Tomogram Enhancement using Iterative Error Correction Algorithm

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Abstract

We developed an iterative algorithm which could improve the resolution of reconstructed tomograms having random attenuation patterns and analyzed the limitation of this algorithm. The simple back-and-forth propagation algorithm has depth resolution about four wavelengths. An iterative algorithm, based on back-and-forth propagation, can be used to improve the resolution of reconstructed tomograms. We analyzed the wavefield for multi-layered specimen and programmed iterative algorithm using Clanguage. Simulation results show that the images get clearer as the number of iterations increases. Also, unambiguous images can be reconstructed using this algorithm even when the layer separation is only two wavelengths. However, this iteration algorithm comes up with an incorrect solution for the number of projections less than five.

I. Introduction

The acoustic microscope was introduced as an alternative to optical, x-ray, and electron microscopy. The conventional scanning laser acoustic microscope(SLAM) generates shadowgraphs at the surface of a specimen which may be opaque to light or may be damaged by x-ray and electron beams. However, the depth resolution of the SLAM is poor due to diffraction and overlapping of the depth-planes. The scanning tomographic acoustic microscope(STAM) has been proposed as a method to overcome the limitations of the SLAM. The STAM uses several projections and the back-and-forth propagation(BFP) algorithm [1]. Using multiple projections generated by different incident wavefields, a clear image of an arbitrary subsurface plane can be obtained. It has been shown that the depth resolution of BFP algorithm is four wavelengths of the insonifying wave. However, when the layer separation becomes less than four wavelengths, overlapping of one layer is seen on the reconstructed image of the other layer being imaged. In order to enhance the resolution of the STAM, we studied STAM using shear waves [2].

On the other hand, an image obtained from multiple projections can be enhanced by employing iterative error correction algorithm. This algorithm involves propagating each incident wavefield through the estimated transmission functions. The results of the numerical propagation are compared against the received data to obtain error wavefields. From error wavefields, the correction terms for each plane can be determined [3, 4].

In this paper, we developed an iterative algorithm which improves the depth resolution of STAM. We analyzed the wavefield for multi-layered specimen and the iterative algorithm based on BFP algorithm. In order to show the performance of iterative algorithm, tomographic reconstruction was simulated for varying of layer separation with random attenuation patterns(Korean penny) and limitation of this algorithm are also examined.

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II. Iteration algorithm for multi-layered specimen

In order to analyze the wavefield for multi-layer specimen, a specimen which is homogeneous except for two layers at z_1 and z_2 as shown in Fig. 1 is considered.

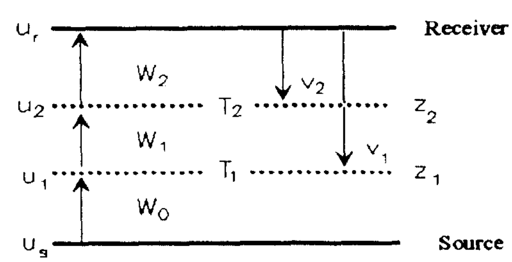


Figure 1. BFP algorithm.

Let transmittance matrix of the layers be T_1 and T_2, respectively. Also, let the sampled wavefield just below z_1 be u_1. Then, For the specimen insonified by sampled source wavefield u_s, the sampled wavefield u_1^+ after passing through the first layer can be driven by

$$u_1^+ = u_1 T_1 = (u_s W_0) T_1, \tag{1}$$

where W_0 is a Toeplitz matrix, representing forward propagation from z_s to z_1 [3, 5].

$$W_0 = \frac{|z_1 - z_s|}{2\pi} \frac{1 - jkr}{r^3} e^{jkr}, \tag{2}$$

where $r = [x^2 + y^2 + (z_1 - z_s)^2]^{1/2}$ and $k = \frac{2\pi}{\lambda}$.

Similarly, the sampled wavefield just below z_2 is u_2 and we can write Eg. (3).

$$u_2 = u_1^+ W_1, \tag{3}$$

where W_1 represents forward propagation from z_1 to z_2.

