Developments in Ultrasonic Phased Array Inspection I

3D-SAFT Ultrasonic Inspection Equipment “Matrixeye™

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ABSTRACT

3D ultrasonic inspection equipment “Matrixeye™” can visualize defects as 3D image with good resolution by the 3D SAFT (Synthetic Aperture Focusing Technique) imaging method. High-speed 3D SAFT imaging process can be achieved by the developed parallel signal process of the ultrasonic echo data collected by a linear or a matrix-array ultrasonic probe. It has the following features.

• 3D image with high resolution can be visualized by the small number of elements.
• Resolution of 3D image is almost constant against a change of depth and a probe frequency.
• Sensitivity of 3D image is good because S/N ratio is improved by SAFT process itself.

In this report, we introduce development of 3D-SAFT technology, its application and the current development activity.

Keywords: Ultrasonic Inspection, Matrix-array probe, 3D, UT, SAFT, Phased array

INTRODUCTION

In recent years, phased array technology, which can control focus depth and can steer angle of transmission ultrasonic beam by using array probes, has been applied to NDT (Non Destructive Test) in various industrial areas world widely.

On the other hand, we had developed and commercialized 3D SAFT (Three-Dimensional Synthetic Aperture Focusing Technology) ultrasonic inspection equipment “Matrixeye™”, which enables a large number of acquired echo data to focus on every point within 3D imaging area.

In this report, we introduce principle of 3D SAFT, functions and applications of the portable 3D SAFT ultrasonic inspection equipment “Matrixeye™EX”. In addition, we introduce basic development results of the advanced 3D SAFT method, which takes phased array technology into 3D SAFT technology.

3D SAFT TECHNOLOGY AND EQUIPMENT

Principle of 3D-SAFT

The principle of 3D SAFT method is explained by referring Fig. 1 as follows.

3D image can be synthesized from a large number of echo data acquired by the electronic scanner on SAFT method. The acquired echo data include more precise information because the acquired ultrasonic waves are propagated through many paths within the inspection object.

3D image synthetic process by SAFT is as follows. In this case, a probe is 8 x 8 matrix array, whose numbers are shown as from P1 to P64 in Fig. 1.

Data acquisition process

(a) Wide-angle ultrasonic waves are transmitted from P1, and its reflected echo is received by the selected elements in advance. After the moment, the all received echo data are converted and saved as digitized echo data in 3D image synthetic circuit in parallel.
(b) The above process is repeated from P1 transmission to P64 transmission.
(c) The parallel processor within the image synthesis circuit synthesizes 3D image within the 3D imaging area from the digitized echo data.

3D image synthetic process (A defect is located at position A)

(a) The amplitude data, extracted from P1-P1 wave data according to a P1-A-P1 flight time T11, is added to the image amplitude value in the mesh A.
(b) After the above process is repeated from a combination of P1-P2 wave data to P64-P64 wave data, the echo peak data of the defect A are added to the mesh A, and it becomes high value as a result of the process.
(c) On the contrary, image synthesis of the position without defect shown as the mesh B. The echo data adding to this position must be a kind of random noise. So, they canceled each other and intensity level of synthesized image in the mesh B must be small value.
(d) After finishing the above process to all meshes of the 3D imaging area, 3D image with good resolution and S/N ratio can be synthesized.

Portable equipment “Matrixeye™EX”

System outline

Initially this equipment had been developed as an application of vertical beam inspection for the in-service inspection of CFRP made aircrafts. We focused to develop user-friendly operation and off-line analysis using the saved imaging data. Then, we had added the angle beam function to this equipment. A picture and a structure of the portable 3D SAFT ultrasonic inspection equipment “Matrixeye™EX” is shown in Fig. 2 and Fig. 3. Specifications of Matrixeye™EX are shown in Table 1. The features of “Matrixeye™EX” are as follows.
(1) Array probe
It enables to use not only linear array probes but matrix array probe.
(2) Multi-channel transmission (Data acquisition circuit)
The change over circuit enables to select 9 channel transmissions at maximum from 64 channel pulsar to intensify ultrasonic transmission energy. And reflected echo data are distributed by another change over circuit to amplifiers and ADCs.
(3) Speedy inspection (Image synthesis circuit)
It enables speedy imaging by the developed parallel processing hardware and algorithm, e.g. B-scan imaging speed can be 70 frames per second at maximum using 64 channel linear array probe.

