ULTRASONIC MEASUREMENT OF MULTI-DIMENSIONAL VELOCITY VECTOR PROFILE USING ARRAY TRANSDUCER

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ABSTRACT

In March 2011, the severe accident of the Fukushima Dai-ichi (1F) nuclear power plant was happened by the earth quack and massive tsunami in Tohoku, Japan. And then, fuel debris was generated within the primary containment vessels (PCVs) of units 1, 2, and 3, respectively. Recently, the decommissioning of 1F is underway to remove the fuel debris, and the inside inspection with robots was conducted so far. Optical techniques have been applied for inspecting the PCVs, but information of the contaminated water leakage has been not unveiled due to non-clear water causing poor visibility of the camera. Therefore, non-optical techniques are required to unveil the leakage location, and we focused on the ultrasonic measurement technique. Ultrasonic measurement can be applied to opaque liquid, high-radioactive, and dark environments. In this study, we have developed the ultrasonic velocity profiler (UVP) system for the investigation of leaking locations. The UVP is based on the pulsed Doppler method, and it can measure instantaneous velocity profile along an ultrasonic beam path. In the original UVP principle, it can measure only one-dimensional velocity measurement. Therefore, we extended the UVP to multi-dimensional measurement. To achieve this, a multi-element sensor was used and an algorithm of three-dimensional (3D) velocity vector reconstruction was developed. The 3D vector measurement is realized by simultaneous receiving Doppler signal at each ultrasonic element. The measurement performance was evaluated by the rigid rotating flow measurement, and the relative error of velocity magnitude and vector angle were minimum –1.6% and 11.2% respectively. In addition, we checked the validity of the system for leakage detection by measuring the simulated leakage flow.

Keywords: ultrasound, velocity profile, vector measurement, array transducer, multi-dimensional.

1 INTRODUCTION

Recently, optical inspections have been implemented for the decommissioning of the Fukushima Dai-ichi nuclear power plant (1F). The objective of these inspections is to assess the conditions within the primary containment vessels (PCVs) of units 1, 2 and 3 at the site, and some achievements has been made so far [1]. However, these inspections have not yet unveiled completely the locations of leaks (the repair of which is vital for fuel debris removal) and accurate distribution of fuel debris (an important factor in deciding the future fuel removal procedure). These inspections are hindered by a high-dose radioactive environment and an opaque environment which becomes from the suspended particulates in the coolant water. Therefore, methods other than optical methods are required to inspect within the PCVs.

Ultrasonic measurement is considered as a promising non-optical inspection method. Ultrasonic sound can be used in opaque liquids and ultrasonic transducers are generally suited to high radiation levels, as used in the decommissioning of Three Mile Island (TMI-2) [2]. In our work, an ultrasonic velocity profiler (UVP) [3] and an ultrasonic phased array sensor were used in combination to identify leakage points [4]. The combination system of UVP and phased array sensor allows for the measurement of two-dimensional (2D) flow velocity vector fields using the Doppler frequency shift of echoes scattered by particles in the liquid.

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Hence, leakage points may be identified by observing behaviour of liquid flow near pipes or walls.

However, real flow is three-dimensional (3D) flow, and measurement system is also required to extend to 3D flow measurement. Peronneau et al. [5] proposed a single element cross beam system using two transducers as a transceiver (transmitter/receiver) to measure 2D at the cross point. Further development of a similar measurement system for measuring 3D by using three transducers was shown in the work of Fox [6]. However, this system is time-consuming since the transducers must be operated separately to avoid the interference of the sound beam. Later, Dunmire et al. [7] developed a 3D measurement system using five transducers (one transmitter and four receivers). With only one transmitter, the measurement occurs at the same time and same measurement volume. In fluid engineering, the area of investigation is wider, therefore depth varying (profile) measurement is necessary. Like Dunmire et al. measurement system, Huther and Lemmin [8] developed three-dimensional with varying depth measurement system in open-channel flow. Based on this idea, Obayashi et al. [9] investigated this system accuracy in rotating cylinder flow. They found that the velocity in receiver line has a relatively high error with the reason of low signal to noise ratio.

