

Compensation for Decay of Signal Strength in Damage Detection by Ultrasonic Imaging: Application to Migration Technique

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A compensating procedure for decay with distance of an ultrasonic wave propagating in a structure is presented. In structural health monitoring, many damage identification techniques involve ultrasonic wave propagation from actuators and reflection from defects. Some of them use imaging techniques to approximate damage configuration, such as location, size, and shape. However, the accuracy of detection result is not good enough to be used for prognostic. We found that the inaccuracy is often caused by decay of wave strength as function of distance when a wave propagates through the structure. Thus, we propose to compensate for geometric decay by multiplying the obtained image intensity with the distances to the actuator and to the sensor. We applied the compensation idea to a migration technique, which is a recently developed damage imaging technique. By adjusting image intensity to compensate for distance between actuator and defect, we were able to achieve a better accuracy for identifying the location of cracks. In addition, an experimental study on the possible errors related to experiment is attached. This idea can be extended to any damage detection techniques which produce images as their final detection result.

Keywords: Structural health monitoring, attenuation compensation, migration technique

I. Introduction

Structural health monitoring (SHM) is an integrated technology of assessing structural damage using an automated procedure. Diagnosis in SHM involves collecting sensor data and processing them to quantify the location, size, and shape of the damage. Many authors use different techniques to achieve a good assessment of structural damage from sensor data. Among them, the ultrasonic wave technologies employing piezoelectric sensors and actuators are widely developed and used¹. Especially in plate structures, many detection results produce images from multiple sensor readings to provide the operator with a general idea of damage location and size^{2,3,4}. The

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migration technique is one of those image-based techniques and has advantages in terms of determining shape of the damage as well as location and size².

However, most imaging techniques, including the migration method, ignore the fact that the accuracy of images is affected by decay of wave signal with distance. This causes two problems, one is that the estimated location is not accurate enough, and the other is that the size is not characterized through the image produced without compensation. A conceptual diagram showing the problem is shown in Figure 1.

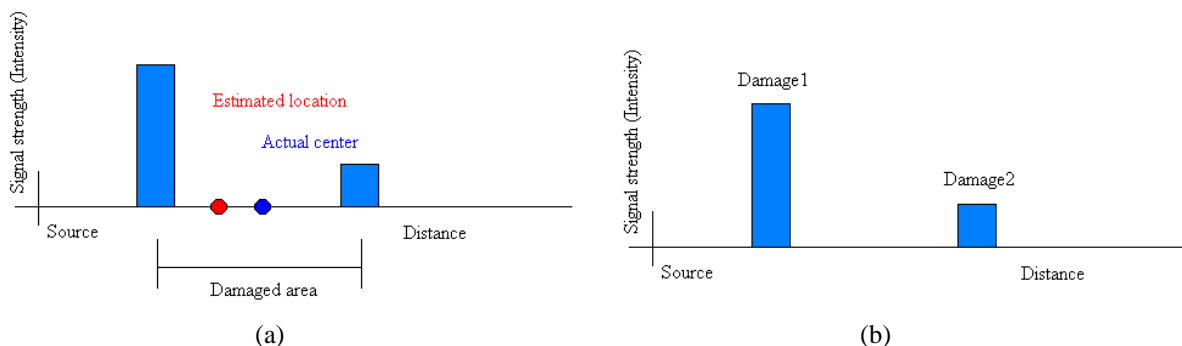


Figure 1. Possible error related to geometrical decay. (a) Error in the estimated center of the damage location. (b) Linking between the size and location by signal strength. If the two damages are of the same size, the damage closer to the source will be greatly amplified.

In addition to that, the unavoidable error in the signal is greatly amplified near the actuator in the real situation. As a result, the image intensity in the sensor shows a combined effect of reflection and distance from damage. For example, the image intensity for small damages that are close to the sensor and actuator is larger than that of large or severe damages that are far from the sensor and actuator.

Recently, An et al. applied a Bayesian approach to improve the quality of images obtained from the migration technique⁵. However, it is found that there exists a bias of the detected damage location due to different sensor-actuator combinations. We have concluded that the bias came from geometrical decay. In addition, the image when the damage is located close to the sensor is an inconsistent way from the image when it is located far from the sensor. This happens because the image intensity depends on the distance from the sensor and actuator as well as damage itself. To compensate the effect of distance on image intensity and to obtain a more accurate representation of the damage, a correction method for signal decay is suggested in this paper.