(4) 3D imaging (Touch panel display, processor and memory)
It enables to synthesis 3D image on 3D View screen and to save 3D imaging data as 32 bit binary data, so called a voxel file. The off-line viewer can display 3D bird's eye view as shown in Fig.4.

(5) Off-line analysis (Touch panel display, processor and memory)
It enables C-scan image regeneration after resetting Gates and DAC (Distance Amplitude Compensation), changing gain by software and evaluation of defect size, S/N ratio and attenuation.

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Figure 2 - Portable Matrixeye™EX

![Diagram of Matrixeye™EX](image)

Software
(1) User-friendly Operation
(2) Gate and DAC Preset
(3) Defect Detection and Sizing
(4) C-scan Images Regeneration
(5) Inspection Report

Interface
USB x 4, Video-out, Giga-Ethernet

CPU: Pentium M
(160GB HDD)

Power Supply
AC and Battery

Display
Touch panel operation

Scanning
Multi-channel transmission

Speedy inspection
Parallel processing & speedy data Acquisition

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Figure 3 - System Overview of Matrixeye™

![Diagram of System Overview](image)
Operation of “Matrixeye™ EX”

Fig. 5 shows the main screen of “Matrixeye™ EX”. Inspectors usually start from this screen. Operation can be divided to three processes as follows.

(1) Preset of inspection
An inspector must choose the measure conditions like probe type, method (Vertical or Angle), shape of inspection object, velocity and imaging area. And he set gates and DAC if necessary. Then he can register this condition as the specified task name.

(2) Inspection
An inspector can set the inspection condition by loading a necessary task name easily. Then he can inspect on real-time B-scan image screen, 3D-View image screen and C-scan image screen. And he can save inspection results as 3D image data.

(3) Off-line analysis (See Fig. 6)
An inspector can open the saved 3D imaging data, and carry out off-line analysis as follows.
   (a) C-scan image regeneration
C-scan image can be generated from the saved imaging data and inspection conditions. B-scan image and A-scan image also can be observed.
   (b) Gate and DAC setting
It enables to change gates and DAC (Distance Amplitude Compensation). And regenerate the new C-scan image.
   (c) Soft gain
It enables to change amplitude of the saved 3D imaging data by software.
   (d) Evaluation
It enables to evaluate size of defect, S/N ratio and attenuation.
Detail operation flow is shown in Fig. 7.

<table>
<thead>
<tr>
<th>Item</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment</strong></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>343x265x146mm</td>
</tr>
<tr>
<td>Weight</td>
<td>6kg (with 1 battery pack)</td>
</tr>
<tr>
<td>Display</td>
<td>10.4 inches</td>
</tr>
<tr>
<td>Power</td>
<td>100V to 240V AC, Li Ion Battery</td>
</tr>
<tr>
<td><strong>Signal Processing</strong></td>
<td></td>
</tr>
<tr>
<td>AD Converter</td>
<td>100MHz(12bit)</td>
</tr>
<tr>
<td>Processing</td>
<td>48 parallel</td>
</tr>
<tr>
<td><strong>Electronic Scanning</strong></td>
<td></td>
</tr>
<tr>
<td>T/R channel</td>
<td>64ch</td>
</tr>
<tr>
<td>Pattern of T/R</td>
<td>Any T/R pattern</td>
</tr>
<tr>
<td>Frequency range</td>
<td>2-25MHz</td>
</tr>
<tr>
<td>Range of gain</td>
<td>0-80dB/0.5dB step</td>
</tr>
<tr>
<td>Output voltage</td>
<td>20V -200V</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>Pentium M</td>
</tr>
<tr>
<td>HDD</td>
<td>160GB</td>
</tr>
<tr>
<td>OS</td>
<td>Windows XP</td>
</tr>
<tr>
<td>Other</td>
<td>USBx4, LAN, Video output</td>
</tr>
</tbody>
</table>
Figure 5 - shows the main screen of “Matrixeye™ EX”.

