Development of Phased-Array Ultrasonic Testing Probe

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Phased-array ultrasonic testing was developed for nondestructive evaluation of power plants. Phased-array UT scans and focuses an ultrasonic beam to inspect areas difficult to inspect by conventional UT. We developed a highly sensitive piezoelectric composite, and designed optimized phased-array UT probes. We are applying our phased-array UT to various parts of power plants.

1. Introduction

Prevention of trouble is a matter of vital importance, particularly in the operation of nuclear and other power plants. With the increase in plant life, assessment of the remaining life of plant components has become an important subject.

Nondestructive inspection is an essential testing method for the safe, long-term operation of plants. Ultrasonic testing (UT) is generally used to inspect the piping systems and pressure vessels of power plants. The UT method shows satisfactory capabilities in detecting and sizing (evaluation of the size of defect) of defects in the portions which have simple geometry and allow ultrasonic waves to propagate smoothly. However, this method is not suitable for testing of parts such as stainless steel castings that do not allow easy propagation of ultrasonic waves, or complex geometry parts that do not allow the testing probe to scan freely.

As an advanced UT method, research on phased-array UT technology is being conducted worldwide. Because ultrasonic-wave beams of the phased-array UT can be electronically controlled, it is possible to detect defects even in the complex geometry parts by electronically scanning, and also to enhance the space resolution by focusing the beam.

This paper describes the development of the probe as the basic technology for the phased-array UT method by referring to the fabrication technique of the piezoelectric composite which is the key element in the probe, probe design considerations, and examples of practical applications of this testing method.

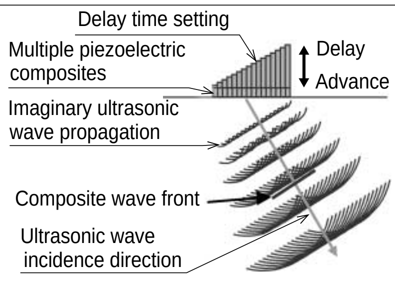
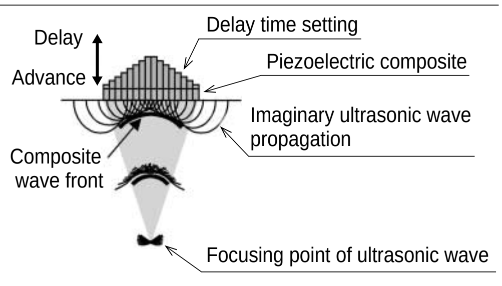
2. Phased-array UT method

2.1 Principle of operation and features

A conventional UT probe consists of a single piezoelectric element, while that for phased-array UT has multiple piezoelectric elements. Each piezoelectric element is independently controlled in its S/R timing to synthesize a waveform for control of ultrasonic-wave beams.

The electronic scanning shown in **Table 1** is an example of scanning made by delaying the sending timing of the right-hand side piezoelectric element. The table shows that the composite wave front inclines to the right side, as a result of which the beam can be transmitted in a similar way to ordinary angle probe. With regard to the electronic focusing, composite wave front is focused on a given point by delaying the beam transmitting timing of the piezoelectric elements located in the middle of array, resulting in a similar effect to that given by a focusing probe. In this way, the phased-array UT method makes it possible to freely change the angle of incidence and the position of focusing of the ultrasonic beam, and is thus expected to be used to inspect areas

Table 1 Principle and feature of phased-array UT

Method	Electronic scanning	Electronic focusing
Control principle		
Features	Probing speed increases as a result of minimization of difficult-to-inspect areas by scanning at various angles of refraction and by electronic scanning.	Space resolution (detecting ability) is improved by ultrasonic-wave beam focusing.

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to which the conventional UT method is not applicable.

2.2 System composition

Fig. 1 shows the composition of the phased-array UT system. Fundamentally, the system is composed of (1) phased-array UT probe, (2) phased-array UT instrument (for control of probe transmitting and receiving signals), and (3) personal computer for control of the phased-array UT instrument. For automatic probing, this system may incorporate a scanner to let the probe scan and a scanner driver to control the scanner. This light-weight system is also suitable for field inspection.

2.3 Applications of phased-array UT

The first major application of the phased-array UT is inspection of complex geometry parts. When conventional UT is used, the inspecting areas must be scanned entirely with the probe. If the inspecting area includes any portion having a straight part that is too short to probe, such a difficult-to-probe portion has to be omitted from inspection. However, such conventionally difficult portions can be inspected by using the beam scanning function of the phased-array UT instead of scanning with probe.