The idea of compensating for attenuation was first proposed in the medical imaging area⁶. When ultrasonic waves are used for medical imaging, the effect of geometric decay causes many problems, and more accurate images are obtained by compensating for attenuation of signals. In this paper, we adopt the compensation procedure into SHM in order to solve the inaccuracy problem and to decompose the size from location simultaneously. We applied this procedure to the migration technique to verify the idea in Chapter 3. We will show numerical results in Chapter 4, and error reduction strategy by this technique in Chapter 5.

II. Geometrical decay in plate wave and compensation

When an ultrasonic pulse runs through a plate, the strength gradually decreases as it propagates. Wave mechanics has shown that the decrease in the amplitude is inversely proportional to the distance at a specified time without damping⁷. The maximum amplitude A has the following relation with the distance d for an impulse input given at a point:

$$A \propto 1/d \quad (1)$$

However, in the actual simulation and experiment, we use a five-peaked tone-burst signal with a central frequency of 150 kHz for successful generation of lamb waves within the plate rather than an impulse input. Therefore, the initial amplitude does not follow the above relation closely because of the transient response and inertia effect. By using the Mindlin plate theory and finite difference simulation, the attenuation of signal with respect to time and distance is calculated, as shown in Figure 2.a. We used 200 x 200 grids in an Al 6061 square plate of 50 x 50 x 0.32 cm to simulate the results.

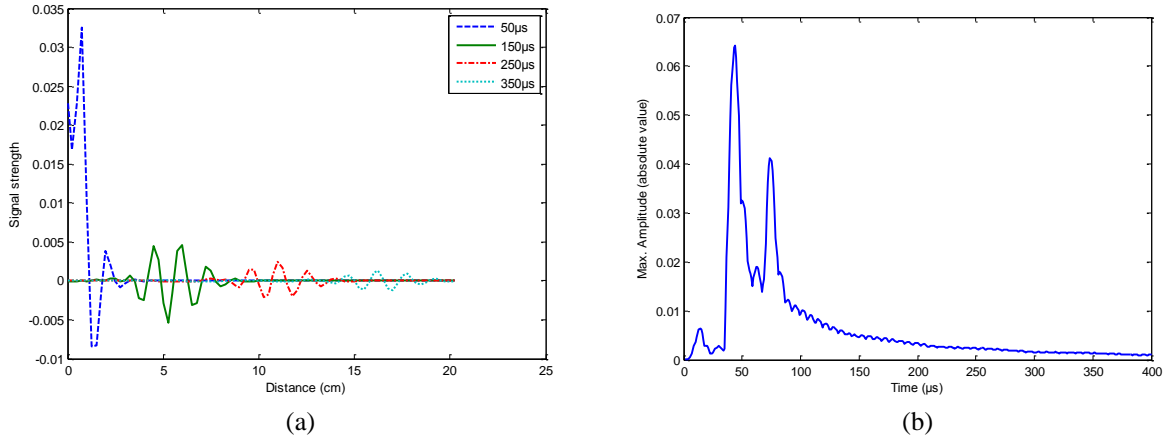


Figure 2. (a)Signal decay with respect to wave propagation in plate, generated from the finite difference model (b) Decay profile in a plate, described by amplitude loss. Wave decays with respect to time as it propagates further from the actuator.

Also, we have obtained the profile of decay of the maximum amplitude as a function of time (see Figure 2.b). The graph fits Eq. (1) well after all the transient effects are gone.

Figure 2.b shows the maximum amplitude specified from simulation at each time step. As time goes by and wave travels further, the signal strength decreases due to dispersion. Thus, the signal strength highly depends on the location of the damage rather than its severity. In the imaging technique, this causes weak signal in the far region, which correlates distance with image intensity. Although human eyes conceive every point in an image equally weighted, but the truth is that the points near the actuator and sensor are greatly amplified due to stronger signal strength.

Since an analytical solution of the tone-burst signal with multiple peaks is not explicitly available, we constructed a compensation curve using curve fitting tool. We assumed that the amplitude A is inversely proportional to time t following this relation:

$$A \propto \begin{cases} 1/(t-t_d) & (t > t_d) \\ 1 & (t < t_d, \text{unknown}) \end{cases} \quad (2)$$

where t_d is a threshold time for the transient region. We assume that the amplitude is uniform during the transient period. From data analysis, we choose $t_d = 58 \mu\text{s}$.

