Research on the SR-CT technique in microstructures testing during dynamic processes

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Abstract. Synchrotron Radiation X-ray Computerized Topography (SR-CT) is an advanced technique, which is a unique combination of synchrotron radiation and computerized topography technique. Different from other conventional materials testing instruments, SR-CT technique has its advantages, such as non-destructive and real-time, etc. Therefore, it may be a powerful materials testing method in dynamic processes. However, there are also some actual problems. The high quality of the reconstructed images needs larger number of projections and much projection collecting time, but it is not allowed in dynamic processes because of sample evolution. Moreover, the noise in the projection images and some other factors reduced the reconstruction quality. The purpose of this work is to apply SR-CT technique in dynamic processes. A numerical simulation, including a generalized noise model considered the real situation of SR-CT experiment, different from the previous work, of SR-CT experiment was performed in order to carry out a quantitative evaluation on actual SR-CT experiment. A kind of iteration method was proposed to improve the quality of reconstructed images. The quality of reconstructed images was evaluated by three image evaluation parameters. The result shows that all three image evaluation parameters have obvious improvement by iteration method. Images from real SR-CT experiment were treated by iteration method to verify the effectiveness of iteration method, and high quality images can be obtained. The iteration method is appropriate and can be applied in the SR-CT experiment in microstructures testing during dynamic processes.

Keywords: synchrotron radiation; computerized topography; numerical simulation; image reconstruction; iteration method; image quality

1 Introduction

SR-CT is an advanced technique with which the cross sections of observed objects can be obtained without sample destructing, which has been widely used in many science fields [1-4]. Some scholars have studied on the algorithms of image reconstruction [5-7], which, however, are mostly based on ideal situation. As SR-CT technique can observe internal structures of samples, it is an excellent method to carry out research on dynamic processes such as apoptosis of plants, material damage and ceramic sintering. In situ observation of dynamic processes under extreme conditions (e.g., high pressure, high temperature, intense radiation, etc.) becomes probable by this technique. When carrying out SR-CT experiment, the sample is placed on a turn table; synchrotron radiation X-ray passes through the sample and is received by a X-ray CCD; the turn table rotates a angle and a projection is collected by X-ray CCD; after the projections within 180 degrees are collected, the cross sections of sample can be reconstructed by reconstruction algorithms (figure 1) [8].
Lots of scholars have studied on the reconstruction methods, but most of them are based on ideal situation. 180 projections (one projection per degree) are enough for reconstruction and the quality of the reconstructed images is quite acceptable in ideal situation without noise in projections [9]. However, are 180 projections enough in real situation? The fact is that the more projections there are, the higher quality of reconstructed images is (usually, more than 1000 projections are required) because of the existence of noise in real situation. However, excessive projections limit the application of SR-CT experiment in dynamic processes. Large number of projections needs much time to collect, which is not allowable in dynamic processes because the samples may change acutely in the period of collecting projections. Therefore, it is essential to find a method to solve this problem. Moreover, in SR-CT experiment there are several crucial factors to the quality of reconstruction images, including the noise of X-ray detector, the vibration of the rotation axis and the heterogeneity of light field. All these factors influence the quality of reconstructed images directly. In this paper, a solution to this problem is proposed: a kind of iteration method was applied for the first time. This method is effective and high quality images can be obtained. SR-CT technique can be used in microstructures testing during dynamic processes.

2 Simulation of real situation

2.1 Introduction of simulation

In SR-CT experiment, the samples are usually a multiple-hole and multiple-grain structures. To be close to real situation, a 3D sample which simulates the ceramic specimen was generated by computer. In the simulated sample, particles are spherical whose diameters are from 6 to 10 pixels, and the 3D matrix is $256 \times 256 \times 256$ pixels. The volume ratio of particles to pores is 11:9 because the particles and the pores can be resolved clearly in this ratio and it is similar to real samples. The 3D simulated sample and its slice image are shown in Figure 2 left column.

In SR-CT experiment, noise which directly influences the quality of reconstructed image has been spotted in projection images. The middle column of Figure 2 shows the ideal projection and projection with white Gauss noise. Both of the two kinds of projections are generated by performing Radon transform on 3D sample [10]. The reconstructed images by ideal projections and projections...
with white Gauss noise are placed at right column of Figure 2. The image reconstructed by ideal projections is quite the same as original image; however, the quality of the image reconstructed by projections with noise is not so good. So how to improve the quality of reconstructed image by projections with noise is the key.

