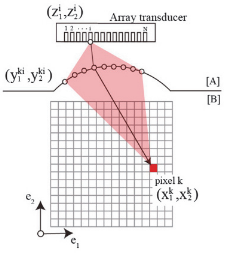
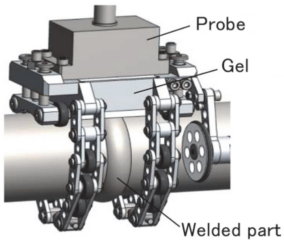
Adaptive Ultrasonic Testing Technology for Imaging Inside of Product with Complicated Shape Surface





KYOHEI HAYASHI[*1] MASAKAZU KAMIBAYASHI[*1]

KIYOTAKA AOKI[*2] KAZUYUKI NAKAHATA[*3]

In view of the reduction of inspection costs and construction time for various products, the establishment of high-efficiency inspection technology is desired. For the inspection of the inside of products with complicated shape surfaces and irregularities caused by welding, surface smoothing processing for ultrasonic testing such as surface grinding and putty filling is required, and excess costs and time are needed. Mitsubishi Heavy Industries, Ltd. (MHI) introduced ultrasonic signal processing technology which does not require smoothing processing for complicated surfaces and developed an inspection technology which allows real-time imaging of minute flaws on the inside of a product.

1. Introduction

MHI's products such as thermal and nuclear power plants and chemical plants operate under harsh environmental conditions in many cases, and there are concerns about damage to facilities due to aging. Therefore, it is important not only to conduct daily maintenance inspections, but also to conduct inspections for damage detection with high precision with due consideration for the types of damage of each facility. On the other hand, in recent years, the need for the reduction of inspection costs and construction time has grown in view of the reduction of maintenance costs along with the electric power liberalization, etc., and more rational inspections are required. As such, MHI developed high-precision ultrasonic testing logic for products with complicated shape surfaces and irregularities caused by welding, with the aim of reducing ancillary inspection work such as surface grinding and reducing excess costs and construction time. In this report, an overview and the state of the development of the technology are described.

2. Issues with conventional ultrasonic testing technology

Ultrasonic testing technology is widely used as a method of nondestructive inspection of the inside of a product. In this method, a probe is directly brought into contact with the surface of a product to propagate ultrasonic waves to the inside, and the position and size of a flaw are estimated by scattered waves received from the flaw. MHI developed phased-array ultrasonic testing technology[(1)] as high-precision inspection technology and has applied the technology to inspection work for various products. The probe used in phased-array testing has a structure in which multiple minute vibration elements that can excite independently are arranged in an array. Therefore, when an appropriate time delay (delay) is given to each element to excite it, the propagation angle of the ultrasonic waves can be changed (steering) and a focusing point can be set (focusing). In addition, any defect on the inside of a product can be imaged from the information obtained by controlling and sending/receiving ultrasonic beams.

However, for ultrasonic testing through complicated shape surfaces with irregularities caused by welding, ancillary work for surface smoothing such as surface grinding and putty filling are required so that the probe can be brought into contact with the surface, and excess costs and time are needed. If ultrasonic testing can be directly conducted from such a surface with irregularities, ancillary inspection work such as surface grinding can be curtailed, and excess costs and construction time can be reduced.

*1 Service Engineering Department, Research & Innovation Center

*2 Manager, Service Engineering Department, Research & Innovation Center

*3 Professor, Department of Civil and Environmental Engineering, Ehime University

To inspect the inside of weld metal with a complicated surface, MHI developed adaptive phased-array ultrasonic testing technology[2]. In this method, a given surface shape (surface with irregularities) is recognized, and based on the obtained data, the excitation conditions of ultrasonic waves are corrected to perform inspection (imaging) of the inside. In this technology, the surface geometry is detected using the phased-array method, and then the delay time for each element is recalculated based on the results of the measured surface geometry. Therefore, this technology had an issue in that it took time to conduct flaw detection twice and calculate the delay time based on the surface geometry.

