Development of New Ultrasonic Transducer for Multi-Dimensional Velocity Profile Measurement Using Ultrasonic Doppler Method

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A new ultrasonic array transducer with a special configuration of five elements, using 5 elements as a transmitter and 4 elements as a receiver had been designed. With this configuration, there are four Doppler frequencies that can be obtained, hence the three-dimensional velocity information along the measurement line can be reconstructed. We evaluated the transducer ultrasound characteristic and performance by sound pressure measurement and fully developed laminar pipe flow. From sound pressure measurement, the 5 elements generate one main lobe (one measurement volume), hence all the Doppler frequencies have the same information (in position and time). Therefore, the three-dimensional measurement is possible. From the flow measurement, the result has a good agreement with theory. Finally, we applied the transducer to a different flow condition, *i.e.* turbulent and swirling flow for a vector measurement.

Keywords: ultrasonic transducer, five-elements array, three-dimensional velocity profile, Doppler, vector

1. Introduction

Ultrasonic Doppler measurement technique was first used in a medical application, proposed by Satomura [1]. Baker [2] performed a one-dimensional blood flow measurement, assuming the blood flow parallel to the vessel axis (unidimensional). However, many areas of clinical interest cannot employ this assumption due to the occurrence of complex flow (multi-dimensional). Peronneau *et al.* [3] proposed a single element cross beam system using two transducers as a transceiver (transmitter/receiver) to measure two-dimensional at the cross point. Further development of a similar measurement system for measuring three-dimensional by using three transducers was shown in the work of Fox [4]. However, this system is time-consuming since the transducers have to be operated separately to avoid the interference of the sound beam. Later, Dunmire *et al.* [5] developed a three-dimensional measurement system using 5 transducers (1 transmitter, 4 receivers). With only 1 transmitter, the measurement occurs at the same time and same measurement volume. In fluid engineering, ultrasonic Doppler measurement was proposed by Takeda [6]. The area of investigation is wider, therefore depth varying (profile) measurement is necessary. Similar to Dunmire *et al.* measurement system, Hurther and Lemmin [7] developed three-dimensional with varying depth measurement system in open-channel flow. Based on this idea, Obayashi *et al.* [8] investigate 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. For example, in the case of the flow inside the reactor of Pressurized Water Reactor (PWR), specifically in the between of reactor core, the flow is three-dimensional swirling flow promoted by the grid spacer. This flow information is very important because it affects the reactor power and cooling. Through a previous study case, this present study proposed a new measurement system using an array transducer with a special configuration of five elements. It consists of one big element at the center as a transmitter and four small elements at the side with a small gap as transmitter/receiver. By using all elements as a transmitter and with the small gap, the received echo is expected to have a good signal to noise ratio, while the challenge is the sound beam interference will occur with the undesired side lobe. With the small gap between transmitter and receiver, one main lobe can be generated and the small receiver could minimize the uncertainty of echo angle from measurement volume to the receiver. Finally, with this configuration, we aim to measure the three-dimensional velocity profile with the same timing of four echo acquisition in one measurement volume with good accuracy.

2. Five elements transducer design and measurement principle

The transducer with five elements is designed and manufactured (see Figure 1) with the specification in Table 1. Using this configuration, the transducer can obtain four Doppler frequencies (f_D) (see Figure 2) from the echo of the measurement volume to each element with a certain echo angle (θ). The echo angle depends on channel distance and receiver position. For the receiver position, we assumed the echo will reach to the middle of the receiver element with the minimized uncertainty since the element size (b) is specifically designed to be very

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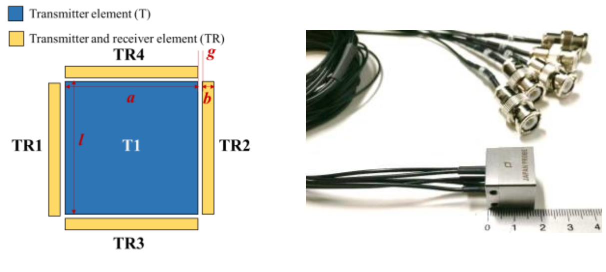
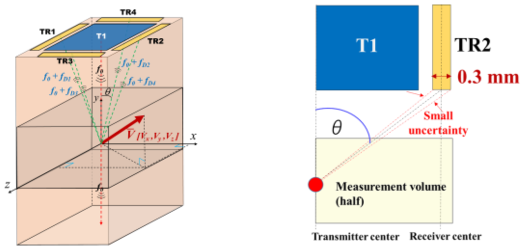


(a) Element configuration.