There are two ways to compensate for attenuation of signal strength. One is to apply the compensation scheme in the time domain, while the other is to apply it in the spatial coordinates. In this paper, we construct the curve in Eq. (2) based on time domain and applied to the received signal directly (Fig. 3). After that, the back propagation stage of migration technique is compensated based on distance. Compensating for back propagation stage is discussed in the next chapter in detail, since it is a unique part of the migration technique.

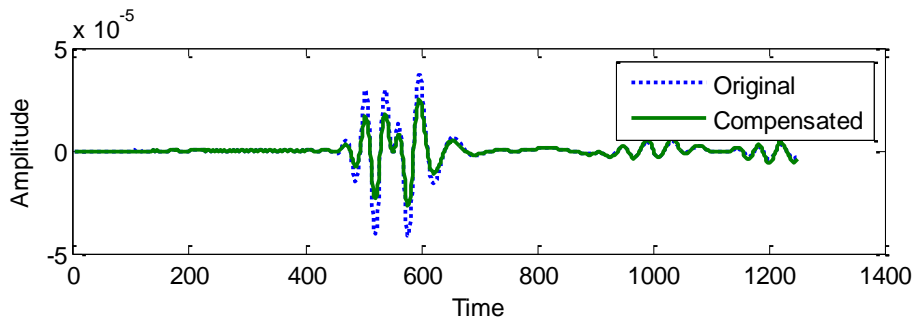


Figure 3. An example of compensated signal displayed on time scale.

In the next section we will discuss how we applied this principle to improve the images from the migration technique. The proposed method may not apply for different imaging techniques, but the principle is still applicable.

III. Application to Migration Technique

The simulation layout for the migration technique is shown in Figure 5. The migration technique comprises two different steps: detection of the reflected wave and back-propagation. Then the image intensity is calculated by cross-correlation of the reflected wave and the back-propagated wave. The reflected wave first travels from the actuator to damaged site and as the wave hits the damage, the reflective wave propagates as if the source is at the point of damage. During these propagation paths, the wave strength decays.

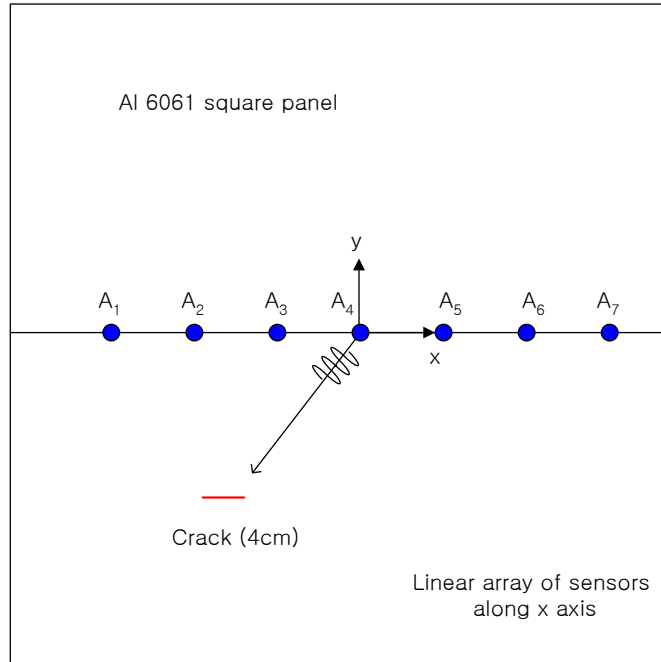


Figure 4. Linear array of actuators/sensors on an aluminum plate

Then the back-propagated wave also decays when traveling the distance between actuator and a point. By calculating the cross-correlation, or convolution, of these two waves, the image intensity has a relation stated at Eq. (3), and the compensated image intensity can be calculated by Eq. (4).

$$I \propto A_{\text{actuated}}^2 \cdot A_{\text{reflected}} \propto 1/d_{\text{actuator-distance}}^2 \cdot d_{\text{sensor-distance}} \quad (3)$$

$$I_{\text{new}} = Id_{\text{actuator-distance}}^2 \cdot d_{\text{sensor-distance}} \quad (4)$$

Where I is the image intensity used to represent the possible damage location in the domain, A is the amplitude of a signal, and d is the distance between the actuator/sensor and the point in the domain.