This time, MHI utilized full-waveform sampling processing technology to increase the precision of ultrasonic signals from a complicated surface in a single flaw detection process and developed high-speed and high-precision adaptive ultrasonic testing technology using the high-speed parallel computation technology of GPGPU (General-Purpose computing on Graphics Processing Units).

3. Overview of adaptive ultrasonic testing technology

3.1 Waveform processing technology

As a new ultrasonic waveform processing technology, FMC/TFM (Full Matrix Capture/Total Focusing Method) technology was used. The FMC/TFM technique is an imaging technique by which a waveform is newly resynthesized from the full-waveform transmitted/received at each element and a flaw image with higher spatial resolution is constructed. This technique is also known as Full-waveform Sampling And Processing (FSAP)[3]. In the phased-array technique, ultrasonic beams are delay-controlled by the hardware and controlled/transmitted for imaging, while in the FMC/TFM technique, with consideration for time delay by post-processing on a PC, virtual ultrasonic focusing beams are created for imaging. **Figure 1** gives a comparison between the FMC/TFM technique and phased-array technology. The FMC/TFM technique delivers higher spatial resolution compared to the phased-array technique and provides flaw imaging with a better SN ratio. In addition, the received waveforms by multipoint measurement are processed and an image is constructed from virtual waves propagated in various directions, facilitating good imaging without lowering the detection sensitivity on an inclined slit relative to the test surface (probe surface) or a curved surface. In addition, the waveform data of all elements of the array probe is reserved, and an imaging with the wave velocity and delay time arbitrarily adjusted can be realized. This technique requires an enormous volume of calculations because the full-waveform data is processed, and conventionally it was difficult to apply to the actual product in terms of the processing time. In recent years, along with the improvement of data processing by PCs and the application of GPGPU, this technique has been reaching a level of practical use.

3.2 Adaptive ultrasonic testing logic

In ultrasonic testing, a medium such as water or gel is used to efficiently transmit ultrasonic waves between the probe contact surface and the product surface, and the detection of flaws from a surface with irregularities is also performed in the same way. In this case, ultrasonic waves are partially transmitted and partially reflected at the interface between the two materials of the medium and the product. Ultrasonic waves transmitted to the inside of the product are refracted at the interface in such a way as to satisfy Snell's law, and at the same time, not only longitudinal waves but also transversal waves are generated by the mode conversion. These waves scatter at a defect point in the product. Therefore, the flaw can be detected by the detection of the scattered waves. In flaw detection from a surface with irregularities, which differs from flaw detection from a uniform surface, imaging of the inside of a product cannot be performed unless reflection/refraction phenomena at an arbitrary interface are considered.

In this research, the imaging of the inside of a product was performed from any given surface with irregularities by the implementation of two-step synthesis processing/imaging (TFM) using the FMC data that was obtained once. In the first step, the surface geometry is imaged using the ordinary FMC/TFM technique and the coordinates of the surface geometry are obtained from the image data. In the second step, with consideration given to ultrasonic waves being refracted according to the surface geometry, the propagation path of the inside of the product is estimated. Here, the logic for satisfying Snell's law at each point of the material surface and calculating a path to the target pixel at high speed was implemented, and high-speed imaging of the internal defect was performed using GPGPU.