These studies are very important to be continuously improved since the flow in fluid engineering often exists with multi-dimensional velocity such as 1F case. Owen et al. designed five elements transducer (one transmitter and four receivers) and constructed 3D velocity vector measurement system [10]. This system achieved 3D velocity vector profile measurement with a compact sensor. However, this system reconstructed 3D velocity vector by synthesizing dual 2D velocity vector, and it used large hardware system due to multi element using. In principle, 3D velocity vector can be reconstructed at least one transmitter and three receivers, and it can be more compact system. Furthermore, measurement hardware also can be optimized to the multi elements UVP system.

The purpose of this study is development of the 3D flow vector measurement system with four elements sensor array and optimized hardware system for multi elements UVP measurement. In this paper, the vector UVP system is described, and the velocity profile measurement performance was validated with a rigid rotating flow. Moreover, this system applied to a simulated leakage flow to confirm the validity of 1F investigation.

2 METHOD

2.1 Ultrasonic velocity profiler

An ultrasonic velocity profiler (UVP) can obtain instantaneous velocity profiles of a fluid and it is based on a pulsed Doppler method. Fig. 1 shows the schematic diagram of the UVP measurement. An ultrasonic transducer emits ultrasonic pulses to a particle mixed in the target fluid. The Doppler frequency which depends on the particle velocity can be obtained from the reflected echo signals by the frequency analysing. The velocity component of ultrasonic propagation direction, v, can be written as follows:

$$v = \frac{cf_D}{2f_c}. \tag{1}$$

where f_D, f_c and c represent the Doppler frequency, the ultrasonic basic frequency of the transducer and the speed of sound in the fluid, respectively. By detecting the Doppler frequency at each measurement position along the beam axis, it realizes to measure the velocity distribution of the fluid. The measurement position, x, can be obtained as follows:

$$x = \frac{c\tau}{2}, \tag{2}$$

where τ is the echo time delay from the transmission time. To detect the Doppler frequency, the UVP method employs a pulse repetition method. Namely, repetition pulses are emitted from the transducer to the particles that be mixed in the target fluid; the Doppler frequency is estimated from the reflected echo waves. Each echo signal accompanies the phase shift because the particle is moved by the flow during the pulse repetition emitting. The auto-correlation method [11] is often used to detect the phase shift between the consecutive two echo signals.

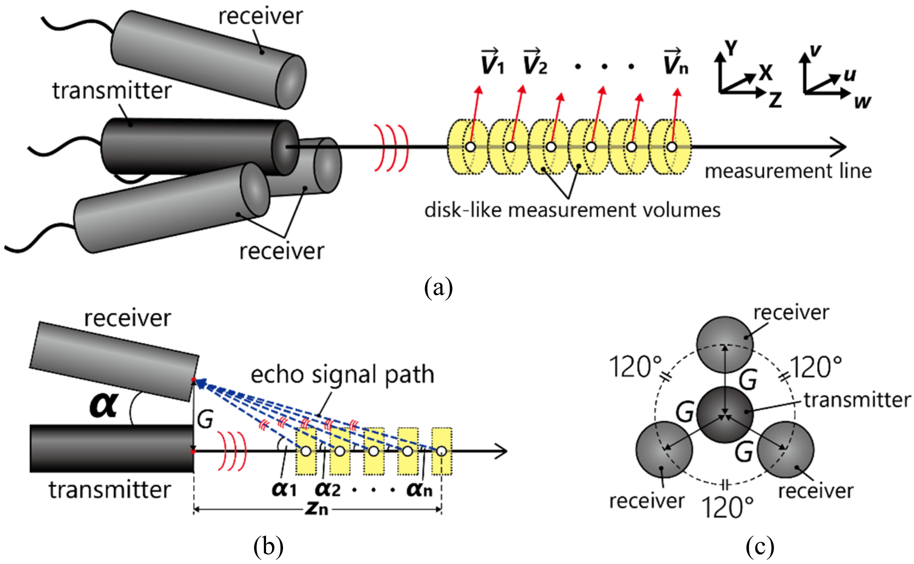

Figure 1: Ultrasonic transducer layout. (a) Overview of vector measurement; (b) Side view of a transmitter-receiver pair; and (c) Front view of the transducer array.