We applied the signal compensation directly, and in addition to that, we calculated $Id_{\text{actuator-distance}}^2 \cdot d_{\text{sensor-distance}}$ at a point (x, y) where we will evaluate image intensity and defining it as our new image intensity to compensate the back propagation stage. With this procedure, we can eliminate the effect of distance from the imaging result.

IV. Numerical Study

In the numerical study, we compare the accuracy of three different techniques: (a) migration technique using stacking², (b) migration technique using the Bayesian approach⁵, and (c) migration technique using the Bayesian approach with attenuation correction. The simulation is done by finite difference scheme using 200 x 200 grids on a

50 x 50 x 0.32 cm square plate with 1250 time steps (1 μ s time interval). A straight, horizontal crack is centered at (-9, -11) cm from the center of the plate, and the size is 4 cm. Those three techniques use the same sensor information.

Figure 6 shows the images obtained from the three methods. The three images do not show a significant difference about the location at a glance, but the error of estimation of crack center location is greatly reduced by attenuation compensation. The crack center location is obtained from taking the mean of entire image. Table 1 summarizes the results.

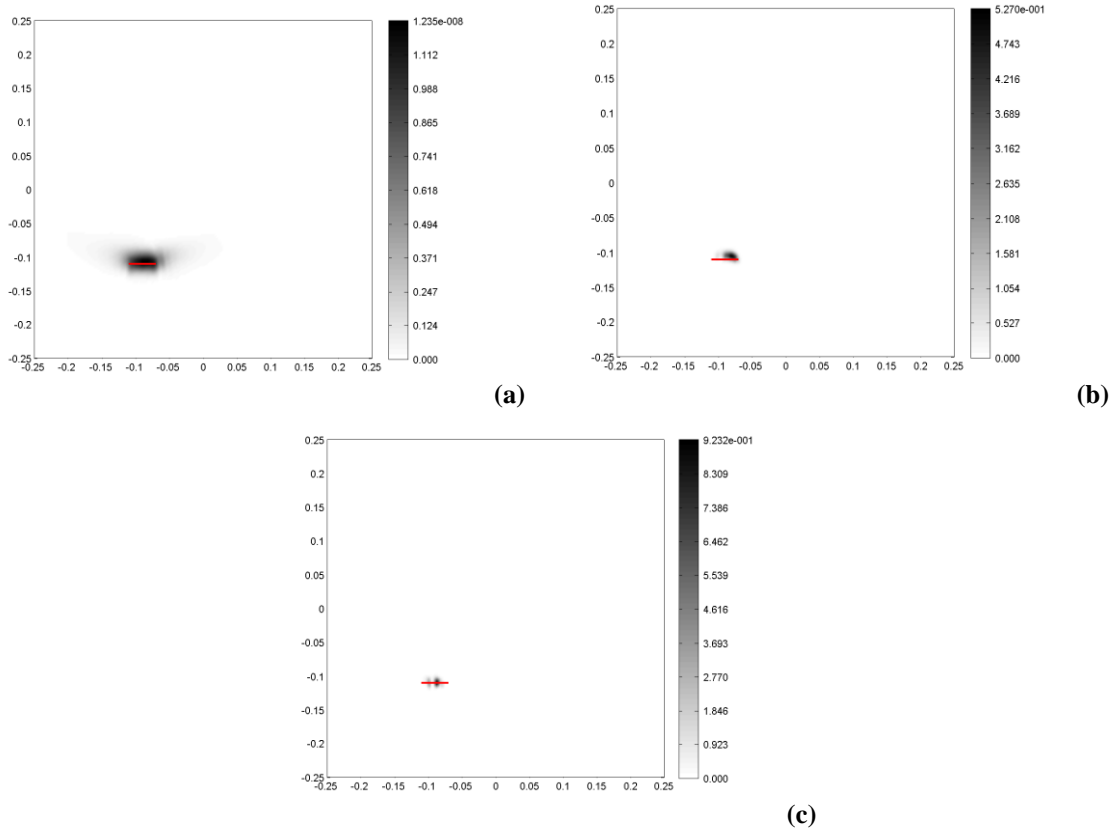


Figure 5. Images from migration technique with the same sensor data. (a) Prestack approach, (b) Bayesian approach, and (c) Bayesian approach with attenuation-correction

Table 1. Comparison of different imaging results.