The wavefield after the second layer u_2^+ is related to u_2 by

$$u_2^+ = u_2 T_2 = u_1 T_1 W_1 T_2, \tag{4}$$

Then, The received wavefield at the receiver can be written as

$$u_r = u_2^+ W_2 = u_1 T_1 W_1 T_2 W_2, \tag{5}$$

where W_2 is represents the propagation from z_2 to z_r.

When the received wavefield is computationally back propagated to z_1, the back propagated field v_1 can be related to the received wavefield by

$$v_1 = u_r W_2^{-1} W_1^{-1}. \tag{6}$$

Substituting u_r using Eq. (5) gives

$$\begin{aligned} v_1 &= u_r T_1 W_1 T_2 W_2 W_2^{-1} W_1^{-1} \\ &= u_1 T_1 W_1 T_2 W_1^{-1} \\ &= u_1 T_1 W_1 (1 + T_2 - 1) W_1^{-1} \\ &= u_1 T_1 + u_1 T_1 W_1 (T_2 - 1) W_1^{-1} \\ &= u_1 T_1 + n_1 \end{aligned} \tag{7}$$

In similar manner, the back propagated wavefield v_2 at z_2 is given by

$$v_2 = u_1 W_1 T_2 + u_1 (T_1 - 1) W_1 T_2 = u_2 T_2 + n_2. \tag{8}$$

The second terms in Eq. (7) and (8) are the noise-like signal components. These components are expected to be canceled out with a number of projections obtained by varying the angle of incidence.

We use the estimate of T_2^e as the transmittance of the second layer in reconstructing the transmittance of the first layer. Thus,

$$T_2^e = T_2 + N_2, \tag{9}$$

where N_2 is the error in the estimate caused by undesired noise-like signal components. The received wavefield is backpropagated through this estimated transmittance of the second layer to the first layer. Then, Eq. (6) is given by

$$v_1^{(1)} = u_r W_2^{-1} (T_2^e)^{-1} W_1^{-1}, \tag{10}$$

where the superscript (1) denotes the estimate in first iteration. Now, Eq. (9) can be written as

$$T_2^e = T_2 (1 + T_2^{-1} N_2). \tag{11}$$

Therefore,

$$\begin{aligned} (T_2^e)^{-1} &= [T_2 (1 + T_2^{-1} N_2)]^{-1} \\ &= (1 + T_2^{-1} N_2)^{-1} T_2^{-1} \\ &\simeq (1 - T_2^{-1} N_2) T_2^{-1} \end{aligned} \tag{12}$$

Substituting u_r and $(T_2^e)^{-1}$ for Eq. (10) gives

$$\begin{aligned} v_1^{(1)} &= u_r W_2^{-1} (T_2^e)^{-1} W_1^{-1} \\ &= u_1 T_1 W_1 T_2 W_2 (1 - T_2^{-1} N_2) T_2^{-1} W_1^{-1} \\ &= u_1 T_1 - u_1 T_1 W_1 N_2 T_2^{-1} W_1^{-1} \\ &= u_1 T_1 - n_1^{(1)} \end{aligned} \tag{13}$$

Eq. (13) can be used to find the estimate of the transmittance of the first layer, T_1^e.

$$T_1^e = T_1 + N_1. \tag{14}$$

Using this estimated wavefield forward propagated through T_1^e to z_2 is found to

$$v_2^{(1)} = u_1 T_1^e W_1 \tag{15}$$

Therefore, the wavefield back propagated to z_2 becomes

$$\begin{aligned} v_2^{(1)} &= u_1 T_1 W_1 T_2 W_2 W_2^{-1} \\ &= u_1 (T_1^e - N_1) W_1 T_2 \\ &= u_1 T_1^e W_1 T_2 - u_1 T_1^e W_1 W_1^{-1} (T_1^e)^{-1} N_1 W_1 T_2 \end{aligned} \tag{16}$$

Substituting Eq. (15) for (16), we get

$$
\begin{aligned}
v_2^{(1)} &= u_2^{(1)}T_2 - u_2^{(1)}W_1^{-1}(T_1^{c})^{-1}N_1W_1T_2 \\
&= u_2^{(1)}T_2 - n_2^{(1)} \qquad (17)
\end{aligned}
$$

Now we can use Eq. (16) to estimate T_2 and find the next estimate of T_1 and use that to find the next estimate of T_2 and so on till we get to the required resolution. Continuing the iterative process using back and forward propagation, the noise terms in Eq. (7) and (8) are expected to be decreased.