**Figure 2.** Comparison of ideal situation and real situation

### 2.2 Noise model

In SR-CT experiment, there are several kinds of noise. The noise here is generalized, which includes noise of X-ray detector, vibration of the rotation axis and heterogeneity of light field. These factors are directly related to the quality of reconstructed images. All these factors were considered and added into projections. The generalized noise model is proposed by formula 1. $\hat{P}$ is the projection image acquired by X-ray CCD; $P$ is the ideal projection which is generated by performing Radon transform on 3D simulated sample; $\Delta i$ and $\Delta j$ represent vibration of the rotation axis; $N$ is white Gauss noise; $AT$ is heterogeneity of light field in the aspect of time; $E$ is other factors.

$$\hat{P}(i, j) = P(i + \Delta i, j + \Delta j) + N(i, j) + AT(i, j) + E(i, j)$$  \hspace{1cm} (1)

#### 2.2.1 Vibration of rotation axis

The vibration of rotation axis in vertical direction and horizontal direction is inevitable although rotary precision of turntable can be quite high. Particularly, in the experiment of ceramic sintering, the change of temperature makes rotation axis expand and shrink and it leads to vibration. In this paper, vibration is added by following form: 40% of projections vibrate and 60% of projections do not vibrate; vibration form is simple harmonic vibration whose vibration amplitude is 2 pixels and frequency is 1000. The vibration form can be described as:

$$\Delta i = \begin{cases} 0 & \text{if } g < 0.6 \\ 2 \times \sin(1000 \times \theta) & \text{else} \end{cases}$$  \hspace{1cm} (2)
\[
\begin{cases}
\Delta j = 0 & \text{if } g < 0.6 \\
\Delta j = 2 \times \sin(1000 \times \theta) & \text{else}
\end{cases}
\]  
(3)

\(\Delta j\) and \(\Delta f\) represent vertical direction and horizontal direction respectively. \(g\) is a random number which is even distributed within the range of 0 to 1. This kind of vibration form is a very simplified model, as the real situation is difficult to detect. This vibration form can basically reflect the influence of vibration on the quality of reconstructed images although it is not the real form.

### 2.2.2 White Gauss noise

The noise caused by projection collection system is mainly white Gauss noise, so white Gauss noise \(N\) is added into projections [11]. After analyzing the background image, the white Gauss noise with signal noise ratio (SNR) 20 db is added into projections [12-13].

### 2.2.3 Heterogeneity of light field

In this paper the heterogeneity of light field is the heterogeneity in the aspect of time, as the heterogeneity in the aspect of space can be ignored in synchrotron radiation light field. However, the light field of synchrotron radiation changes greatly after injecting charged particles. As time goes by, the intensity of light field attenuates slowly. The factor of heterogeneity of light field can be described as:

\[AT(i, j, \theta) = -k \times \theta \]  
(4)

\(k\) is the attenuation velocity coefficient and \(\theta\) is the angle at which projection is collected. Time and \(\theta\) demonstrate linear relationship, as the time of collecting one projection is a fixed value. For example, when image depth is 8 bit; \(k = 0.2\); the maximum value of \(\theta\) is 180 degrees; the first projection image is 36 gray scales higher than the last projection image (figure 3 (b) and (c)). This simulation of heterogeneity of light field is very simple, but it can reflect the real situation in SR-CT experiment basically.

![Figure 3. Projections.](image)

(a) (b) (c)

Figure 3. Projections. (a) is the projection collected from real SR-CT experiment. (b) and (c) are projections generated by Radon transform. Image (b) is collected at the angle 1 degree and (c) is collected at the angle 180 degree.

### 3 Treatment of reconstructed image

When applying SR-CT technique in dynamic processes such as the process of ceramic sintering, the time of collecting projections must be controlled in short time because of the evolution of samples. In static experiment, the number of projections is usually more than 1000 because the more projections there are, the higher quality of reconstructed images is. The projection collecting time is usually one or several hours, which is acceptable in static processes. But the projection collecting time must be limited in several minutes in the experiment of dynamic process. We can only collect 180 or less projections but it leads to the result that the quality of reconstructed images is not a great satisfaction.
How to improve the quality of reconstructed images by using so a few projections is a key point of this section. Radon transform is applied in processing the reconstructed image. The Radon transform of an image represented by the function \( f(x, y) \) can be defined as a line integrals through \( f(x, y) \) along the direction of \( y \) axis which is located at angle \( \theta \) off the y-axis (figure 4)[10, 14].