Imaging method	Estimated location (cm)	Error (cm)
Actual	-9.00, -11.00	-
Prestack migration	-8.11, -10.40	1.073
Bayesian approach	-8.27, -10.57	0.847
Bayesian approach with attenuation correction	-8.86, -10.83	0.220

Also, to check if our formula for compensation is valid, we also simulated several crack locations to check if they are giving consistent level of image intensity with respect to size. The result is shown in Figure 6 and Table 2.

Table 2. Comparison of imaging results.

Crack location	Estimated location (cm)	Error (cm)	Max. Intensity
(-7, -15) cm	(-6.63, -14.65) cm	0.509 cm	1.047 x 10 ⁻¹¹
(-12, -3) cm	(-13.02, -3.17) cm	1.034 cm	4.998 x 10 ⁻¹²

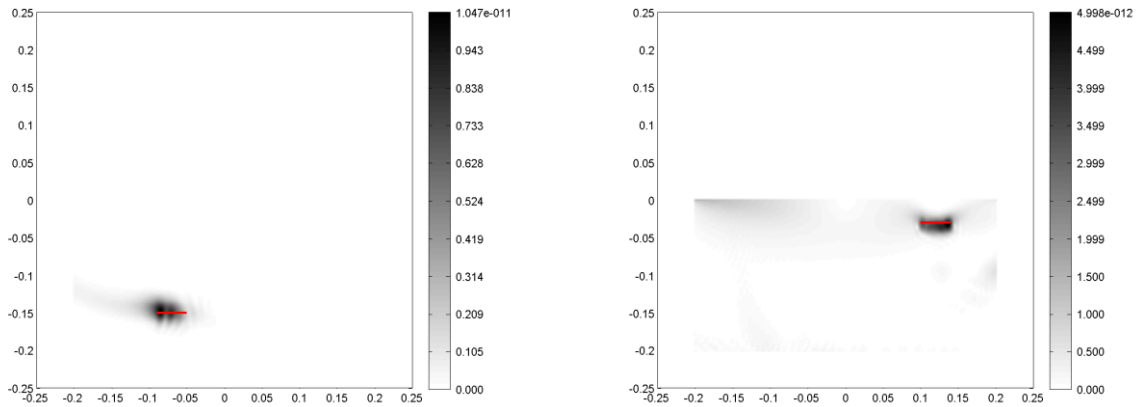


Figure 6. Image intensity distribution for a single actuator image. Total 7 images are available for each damage configuration, but the images with the maximum intensity for each case are displayed here.

By principle, all images of a crack regardless of the actuator location should provide the same value of image intensity. However, we observed that the image intensity of a closer actuator is still greater than the others. This is because that the crack orientation, reflection angle and other minor characteristics are not fully considered in the compensation procedure. We did not include them in our procedure since they only have a minor effect, and they tend to be easily contaminated by the error in real situation.

However, this numerical example assumes that there is no random error, which is generally not true for a structural health monitoring procedure. Hence, we also performed an experiment to verify the level of error associated with detection result and compensation procedure. This is discussed in the next chapter with detail.

V. Experimental Study

To examine the effect of errors associated with the image intensity, we tested a plate with the same configuration shown in Figure 4. Figure 8 shows the plate we used for an ultrasonic testing experiment. The PZT actuators are attached to the plate, each of them acts as an actuator and a sensor. We used an NI PXI-1000B for data collection with LabView.

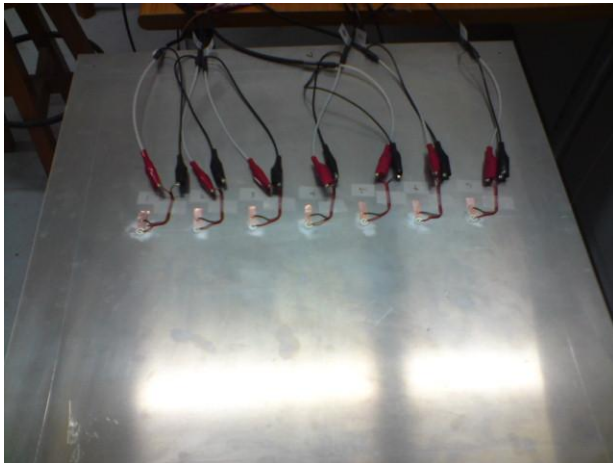


Figure 7. PZT array for an aluminum plate.

