DEVELOPMENT OF PLANAR ARRAY PROBES FOR DETECTION OF THREE-DIMENSIONAL DEFECT

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Abstract: In the present study, two types of multi-channel planar array probes have been developed. The first is planar pitch-catch array probe and the second is planar tandem array probe. Both of them are designed to detect weld defects in structural connection based on the normal-beam and angle-beam techniques, respectively. The planar pitch-catch array probe is the assembly of 16 normal-beam transducers arranged in 4-by-4 matrix, and the planar tandem array probe is the assembly of 15 angle-beam transducers arranged in 3-by-5 matrix. The ultrasonic detection system, which is designed to use with these probes, is developed for fastness and compactness. The 3D-SAFT algorithms, which are applicable and appropriate to both types of probes, are studied and developed. The 3D-SAFTs are applied to the A-scans obtained by the flaw detection system and make the interpretation of internal defect information.

1. INTRODUCTION

In the Great Hanshin Earthquake, brittle fracture caused the collapse of steel bridge piers. The results from many investigations had been reported that the brittle fracture was originally expanded from the weld defect in the structural connection. Therefore, in viewpoint of retrofitting works of the existing bridges, it is necessary to observe the internal condition and information of the structural connections, nondestructively.

Ultrasonic testing, one of techniques in nondestructive testing, has been widely used for in-situ inspection of in-service structures (Achenbach 2000). Main tasks of ultrasonic testing are to detect flaws and defects inside the structural connection and to give accurate information of defect such as shape, size, and orientation. In the conventional testing, single-probe technique is the most widely used method (Krautkrämer et al. 1983). This method refers to the procedure that uses one reversible transducer (longitudinal or shear waves) to scan for the location of defects in structures. However, this technique, sometimes, leads to the lack of information of defects, which reflect the incident waves in two or three dimensions.

Therefore, in order to increase the detectability of defects, two-probe testing techniques have been developed such as the time-of-flight diffraction (TOFD) technique and the tandem technique. In those methods, transmitter and receiver are separated and the receiver is mechanically scanned for the reflected wave.

Unfortunately, such methods face three major problems. First, scanning the probe mechanically will cause error in evaluation of position of defects. Second, during manual scanning, thickness of coupling material between the probe and specimen changes. As a result, the wave amplitude will be

Figure 1 Planar Pitch-Catch Array Probe

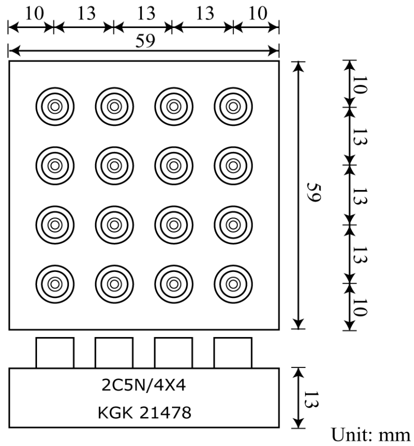

Figure 2 Geometry of Planar Pitch-Catch Array Probe

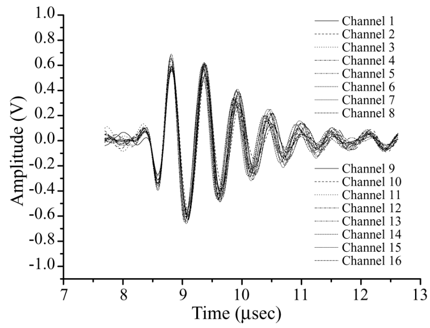

Figure 3 Longitudinal Wave Signals from The Planar Pitch-Catch Array Probe

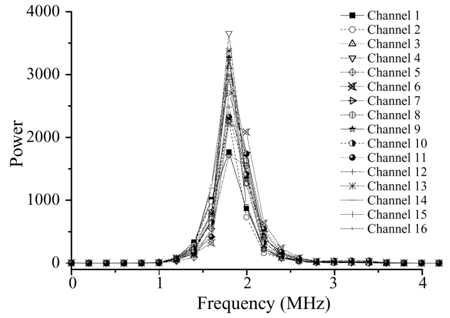

Figure 4 Spectrum of Longitudinal Wave Signals

relatively changed. Third, inspection for one target area spends long time for mechanically manual scanning and recording the A-scans. Furthermore, inspection of bridge components is difficult due to the restriction of inspection time and lack of accessible space. Therefore, in order to cope with such problems, the planar array probes with the fast ultrasonic flaw detection system should be developed.

