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Measurement System for Flow Mapping and Shape Detection using Sectorial Array Sensors

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The Fukushima Dai-ichi nuclear power plant (FDNPP) was damaged by the Great East Japan Earthquake 10 years ago. Reactor cores of units 1, 2, and 3 were melted and large amounts of fuel debris generated to reactor pressure vessel (RPV) and primary containment vessel (PCV). Researchers have a number of measures and techniques to detect the location of fuel debris and leakage point in RPV and PCV. In recent years, ultrasonic waves, with their light-free and high radiation-resistant properties, have led researchers to propose a number of methods for the application of ultrasonic techniques to fuel debris and leakage point detection. This paper proposes a method to detect the location of fuel debris and leakage point by ultrasonic sectorial array sensors using Ultrasonic Velocity Profiler (UVP), Full Matrix Capture (FMC), and Total Focusing Method (TFM), respectively. A mock-up experiment has performed in a laboratory-scale tank where simulated fuel debris and leakage points were placed. The sectorial array sensors were applied to measure the shape of simulated fuel debris and flow around it. The results of the experiment have demonstrated that the sectorial array technique can be applied in leakage point and fuel debris detection.

Keywords: Fukushima Dai-ichi NPP, Decommissioning, UVP, Sectorial array sensors, TFM

1. Introduction

During the 2011 Great East Japan Earthquake, the Fukushima Daiichi nuclear power plant (FDNPP) suffered severe damage. The core temperature is rising because the reactor cannot be cooled properly due to power failure caused by the earthquake and tsunami coming after. That led to the melted down of core and a large amount of radioactive fuel debris was deposited through the core in the reactor pressure vessel (RPV) and primary containment vessel (PCV). After the disaster, the Japanese government has been actively organizing efforts to respond to the disaster, and in the mid- and long-term roadmap towards 1F decommissioning issued by the Japanese government in 2019 [1], the detection of fuel debris deposited in the PCVs and RPVs and leakage points on the PCVs and RPVs has become a priority for advancing the decommissioning of the nuclear power plant. In this regard, various efforts have been made, including the use of various types of robots instead of human power to enter the reactor for investigation, the use of optical equipment for investigation, etc. [2].

At same time, ultrasound has been applied to this task. Ultrasound has characteristics not found in optical measurements: it is independent of radiation, light intensity, and environmental turbidity, and it can make measurements in real time [3]. These advantages of ultrasound have led it to be used in the investigation of nuclear reactor interiors as early as the Three Mile Island nuclear accident in the United States [4]. Among ultrasonic techniques, the ultrasonic velocity profile (UVP) is a measurement technique that cannot be ignored. Using the UVP we can obtain real-time velocity profiles inside the fluid, and combined with other measurement techniques, we can more accurately determine the environment and flow velocity of the fluid. Prior to this study, the UVP method has been applied to leakage detection by R. Nishiwaki et al. and T. Ihara et al. [5, 6], and shape reconstruction using phased array transducers by T. Kawachi et al. [7]. Meanwhile, sectorial array transducers have been applied to obtain leakage point by H. Kikura et al. combined with UVP [8] and two-phase flow measured using sectorial array transducer combined with UVP and PIV by M. Batsaikhan [9].

In this study, 2D ultrasonic shape measurement experiments and UVP experiments were conducted using a sectorial array transducer in order to detect the location and shape information of the simulated leak port and simulated fuel debris. During the 2D shape reconstruction conducted by sectorial array transducer, the full matrix capture (FMC) method and total focusing method (TFM) algorithm were applied. By combining the results of both shape measurement and flow velocity profile, the location and shape information of the simulated leak and simulated fuel debris can be more accurately inferred.

2. Method

2.1 Principle of ultrasonic velocity profile

UVP technology is based on pulsed ultrasound echography [3], when the ultrasound beam emitted by the transducer collides with the tracer particles in the fluid, a reflected beam will be generated on the surface of the tracer particle, which is opposite to the direction of the emitted ultrasound beam and is called echo signal. The echo signal will be received by the transducer. Because the particles remain in motion during the process, the echo signal is Doppler-shifted compared to the emitted ultrasound beam. By analyzing the Doppler shift frequency, the velocity of the tracer particle can be measured and thus the velocity of the fluid can be known. The distance from a tracer particle to a transducer and the velocity of this tracer particle can be expressed as Eq. 1 and Eq. 2:

$$x = \frac{cT}{2} \tag{1}$$

$$u = \frac{cf_d}{2f_0} \tag{2}$$

Where T is the time delay and c is the sound velocity, f_0 is the basic frequency of the transducer, f_d is the Doppler-shift frequency, processing the f_d is the main part of UVP method.