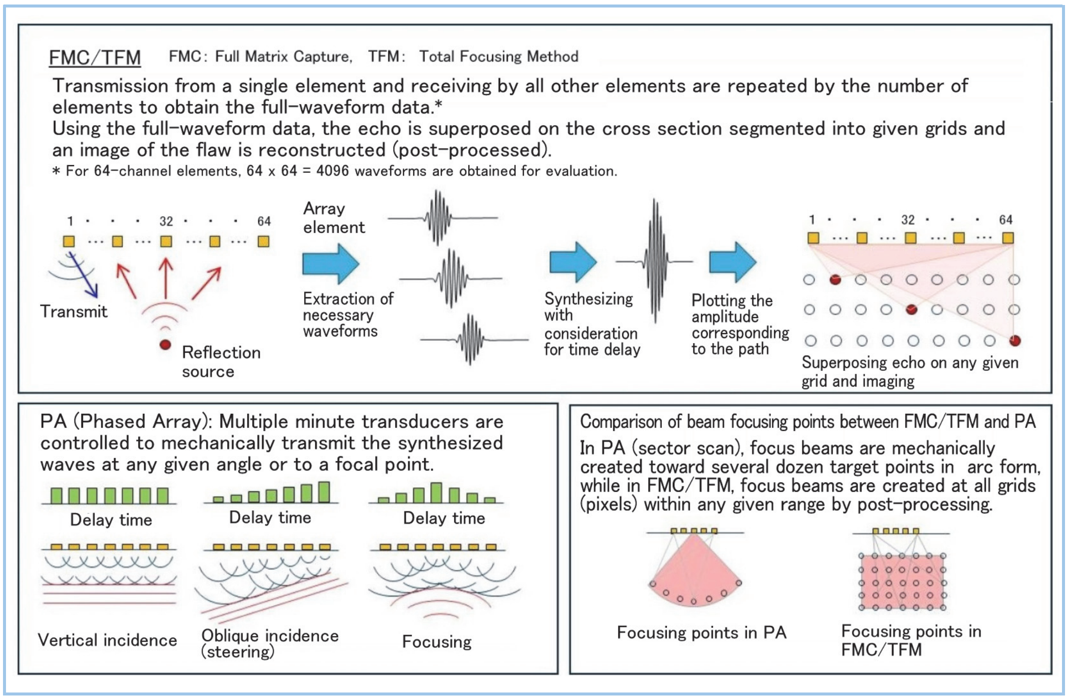


Figure 1 Comparison between FMC/TFM technique and Phased-Array (PA) technique

3.3 Logic for estimating the surface geometry

Figure 2 presents the results of recognition of the surface geometry. First, a probe is set at a given position on the product surface, and a primary image is obtained by FMC/TFM. This obtained image consists of pixels, and each pixel has data of beam path and echo height. Next, the pixel with an echo height exceeding the threshold and the maximum echo intensity in each given pixel array is extracted as an assumed shape boundary point. In this processing, the image is subjected to concurrent processing in the horizontal direction (in the direction of the array of vibration elements) at a given pitch and the surface geometry is obtained as point group data. In this way, the process was simplified, concurrent processing was made possible, and furthermore, high-speed processing was realized by GPGPU.

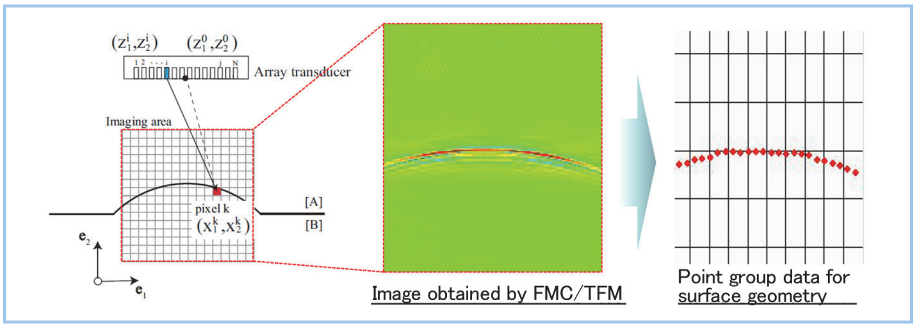


Figure 2 Surface geometry mapping technology by ultrasonic testing

3.4 Imaging of inside by waveform re-synthesis using Fermat's principle

Figure 3 illustrates the results of imaging of the inside of a product with a curved surface. When ultrasonic waves enter the inside of a product with a wave velocity of c_B (wave velocity of product material) from the medium with a wave velocity of c_A (wave velocity of water or gel in this case), the ultrasonic waves refract at the interface between the medium and the product surface, while the propagation path from the element to the target analysis position in the product varies by the curvature of a curved surface. The propagation path is uniquely determined by Snell's law, but in this case, Fermat's principle is used to derive the propagation path which requires the shortest ultrasonic propagation time. Fermat's principle is the principle that light or waves such as ultrasonic waves propagate between two points along the path that requires the least amount of time, and this path satisfies Snell's refraction law. If the propagation path to each pixel can be calculated, the focusing beam to the pixel can be synthesized with consideration for the delay of each element and imaging of the inside of a product can be performed. As described above, for imaging, several processing steps must be continuously performed, but the waveform required for a series of processes is acquired only once, resulting in an increase in the speed of flaw detection.