2.2 Three-dimensional velocity vector measurement

Originally, the UVP method obtains one-dimensional velocity profiles (one velocity component on the measurement line) as described at previous section. However, coolant flow structures inside the PCVs are complex due to internal structures and fuel debris; it is needed to extend the UVP to 3D measurement to enhance the efficiency of leak location detection. To extend the velocity component to 3D measurement, some methods have been proposed. Fox et al. [6] proposed a crossbeam method by using three transducers to obtain three velocity components. However, this method is time-consuming since each transducer measurement must be operated separately to avoid the sound beam interference, and it is a spatial point measurement. In contrast, Huther et al. [8] developed 3D velocity vector profile measurement system along on beam line by using five transducers (one transmitter and four receivers). This system obtains the Doppler frequencies from each measurement volume at each receiver simultaneously and reconstructs velocity vector profile; the instantaneous velocity vector profile measurement can be achieved. Using this principle, Owen et al. [10] manufactured

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the five elements transducer. They achieved 3D velocity vector measurement by one transducer although measurable depth was only approximately 50 mm because the receiver element width was smaller, and the echo sensitivity was decreased.

In this work, to extend the measurable depth and for more compactification of transducer system, the four-transducer array was used. The transducer layout is shown in Fig. 1. The transducer array consists of one transmitter and three receivers (each transducer has a disk shape ultrasonic element). The receivers are equally spaced around the transmitter at 120-degree intervals, with a gap distance G between the transmitter and each receiver. To receive echo signals on the measurement line, each receiver has an angle α between it and the transmitter.

When the tracer particle passing through the n-th measurement volume, three Doppler frequencies, f_{D1n}, f_{D2n} and f_{D3n}, can be obtained from the three receivers. Then, the three velocity components are reconstructed by following equation:

$$\begin{bmatrix} u_n \\ v_n \\ w_n \end{bmatrix} = \frac{c}{2f_0} \begin{bmatrix} \dfrac{2f_{D1n} - 4\left(f_{D2n} + f_{D3n}\right)}{3\sin\alpha_n} \\ \dfrac{f_{D2n} - f_{D3n}}{0.866\sin\alpha_n} \\ \dfrac{f_{D1n} + f_{D2n} + f_{D3n}}{3(1+\cos\alpha_n)} \end{bmatrix}, \tag{3}$$

where, c is the speed of sound, f_0 is the basic frequency, and α_{n} is the angle between the transmitter and receiver at the centre of n-th measurement volume, respectively. The angle α_{n} is estimated by measurement position:

$$\alpha_n = \tan^{-1}\left(\frac{G}{z_n}\right), \tag{4}$$

where, z_n is the z direction distance from the centre transmitter. To detect the Doppler frequency from each receiver, the auto-correlation method [11] was used. The auto-correlation method detect the Doppler phase shift generated by particle moving with quadrature demodulation. In order to reconstruct the velocity vector using eqn (3), the Doppler frequency of the receiver on-axis component should be detected. However, a real Doppler frequency includes other velocity components due to an uncertainty of the echo receivable angle. To suppress the influence of the angle uncertainty and extract the Doppler frequency of on-axis component, beam-axis phase shift was subtracted from detected phase shift at each receiver. The beam-axis phase shift was detected by centre transducer. Namely, the Doppler phase shift, $\Delta\theta_{0\mathrm{i}}$ was obtained by following equation:

$$\Delta\theta_{0i} = \tan^{-1}\left(\frac{\mathrm{Im}\left[\left(s_{0,j}s_{i,j}^{*}\right)\left(s_{0,j+1}s_{i,j+1}^{*}\right)\right]}{\mathrm{Re}\left[\left(s_{0,j}s_{i,j}^{*}\right)\left(s_{0,j+1}s_{i,j+1}^{*}\right)\right]}\right), \tag{5}$$

where, subscript of i and j are the receiver index and pulse repetition index, respectively. Character s is the complex signal detected by the quadrature demodulation of the echo signal.

