuously recorded in videos with an image size of 1000 x 1000 pixels in color. The data measured by the electrodynamics sensor are also recorded with both processes occurring at the same time. All the preprocessing and processing stages of the image are done off-line. Preprocessing such as video framing, frame background selection and frame with particles selection are performed using Virtual Dub application program. Meanwhile, processes to produce image with absolute value and threshold are done using Matlab. The process to identify the sensing area, image conversion and scaling are done using Adobe Photoshop. Finally image is displayed using Matlab.

3. Results & discussion

This section focuses on the digital image processing from the video data captured by CCD camera and image reconstruction processes based on LBP, FBP and LSR methods. Images produced by both techniques will be compared. Results from image reconstruction processes by LBP, FBP and LSR methods and validation process above have highlighted some information. Firstly, the image reconstructed using least square with regularization method is similar with the image captured by CCD-camera whereby condition number obtained by LSR method is better than others. Secondly, the image reconstructed using FBP is accurate in detecting the location of the charge but it did not distinguish between two or more charges in sensing area. But LSR method has capability to solve this problem. Finally, the mage reconstructed using LBP is focused on the sensor location. It means that LBP method is not suitable to reconstruct the image for electrical charge tomography because of its non-linearity to the sensing mechanism. Thus, it shows that LSR method provides good promising result in terms of accuracy and stability of the image being reconstructed. It means that LSR method produces better image stability than any other methods including CCD camera.

4. Conclusion

The results from image reconstruction processes by LBP, FBP and LSR methods and validation process above have highlighted some information. Firstly, the image reconstructed using least square with regularization method is similar with the image captured by CCD-camera whereby condition number obtained by LSR method is better than others. Secondly, the image reconstructed using FBP is accurate in detected the location of the charge but it did not distinguish between two separately charge in sensing area. But LSR method has capability to solve this problem. Finally, the mage reconstructed using LBP is focused on the sensor location. It means that LBP method is not suitable to reconstruct the image for electrical charge tomography because of its non-linearity to the sensing mechanism. Thus, it shows that LSR method provides good promising result in terms of accuracy and stability of the image being reconstructed. It means that this paper is success to achieve their objective as mention earlier. The image produced by LSR method is better in terms of its accuracy, stability and suitability to be used in industries. In addition, more work should be done in validating the proposed algorithm such as computation of image error and quality of the image using duty ratio, signal
to noise ration and structure correlation as well as improving ill-posed of sensitivity matrix in mathematical modeling. For this system to be used in real industry environment, more work on hardware and software systems should be carried out to warranty their data and algorithm is well organized and developed.

References


Table 1. Condition number from various regularization parameter $\beta$ for LSR images

<table>
<thead>
<tr>
<th>Images</th>
<th>Condition Numbers of ill-posed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image captured by CCD camera</td>
<td>$1.63 \times 10^3$</td>
</tr>
<tr>
<td>Image reconstructed by LSR</td>
<td>224.53</td>
</tr>
<tr>
<td>Image reconstructed by FBP</td>
<td>$5.15 \times 10^5$</td>
</tr>
<tr>
<td>Image reconstructed by LBP</td>
<td>$7.63 \times 10^5$</td>
</tr>
</tbody>
</table>

Figure 1. Two and three-dimensional Total Sensitivity map, $S$.

Figure 2. Particles imaging technique
Figure 3. Schematic flow of the algorithm for image processing

- Extract video frame
- Select frame background
- Select best frame with particles
- Produce a single image with absolute value and threshold by
- Identification of sensing area
- Change image mode (grayscale) and size (pixels)
- Display image of particle concentration

Figure 4. Images produced from preprocessing and processing stages

(a) Image with absolute value and threshold
(b) Image with identified sensing area
(c) Image with mode (grayscale) and size (16 X 16 Pixels)
(d) Image of particle concentration

Figure 4. Images produced from preprocessing and processing stages
Figure 5. Image being compared: (a) Image recorded by CCD Camera (b) Image reconstructed by LSR method (c) Image reconstructed by FBP method and (d) Image reconstructed by LBP method.