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Development of Advanced UVP Instruments Applicable to 3-D Velocity Vector Measurement

Naruki Shoji[1], Hideharu Takahashi[2], and Hiroshige Kikura[2]

[1] Graduate Major in Nuclear Engineering Course, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[2] Lab. for Advanced Nuclear Energy, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

A new UVP instruments applicable to 3-D velocity vector measurement was developed. The instruments consist of four channel UVP measurement channel, and four ultrasonic elements array sensor (1 transmitter and 3 receivers). With this configuration, there are three Doppler frequencies can be obtained, hence the three-dimensional velocity information along the measurement line can be reconstructed. In this study, we confirmed the measurement principle experimentally using by the developed UVP instruments. As the experiment, we performed the piping flow measurement, and reconstructed the velocity vector profile with four elements array sensor. As the result, the three-dimensional velocity vector profile was obtained by the measurement system.

Keywords: 3-D velocity vector, Hardware development, Signal processing

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 (2-D) flow velocity vector fields using the Doppler frequency shift of echoes scattered by particles in the liquid. Hence, leakage points may be identified by observing behavior of liquid flow near pipes or walls.

However, real flow is three-dimensional (3-D) flow, and measurement system is also required to extend to 3-D flow measurement. Peronneau *et al.* [5] proposed a single element cross beam system using two transducers as a transceiver (transmitter/receiver) to measure 2-D at the cross point. Further development of a similar measurement system for measuring 3-D 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 3-D measurement system using 5 transducers (1 transmitter and 4 receivers). With only 1 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. Previously, we designed five elements transducer (1 transmitter and 4 receivers) and constructed 3-D velocity vector measurement system [10]. This system achieved 3-D velocity vector profile measurement with a compact sensor. However, this system reconstructed 3-D velocity vector by synthesizing dual 2-D velocity vector, and it used large hardware system due to multi element using. In principle, 3-D velocity vector can be reconstructed at least 1 transmitter and 3 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 3-D 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 using this system is demonstrated with piping flow.

2. Three-Dimensional Velocity Vector Measurement

2.1 Principle

In this study, we considered three-dimensional (3-D) velocity vector profile measurements with four ultrasonic elements and UVP principle to simplify the sensor configuration. The principle of 3-D velocity vector profile measurement is illustrated in figure 1, and the sensor configuration is illustrated in figure 2. The sensor unit consists of one transmitter and three receivers. The receivers are installed at 120-degree intervals with each receiver, and the transmitter is in its center. Each receiver gets the echo signals included Doppler frequency, and can calculate a velocity component along with receiving line. Each velocity component can be obtained as the following equation.

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} v_z \cos\alpha + v_x \sin\alpha \\ v_z \cos\alpha - \dfrac{\left(v_x - v_y\right)\sin\alpha}{2} \\ v_z \cos\alpha - \dfrac{\left(v_x + v_y\right)\sin\alpha}{2} \end{pmatrix} \tag{1}$$

where v_x, v_y and v_z represent each velocity component in the Cartesian coordinate system, and α is the angle between measurement line and receiving line. The receiving angle α is decided by measurement depth z, and it can be calculated by the following equation.

$$\alpha = \tan^{-1}\left(\frac{G}{z}\right) \tag{2}$$

where G is the distance between transmitter element and receiver element as shown in figure 2. By using Eq. (1) and (2), the 3-D velocity vector $\vec{V}$ can be reconstructed by following equation.

$$\vec{V} = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} \dfrac{2v_1 - (v_2 + v_3)}{3\sin\alpha} \\ \dfrac{v_2 - v_3}{\sin\alpha} \\ \dfrac{v_1 + v_2 + v_3}{3\cos\alpha} \end{pmatrix} \tag{3}$$

Therefore, the 3-D velocity vector profile on the measurement line can ben obtained by calculating the velocity vector using the Eq. (3) at each position.

2.2 Measurement system

To measure a 3-D velocity vector profile with four ultrasonic elements, the UVP measurement hardware which can control four elements was designed and implemented as shown in figure 3. The hardware circuit consists of high voltage pulsers (up to 200 $V_{p\text{-}p}$), programmable gain amplifiers (up to 55 dB) and band-pass filters as echo signal receiver, an eight-channel A/D converter (sampling rate is 50 MS/s, and bit resolution is 12 bit), and other power supply components. The developed hardware performed by 12 V DC power supply. And these circuits are controlled by a FPGA (field programmable gate array) board. The received echo signals are recorded on the DDR3 memory implemented on the FPGA board, and the recorded all echo data is transferred to the host computer through an USB 3.0 cable in real-time. After that, the signal processing is carried out based on Eq. (3) in the host computer. Moreover, the developed hardware size is about 150 mm × 150 mm to mount to a robot system in the future. The developed UVP hardware can control 8 ultrasonic elements simultaneously, but in this time, we used only 4 channels for the measurement. Figure 4 shows the measurement setup. In this study, LabVIEW 2019 (NI) was used for the hardware control and the signal processing of four elements velocity vector UVP measurement.