The above principle is obtained in a one-dimensional environment. In a two-dimensional environment, UVP measurements are usually performed by two transducers. As shown in Figure 1, two transducers emit two ultrasonic beams at the same time, which propagate forward along two measurement lines and intersect at a point where the velocity on each measurement line is calculated in the same way as in the one-dimensional case, and after obtaining the velocities on the two measurement lines, the final velocity at the point is obtained by synthesizing the equations as shown in Eq. 3, Eq. 4, and Eq. 5. We can find that the more intersection points of the measurement lines, the more velocities are measured in the same area and the more accurate the measurement is.

$$u_1 = V_x \sin\alpha + V_y \cos\alpha \tag{3}$$

$$u_2 = -V_x \sin\alpha + V_y \cos\alpha \tag{4}$$

$$\boldsymbol{u} = \begin{pmatrix} V_x \\ V_y \end{pmatrix} = \begin{pmatrix} \dfrac{u_1 - u_2}{2\sin\alpha} \\ \dfrac{u_1 + u_2}{2\cos\alpha} \end{pmatrix} \tag{5}$$

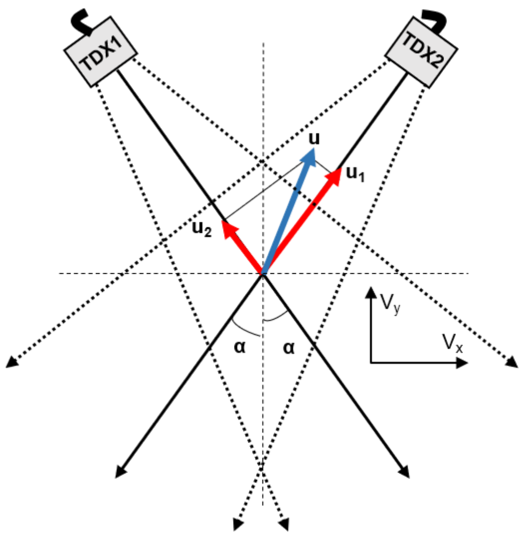
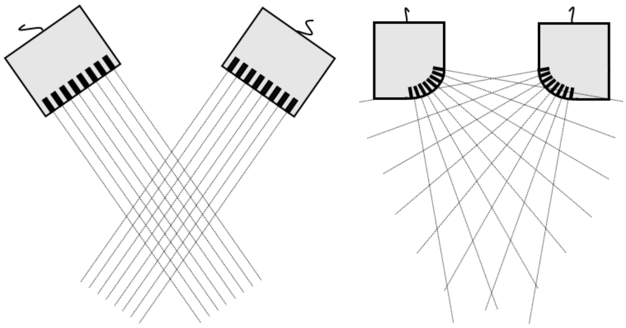


Figure 1: Basic principle of vector reconstruction using two transducers



(a) Linear array transducer (b) Sectorial array transducer

Figure 2: Measurement range with 2 types of array transducer

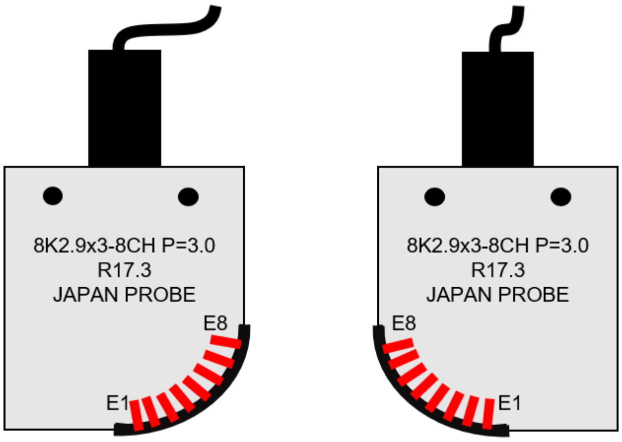


Figure 3: Schematic diagram of sectorial array transducer

2.2 Ultrasonic array transducer

In contrast to a single transducer, an array transducer contains multiple array elements within a single probe, which means that it can emit multiple ultrasonic beams simultaneously. Similar to the one-dimensional case, two-dimensional measurements can be measured by a combination of at least 2 array transducers. The spatial resolution of the measurement can be significantly improved by using such transducer.

