# On-Site Bridge Inspection with Partial CT by 3.95Mev X-Band Linac Source

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Abstract: Since more and more bridges built several decades ago in Japan have become aged and dangerous, the non-destructive evaluation of those bridges is really an urgent problem. CT system with portable 3.95MeV linacs for bridge inspection is considered to work on-site, considering the law of Japanese radiation protection allows using linacs up to 4MeV outside radiation controlled area. The system would confirm the internal steel situation of bridges and analyze structural strain and stress with 3D model built from sectional imaging to evaluate load-bearing performance. The reconstruction process of bridge imaging is based on partial scanned data because bridge shape confines possible scanning angle to smaller than 180° and a few translations. A small concrete sample with internal steel bars and attachment accessories is scanned in laboratory as preliminary work.

**Keywords**: CT, Linacs, X-ray, NDE

## 1. Introduction

Computed tomography (CT) technology has been undergoing rapid development since announced in 1970s.[1] Credited to CT technology, human's vision ability has been greatly extended to acquire clear interior imaging in biomedical diagnose and many other non-biomedical fields, such as detect interior structure of manufactures nondestructively like bridges. Since more and more bridges built several decades ago in Japan become too old to maintain a satisfactory safety situation, and collapse accidents are even caused due to bridge aging, the non-destructive evaluation of bridges has become a very urgent problem. CT system with linacs under 4Mev for scanning, which is permitted by Japanese law to be taken out of controlled area, is considered to work on-site and evaluate load-bearing performance by confirm the soundness situation of internal steel rods inside bridges[2]. Mechanical analysis for 3D model built with slice images would be carried out as well.

The reconstruction process of bridge imaging is based on partial scanned data with translation and limited rotation angle as indicate in figure 1, because bridge shape confines possible inspect angle to smaller than 180°. In order to achieve higher imaging quality besides maintain efficiency, the Filtered Back Projection (FBP) and Iterative Reconstruction (IR), which are developing with very strong momentum in modern CT, are studied and applied to a small sample with incomplete measured data with 950keV linac in laboratory. The modeling and meshing are processed with reconstructed slice images.

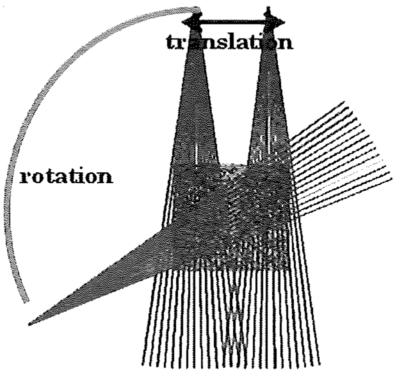

**Fig.1 Partial scanning**

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## 2. Experiment System

The small sample is a concrete cylinder that contains steel rods inside it. Additionally, one aluminum sample, one lead sample and a battery are attached on top of the concrete sample for comparison. Figure 2 shows the experimental system. The X-ray emitted by 950kev linac (Fig.2 a) transmitted through the sample on the remotely controlled rotation stage (Fig.2 b) and reached the detector (Fig.2 c), which would pick up the projection data containing attenuation information. Figure 3 gives the transmitted image of the sample.

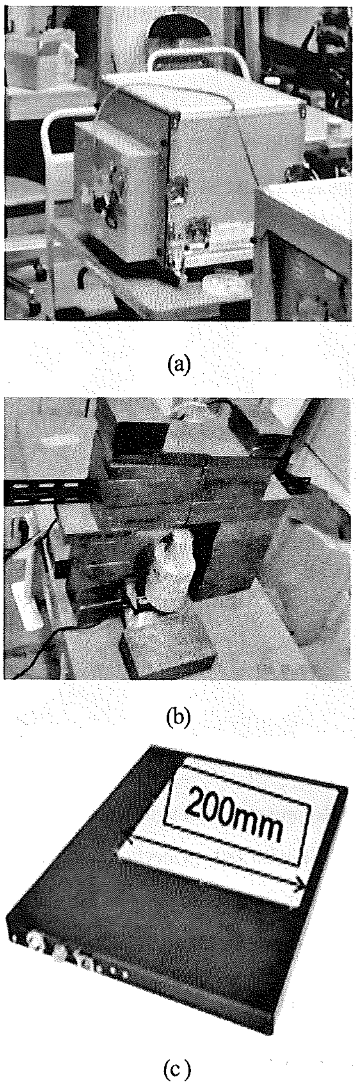


**Fig.2 The 950keV CT imaging system for small sample (a) 950keV linac; (b) Concrete sample on rotation stage; (c) Detector**

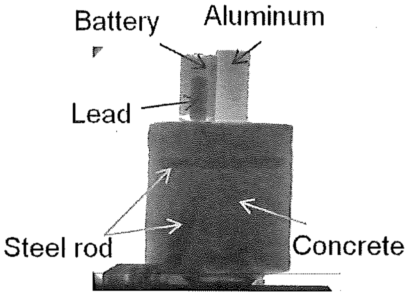


**Fig.3 The transmitted image of sample**

## 3. Reconstruction Algorithms

The projection data is reconstructed with two fundamental algorithms, the Filtered Back Projection (FBP) and Iterative Reconstruction (IR). Their methods are briefly introduced and the reconstruction results are also compared and analyzed.