To check the effect of errors, we evaluated the signal by averaging ten experiments under the same environment, and compared it with a single test. Figure 8 shows the clear difference between the image before and after compensation for signal decay.

Figure 9.(a) shows the imaging result by actuator 4 (located at the center), and Figure 9.(b) shows the imaging result for the same actuator and the same sensor data with compensation for decay.

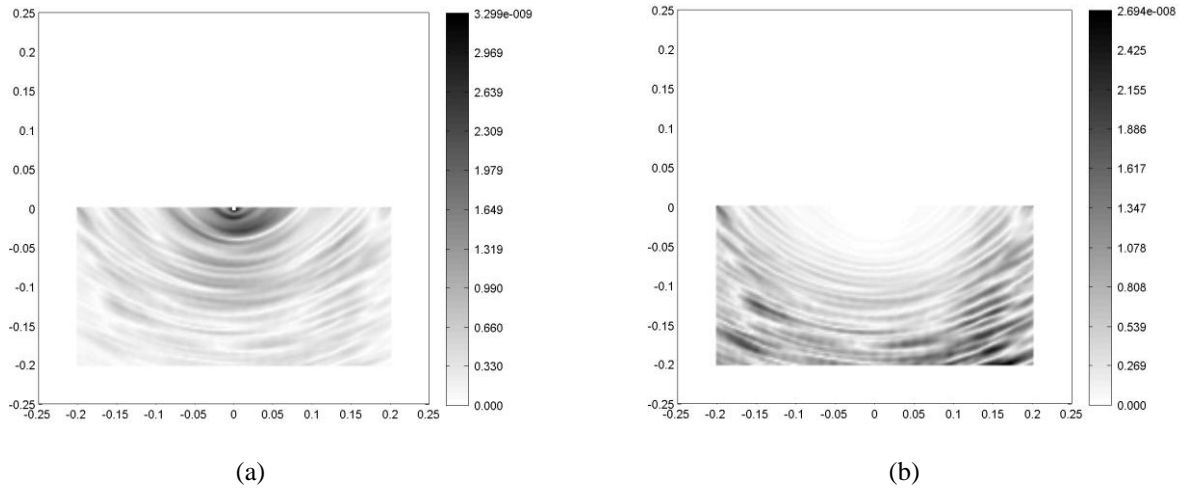


Figure 8. Imaging result of pure noise from experiment. This image is generated based on the difference between 10 tests averaged and a single test

VI. Concluding remark

In structural health monitoring, many diagnostic techniques using ultrasonic wave propagation and reflection has been suggested. There are techniques that reduce location error by time of arrival, but it is not sufficient enough for decomposing the effect of signal strength and distance. The location from the image obtained from diagnosis mainly depends on the time of arrival, but the effect of signal strength still remains in the image. In previous study on the migration technique, our group has discovered the biased error due to this feature. In order to compensate for the bias error of detecting crack location, we suggested a compensation for decay of signal strength for ultrasonic imaging techniques. The motivation for this application is to improve numerical accuracy of detection techniques suitable for transferring to prognostic stage. Since the prognosis process involves a large amount of uncertainty compared to diagnosis, a small error may be critical for evaluating remaining lifecycle of the structure.

We expect to achieve two characteristics from compensation of the decay of the signal, a better accuracy of the crack location and find a credible bound for each actuator-sensor pair. We applied our idea to Migration technique to improve it with compensation. The numerical result showed an improvement of the crack center estimation in terms of accuracy. Moreover, by testing several locations, we were able to see the size is mainly related to the image intensity value after compensation.

We also performed an experiment to show the effect of errors, and how we can reduce the error in the near region by compensation of signal decay. Usually, a far region from a sensor or an actuator is not of our interest in structural diagnosis. However, it was very hard to find that how far is far enough to ignore the diagnostic error or ghost images. This scheme provides a framework for defining the region. We still need more practical tests to prove the usefulness of error reduction scheme.

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