In this study, the specification of constructed four elements array sensor is below: the basic frequency of each element is 4 MHz, and the element diameter is 5 mm. Also, the distance between transmitter element and each receiver element is set to 10 mm.

And to detect a Doppler frequency, the auto-correlation method [11] was used in this system. The process using this method is performed to obtained echo signals of each receiver. After that, the velocity reconstruction process is applied to detected velocity components using Eq. (3).

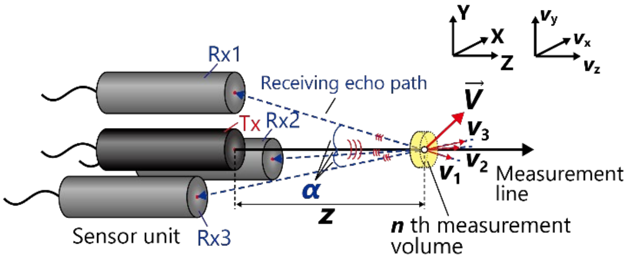


Figure 1: Principle of 3-D velocity vector measurement with four ultrasonic elements.

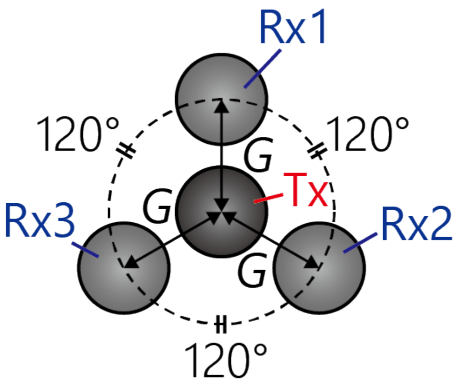


Figure 2: Sensor layout of four elements array.

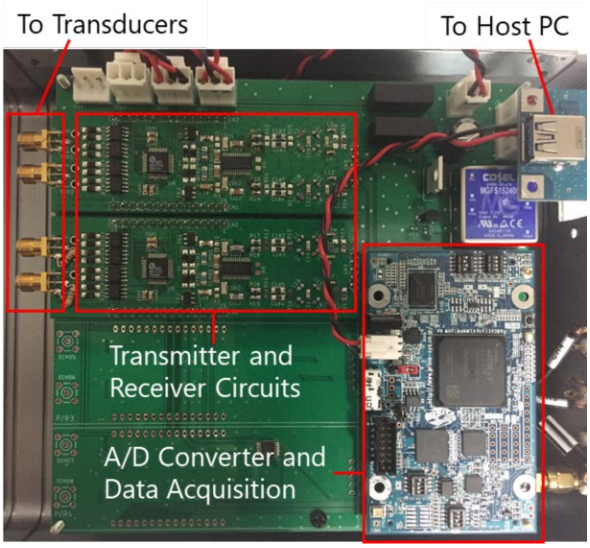


Figure 3: Developed UVP measurement hardware device.

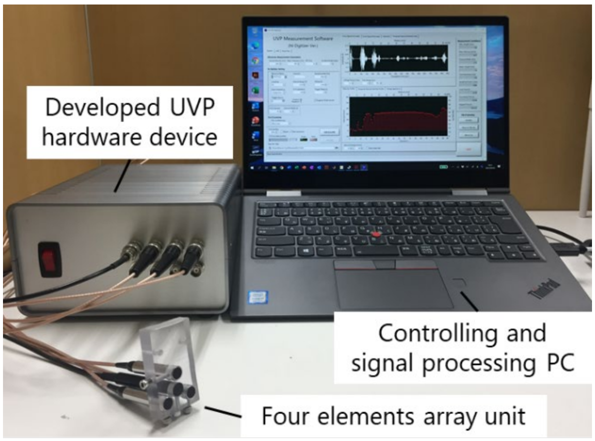


Figure 4: Measurement system.

3. Experiment

The experimental setup is illustrated in figure 5. To demonstrate the 3-D velocity vector profile measurement, the experiment was performed with vertical water piping flow, and we confirmed the measurement principle with four elements array. The pipe diameter was 50 mm, and the pipe material was plexiglass. The test section was located at approximately 800 mm from the flow entrance. The nylon particles (mean diameter: 80 µm) were mixed in water as tracer particle. The flowrate was set to approximately 0.13 m^3/s in this experiment. The array unit was installed at an angle of 0 degrees to the wall to transparent within the pipe. Other measurement conditions are summarized in table 1.

4. Results and Discussion

Figure 6 shows the experimental results of piping flow measurement with developed UVP system. Figure 6 (a) is YZ plane view, (b) is XZ plane view, respectively. In these figures, black line represents the pipe wall. And the center of the transmitter is at the origin (x, y, z) = (0, 0, 0). The piping flow is almost one-dimensional flow; therefore, the measured velocity vectors should be direct to y direction. In figure 6 (a), there was the influence of multiple echoes around z = 18 mm region. It is considered that the incident angle was 0 degree and the echo from the wall came directly. And the velocity magnitudes were underestimated in near region less than 10 mm, because this region is out-range of receivable angle of receiver elements, and the signal-to-noise ratio was decreased. Thus, it needs to design the sensor layout and size to focus on the near region. However, the measured velocity vector profile was captured the one-dimensional flow patter in the pipe. Therefore, we confirmed measurement principle of 3-D velocity vector profile measurement with four elements array.