In general, the data of ultrasonic testing are presented in form of unprocessed radio frequency (RF) signals or A-scans. These A-scans are very difficult to evaluate and may lead to unreliable inspections. Therefore, image reconstruction systems have been developed and introduced to ultrasonic testing for managing and analyzing the A-scans. One of the famous imaging systems is synthetic aperture focusing technique (SAFT), which is originally used in radar system for military and surveillance missions (Soumekh 1999). With the application of the SAFT imaging, information of defect in form of images is obtained accurately and easy to evaluate with reliability.

The objectives of this study are 1) to propose multi-channel array probes in order to increase detectability of three-dimensional defects, 2) To develop the fast and compact in-situ ultrasonic flaw detection system, and 3) To propose the 3D-SAFT imaging algorithms, which are applicable to the planar array probes.

2. MULTI-CHANNEL PLANAR ARRAY PROBES AND FLAW DETECTION SYSTEM

In this study, two types of planar array probes have been developed. The first is the planar pitch-catch array probe and the second is the planar tandem array probe. Both of them are designed to use in different situations. The planar pitch-catch array probe is based on the normal-beam technique, while the planar tandem array probe is based on the angle-beam technique.

2.1 Planar Pitch-Catch Array Probe

The planar pitch-catch array probe has been developed with the assembly of 16 normal-beam transducers in form of 4-by-4 matrix as shown in Figure 1. Geometry is shown in Figure 2. This array probe has 16 channels. Each channel generates longitudinal wave with central frequency of 2MHz.

Figure 5　Planar Tandem Array Probe

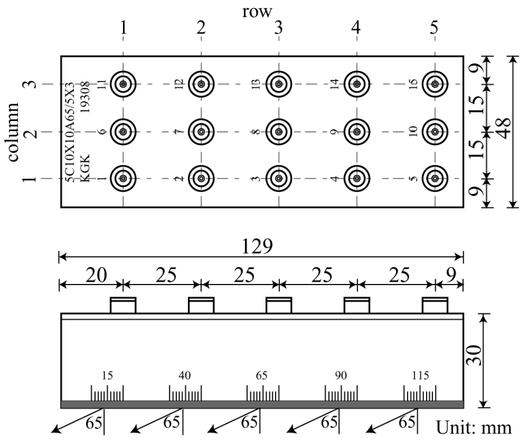

Figure 6　Geometry of Planar Tandem Array Probe

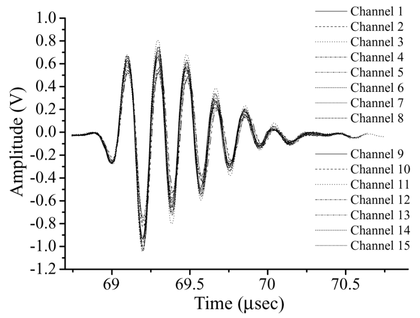

Figure 7　Shear Wave Signals from The Planar Tandem Array Probe

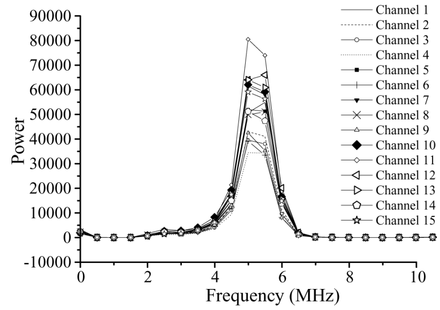

Figure 8　Spectrum of Shear Wave Signals

The wave signals generated from each channel are observed and shown in Figure 3. Applying Fourier transformation to these waveforms gives frequency spectrums as shown in Figure 4. Spectrums of all waveforms show almost practically agreement.