Figure 6 - Off-line Analysis using saved 3D image data
Main functions of Matrixeye™ EX are introduced as follows:

1. **Measure Condition** setting
   - Probe (Linear/Matrix array)
   - Method (Vertical/Angle beam)
   - Object (Flat/Cylindrical)
   - Imaging Area, Velocity, etc.
   - Generate Flight Time Tables

2. **DAC/GATE Setting**
   - Preset DAC
   - Preset Gates
   - Preset Alarm levels

3. **Store Task**
   - Save Task name
     - Table data & measure parameters
     - Register Task conditions

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**Function of “Matrixeye™ EX”**

Fig. 8 shows the screen of “Measure Condition.” An inspector can set inspection parameters e.g. probe information (linear/matrix), transmission/reception pattern, gain, pulsar voltage, imaging area, velocities, wedge height and shape of inspection object (flat/cylindrical). After an inspector finishes setting, he can confirm positions of imaging area, surface position of inspection object and beam angle on the screen. An inspector can set these parameters as he is observing received waves (A-scan image) of any combination of transmission and reception on this screen (It’s not shown on Fig. 8).
(2) “DAC/GATE Setting”

Fig. 9 shows the screen of “DAC/GATE Setting”. DAC can be set along three beam paths, which consist of center path, upper path and lower path. An operator can set DAC curve by set square area on SDH images one after another. Then, DAC curves are automatically created. So, DAC curve enable to compensate amplitude two dimensionally on B-scan image as shown on Fig. 9.

An inspector can set four gates at maximum on the B-scan image by clicking a start depth and an end depth, and then the gate position is displayed on B-scan image and A-scan image shown in right and low figure on Fig. 9.

(3) “Live (B-scan image)”

Fig. 10 shows a B-scan image of 5mm high slit within 30mm thick SUS test piece. Gate function enables to detect peak level in the setting gate. The alarm window of the gate becomes red when the peak level is over the Gate level. Distance window shows 5.1mm as the measuring result of the slit height.
Fig. 11 shows a 3D View image of 5mm high slit and 2mm high slit of 30mm thick SUS test pieces. It’s the inspection result acquired by scanning a 32 channels linear-array probe, whose position is measured by wired encoder. A 3D View image, which consists of a plane view (X-Y view) and two cross-sections view (X-Z view and Y-Z view), is displayed from the synthesized 3D image data.

“Matrixeye™EX” enables to use a matrix-array probe. Fig.12 shows a 3D View image of the same test piece. In this case, the inspection result of Matrix-array probe is almost same as a linear-array. But, a Matrix-array probe enable to display 3D image without physical scanning. It is expected to have some advantages on inspections with narrow space and curved surface.

It’s possible to measure a height and length of a defect on the 3D view image screen.

(4) “Scan (3D View image)”
Fig. 11 shows a 3D View image of 5mm high slit and 2mm high slit of 30mm thick SUS test pieces. It’s the inspection result acquired by scanning a 32 channels linear-array probe, whose position is measured by wired encoder. A 3D View image, which consists of a plane view (X-Y view) and two cross-sections view (X-Z view and Y-Z view), is displayed from the synthesized 3D image data. “Matrixeye™EX” enables to use a matrix-array probe.

Fig.12 shows a 3D View image of the same test piece. In this case, the inspection result of Matrix-array probe is almost same as a linear-array. But, a Matrix-array probe enable to display 3D image without physical scanning. It is expected to have some advantages on inspections with narrow space and curved surface.