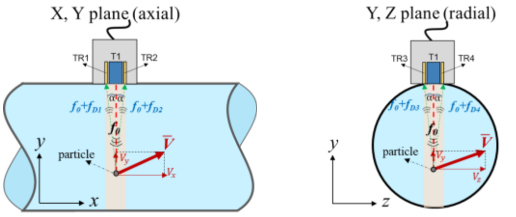
(b) Manufactured transducer.

Figure 1: Five elements transducer design.



(a) Four Doppler frequencies

(b) Echo angle (θ)



(c) Axial plane view.

(d) Tangential plane view.

Figure 2: Five elements transducer measurement principle.

small (approximate the wavelength). Finally, using the four Doppler frequencies from one measurement volume, the three-dimensional velocity, *i.e.* axial velocity (V_x), radial velocity (V_y) with the information of f_{D1} and f_{D2}, tangential velocity (V_z) with the information of f_{D3} and f_{D4} and vector in axial plane view (V_x-V_y) and tangential plane view (V_z-V_y) can be reconstructed with the equations below.

$$V_x = \frac{c}{2f_o}\frac{f_{D1} - f_{D2}}{\sin\theta} \quad (1)$$

$$V_y = \frac{c}{2f_o}\frac{f_{D1} + f_{D2}}{1+\cos\theta} \quad (2)$$

$$V_z = \frac{c}{2f_o}\frac{f_{D3} - f_{D4}}{\sin\theta} \quad (3)$$

$$\overline{V}_{axial} = \sqrt{V_x^{\,2} + V_y^{\,2}} \quad (4)$$

$$\overline{V}_{\tan gential} = \sqrt{V_z^{\,2} + V_y^{\,2}} \quad (5)$$

Table 1: Design of new transducer for 3D velocity measurement

Specification	Detail
Basic Frequency (f_o)	4 MHz
Wavelength in water, 20 °C (λ)	0.37 mm
Transmitter element width (a)	5 mm
Receiver element width (b)	0.3 mm
Transmitter- receiver gap (g)	0.1 mm
Element length (l)	5 mm

3. Experimental apparatus

The developed transducer was evaluated experimentally for the ultrasonic propagation characteristic, flow measurement evaluation in the reference flow, and applicability to measure three-dimensional swirling flow. The experiment consists of sound pressure measurement, fully developed laminar, turbulent and swirling flow measurement. Each experiment was conducted with same measurement system (Figure 3) which are five elements transducer (manufactured by Japan probe), 8 channel pulser receiver (Japan probe JPR-10C-8CH3R), and 8 channel A/D converter (National Instrument PXI-1033). The measurement system used LabVIEW software to process the echo signal (Doppler signal) into the velocity profile with autocorrelation technique [9].

3.1 Sound pressure measurement

The ultrasound propagation characteristic was investigated by sound pressure measurement. The transducer transmits with all elements simultaneously in water (20°C) and the needle hydrophone (diameter 0.5 mm) collects the pressure data in several positions with the spatial resolution of 1 mm, controlled by XYZ stage (see Figure 4).

3.2 Fully developed laminar flow measurement

To check the measurement performance, the measurement was being conducted in fully developed laminar flow on a vertical pipe apparatus (Figure 5) which has a good theoretical reference. The pipe inner diameter (D) is 50 mm with the water as the working fluid, Reynolds number (*Re*) 420 and the tracer particle, Nylon with a diameter of 80μm is dispersed. To ensure the flow is fully developed laminar flow, the measurement is conducted in the position of 30D from the inlet where the theoretical of the fully developed laminar flow pipe length is 21D (0.05*ReD*). The experiment conditions and measurement parameters are given in Table 2.

Table 2: Fully developed laminar flow experiment condition and measurement parameters

Condition and parameter	Detail
Reynolds number (*Re*)	420
Pulse repetition frequency	100 Hz
Number of repetitions	128
Number of profiles	2,000
Number of cycles	4
Channel distance	0.74 mm

3.3 Turbulent and swirling flow measurement

After applying in the reference flow (laminar flow), the transducer was applied in different flow conditions which are turbulent and swirling flow in horizontal pipe apparatus (Figure 6) to check further the measurement system capability. Swirling flow can be generated if the swirl generator (rotating pipe) is activated. The experiment conditions and measurement parameters are given in Table 3

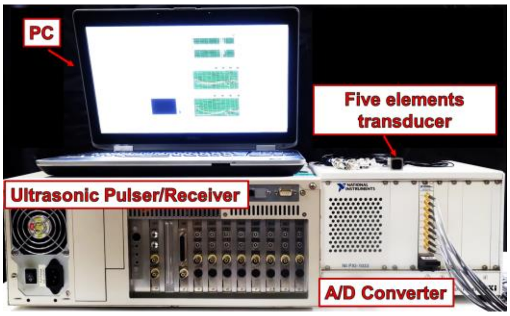


Figure 3: Measurement system.