The second application is inspection of parts made of high-noise materials such as stainless steel castings and weldings. Coarse grain crystals contained in these parts deflect and scatter the ultrasonic waves and lower the propergation. By focusing an ultrasonic-wave beam on these parts, the defect echo level is made clear and the signal-to-noise ratio is improved.

In addition to the above, when piezoelectric elements of a phased-array UT probe are divided into groups, speed of inspection can be increased by switching each group electrically instead of scanning with probe.

3. Development of high-performance probe for phased-array UT

As mentioned above, phased-array UT is expected to be used to inspect parts which conventionally are difficult to inspect. Unlike the conventional UT, the probe for phased-array UT has special parameters such as scanning range and focusing range of ultrasonic-wave beams and its performance depends largely on the number and size of piezoelectric elements. The basic technology developed by Mitsubishi Heavy Industries, Ltd. (MHI) for phased-array UT probes is described below.

3.1 Structure of highly sensitive piezoelectric composite

Improvement of the characteristics of ultrasonic-wave piezoelectric composite is considered to be the first task for enhancement of the performance of phased-array UT. Conventional piezoelectric elements

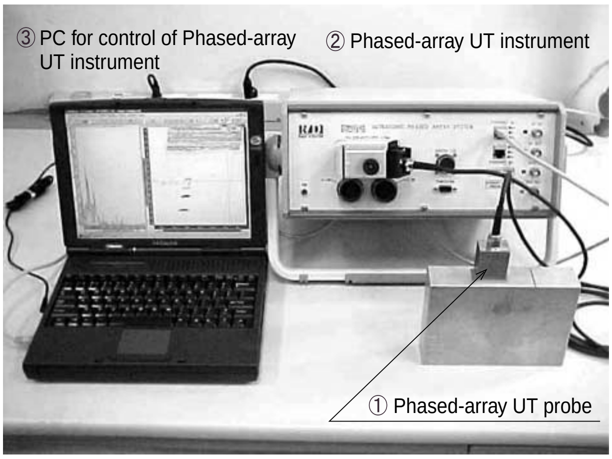


Fig. 1 Composition of phased-array UT system

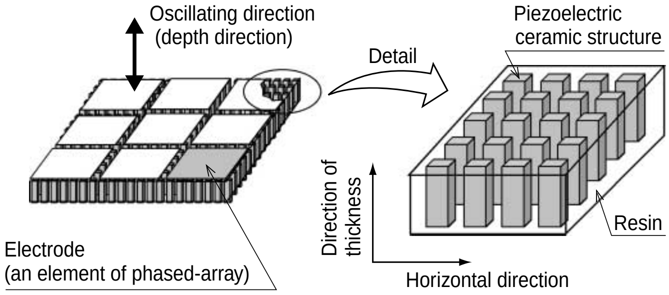


Fig. 2 Structure of piezoelectric composite

are made of piezoelectric ceramics such as lead zirconate titanate (PZT). When a piezoelectric composite is fabricated so that the thin structures made of piezoelectric ceramics are set in array as shown in **Fig. 2**, and compacted into a composite by filling resin, the effects will be as follows:

(1) Resin filled between piezoelectric structures acts as damping material to reduce the pulse duration of the ultrasonic waves, improving resolution in the direction of depth.

(2) Oscillation in the direction of thickness becomes predominant and suppresses the resonance in the horizontal direction, minimizing useless radiations and improving directivity.

(3) Decrease in acoustic impedance improves matching and signal-to-noise ratio.

(4) Mechanical Q value (Q_m: an index representing the damping characteristics of piezoelectric composite) becomes smaller, expanding the band width.

In preparation for the design of an excellent piezoelectric composite such as that described above, the oscillation characteristics were evaluated by the finite element method.

The essential parameters in the design of piezoelectric composites are PZT volume factor and Young's modulus of resin filler. The shape of PZT structure is also considered to have an influence on the mutual interference in the horizontal direction.