2.2　Planar Tandem Array Probe

Figure 5 is the planar tandem array probe and its geometry is shown in Figure 6. It is an assembly of 15 angle-beam transducers arranged in form of 3-by-5 matrix (3 columns and 5 rows). Each channel is reversible type and can transmit shear waves with angle of refraction of 65 degree. The waves propagate in the same direction for all channels. Each channel has central frequency of 5 MHz.

The plot of received waveforms of all channels is shown in Figure 7 and the plot of their spectrums is in Figure 8. All waveforms and spectrums show practically identical shapes.

Results from both array probes show that all waves generated from each channel have the same properties in shape and frequency. Each channel can receive waves generated from another channels. Therefore, the two-probe technique can be used properly in both probes.

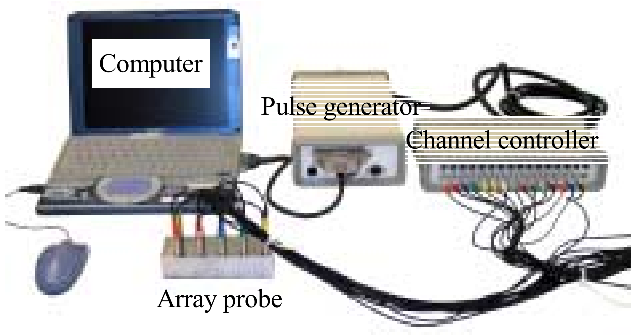

Figure 9　Ultrasonic Flaw Detection System

2.3　Ultrasonic Flaw Detection System

In this study, we developed the ultrasonic flaw detection system, which is compatible to the planar array probes. The system consists of personal computer, pulse generator, and channel controller. They are connected to array probe as shown in Figure 9.

Channel controller is used for controlling channels of transmitter and receiver. Personal computer is used for data acquisition and controlling pulse generator, which is used for sending wave pulses. In our system, each channel is used for transmitting incident waves and receiving reflected waves generated from another channels. Therefore, a total of 256 and 225 files of

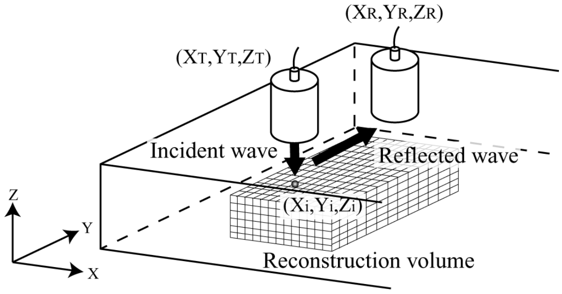

Figure 10 3D Pitch-Catch SAFT

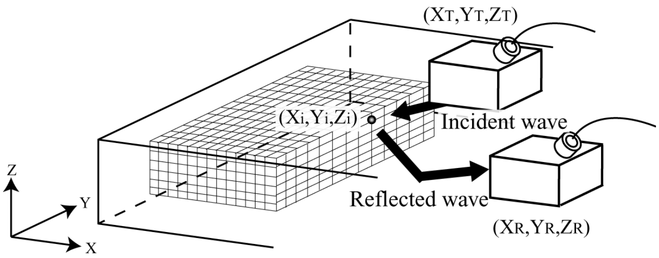

Figure 11 3D Tandem SAFT

the A-scans can be, respectively, obtained from the pitch-catch and tandem array probes without time consumption, which is appropriate for in-service inspection.

3. 3D-SYNTHETIC APERTURE FOCUSING TECHNIQUE

SAFT processing relates to many parameters, such as coordinates of probe position and reconstruction areas, direction of wave incidence, material wave velocities, received A-scans, and possible sound paths. In this chapter, the specific 3D-SAFT algorithms for the planar pitch-catch and tandem array probes are proposed.