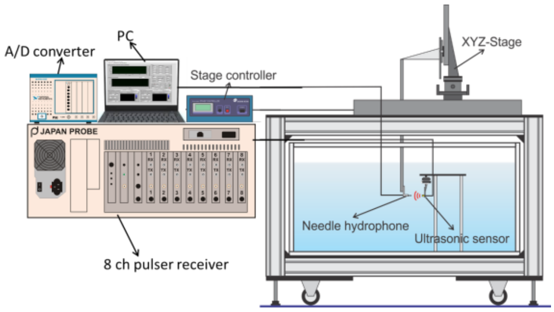


Figure 4: Sound pressure measurement in water.

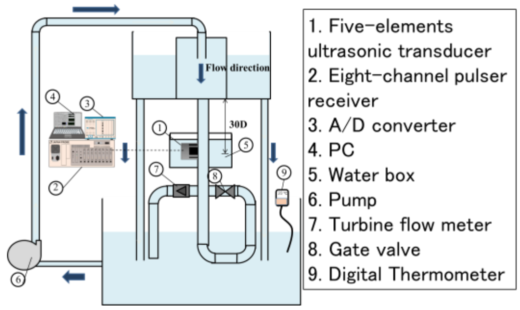


Figure 5: Vertical pipe apparatus.

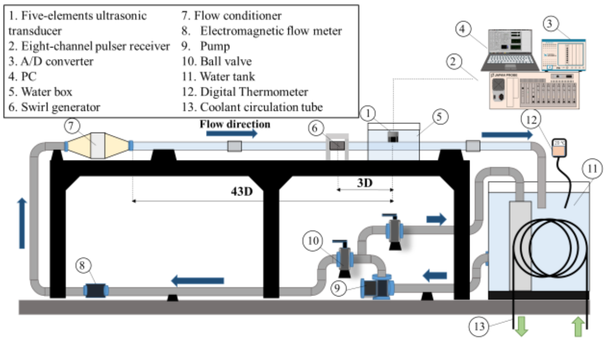


Figure 6: Horizontal pipe apparatus.

Table 3: Turbulent and swirling flow experiment condition and measurement parameters

Condition and parameter	Detail
Reynolds number	13,000
Pipe inner diameter (*D*)	50 mm
Motor frequency (in swirling case)	600 rpm
Pulse repetition frequency	2,000 Hz
Number of repetition	128
Number of profile	5,000
Number of cycles	4
Channel distance	0.74 mm

4. Results and Discussion

4.1 Sound pressure measurement

The transducer sound pressure characteristic recorded by the hydrophone is plotted in the color graph in dB scale (Figure 7). From the result, we confirmed that there is one main lobe of the transmission wave of all elements, hence one measurement volume for all transmitter/receiver and no side lobe found. Therefore, the measurement principle defined in section 2 can be applied and three-dimensional velocity measurement can be possibly done.

4.2 Fully developed laminar flow measurement

The measurement result (Figure 8) is the average of 2000 instantaneous three-dimensional velocity profile. The result of the axial velocity is compared to the theory (laminar parabolic curve). The comparison is in a good agreement except in the region of near field (0-8 mm) and far field (40-50 mm). The result is acceptable, considering in the near field, the sound intensity is oscillating and in the far field, the sound intensity is weaker. The radial and tangential velocity are found to approach zero value with a small standard deviation which is as expected in the fully developed laminar flow. With this array elements configuration, there will be a elements cross-talk, mainly between the center transmitter and side receiver, however, since the gap is very small, the cross-talk will only effect the initial measurement region, which overlaps with the near-field region. Finally, we can confirm the capability of the measurement system in the three-dimensional flow measurement.

4.3 Turbulent and swirling flow measurement

The measurement result of turbulent and swirling flow is an average of 5000 instantaneous three-dimensional velocity profile, plotted into vector profile in axial and tangential plane view. The result of turbulent and swirling flow can be seen in Figure 9 and 10 respectively. From the result of turbulent flow, the comparison with single element transducer is in a good agreement. In the swirling flow result, we can find higher standard deviation (compare to laminar flow), higher radial and tangential velocity which is the behaviour expected in swirling flow. Finally, we confirm that the measurement system can be applied to measure the three-dimensional velocity profile in different flow condition.