Fig. 2 shows flow diagram for processing iteration algorithm. This process is repeated until a clear reconstruction of each layer without overlap from the other layer is obtained.

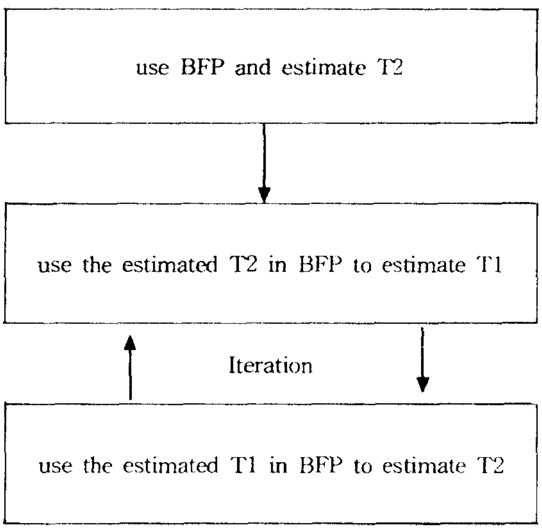


Figure 2. Flow diagram of iteration algorithm.

Ⅲ. Simulations and analysis

In order to investigate the performance of our technique, we use a specimen having three-dimensional object with a planar structure. It is assumed to have no attenuation except for two thin layers separated by a distance of several wavelengths. The attenuation patterns of the layers, the top and bottom side of the Korean penny, are obtained by using scanner as shown in Fig. 3.

For the simulation of tomographic reconstruction, the specimen rotation scheme was employed[1]. The specimen rotation scheme, rotating circularly with a constant angular increment through 360°, produces a number of projections.

Fig. 4 shows reconstructed images for twenty iterations with the layer separation of the two wavelengths. Fig. 4-(a), (b), (c) and (d) are obtained by using four, five, six and nine projections, respectively. Results show that the tomograms get clearer as the number of iterations increases, but there are still overlapping in four projections case.

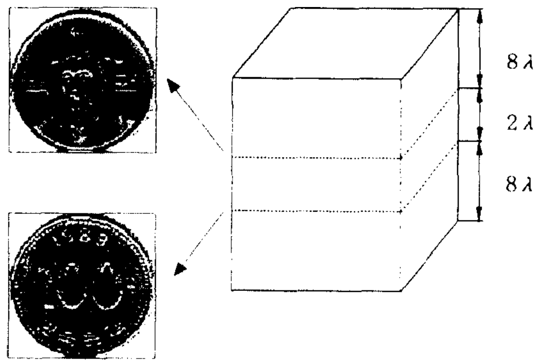


Figure 3. Simulated patterns of the layer of interest within the specimen.