3.1 3D Pitch-Catch SAFT

Figure 10 demonstrates the principle of the 3D pitch-catch SAFT algorithm. Reconstruction volume (volume of inspection) is divided into many voxels with their coordinates (X_i,Y_i,Z_i). Transmitter (X_T,Y_T,Z_T) generates wave with certain direction and receiver (X_R,Y_R,Z_R) gains the A-scan of reflected waves.

Assuming the considering voxel (X_i,Y_i,Z_i) in Figure 10 is a part of defect, the incident wave is incident to and reflected at this voxel and returned to the receiver by the assumed sound path illustrated in the figure. The sound paths of incident and reflected waves are pre-assumed in the SAFT process. All possible sound paths should be considered for an A-scan of a pair of transmitter and receiver. However, many assumptions of sound paths generally result in the artefacts (ghost images), which are caused from mistake assumption of sound path. Therefore, in this pitch-catch SAFT algorithm, the sound paths of the incident and reflected waves are considered only the direct path, which is the straight-line connecting the probe to the voxel. Then, the time of flight (TOF) is determined as follows:

$$TOF = \left(L_{IN}+L_{REF}\right)/C_P \quad (1)$$

$$L_{IN} = \sqrt{(X_T-X_i)^2+(Y_T-Y_i)^2+(Z_T-Z_i)^2} \quad (2)$$

$$L_{REF} = \sqrt{(X_R-X_i)^2+(Y_R-Y_i)^2+(Z_R-Z_i)^2} \quad (3)$$

where L_{IN} and L_{REF} are lengths of incident and reflected paths, respectively. C_P is longitudinal wave velocity of material.

Amplitude value of received A-scan is added up to that voxel with respect to the TOF as followings:

$$H(X_i,Y_i,Z_i) = f\left(TOF\right) \quad (4)$$

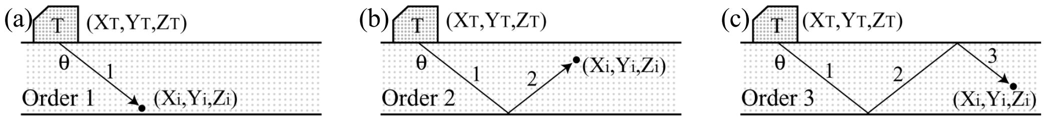

Figure 12 Dependency of Incident Path of Wave on Boundary of Specimen: a) 1st , b) 2nd , and c) 3rd Orders

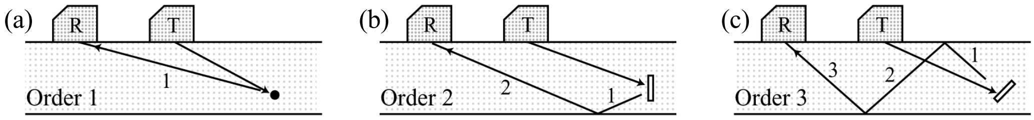

Figure 13 Dependency of Reflected Path on Defect Orientation: (a) 1st , (b) 2nd , and (c) 3rd Orders