### 3.1 Filtered Back Projection (FBP)

FBP as an analytic reconstruction algorithm has become the gold standard of almost all current CT appliances[3]. It always based on the X-ray transform function and analytic algorithm derived upon model properties to get discrete solution.

The original function $f(x,y)$ denotes the density property or attenuation efficiency of X-ray going through the measured object and the projection $p(\theta,t)$ the attenuation values. Define the inverse Fourier transform of $f(x,y)$ as

$$f(x,y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F(u,v)e^{j2\pi(ux+vy)}dudv \tag{1}$$

with the equal expression under polar coordinate system

$$f(x,y)=\int_{0}^{2\pi}d\theta\int_{-\infty}^{\infty}F(\omega\sin\theta,\omega\cos\theta)e^{j2\pi\omega(x\sin\theta+y\cos\theta)}\omega d\omega \tag{2}$$

The Fourier transform of projection $p(\theta,t)$ is

$$P_\theta(w)=\int_{-\infty}^{\infty}p(\theta,t)e^{j2\pi\omega t}dt \tag{3}$$

According to the Fourier Slice Theorem, the one-dimensional Fourier transform of a parallel projection is equal to a slice of two-dimensional Fourier transform of the original function. Therefore, it should be possible to estimate the original function by performing a two-dimensional inverse Fourier transform with the given projection data[4].

So by

$$F(\omega\sin\theta,\omega\cos\theta)=P(\omega,\theta), \tag{4}$$

we can get

$$
\begin{aligned}
f(x,y) &= \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} P(\omega,\theta) e^{j2\pi\omega(x\sin\theta + y\cos\theta)} \omega d\omega \\
&= \int_0^{2\pi} d\theta \int_0^{\infty} P(\omega,\theta) e^{j2\pi\omega(x\sin\theta + y\cos\theta)} |\omega| d\omega \\
&= \int_0^{2\pi} d\theta \int_{-\infty}^{\infty} P_1(t)\delta(x\sin\theta + y\cos\theta - t) dt
\end{aligned}
\tag{5}
$$

where

$$
P_1(t) = \int_{-\infty}^{\infty} P(\omega,\theta)|\omega| e^{j2\pi\omega t} d\omega \,. \tag{6}
$$

This process adapts filter kernel

$$
h(t) = \int_{-\infty}^{\infty} |\omega| e^{j2\pi\omega t} d\omega \tag{7}
$$

to weight the Fourier transform of projection before back projection.

This algorithm can effectively eliminate the blurring artifact. However some errors may still be introduced due to discretization and model building in FBP and the imaging quality becomes much worse under noisy circumstance [5].

### 3.2 Iterative Reconstruction (IR)

Iterative reconstruction (IR) technique always uses estimate or prior information such as empty data or FBP reconstruction data as initial value to create artificial raw data. The raw data is compared and corrected with real measured data until reaching a general rule[6].

The most basic and classic IR algorithm is algebraic reconstruction technique (ART), which is adopted in this paper to compare with the reconstruction result by FBP. The process is run for solving the equation

$$
Ax = b \tag{8}
$$

where x is value at each pixels denoting the density property information of the measured object and b the projection data measured in the experiment. A is the integration matrix. The iteration process to solve the above equation adopted Kaczmarz method

$$
x_{k+1} \leftarrow x_k + \lambda_k \frac{b_i - \langle a_i, x_k \rangle}{\|a_i\|_2^2} a_i \,. \tag{9}
$$

IR algorithm can reduce many artifacts effectively. However, it requires high demanding for computational hardware ability. Since all projection data should be available before the iterative reconstruction starts and the reconstruction process is repeated several times, it costs quite large memory and long time to obtain the final imaging[5]. While as the computer hardware has undergoing rapid progress, iterative reconstruction algorithm has re-emerged and become a hot topic in CT reconstruction field[7][8].

### 3.3 Reconstruction with Partial Scanned Data

Both algorithms are applied to reconstruct images of the small sample scanned by 950keV LINAC with 180° and 120° projection data. The results of one slice in the upper part consisting aluminum sample, lead sample and a battery, is showed as figure 4, denoting that ring artifacts and blurring is apparent in FBP imaging and the blurring effect becomes more serious as scan angle reduces in both algorithms. ART imaging is a little clearer under partial scanning situation but it takes 20min to do the calculation, much longer than FBP which only takes 3sec. Generally speaking, both algorithms can give identifiable imaging to discern interior structures. Although the ART algorithms are seems to have some merits, it's still far less computational effective compared with FBP.