As shown in Figure 2, compared with linear array transducers, sectorial array transducers have wider measurement range when element numbers are same. Based on this, sectorial array transducer is selected in this experiment. The schematic diagram of an 8 channels sectorial array transducer is shown in Figure 3.

2.3 Full matrix capture and total focusing method

Firstly, in order to introducer the full matrix capture (FMC) and TFM, the introduction of traditional phased array (PA) process will be conducted. PA technology uses multiple independent transmit-receive channels. In the transmission process, the standard PA system imposes a time delay on each element of the PA transducer, so as to generate an ultrasonic beam with specific acoustic characteristics through the interference of each wave surface. In the receiving process, the system also applies a time delay to the signals received by each element so that they are in phase during the hardware summation process. The summed and digitized A-scan signal is transmitted to the computer for display and recording.

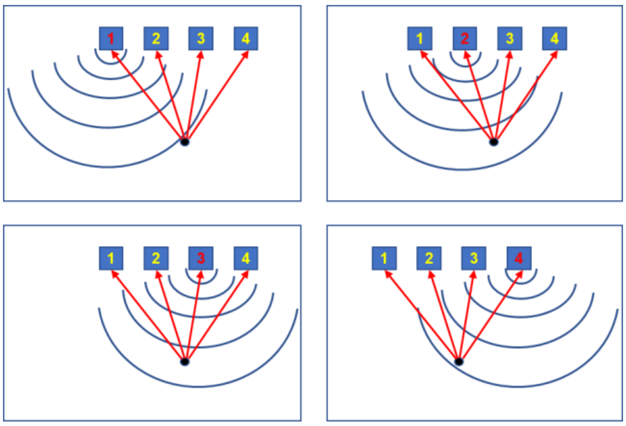
Comparing to traditional method, the FMC is a data method based on ultrasonic array transducer. In an array ultrasound, when one array element emits an ultrasonic beam, a different order on the reception of other array elements leads to a change in the result. In the FMC method, each possible transmit/receive combination in an array ultrasound (number of array elements is n) is formed into a $n \times n$ matrix, which is the full matrix. In the traditional PA acquisition process, the original basic signal is processed at the hardware level, so it cannot be used for offline software processing. In contrast, FMC technology involves capturing and recording all possible time-domain signals (A-Scans) from each pair of transmitter-receiver elements in the array [10], as shown in Figure 4.

TFM is an algorithm based on the FMC method. Usually it is called TFM post-processing. The TFM post-processing algorithm processed as follows:

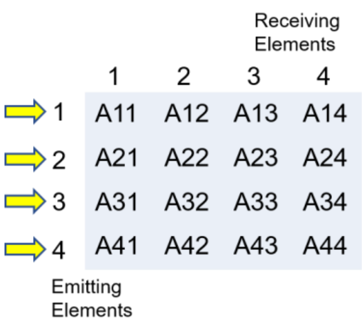
Divide the target area (in the X, Z plane) into a grid. Then the signals from all the elements in the array are added together to synthesize the focal point of each point in the grid. The image intensity at any point in the scan I(x, z) is given by the Eq. 6 [11]:

$$I(x,z) = \left| \sum h_{tx,rx} \left(\frac{\sqrt{(x_{tx}-x)^2+z^2}+\sqrt{(x_{rx}-x)^2+z^2}}{c_1} \right) \right| \quad \text{for all tx, rx} \tag{6}$$

The resolution has been improved significantly and the signal noise ratio (SNR) is also increased. In addition, the TFM image increase the probability of locating defects at the edge of the measurement location.