Table 1: Measurement conditions.

Ultrasonic frequency	4	MHz
Pulse repetition frequency	2	kHz
Number of cycles	4	-
Number of repetitions	128	-
Spatial resolution	0.74	mm
Temporal resolution	64	ms
Supply voltage	140	V_{p-p}
Incident angle	0	degrees
Number of profiles	2,000	-

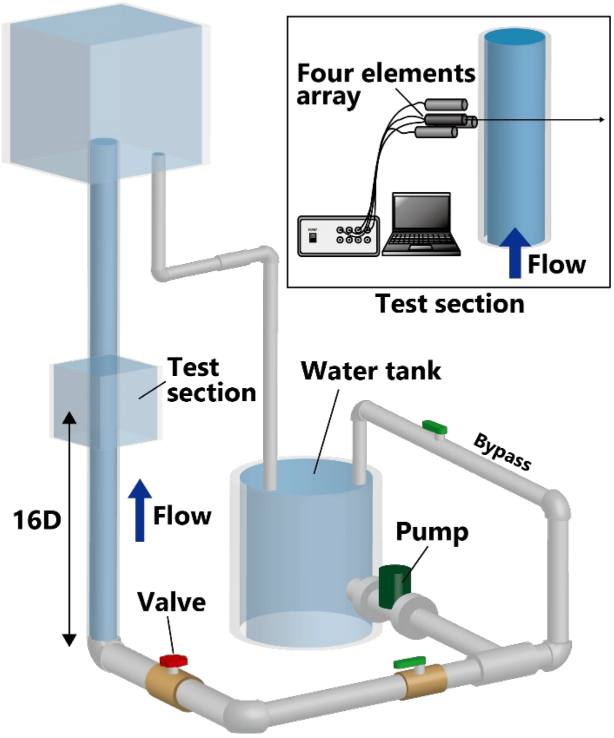
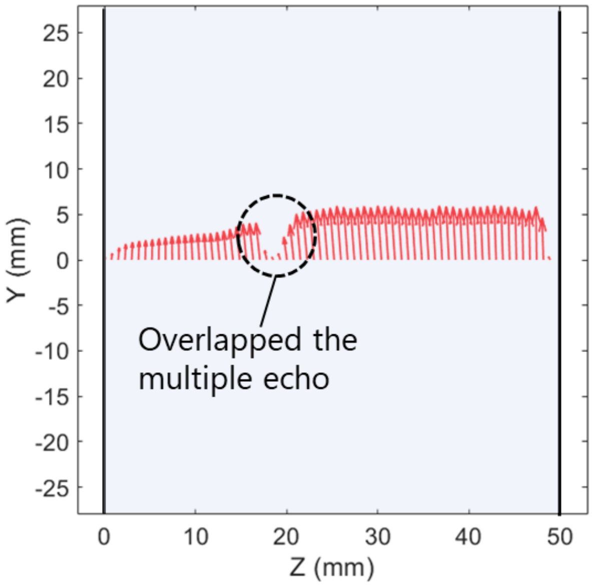
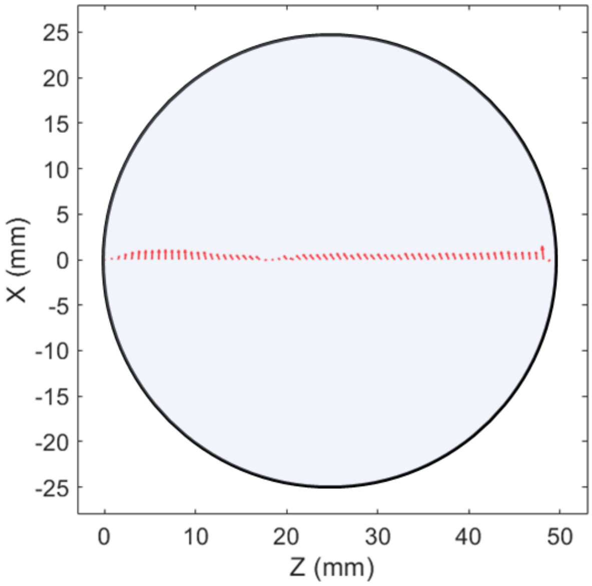


Figure 5: Experimental setup.



(a) YZ plane view



(b) XZ plane view

Figure 6: Mean velocity vector profile of piping flow measurement.

5. Summary

The new sensor configureation of four elements array has been proposed and the measuremetn hardware system has been developed. Through the experiment of piping flow measurement, we confirmed that it can be obtain 3-D veloctiy vector profile on main lobe beam. In the future, we validate the measurement accuracy of this system, and continue improvement the 3-D flow vector measurement in the view point of hardware, signal processing and sensor configuration.

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