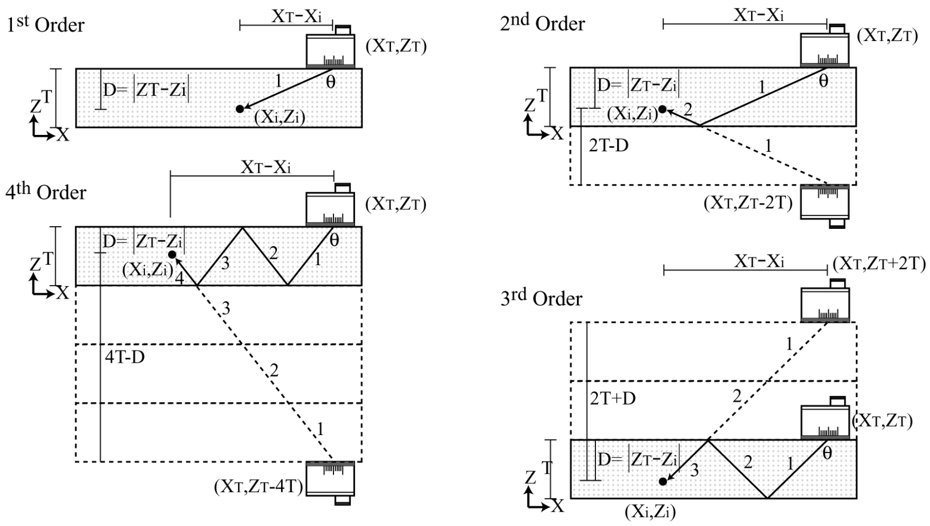

Figure 14 Determination of Lengths of Boundary-Reflected Sound Paths

where $H(X_i,Y_i,Z_i)$ is amplitude intensity at specific voxel (X_i,Y_i,Z_i) and f(TOF) is amplitude of considering A-scan at time TOF.

Then the summation of amplitude values at the specific voxel is done for A-scans of another pairs of transmitter and receiver from 1 to A as follows:

$$H(X_i,Y_i,Z_i) = \sum_{a=1}^{A} f_a(\mathrm{TOF}) \tag{5}$$

Conducting the process in Eq. (5), the voxel, which respects to the actual defect, will be resulted in high intensity of amplitude values.

3.2 3D Tandem SAFT

In case of single-probe method, the sound paths for angle-beam technique are certain and simply assumed. However, assumption of sound path is difficult in case of tandem technique. Unlike the pitch-catch SAFT, the tandem SAFT, demonstrated in Figure 11, involves boundary condition of the test steel plate. In this section, the incident path is considered separately of the reflected path.

Incident path can be certainly determined, because the direction of wave incident in the test specimen is known. Figure 12 demonstrates the incident paths of waves to specific pixel (X_i,Y_i,Z_i). As shown in figure, the incident path depends on the angle of refraction and boundary of test specimen. As a result, waves propagate in steel plate can have multiple reflection at boundary before the reflection at defect. Therefore, we classify the incident paths into many orders, for ease, referring to a number of straight lines composing the sound paths. For example, the incident paths are of orders 1, 2, and 3 in cases of Figures 12(a), (b), and (c), respectively.

In many testing situations, the thickness of test specimen and the angle of refraction are given. As a sequence, an order, n, of the incident path of waves, generated by transmitter (X_T,Y_T,Z_T), propagating to the specific pixel can be determined using following formula:

$$\text{Order n=integral part of}\left[\frac{\sqrt{(X_T\text{-}X_i)^2+(Y_T\text{-}Y_i)^2}}{T\times\tan\theta}\right]+1 \tag{6}$$

where T is the plate thickness and θ is the angle of refraction.

Reflected path also depends on boundary of test object as the incident path, but it is more complicated because it additionally depends on the orientation of defects as shown in Figure 13. As same as the incident path, the reflection paths in Figures 13(a), (b), and (c) are, respectively, classified to orders 1, 2, and 3.

In order to determine lengths of sound paths of any orders, we propose an idea as demonstrated in Figure 14. Sound paths of waves, which are reflected at boundary, are unwrapped to be straight line as shown by dashed line. For odd-number orders such as 3^{rd} order, sound path is flipped up making a straight line from voxel (X_i,Y_i,Z_i) to new probe position (X_T,Y_T,Z_T+2T). On the contrary, sound paths are flipped down in cases of even-number orders such as 2^{nd} and 4^{th} orders. Equation for the lengths of the sound paths for any orders (n) can be summarized as followings:

$$\text{Length of sound path at } n^{th} \text{ Order: } \sqrt{(X_T\text{-}X_i)^2+(Y_T\text{-}Y_i)^2+\Delta Z^2}\quad , \tag{7}$$

$$\Delta Z=\eta\cdot T+(-1)^{n+1}\cdot D\quad \begin{cases}\eta=n-1 \text{ for n=odd number}\\ \eta=n \text{ for n=even number}\end{cases} \tag{8}$$

where $D=|Z_T\text{-}Z_i|$.