It’s possible to measure a height and length of a defect on the 3D view image screen.
APPLICATION TO SCC INSPECTION

Summary of application

In this chapter, we introduce the test result of Stress Corrosion Cracking (SCC) by using 3D SAFT method. A test piece of stress corrosion cracking was supplied from JSNDI (Research committee for ultrasonic inspection of artificial SCC).

Test condition.

The test pieces are made from austenitic stainless steel. SCC is located in of the test pieces as shown in table 2. The SCC test pieces were inspected by 10MHz and 5MHz linear-array probes with angle beam technique using “MatrixeyeTM”. The 3D imaging data of SCC are acquired by scanning the probe in parallel with SCC defects from both side of SCC using wired encoder as shown in Fig. 13. In the case of share wave testing, 5MHz linear array probe was applied to perform 57 degree angle beam by contact testing technique. In the case of longitudinal wave testing, 10 MHz linear array probe was applied to perform 32 degree angle beam by immersion technique. The conditions of SCC test are shown in Table 3.

![Conditions](image)

Table 2 - Specification of SCC test piece 005 and B5

<table>
<thead>
<tr>
<th>Items</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material of test piece</td>
<td>austenitic stainless steel</td>
</tr>
<tr>
<td>Location of SCC</td>
<td>in base material</td>
</tr>
<tr>
<td>Size of test piece 005</td>
<td>300mm x 70mm x t9</td>
</tr>
<tr>
<td>Size of test piece B5</td>
<td>170mm x 70mm x t19</td>
</tr>
</tbody>
</table>

Test result

Most of defects detected by surface examination of the test pieces 005 and B5 were detected by 3D SAFT method using “MatrixeyeTM”. In the case of testing 005, though nine or ten SCC flaws are located in parallel in the same test piece, it was possible to detect all of them by only one scanning as shown in Fig. 14. In the case of testing B5, it was possible to visualize a tip of SCC clearly by 32 degree longitudinal angle beam as shown in Fig. 15. Its sizing result was 4.4mm. But, actual height of SCC is unknown because it has not been cut yet.
Consideration

This method enables to visualize whole inspection area with high resolution by simple setting of test condition. It’s possible to detect small defects like SCC without over-sight. The acquired result is not only in good accordance with the actual defects’ situation but also easy to understand by visual and quantitative output. It is expected to apply to detection, sizing of flaw in weld and inspection of pipe wall thinning in periodical inspection of Nuclear Power plants.

Figure 13 - A picture of equipment and test piece

Figure - 14 Inspection result of test piece 005 from SCC open side (Share wave, 57degree)
Figure 15 - Inspection result of test piece B5 from SCC open side (Longitudinal wave, 32 degree)

<table>
<thead>
<tr>
<th>Items</th>
<th>Linear-array angle bean inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing method</td>
<td>Share wave /Contact testing</td>
</tr>
<tr>
<td></td>
<td>Longitudinal wave / Contact testing</td>
</tr>
<tr>
<td>Couplant</td>
<td>Water (Velocity : 1,480 m/s)</td>
</tr>
<tr>
<td>Frequency of probe</td>
<td>5MHz</td>
</tr>
<tr>
<td>Element of probe</td>
<td>1x64 (1.0mm pitch)</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Wedge</td>
<td>Polystyrene (Velocity:2,330 m/s)</td>
</tr>
<tr>
<td>Velocity of base material</td>
<td>3100 m/s</td>
</tr>
<tr>
<td>Imaging area</td>
<td>X: 32mm</td>
</tr>
<tr>
<td></td>
<td>Y: 1mm (Scanning wise)</td>
</tr>
<tr>
<td></td>
<td>Z: 40mm</td>
</tr>
<tr>
<td>Beam angle (Calculated)</td>
<td>57 degree</td>
</tr>
<tr>
<td>Path length to center</td>
<td>19mm, 33mm, 66mm</td>
</tr>
<tr>
<td>Gain</td>
<td>30 dB</td>
</tr>
<tr>
<td>Averaging</td>
<td>1</td>
</tr>
<tr>
<td>T/R pattern</td>
<td>Transmission64, Reception15 (relative)</td>
</tr>
<tr>
<td>SAFT range</td>
<td>10 degree</td>
</tr>
<tr>
<td>Scan pitch</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Table 3 - The conditions of SCC test
ADVANCED 3D-SAFT