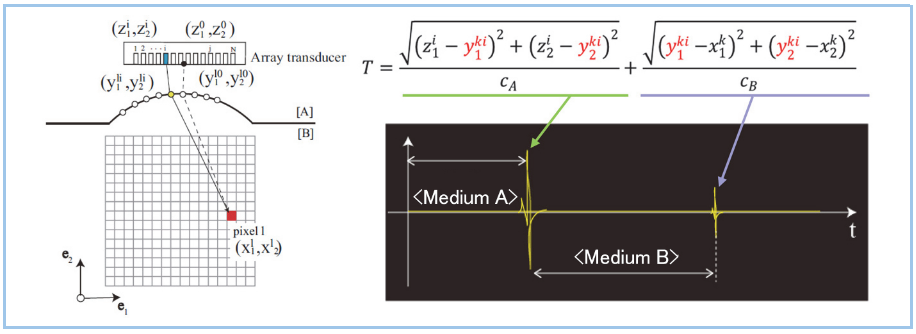


Figure 3 Computation technology for complementing refraction of ultrasonic waves due to surface irregularities

3.5 Construction of adaptive ultrasonic testing software

Trial software including the waveform processing program described in 3.2 to 3.4 was made. GPGPU parallel computation was adopted for calculation in this software, and the speed of a series of processes was increased by the system shown in **Figure 4** (a). Figure 4 (b) is a comparison of the processing time between conventional CPU computation and GPGPU parallel computation. Intel Corporation's Core i7-6700K is used as a single core for the CPU, and NVIDIA Corporation's GeForce GTX970 is used for GPGPU computation. As the number of pixels in imaging increases, the computation time increases linearly, but in GPGPU computation, the gradient is very small and the computation speed is more than 10 times higher than that in CPU computation. A total of 200,000 pixels, which is adequate for performing a detailed imaging of the inside of a general tube welded part (in the range of 40 mm x 50 mm), can be imaged within one second.

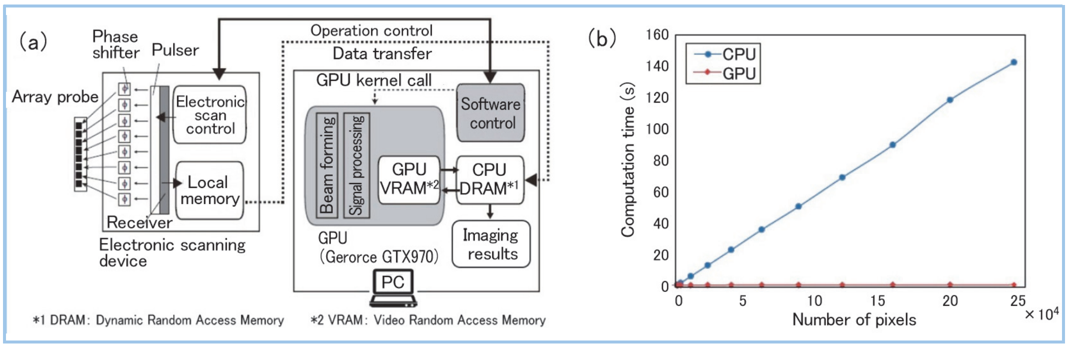


Figure 4 (a) Adaptive ultrasonic testing system, (b) Imaging computation processing time by this system