To evaluate the damping characteristics, the

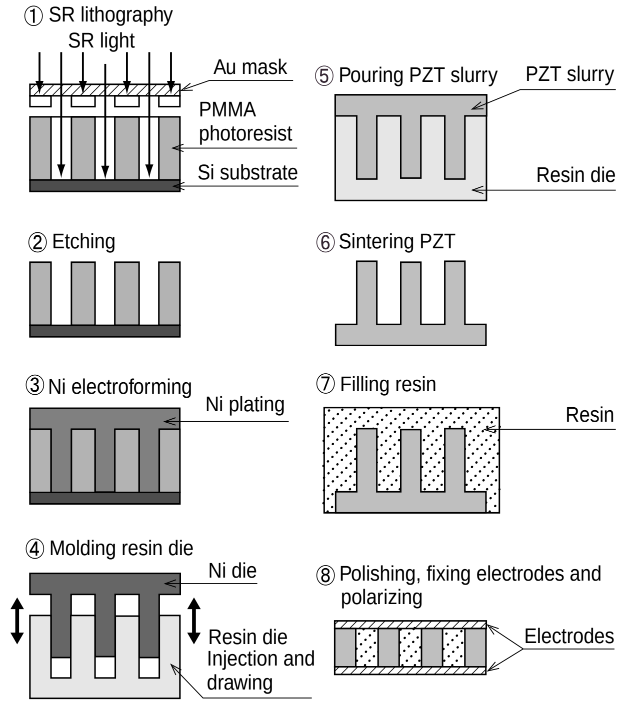


Fig. 3 Production process of piezoelectric composite
The process from step (1) to (4) is called the LEGA process.

oscillating transient response of the piezoelectric composite was analyzed by applying impulse potential.

The analyses have revealed the following characteristics:

(1) The Q_m reaches its lowest level when the volume factor of composite is 25%; it is equivalent to about one half that of the Q_m of a conventional PZT transducer.

(2) The Q_m value levels off when the aspect ratio is over 10. For fabrication of an approx. 5 MHz piezoelectric composite, it will require a three-dimensional microfabrication technique to shape a structure about 200 μm high and about 20 μm wide.

As the pulse duration of transmitting and receiving ultrasonic waves decreases with Q_m value, favorable oscillating characteristics are obtained.

From the results of the analysis mentioned above, the PZT structures constituting a piezoelectric composite must be a microscopic structure with a high aspect ratio of several tens μm in width to several hundreds μm in height. As it was difficult to shape such a microscopic structure by conventional techniques such as dicing, the LIGA process (Lithographie, Galbanoformung, Abformung) for high-accuracy microfabrication technique was employed for the production of piezoelectric composite.

The LIGA process is a microfabrication technique developed in early '80s by The Nuclear Research Center, Karlsruhe, Germany. It is a combination of the processes of X-ray lithography (exposure) to shape deep grooves, electroforming (plating) and molding.

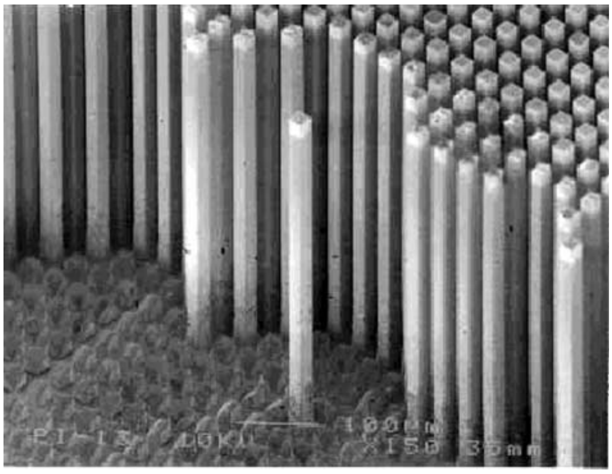


Fig. 4 SEM of piezoelectric composite Ni die
Part of Ni die fabricated by the LIGA process (array of 20X20 μm, 500 μm high Ni structures) is shown.

The synchrotron radiation (SR) rays used as the X-ray source have sufficient intensity and directivity to shape a three-dimensional structure with a high aspect ratio of several hundreds μm in depth to several μm in width.

Fig. 3 shows a schematic of the piezoelectric composite production process. The grooves corresponding to PZT structures are shaped for photoresist (photosensitive material) by irradiation of SR light. The die is made by plating the photoresist with Ni. The Ni-plated die is used to cast a resin mold. Piezoelectric ceramic slurry is poured in the resin mold and solidified to the shape of PZT structures, and then sintered. Finally, resin is poured in the skeleton of the PZT structures to fill up the space in it, and is then solidified to complete a piezoelectric composite.