And the mark * represents the conjugate. From this equation, the Doppler frequency of each receiver is estimated by following equation:

$$f_{Di} = \frac{\Delta\theta_{0i}}{2\pi T}, \tag{6}$$

where, T is the pulse emission interval time. By using eqns (3)–(6), the velocity vector profile can be reconstructed.

3 VALIDATION OF MEASUREMENT PERFORMANCE

To validate the measurement certainty and accuracy, the rigid rotating flow was measured by the developed system, and the measurement results were compared with theoretical velocity vectors.

3.1 Experimental apparatus

The experimental apparatus for the rigid rotating flow measurement is shown in Fig. 2. As the fluid, tap water was packed in the acrylic cylinder (inner diameter was 154 mm, and wall thickness was 3 mm), and nylon particles were mixed in the water as the tracer particle. The cylinder was rotated by the stepping motor to generate rotating flow inside the cylinder. The rotation speed was controlled by the personal computer. The transducer array was installed at 10 mm from the centre of the cylinder. In the cylinder, the rotating flow is generated, and the theoretical flow vector can be calculated by following equations:

$$\begin{aligned} v_{theo} &= r_x \omega \\ w_{theo} &= r_z \omega \end{aligned} \tag{7}$$

where, r_x and r_y are x and y components of distance from the cylinder centre, respectively. To evaluate the measurement performance, the measured velocity vectors are compared with the theoretical vectors calculated by eqn (7). The detail of experimental conditions and measurement conditions are shown in Table 1. In this experiment, the distance between the transmitter and cylinder centre was set to 3 position (–1 mm, 2 mm and 8 mm) to validate the effect of the velocity vector angle.

To realize the three-dimensional velocity vector profile measurement, the measurement instruments was developed. The photograph of developed instruments is shown in Fig. 3. The measurement system consisted of four-transducer array, laboratory made ultrasonic pulser/receiver, and signal processing personal computer. The pulser/receiver included the ultrasound drive circuit, echo signal amplifier and filter, and A/D converter. In this experiment, 150 V and 4 cycle rectangular wave was applied to the transmitter to generate pulsed ultrasound. Echo signal amplifier was set to 55 dB in each receiver. And the A/D converter recorded the echo signals with a sampling speed of 50 MS/s. The recorded signals were transferred to the computer through a USB 3.0 cable. The signal processing was performed in the computer based on eqns (3)–(6), with the programming software LabVIEW 2019 (National Instruments).