(a) Transmit/receive combination in FMC method (4 elements)



(b) 4×4 full matrix generated by FMC

Figure 4: Principles of full matrix capture method

3. Experimental setup and configuration

In this study, both UVP experiment and 2D shape reconstruction experiment were carried out. In the UVP experiment, an 8ch/side ultrasonic sectorial array transducer from Japan Probe was applied, and the UVP-DUO multiplexer was used in signal receiving and processing. In 2D shape reconstruction experiment, transducer kept same with UVP experiment, and the pulse receiver utilized the JPR-10C-8CH from Japan Probe. Two experiment conducted one by one.

The experiments were conducted in a laboratory scale tanks, which is a rectangular acrylic box with a size of 1200 mm×450 mm×450 mm. Tap water was the measured fluid in this experiment, and the height is 290 mm from the bottom. Nylon particles with 8μm diameters was used as tracer particle in this experiment (Ideal particles should have specific weight similar to that of the fluid they flow in, but should have different acoustic impedance to form strong reflections). Two sectorial array transducers were placed into the water, and with a height of 150 mm, the distance between two transducers is 90 mm, and they are placed above the leakage point of the fluid container (shown in Figure 5). The flow was controlled by the control value and the flowmeter, the flow rate was controlled in the 10L/min and the accuracy of it is ±5%. The parameters of UVP measurement and shape reconstruction measurement are shown in Table 1 and Table 2.

Table 1: 2D shape reconstruction measurement parameters

Parameters	value
Cycles number	8
PRF [kHz]	2.6
Supplied voltage for each element [V]	150
Maximum depth [mm]	294
Number of profiles per elements	3600
Gain	30
Number of channels	265
Channel distance [mm]	0.75
Channel width [mm]	0.75
Sound speed [m/s]	1507
Frequency [MHz]	8

Table 2: UVP measurement parameters

Parameters	value
Cycles number	4
Supplied voltage for each element [V]	150
Sampling rate [MHz]	60
Gain	30
Sound velocity [m/s]	1507

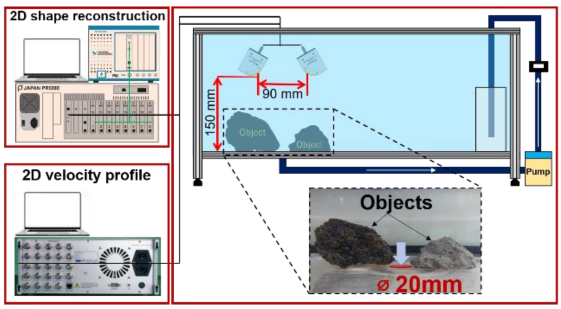


Figure 5: Schematic diagram of experiment setup

4. Result and discussion

To optimize the result of the experiment, the sectorial transducers are placed at an angle of 20 degrees to ensure that the signals emitted from all elements can participate in the measurement and forming images. Meanwhile, to make the result more accurate, the experiment of shape measurement was repeated 5 times by changing the location of transducers horizontally. Transducers are connected to the ultrasonic pulse receiver (JPR-8CN, Japan Probe). Then, After the UVP measurement, the UVP result was combined with the shape measurement result manually. The shape measurement result was shown in Figure 6, the UVP result was shown in Figure 7.

After measurement, the result of UVP and shape measurement was overlapped as shown in Figure 8, we can clearly find that the simulated leakage point and fuel debris detected using the TFM method is consistent with their presumed location. This result demonstrated that the TFM worked successfully in the two-dimensional shape measurement.