This research work was carried out under the guidance of Prof. Susumu Sugiyama, Department of Science and Technology (Robotics), Ritsumeikan University, and using the university's SR light source facility (AURORA) for completion of the piezoelectric composite by the LIGA process. **Fig. 4** shows a photomicrograph of a Ni die for piezoelectric composite trial-fabricated using the LIGA process.

The Q_m value of the prototype piezoelectric composite is found to be as low as about 50% that of a single-structure PZT transducer. The superiority of the piezoelectric composite over PZT transducers in oscillating characteristics was also confirmed by experiments.

3.2 Design and fabrication of probes

For practical application of the phased-array UT, it is important to design a probe which is suited to the portion of the pipes and vessels to be inspected. The design procedures used for it are as follows:

To start with, the inspection conditions including the focusing radius of ultrasonic-wave beam, focusing position, scanning range, etc. are determined for

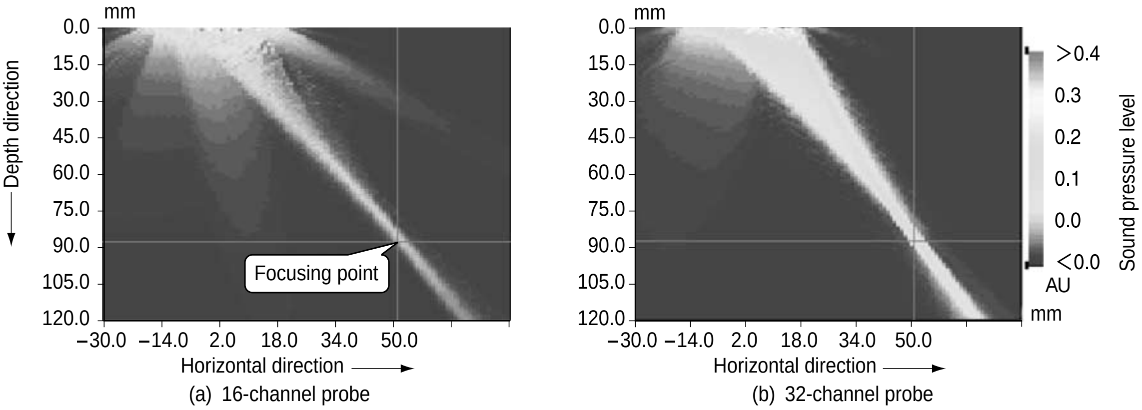
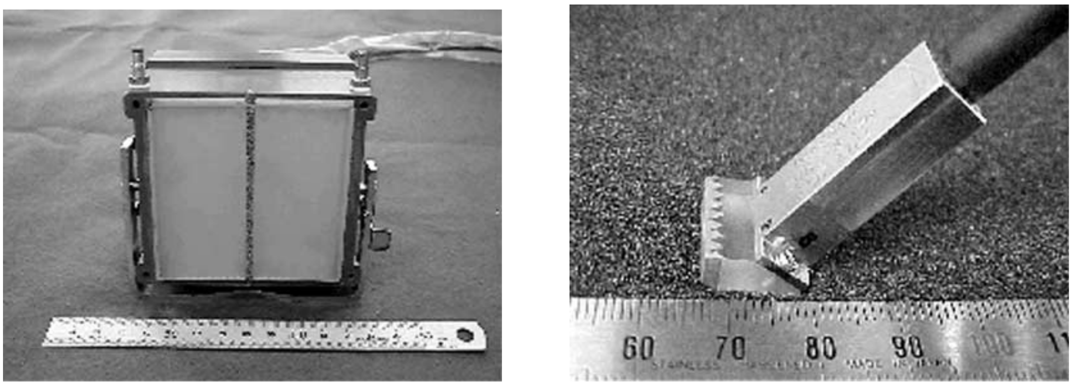


Fig. 5 Results of acoustic numerical analysis
Difference in distribution of sound field by the number of probe channels is shown.



(a) For SUS castings (b) For small-diameter piping (with shoe)

Fig. 6 Appearance of various phased-array probes
Typical phased-array probes designed and fabricated are shown.

the intended inspection area. These conditions may be obtained from the indication of drawings if the inspect area is relatively simple in structure, or by the ray trace simulation method in the case of complex geometry parts.

The array parameters of the inspection conditions are computed from the array parameter calculation equation, and the parameters are used to analyze the sound field of phased-array to ensure that the ultrasonic-wave beam is adequate. When it has been confirmed that the beam is adequate, the probe is fabricated according to the array parameters.