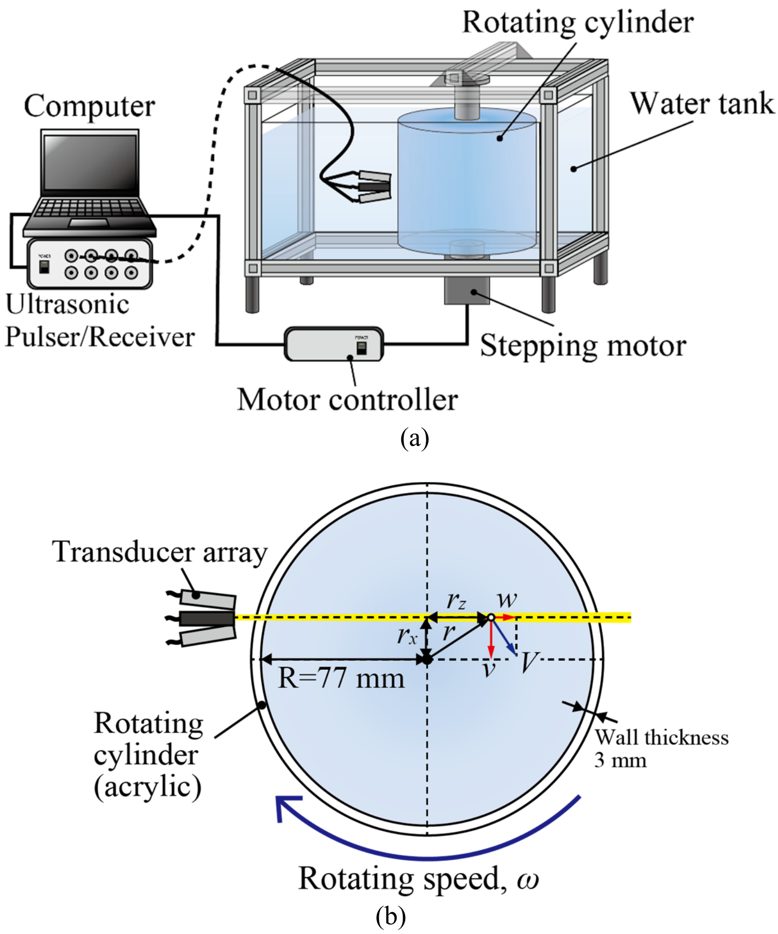

Figure 2: Experimental setup of the rigid rotating flow measurement. (a) Experimental setup; and (b) Schematic diagram of rigid rotating flow measurement.

Table 1: Experimental conditions of the rigid rotating flow measurement.

Condition and parameter	Detail
Water temperature	25°C
Speed of sound (c)	1,497 m/s
Rotating speed (ω)	600 rpm
Transducer distance between cylinder center (r_x)	−1 mm, 2 mm, 8 mm
Basic frequency (f_0)	4 MHz
Active ultrasonic element diameter	5 mm
Angle between transmitter and receiver	8 degrees
Gap distance (G)	8 mm
Spatial resolution	0.75 mm
Time resolution	64 ms
Number of profiles	1,000

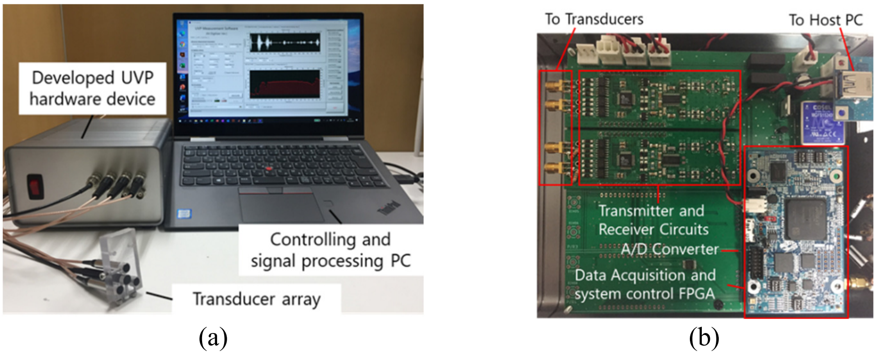

Figure 3: Developed measurement system configuration. (a) Overview of the system; and (b) Internal hardware.

3.2 Results and discussion

The comparison of velocity vector profile between measured and theoretical values are shown in Fig. 4. Fig. 4(a) is the result in the condition of $r_x = -1$ mm, (b) is $r_x = 2$ mm, and (c) is $r_x = 8$ mm position, respectively. Each vector profile is mean of a 1,000 dataset. The horizontal axis is the measurement position from the cylinder centre normalized by cylinder radius R. In the region of r/R = –1 to 0, the receivers were difficult to obtain echo signals due to receivable angle limitation. Therefore, the measurement results are indicated only r/R = 0 to 1. Blue arrows mean theoretical vector, and red allows mean measured vector by the developed system. Figs 5 and 6 show the comparison of theoretical and measured velocity magnitude and vector angle, respectively. These values were calculated by following eqn (8).

