ABSTRACT
Phased array ultrasonic testing techniques have become widespread in various industrial fields. They are one of the core technologies for in-service inspections of nuclear power plants with well-demonstrated abilities for sizing stress corrosion cracking in weld metal. In the phased array techniques, target objects are scanned with focused ultrasonic beams emanated from an array probe. We have been developing a novel phased array system called 3D Focus-UT which enables us to scan target objects volumetrically at one time with focused beams emanated from a matrix array probe. The system has three main advantages compared with conventional phased array techniques: 1) an increase in inspection speed by 3D scanning; 2) higher spatial resolution that comes from point-focused ultrasonic beams created by a matrix array probe; and 3) easy-to-understand inspection results displayed as 3D rendered images fused with 3D-CAD data. In addition to features of the 3D Focus-UT, this paper describes some examples of 3D scanning in test objects.

INTRODUCTION
Phased array techniques have become widespread in various industrial fields, because they have two major advantages over conventional ultrasonic techniques: the beams can be swept and focused without moving the probes [1]. For nuclear power plants, especially, they have become one of the core technologies for in-service inspections, since they have demonstrated abilities for sizing stress corrosion cracking (SCC) in weld metal.

In conventional phased arrays, ultrasonic beams are emanated from a one-dimensional (1D) array probe, and swept two-dimensionally along an array of elements. One of the most commonly used scanning pattern is probably the “sectorial scan”. Phased arrays have brought about a significant increase in inspection speed. We call these conventional phased arrays 2D phased arrays to distinguish them from a 3D method we have proposed.

In order to get higher inspection speeds, we have been developing 3D phased arrays; a schematic image is shown in Fig.1. With a matrix array probe, target objects can be scanned volumetrically at one time or at least in less time than 2D phased arrays, and scanned data can be evaluated in 3D. Therefore, the total inspection time is much shorter than for 2D phased arrays. In addition, detectability is also improved because of the point-focused beams created by the matrix array probe.

SYSTEM
We have developed a 3D phased array system called 3D Focus-UT, as shown in Fig. 2. The system has three main advantages compared with the 2D phased arrays.

1) Speed: an increased inspection speed due to the 3D scanning.
2) Resolution: higher spatial resolution that comes from point-focused ultrasonic beams created by a matrix array probe.
3) 3D imaging: easy-to-understand inspection results displayed as 3D rendered images fused with 3D-CAD (computer aided design) data.
In 3D scanning, we have to handle larger amounts of data in a short period of time than in 2D phased arrays. Thus, the equipment must have a capability for fast data processing. The 3D Focus-UT has multi-channel high-speed circuit boards, which have the ability to transmit or receive ultrasound signals from each of the 256 elements in a probe simultaneously. Additionally, real time 3D data acquisitions are possible as well as the conventional 2D scanning. Various patterns of 3D scanning can be chosen by giving appropriate delay times to each element in the matrix array probe. However, it is not a straightforward task to obtain the delay times due to the complexity of 3D calculations. In order to make the task easier, the 3D Focus-UT has software to calculate the delay times for any 3D scanning by ultrasonic propagation analysis associated with 3D-CAD. Operators can set the delay times and other parameters easily by checking propagation paths of ultrasound beams on 3D-CAD screens. The delay times are output as a file, so that the calculations are required only for the first scanning.

In addition to the data processing, another of the technical challenges in 3D phased arrays is how to visualize the 3D scanned raw data. The 3D Focus-UT is equipped with software to visualize and evaluate the scanned data in 3D. The scanned raw data are converted to voxel data by implementing appropriate interpolations. The resultant voxel data are displayed as 3D images by using well-known volume rendering methods and saved as a data file [2]. The operators can see the 3D images at any time after the data acquisition. Although the scanned raw data are inherently discrete and biased in space, the voxel data have no space between data points. Therefore, excellent visibility is kept in any line of sight. The conversion time is a few seconds. By cutting the voxel data at a selected plane in the measurement window, the distance between any two points (e.g., two echo peaks) can be measured.

Another significant feature of this software is the function to superimpose 3D-CAD data upon the voxel data. This technique reduces the evaluation time of 3D inspection results, because we can easily relate specific features on 3D-CAD data to 3D echoes reflected from them.
APPLICATIONS

FBHs in a Stainless Steel Test Piece

A 3D image of flat bottom holes (FBH) in a stainless steel test piece is shown in Fig. 3 (a). The test piece had a thickness of 70 mm and 25 FBHs each with a depth of 20 mm. The diameters of the FBHs were 1 and 2 mm as illustrated in Fig. 3 (b). The 3D-CAD images of the FBHs and the inside walls of the test piece were superimposed on the echo image.

The probe used in this case was designed to emanate longitudinal waves at 2 MHz. The probe had 256 (16×16) elements. Delay times were calculated to focus the sound field at approximately 50 mm into the test piece. The pattern of the 3D scan in this case was rotational sector scan, which was composed of 24 sectors positioned around the center line of the sectors in increments of 7.5 deg as illustrated in Fig. 3 (b). The insonification angle in each sector was swept from -30 to 30 deg in increments of 1.5 deg. Thus, the total number of focal points was 984. The whole scan was performed electrically as the probe was kept at a one position without moving, and the entire time from beginning the 3D scanning to obtaining the 3D image was several seconds.

The huge disk-like echo is the bottom echo, and the large and small cloud-like echoes above the bottom echo correspond to FBHs of diameters of 2 and 1 mm, respectively. The colour denotes reflection intensity. Each FBH echo is positioned at a correspondent chimney-like CAD image of FBH. The correspondence of echoes and their reflection sources is easily determined. If echoes are shown at positions where no reflection sources should exist, the echoes indicate some defects are there.

Figure 3 - (a) 3D image of FBHs in a stainless steel test piece and (b) scanning pattern.
Bolts

Fig. 4 (a) shows a 3D image of a thread and a slit as a simulated defect on a bolt of 24 mm diameter. The slit was 3.2 mm deep and was made by EDM (electronic discharge machining). The pattern of the 3D scanning and the longitudinal wave probe were the same as used in the FBH case. The probe was set on top of the bolt as illustrated in Fig. 4 (b).

The thread echo and the slit echo are clearly shown in Fig. 4 (a). In the case of the 2D phased arrays, the probe or the bolt has to be rotated mechanically. But 3D phased arrays do not require any mechanical motions in bolt inspections. Therefore, the inspection speed is improved significantly.

CONCLUSIONS

We have developed a 3D phased array system called 3D Focus-UT. The 3D phased arrays offer significant advantages over 2D phased arrays especially in terms of inspection speed due to the 3D scanning and 3D visualization. Although the basic techniques of 3D phased arrays have been developed, a number of challenges remain before actual inspections in places such as nuclear power plants can be made. Investigations for applications are underway.

REFERENCES