Fig. 5 shows an example of analysis of sound fields. In this instance, sound fields of ultrasonic-wave beams of 16-channel and 32-channel probes are analyzed with refraction angle of 30^{o} and focusing depth of 90 mm. According to Fig. 5, the 32-channel probe forms a satisfactory ultrasonic-wave beam, while the beam of the 16-channel probe is not intense at the point of focusing and carries side lobes. In this case, the 32-channel probe needs to be selected. UT probes are fabricated according to the array parameters which have been determined as mentioned above. **Fig. 6** shows typical phased-array probes used to inspect stainless steel castings and small-diameter pipings. In addition to these, probes suitable for inspecting curved portion of nozzle stub on pressure vessels, high-speed inspection on piping and other purposes have been fabricated.

4. Flaw detection tests

Flaw detection tests with the phased-array UT probes which have been specially fabricated were conducted on a mock-up test piece. The object of the tests was to inspect the welding of piping and nozzle stub. Due to the presence of nozzle stub and weld reinforcement of weld, this area does not provide a sufficient length of straight portion for UT probe scanning from the nozzle stub side. Therefore, this area has been inaccessible in ultrasonic tests. To solve this problem, a small-sized phased-array UT probe was fabricated to scan this area with ultrasonic-wave beam. The inspection conditions in the area were 8.7 mm for focusing depth, 2.0 mm for focusing diameter and 35^{o} to 71^{o} for angle of refraction for scanning. **Fig. 7** shows the result of the test conducted on the mock-up test piece which has an EDM slit to the depth of 10% of the wall thickness. This figure produced by a method known as S scope displays the area corresponding to the angle of refraction of the phased-array UT. When the image of the groove profile is superimposed on this figure, it becomes obvious that a 10%-deep slit has been distinctly detected in the vicinity of the weld. In addition to the above-mentioned UT probe for application to complex geometry parts, another UT probe suitable for inspection of the curved portion of pressurizer nozzle stub is now being devised.

For inspection of stainless steel castings, a T/R (different transmitting and receiving elements) mode type phased-array UT probe has been developed. Stainless steel castings, as mentioned previously, are materials containing coarse grain crystals which become a source of high noise on the inspection signals. Attempts to reduce the noise were made by focusing the ultrasonic-wave beam and by devising the T/R mode type phased-array UT probe. It is now likely that use of this probe will make it possible to distinctly detect an EDM slit to a depth of 10% of the wall thickness of a 75 mm-thick cast test piece.

5. Conclusion

MHI has developed a phased-array ultrasonic testing method that permits scanning and focusing of ultrasonic-wave beams for the purpose of inspecting the complex geometry parts and the parts made of high-noise materials which have been difficult with the conventional UT method. Specifically, the following technologies have been established:

(1) Fabrication of high-sensitive piezoelectric composite by utilizing microfabrication technique

(2) Establishment of optimal designing procedures using sound field analysis

Furthermore, the newly developed UT probes were actually used to inspect the complex geometry parts of piping and the parts made of stainless steel castings, and this demonstrated that they were applicable to the inspection of the parts for which conventional UT methods have been unusable.

Currently, MHI uses the phased-array UT probes in the inspections of elbow parts and nozzle stub welds in actual plants for verification of their effectiveness. MHI intends to continue to design other types of UT probe suitable for inspection of pipings and pressure vessels different in shape and size and, at the same time, to improve the UT flaw detection technology by making use of the advantages of phased-array UT method. These efforts of MHI will enhance the performance of the current phased-array UT technology, especially in its flaw detecting ability and size-determining ability in various fields of practical applications.

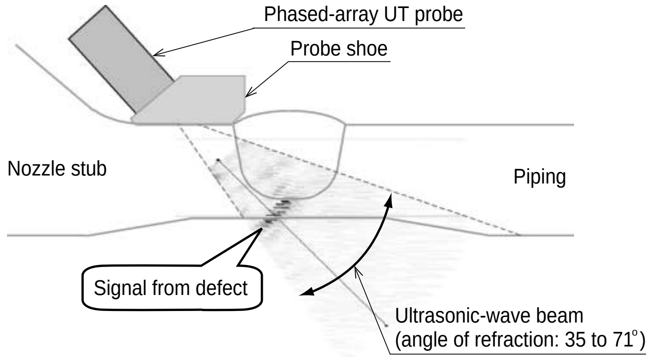


Fig. 7 Result of mock-up test using phased-array UT
An example of probing wave pattern of phased-array UT on mock-up test piece having an EDM slit is shown.

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