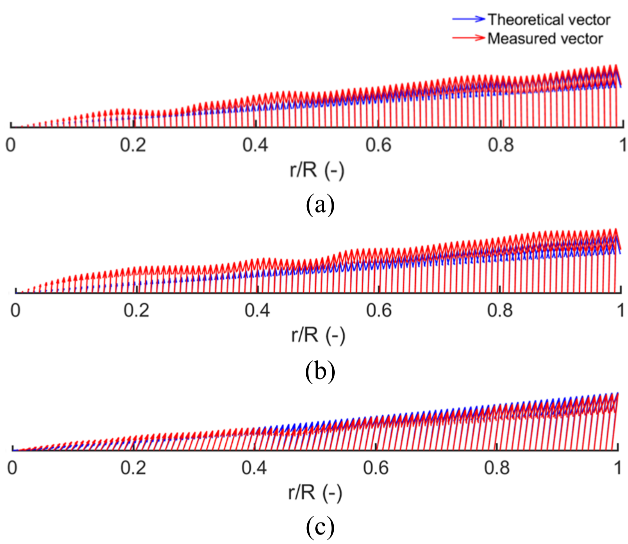

Figure 4: Result of vector profile measurement in the rotating flow. (a) $r_x = -1$ mm; (b) $r_x = 2$ mm; and (c) $r_x = 8$ mm.

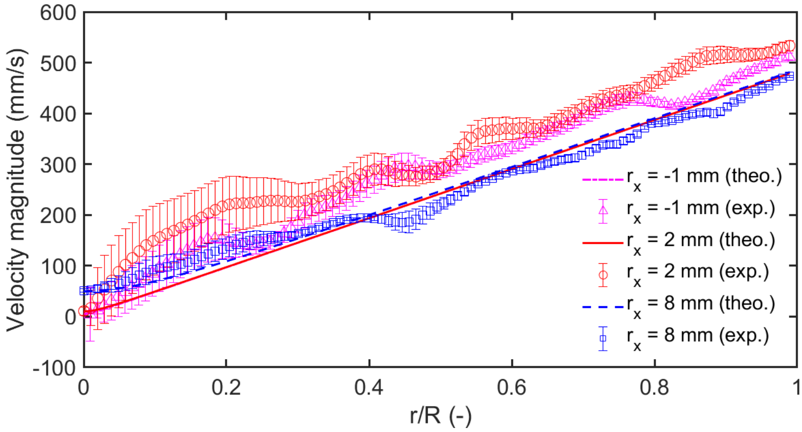

Figure 5: Comparison of theoretical and measured velocity magnitude.

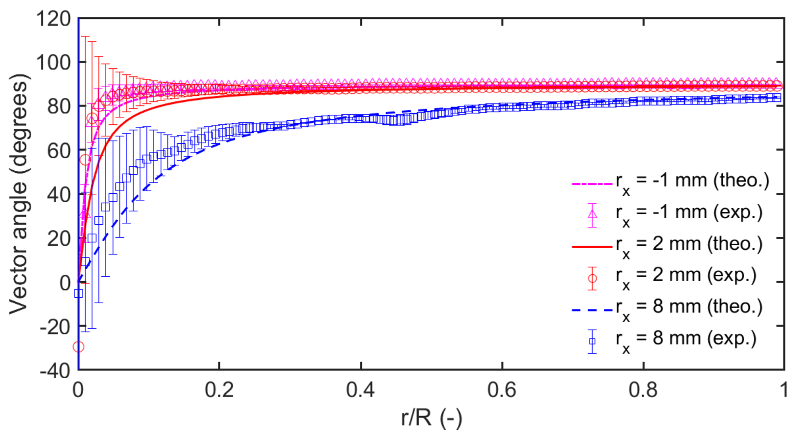

Figure 6: Comparison of theoretical and measured vector angle.

$$
\begin{aligned}
|V| &= \sqrt{v^2 + w^2} \\
\theta &= \tan^{-1}\left(\frac{v}{w}\right).
\end{aligned}
\qquad (8)
$$

In these figures, error bars represent the relative error from the theoretical values. As for the absolute velocity profiles, the spatial averaged relative errors of $r_x = -1$ mm, 2 mm, and 8 mm were –20%, –31% and –1.6%, respectively. And the spatial averaged errors in the vector angle were –24.4%, 16.6%, 11.2%, respectively. Namely, the error increased for vectors that the velocity component was dominated by the lateral component. In this work, the auto-correlation method was used to detect the Doppler frequency at each receiver, however, the method has weakness for very low velocity component. The developed algorithm calculates the phase difference between centre transducer and each receiver to cancel the beam axis Doppler component, but the Doppler component in the beam axis direction was close to zero, which may have increased the error. Nevertheless, each measured vector profile by developed system was captured the rotating flow characteristic.