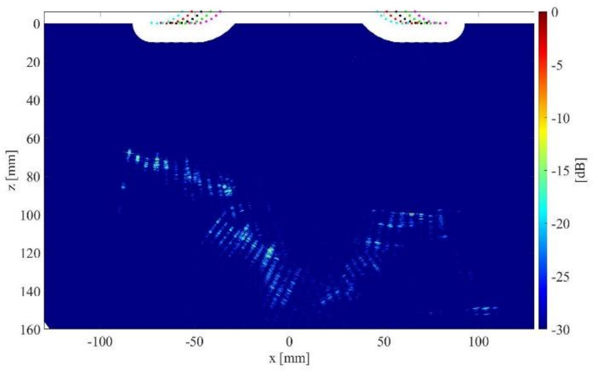


Figure 6: Result of 2D shape reconstruction using TFM algorithm

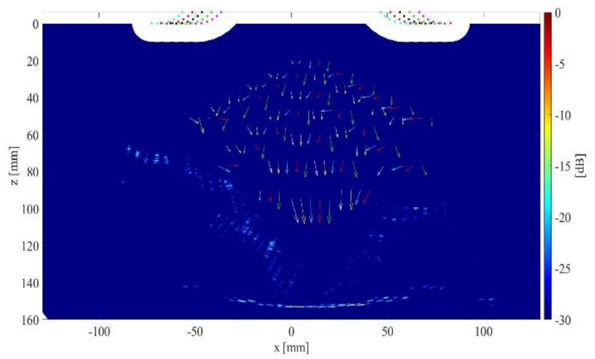


Figure 7: Result of 2D velocity profile using UVP method

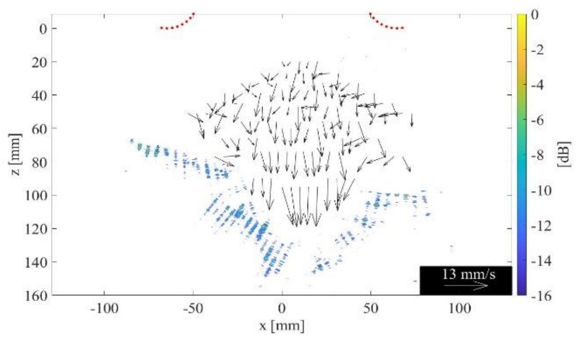


Figure 8: overlapped result with velocity profile and shape reconstruction

5. Conclusion

In the present study, a method for real-time measurement of fluid velocity profiles and in-plane reconstruction of shapes using ultrasound was proposed for the detection of internal reactor leaks and fuel debris in the disassembly of the Fukushima Daiichi nuclear power plant. To make the method more accurate, a sectorial array transducer with TFM algorithm was used for the experiment. 5 measurement results were integrated in a figure to make the result less defection, and the experimental results show a high match between the shape reconstruction using the TFM algorithm and the flow velocity measurements using the UVP method, which demonstrates the validity of this experiment and this method.

References

[1] Tokyo Electric Power Company Holdings Corporation: "Progress of Medium- and Long- Term Roadmap" (2019). http://www.tepco.co.jp/decommission/information/committee/roadmap_progress/pdf/2019/d191219_05-j.pdf (Reference date: April 4, 2021).

[2] Tokyo Electric Power Company Holdings: Decommissioning Plan of Fukushima Daiichi Nuclear Power, Inc. (TEPCO). http://www.tepco.co.jp/en/decommision/index-e.html (accessed 17.05.28).

[3] Takeda Y: Development of an ultrasound velocity profile monitor, Nuclear Engineering and Design, 126 (2) (1991), 277-284.

[4] Beller L S. et al.: Three Mile Island Reports, GEND-INF-012, Idaho Falls, Idaho, USA, (1984).

[5] Nishiwaki R, et al.: Development of a remote water leakage localization system combined with phased array UVP and robot, 11th International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, (2018).

[6] Kikura H, et al.: Study on ultrasonic measurement for determination of leakage from reactor vessel and debris inspection, The 11th National Conference on Nuclear Science and Technology, (2015).

[7] Kawachi T, et al.: A study on two-dimensional vector flow mapping by Echo-PIV with total focusing method, WIT Transactions on Engineering Sciences, 120 (2018), 275-286

[8] Kikura H, et al.: Study on ultrasonic measurement for determination of leakage from reactor vessel and debris inspection, The 11th National Conference on Nuclear Science and Technology, (2015).

[9] Batsaikhan M, et al.: Velocity measurement on two-phase air bubble column flow using array ultrasonic velocity profiler, Multiohase Flow: Theory and Applications, (2018), pp. 89-100.

[10] Patrick T & Daniel R: Development and validation of a full matrix capture solution, The 9th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, (2012).

[11] Holmes C, Drinkwater B, Wilcox P, Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation, NDT&E International, (2005).