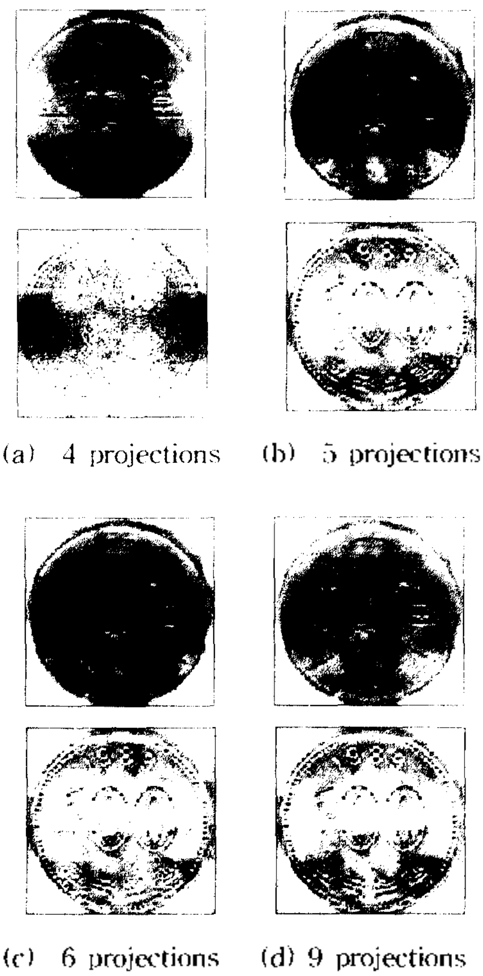
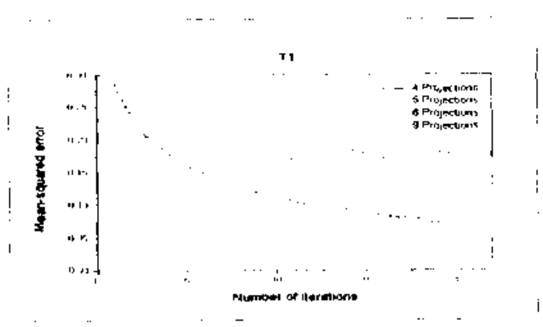
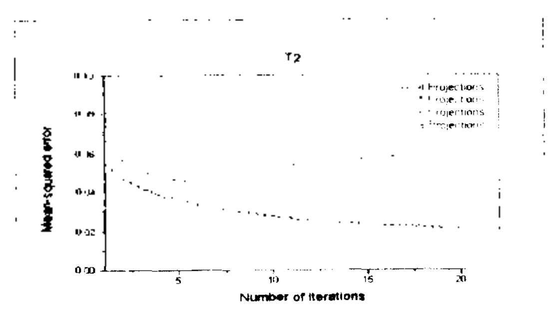


Figure 4. Reconstructed images versus number of the projections (iterations = 20).

Fig. 5 shows mean-squares-error(MSE) versus the number of iterations, for several case of the projections. As we expected, The errors decreases as the number of iteration increases.



(a) T_1



(b) T_2

Figure 5. MSE in the reconstructed image versus number of iterations.

Fig. 6 shows the reconstructed images obtained with none, one, five and twenty iterations, respectively. The images reconstructed using BFP with no iteration have out-of-focus image(overlapping). Again, the images get clearer as the number of iterations increases.

Ⅳ. Conclusions

In this paper, we developed an iterative algorithm which could improve the resolution of reconstructed tomograms and demonstrated the limitation of this algorithm. This algorithm, based on back-and-forth propagation algorithm, has the depth resolution about two wavelengths after five projections. However, presented iteration algorithm taking more computing time than the simple back-and-forth propagation algorithm, there exists trade-off computational efficiency and resolution of reconstructed image.

References

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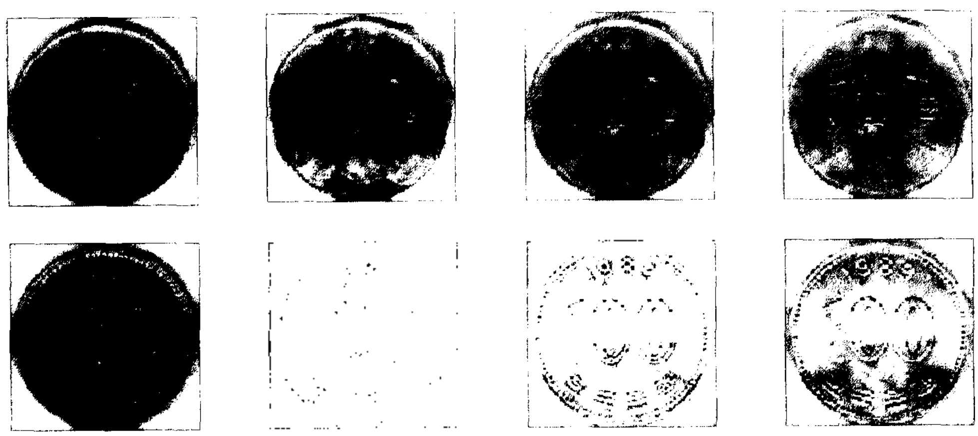

(a) BFP (b) 1 iteration (c) 5 iterations (d) 20 iterations

Figure 6. Reconstructed images using BFP and iteration algorithm(projections = 9).

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