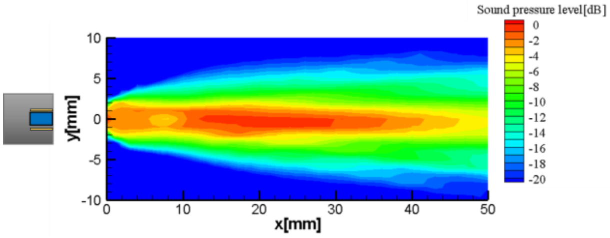
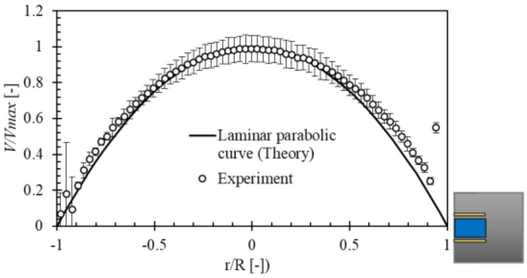
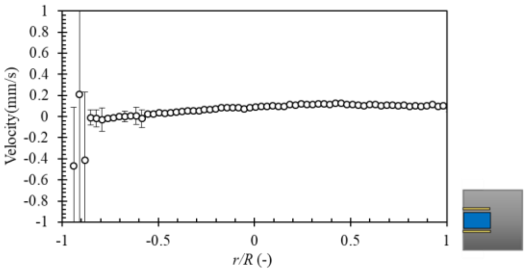


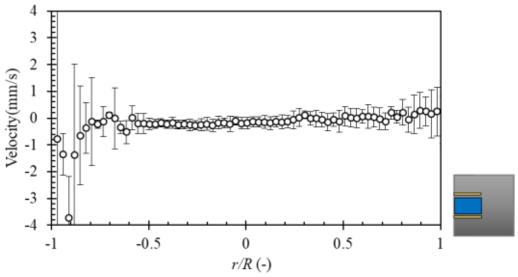
Figure 7: Sound pressure measurement result.



(a) Axial velocity (V_x).

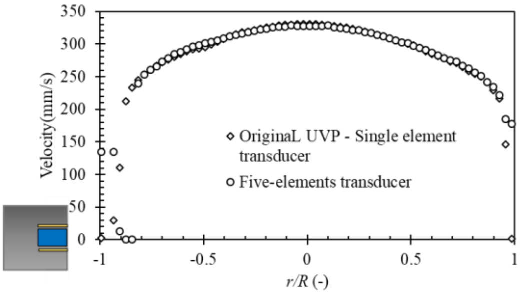


(b) Radial velocity (V_y).

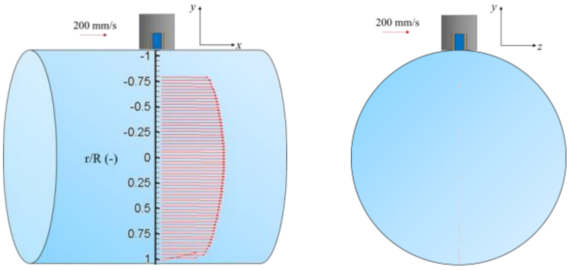


(c) Tangential velocity (V_z).

Figure 8: Three-dimensional velocity profile of fully developed laminar flow



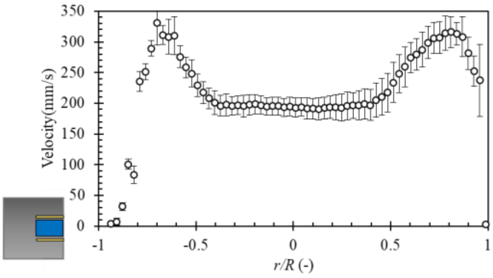
(a) Axial velocity (V_x).



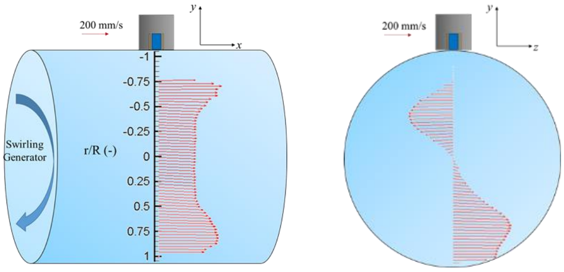
(b) Axial plane view.

(c) Tangential plane view.

Figure 9: Three-dimensional velocity measurement of turbulent flow



(a) Axial velocity (Vx).



(b) Axial plane view.

(c) Tangential plane view.

Figure 10: Three-dimensional velocity measurement of swirling flow

5. Summary

The new configuration of five elements transducer has been designed and the three-dimensional velocity profile measurement system has been developed. From the sound pressure measurement, we confirmed that three-dimensional measurement is possible since one main lobe is generated (one measurement volume) with no side lobe. From the flow measurement, we confirm the performance by fully developed laminar flow measurement and the capability to measure flow in different conditions.

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