3.6 Construction of adaptive ultrasonic testing system

To conduct ultrasonic testing for complicated shape surfaces using the aforementioned waveform processing logic, an equipment configuration that allows the implementation of general FMC/TFM ultrasonic testing is needed, an appropriate medium must be filled between the product surface and the array probe, and an environment which allows the efficient transmission and receiving of ultrasonic waves is required. In conventional adaptive phased-array flaw detection technology, a local immersion method was used by which an array probe and a product surface are immersed in water for the detection of flaws. But this method may not be applied due to certain structural or operational constraints. Therefore, as an ultrasonic propagation medium, ultrasonic transmission gel with ultrasonic propagation properties equivalent to water, was used. Even if this gel is strongly pressed against a product, it will not damage the surface, and it also has a high fitting affinity with irregular surfaces. We also developed a scanner that scans irregular surfaces while stably holding an array probe set on gel.

3.7 Verification using sample

Using the test specimen with a convex portion (10 mm in height, 30 mm in width) which mimics an excess weld metal, shown in **Figure 5** (a), a verification test was conducted. In the inside of the specimen, five circular Side Drill Holes (SDH) of 2 mm in diameter were made as simulated defects. The surface geometry estimation results by the developed waveform processing logic and the surface geometry measured by the laser surface measuring instrument were compared. The comparison results showed that the surface geometry estimation error was 100 µm at maximum. The results of the imaging of the inside of the specimen are depicted in Figure 5 (b), in which five SDHs are separately imaged and the position estimation accuracy of ±0.5 mm is satisfied. The time taken in the imaging is within one second/cross section, and real-time inspection can be realized.

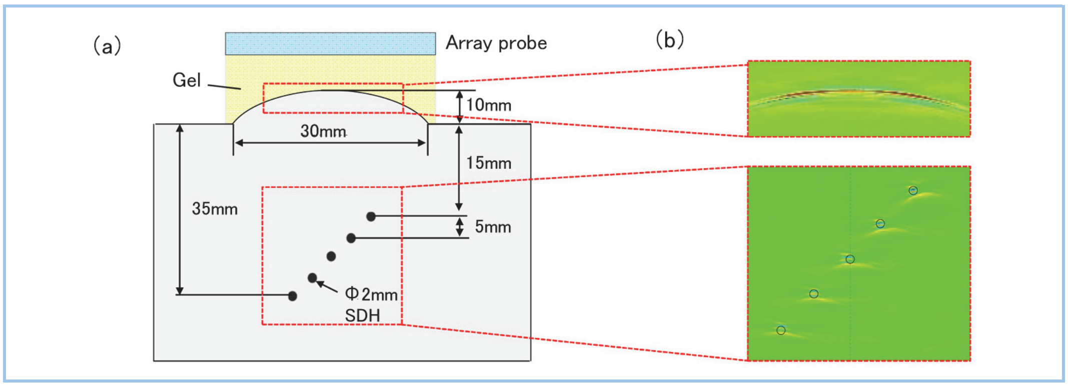


Figure 5 (a) Test specimen for verification, (b) Adaptive ultrasonic testing results

4. Conclusion

We established a basic technology for high-speed adaptive ultrasonic testing which allows real-time detection of minute side holes inside of a product from a complicated surface with irregularities such as excess weld metal. This technology allows ultrasonic detection of internal defects at a practical processing time (within one second/cross section), and it is expected to contribute to the reduction of inspection costs and construction time. We will upgrade this technology by promoting verification tests on actual equipment in the future and contribute to the improvement of the operating rate of MHI's plant equipment.

References

(1) M.Urata et.al., “Non Destructive Inspection Technology for Thermal Power Plants” Mitsubishi Heavy Industries Technical Review Vol. 52 No. 4 (2015)

(2) T.Kimura et.al., “Advanced Phased Array Technology to Support the Reliability of the Nuclear Power Plant” MitsubishiJuko Giho Vol.44 No.1.(2007)

(3) K.Nakahara et.al., “Flaw Reconstruction from Scattering Amplitude using Full-waveform Sampling and Processing (FSAP)” Journal of JSNDI Vol.59 No.6.(2010)