As same as the principle of the SAFT in the pitch-catch method, the time of flight (TOF) is determined as follows:

$$\text{TOF}=\left(L_{IN}+L_{REF}\right)/C_S \tag{9}$$

where C_S is the shear wave velocity. L_{IN} and L_{REF} are determined from Eq. (7).

As mentioned that the reflected path depends on test object boundary and orientation of defects, therefore, for a pair of transmitter and receiver, the order of the reflected path (n_r) is varied from 1 to appropriate numbers (N). The amplitude intensity at specific voxel (X_i,Y_i,Z_i) for a number (A) of A-scans can be written as:

$$H(X_i,Y_i,Z_i)=\sum_{a=1}^{A}\left(\sum_{n_r=1}^{N} f_a(\text{TOF})\right)\quad . \tag{10}$$

4. APPLICATION OF 3D SAFTs TO FLAW DETECTION SYSTEM

In this chapter, the planar array probes with the 3D-SAFTs are applied to the specimens in order to verify the validity and advantage of this system.

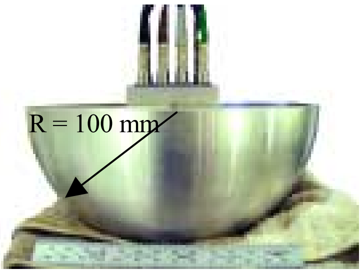

Figure 15 Experimental Setup of The Pitch-Catch Array Probe.

4.1 Graphical results of the planar pitch-catch array probe

Experimental setup and specimen are shown in Figure 15. The half spherical specimen with radius of 100 mm is used as test specimen. The bottom surface of this specimen has a curvature shape, which is supposed

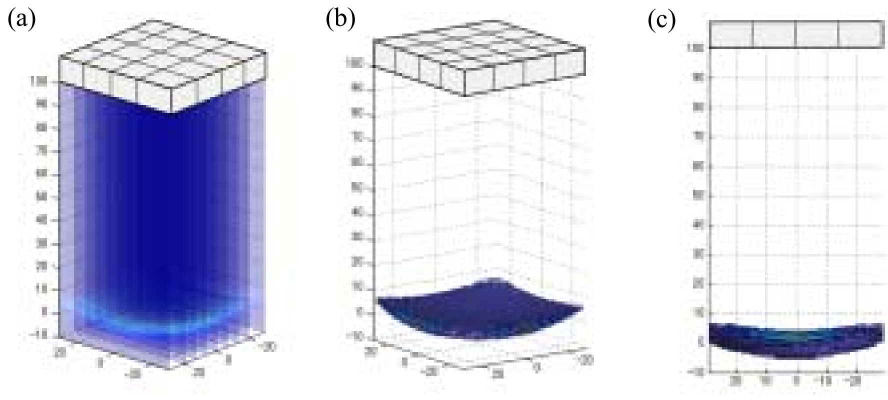

Figure 16 Images of Bottom Surface of Half Spherical Specimen: (a) Sliced-Plane Image, (b) and (c) Isosurface Images

to reflect the waves in three dimensions.

The 3D pitch-catch SAFT is applied to the A-scans gained by the planar pitch-catch array probe. The graphical result of the half spherical specimen is shown in Figure 16. Figure 16(a) shows the volumetric data in form of sliced-plane image, while Figures 16(b) and (c) show by isosurface images. Both types of image interpretations show information of three-dimensional curve at specimen bottom surface.

However, the isosurface images of the volumetric data, shown in Figures 16(b) and (c), give us in-depth information of orientation, location, and shape in three dimensions. Therefore, it is strongly recommended for interpretation of the volumetric data.