4 SIMULATED LEAKAGE FLOW MEASUREMENT

To verify the applicability to a leakage detection of the developed system, the simulated leakage flow measurement was performed. We verified whether it is possible to identify the leakage position by scanning the sensor position mechanically and obtaining a three-dimensional flow map.

4.1 Experimental apparatus

Fig. 7 illustrates the experimental setup of the simulated leakage flow measurement. The tap water injected in the water tank (1.2 m × 0.4 m × 0.4 m). The simulated leakage hole was set to the bottom of the water tank, and the hole diameter was 20 mm. The tanked water was

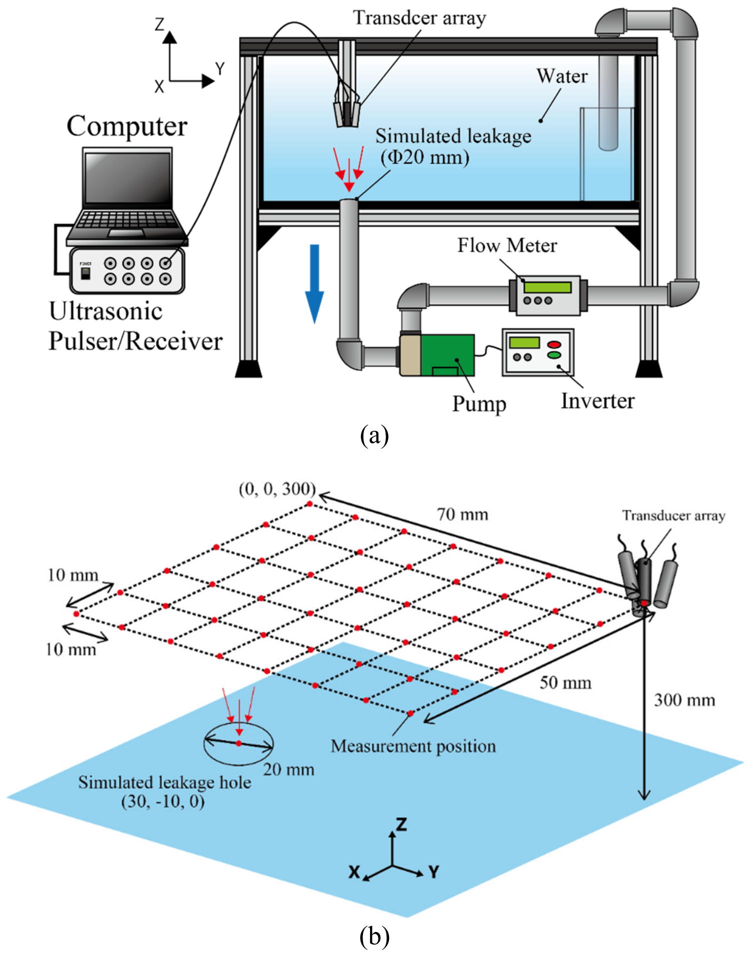

Figure 7: Experimental apparatus of simulated leakage flow measurement. (a) Experimental apparatus; and (b) Schematic diagram of measurement position.