Coordinate \((x', y')\) and \((x, y)\) have the relationship that:

\[
\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}
\]

(5)

Radon transform can be represented as:

\[
R(\theta, x') = \int_{-\infty}^{\infty} f(x', y') \, dy'
\]

(6)

![Figure 4. Schematic diagram of Radon transform.](image)

The treatment process of reconstructed images is an iteration process: firstly, reconstructing the image by using projections collected in real SR-CT experiment (usually less than or equal to 180 projections) through filter-back-projection algorithm [14]; secondly, performing Radon transform on reconstructed image in first step at 360 angles (interval angle is 0.5 degree); thirdly, reconstructing the image by 360 projections generated in the second step and a new image is obtained; then repeating the second and the third step and entering the iteration process. The flowchart of this treatment is shown in figure 5 and the reconstructed binary images are shown in figure 6.

![Figure 5. Flowchart of iteration process](image)
Figure 6. Reconstructed binary image. (a) is the reconstructed image without treatment. (b) is the image with 1 time iteration. (c) is the image with 3 times iteration

The treatment of iteration method can be regarded as a special mean filter carried out on the projection line. Some pixels of image are shown in figure 7 and the principle of iteration method can be explained. When the number of projections is not enough, OA and OB passing through point 1 but 2 are two adjacent projection lines located at origin of coordinates. If point 2 is an error point, the information of point 2 can not be transferred to point 1 when performing back projection process. But if you double the number of projections (reduce the interval angle by half), point 1 and point 2 can be connected by projection line OC. The process of projection can be seen as accumulation on projection line. Correspondingly, the process of back projection can be seen as equal division on projection line. Every point on the projection line is distributed equally. This method is different to traditional mean filter, because it can not only eliminate noise but also keep the details resolution of images. In the whole reconstructed image, the points with the relationship like point 1 and point 2 are in plenty, so the effect of iteration method is remarkable.

Figure 7. Explanation of iteration method

Image evaluation parameters are needed for evaluating the quality of reconstructed images. In this paper, covariance correlation coefficient, normalized mean square distance and normalized average absolute distance are applied to evaluate the quality of images [14]. Covariance correlation coefficient is used for measuring the degree of closeness between reconstructed image and original image. The more similar two images are, the greater covariance correlation coefficient is. Normalized mean square distance and normalized average absolute distance are used to measure the difference between two images, and small value on these two parameters demonstrates high quality of reconstruction. The value of evaluation parameters of reconstructed images are shown in Table 1. It can be concluded from table 1 and figure 6 that the quality of images treated by iteration method is
much better than the quality of images without treatment. The image is the most acceptable after 3 times iteration.

The iteration method is executed on the images reconstructed from real SR-CT experiment projections. This experiment which aims at detecting the microstructure evolution of dynamic process in ceramic sintering process was performed at the BL13W1 beamline in Shanghai Synchrotron Radiation Facility. The available tunable energy range of this system is 8–72.5 KeV and the resolution of X-ray detector is 7 μm/pixel and the field of view is 1.4 cm (width) ×5 mm (height). The X-ray with energy of 20 keV was selected in this experiment. The experiment sample is silicon carbide (SiC) particles tacked in quartz capillary with the external diameter 1 mm. The reconstructed images of this experiment are shown in figure 8.

| Table 1. Evaluation parameters of reconstructed images |
|-------------------------------------------------------|
| Image without treatment | covariance coefficient | normalized mean square distance | normalized average absolute distance |
| Iterate 1 time | 0.7832 | 0.6488 | 0.3141 |
| Iterate 2 times | 0.8380 | 0.5709 | 0.2431 |
| Iterate 3 times | 0.8675 | 0.5156 | 0.1983 |
| Iterate 4 times | 0.8515 | 0.5650 | 0.2381 |

From figure 8, we find that the quality of images treated by iteration method is improved obviously. Particles keep the original shape and can be distinguished from noise; the noise points and ring artifacts are well eliminated, which is difficult to achieve for other treatment method. Over segmentation and statistical error can be reduced when performing information extraction of ceramic sintering process [15-17]. So the iteration method can be applied in dynamic processes.

4 Conclusion

In this work, a 3D simulation sample was generated according to real experiment samples in order to carry out quantitative analysis on the quality of reconstructed images. The real situation in SR-CT experiment was considered such as the noise of X-ray detector, the vibration of the rotation axis and the heterogeneity of light field and these factors were added into simulation experiment. A generalized noise model that includes all factors which influence the quality of reconstructed images directly was proposed.
To improve the quality of reconstructed images, a kind of iteration method was proposed, which overcomes the problem that projections are not enough in dynamic process and noise exists in projections. Three image evaluation parameters were applied. Simulation results and experiment results show effectiveness of this method simultaneously.

In the images that were treated by iteration method, ring artifacts and error points are well eliminated and noise can be distinguished from particles and holes by image binarization, which is quite useful for image segmentation and particles statistics in process of information extraction. The influence of noise was reduced by iteration method. The SR-CT technique can be used in microstructures testing during dynamic processes and high quality reconstructed images can be obtained.

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