In this chapter, we introduce development of the advance of 3D SAFT. As we introduce in this paper, the transmission beam behavior isn’t controlled because transmission beam must be propagated from one point (element) theoretically in the current 3D SAFT method. We thought of the new method, by which the position of imaginary sound sources can be generated and scanned by the electronic transmission delay control of multi elements in a linear and a matrix array probe. We had confirmed the feasibility of this method by evaluating the behavior of the ultrasonic wave transmitted from imaginary sound sources by our original acoustic simulation code (SOSUM: Sound Sources Superimposed Method). This method is expected to improve the phased array method by changing an imaginary sound source to a focus point by this method. The outline of The advance 3D-SAFT is shown in Fig. 16.

Figure 16 - Out-line of Advanced 3D SAFT method

Method of advance 3D-SAFT

Fig. 17 shows the advanced 3D SAFT method of Imaginary Sound Source mode. In this case, transmitted ultrasound is as if it was propagated from an imaginary sound source. The received echo data are added to all meshes on the imaging area according the calculated flight times one after another as shown in Fig.17. As a result of this process all echo data can be focused to every mesh on the imaging area.

On the contrary, Fig. 18 shows the advanced 3D SAFT method of Real Focus mode. In this case transmitted ultrasound is focus to a focus point as same as Phased-array method. But, even in this case the received echo data are added to all meshes on the imaging area according the calculated flight times one after another. As a result of this process, all echo data can be focus to not only a focus depth but also every other meshes on the imaging area within the beam profiles.
Test result.

Fig. 19 shows images of SDH test piece combining four B-scan images using 5MHz 64channel linear array probe by the current SAFT method and the advanced SAFT method. In all images, resolution of SDH images are equally good from shallow to deep as a good feature of SAFT method. But, in the case of real focus mode, noisy image is observed in shallow area.

S/N ratios (Signal to Noise ratio) of the SHD images were evaluated by the off-line analysis program as shown in Fig. 20. A C-scan image of SDH is generated by the gate drawn near SDH depth. S/N ratio (N) is calculated from standard deviation (σ) and mean value (Mean) of background and a peak level of SDH image (Max). Fig. 21 shows the result of S/N evaluation. S/N ratio of the current 3D SAFT method is gradually reduced along depth. The result of Imaginary Sound Sources mode is good S/N ratio around 30mm depth. The real focus mode has two peaks before and after focus depth. Around the peak levels S/N ratio of SDH images can be improved 40 dB at maximum compare with the current 3D SAFT. So, if these conditions can be optimized, this method has a possibility to improve an inspection performance revolutionarily. But in the next step, Sound Source mode, S/N ratio in deep area should be improved in the case of the Imaginary, and S/N ratio near focus depth should be improved in the case of the real focus mode.
(1) Original SAFT method: No focus depth

(2) Imaginary S.S mode: (Depth: -35mm)

(3) Real focus mode: (depth: 45mm)

(4) Real focus mode: (depth: 70mm)

Figure 19 - SDH image synthesized by 3D SAFT method

C-scan image generated by gate-1

Amplitude of image

Max = \( n \times (STDV) + \text{Mean} \)

SDH Image

\( \sigma \) (STDV)

Mean

Background

Gate-1

Figure 20 - S/N evaluation method

S/N Ratio of SDH image

Bottom near focus depth

Amplitude of SDH image

Figure 21 - Advanced 3D SAFT basic test result
REFERENCES


2) Abe Motohisa, Hirokazu Karasawa, “Matrixeye Portable 3D Ultrasonic Inspection System”, TOSHIBA REVIEW Vol.60, No.4, 2005, PUBLISHED by TOSHIBA CORPORATION.