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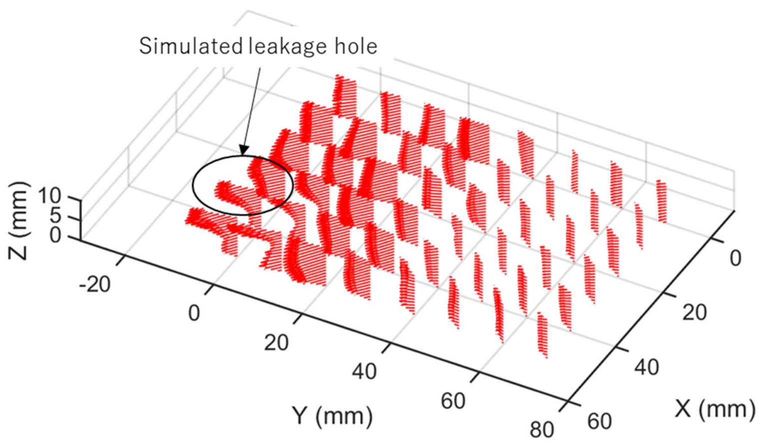
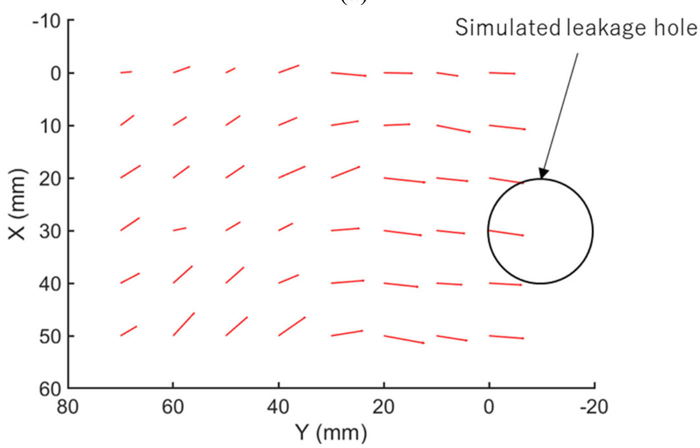
Table 2: Experimental conditions of the simulated leakage flow measurement.

Condition and parameter	Detail
Water temperature	25°C
Speed of sound (c)	1,497 m/s
Leakage hole diameter	20 mm
Leak flowrate	7 L/min
Basic frequency (f_0)	4 MHz
Active ultrasonic element diameter	5 mm
Angle between transmitter and receiver	8 degrees
Gap distance (G)	8 mm
Spatial resolution	0.75 mm
Time resolution	128 ms
Number of profiles at each position	100



(a)



(b)

Figure 8: Result of the three-dimensional flow mapping of the simulated leakage flow measurement. (a) 3D view; and (b) xy-plane view.

circulated at 7 L/min from the hole. In this experiment, the transducer array was installed at 300 mm from the bottom of tank, and to obtain the three-dimensional flow map, the transducer array was moved to x and y direction. The measurement position was changed in 50 mm × 70 mm area and the moving pitch distance was set to 10 mm. The centre of leakage hole was (x, y, z) = (30, –10, 0), where the z is the distance from the bottom of tank. The detail of the experimental condition is shown in Table 2. The measurement instrument and conditions were almost same with previous section.

4.2 Results and discussion

The experimental result of simulated leakage flow measurement is shown in Fig. 8. Fig. 8(a) is the three-dimensional vector map around the leakage hole, and (b) is the xy-plane view of it at z = 0 to 10 mm. Where the Fig. 8(b), each velocity vectors are averaged in the region of z = 0 to 10 mm. at the far from the leakage hole, the velocity was low. On the other hand, the velocity vectors with higher velocities toward the simulated leakage hole were observed by developed system. Namely, it was shown that tracking the velocity vector during the flow mapping process can be utilized to identify the location of leakages.

5 CONCLUSION

To detect the coolant water leak positions of Fukushima-Daiichi nuclear power plant, the 3D velocity vector measurement system was developed by using four ultrasonic transducers array and the ultrasonic velocity profiler principle. The velocity vectors were reconstructed with the simultaneous obtained Doppler frequencies at each receiver by the developed algorithm. The measurement performance was evaluated by the rigid rotating flow measurement, and the relative error of velocity magnitude and vector angle were minimum –1.6% and 11.2% respectively. Moreover, the applicability to detection of leakage position was verified by the simulated leakage flow measurement. As the result, it was shown that tracking the velocity vector during the flow mapping process can be utilized to identify the location of leakages. In future work, we will improve the measurement accuracy and contribute to the identification of leakage position in 1F.

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