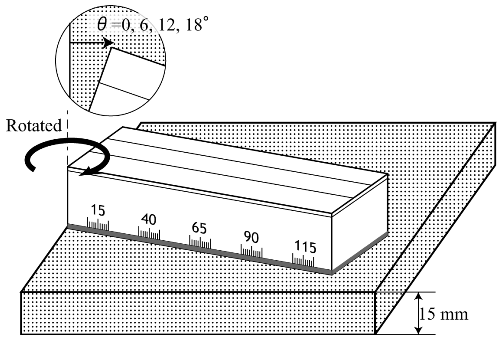

Figure 17 Experimental Setup of The Tandem Array Probe

4.2 Graphical results of the planar tandem array probe

In this section, we use the steel plate, which has 15 mm in thickness, for the experiment. Experimental setup is shown in Figure 17. Plate edge of this plate is supposed to be the planar defect. In order to confirm the detectability of three-dimensional planar defect, we rotated the probe around one corner making the plate edge angled to the probe front for 0, 6, 12, and 18 degrees.

Top views of the isosurface images for θ = 0, 6, 12, and 18 degrees are compared and shown in Figures 18(a), (b), (c), and (d), respectively. Red lines indicated in the figures are actual orientation of plate edges. In case of θ = 0˚, isosurface image shows the same orientation with plate edge.

In cases of inclined orientation at θ = 6˚ and 12˚, isosurface images in columns 1 and 2 show very good relation with actual plate edge orientation. The reason that isosurface images in column 3 do not show good relation with actual orientation can be explained based on probe geometry. The waves generated from transmitters in column 1 can be detected by receivers in columns 2 and 3, and the waves generated from transmitters in column 2 can be relatively detected by receivers in column 3. However, the waves generated by transmitters in column 3 cannot be detected, because there is no column of receivers to detect reflected waves.

In case of θ = 18˚, images do not relate to plate edge for all columns, because angle of plate edge to the probe front is very large so that the reflected waves cannot be efficiently detected.

Note that we cannot gain any three-dimensional information, such as orientation and shape as shown in Figures 16 and 18 by using only a single-probe technique. These results show the importance and necessity of the three-dimensional ultrasonic flaw detection system.

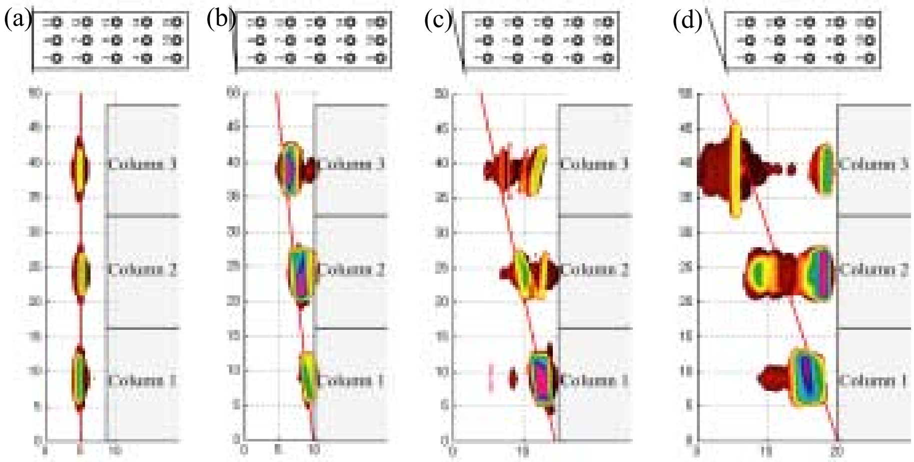

Figure 18 Comparison of Top Views of Isosurface Images of Specimen Edge at ϴ= (a) 0˚, (b) 6˚, (c) 12˚, and (d) 18˚

5. CONCLUSIONS

In this study, multi-channel planar pitch-catch array probe and planar tandem array probe have been developed to improve detectability of three-dimensional defect. The ultrasonic flaw detection system and specific 3D-SAFT imaging algorithms have been particularly developed to use with these array probes.

Advantages of the planar array probes and flaw detection system are 1) no mechanical scan required, 2) saving inspection time, 3) increasing detectability of three-dimensional defect, and 4) with application of 3D-SAFT system, three-dimensional information of defect can be obtained with high accuracy.

The results of this study show great contribution to current ultrasonic detection technique that the defect information can be greatly extracted by using the planar array probe with application of 3D-SAFT.

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