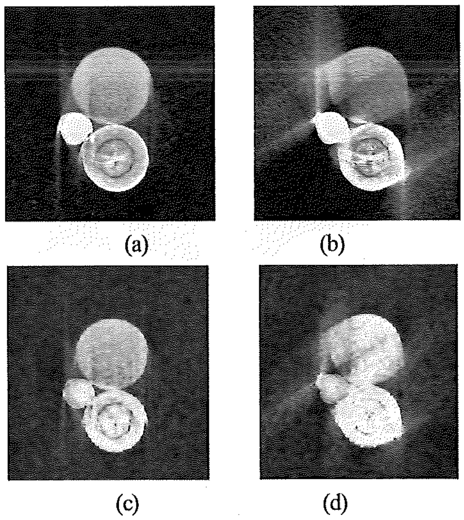


**Fig.4 Reconstructed imaging of a small sample**

**(a: imaging by FBP with 180° projection data; b: imaging by FBP with 120° projection data; c: imaging by IR with180° projection data; d: imaging by IR with120° projection data)**

## 4. 3D Model Building

### 4.1 Sectional Imaging

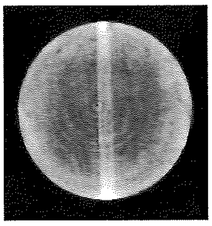
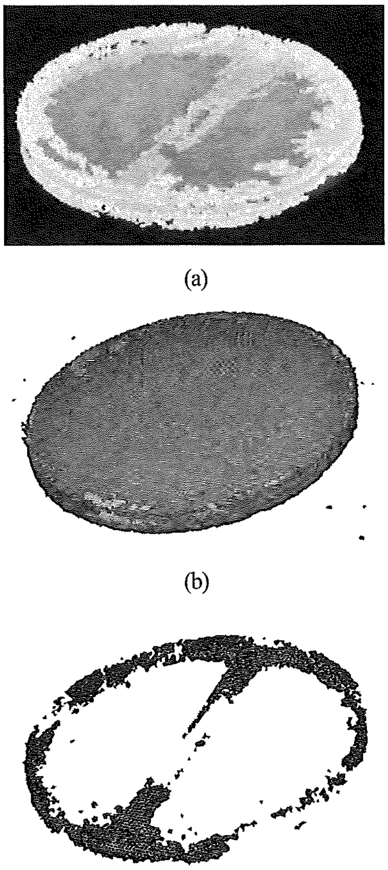


**Fig.5 Image of slice 50**

The whole sample is divided into 95 slices and each sectional image is reconstructed with 180° projection data. Image of slice 50 is showed here in figure 5 as example, indicating that the inner steel rod is identifiable.

### 4.2 3D Model Building and Meshing


(a)

(b)

(c)

**Fig.6 Modeling and meshing of middle part of sample**
**(a: 3D model of middle part of sample; b: meshing of middle part of sample; c: steel rod in meshing of middle part of sample is not well distinguished from concrete)**

V-CAT system of structure modeling developed by Riken, Japan, is adopted for model building and meshing.[9] However, since V-CAT system identifies structure through discerning the imaging color difference, accurate discrimination of inner structure color is highly demanded to build correct model. Although the obtained sectional images are very clear to recognize steel rods, there is still too much noise for modeling with V-CAT system. Figure 6 gives the model of only middle part of sample for the sake of easier color recognition, where an inner steel rod is set horizontally. The modeling process is not so good as expected due to low signal /noise ratio. Lake of penetration ability, revealed by too small color deference between concrete and steel rod in the middle of the sample, also has bad influence reducing that concrete and steel rod cannot be well distinguished (Fig 6 c).

### 4.3 Summary

The method of modeling and meshing with reconstructed sectional images is tested with the small sample while low signal /noise ratio and lake of penetration ability attribute to the unsatisfied accuracy that it affects judgment about the soundness of inner steel rod and mechanical analysis to some extent. Taking into account that partial CT imaging would be inevitably vaguer, improvement of experiment for better signal /noise ratio and penetration ability is required.

## 5. Conclusion

In order to develop the CT inspection system, a small sample is scanned using X-ray linac and imaging is reconstructed with projection data by FBP and ART methods. Both of them are showing promising potential to identify interior structure with partial measured data, while the S/N ratio and penetration is still not enough for modeling and meshing. To improve the experiment result, a line sensor with collimator is considered to reduce scattered X-ray and raise the S/N ratio in future work.

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