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An instantaneous velocity vector measurement using conventional ultrasonic transducers

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A new profiling method of velocity vectors using three conventional transducers is proposed in this study. Since the conventional transducers include uncertainty for the detection points on receivers, a new configuration of transducers was constructed to minimize the uncertainty. The configuration consists of a central emitter and two side receivers. Measurable distances are theoretically determined by the configuration, thus a feasibility test for the measurable distance was firstly carried out in a towing tank facility. The distance was evaluated by measured velocities, and it was confirmed that the measurable distance agreed well with the theoretical distance. The other feasibility test was completed to assess the velocity vector measurement in the measurable distance, and the measured vectors showed a good agreement to reference values. As an application of the new method, the Reynolds stress in a turbulent pipe flow was measured, and it showed a good agreement with the PIV result.

Keywords: Ultrasound Velocity Profile, Vector profiling, Conventional transducer, Turbulent flow

1. Introduction

Ultrasound Velocity Profile (UVP) is one of the efficient measurement techniques in fluid engineering because it allows measuring opaque flows without intrusions in flow fields. Since it also provides high temporal resolution, the UVP is widely used in many fluid fields. However, a disadvantage is that only one vector on a measurement line can be obtained. Namely, it is less informative when turbulent flows are measured. In response to this problem, there are many challenges about velocity vector profiling methods called vector-UVP, and special transducers such as a focusing transducer, a phased array transducer, and an element array transducer were adopted in the vector-UVP studies [1–3]. However, these transducers also have other problems. For example, large errors in a receiver can be included with the focusing transducer. A reduction of time resolution is unavoidable in the case of phased array transducer because the phased array setup requires a certain scanning time for the measurement plane. Besides, the element array transducer has lower availability than the UVP because special transducer designs are required for each measurement cases. Additionally, expenses by the purchase of them are required, and the expenses also remind for the above-mentioned transducers. For these reasons, the vector-UVP is not commonly used in the fluid engineering fields, even though it can offer more information than the UVP. In this study, a new method for measuring velocity vectors with conventional transducers is suggested. A new configuration with conventional transducers was constructed to minimize uncertainty about the detection points on receivers. In this paper, we introduce this new methodology and show results of its feasibility tests performed in towing tank facility and a turbulent pipe flow.

2. Measurement principle

2.1 Configuration of transducer

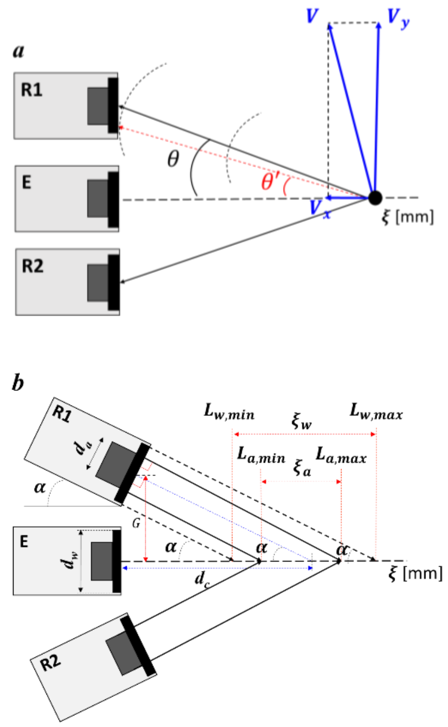

Figure 1: A measurable distance determined by the configuration of conventional transducers. E is central emitter and R1 and R2 are tilted side receivers.

In the general configuration of vector UVP with conventional transducers (Figure 1(a)), there is an uncertainty to determine the detection points on receivers because the sensor diameter of the transducer is quite large compared to measurement length. For example, the included angle between an emitted line and a reflected line becomes θ with an assumption that the echo signals are always detected at the center points of each receiver, even though the actual angle is not θ but θ'. This uncertainty can be minimized by giving angles on the receivers as shown in Figure 1(b). With this configuration, the detecting points at the receivers can be known if we assume that the echo signal is sensed by the nearest point of receivers from the reflected point by a media, and the measurable distance (ξ_a) can be also theoretically estimated by the active diameter (d_a) of the transducer. In the measurable distance, the reflected lines are perpendicular to the receiver surface, then the angle between the emitted and the reflected line becomes the tilted angle of the transducer (α). Consequently, the vector-UVP equation can be expressed in Eq. (1) where V_{R1} and V_{R2} are receiver direction velocities.

$$V_x = \frac{V_{R1} + V_{R2}}{1 + \cos\alpha}, \quad V_y = \frac{V_{R1} - V_{R2}}{\sin\alpha} \qquad (1)$$

To discuss the measurable distance in more detail, it is likely that the ultrasound detected at areas other than the d_a is transferred by oscillating a wear plate. Accordingly, a measurable distance depending on the whole diameter of the transducer (d_w) was also considered. The information about theoretical measurable distance is summarized in Table 1, and the distance between the center of emitter and center of each receiver (G) was 8.9 mm. About the conventional transducer, not only the emitter and but also the receivers were made up of TX4-5-8-40 (Met-Flow S.A) which f_0, d_a and d_w are 4 MHz, 5 mm and 8 mm, respectively.

Table 1: Geometric information about transducer configuration changed by receiver angles

	α = 5°	α = 10°
$L_{a,\,min}$ [mm]	74.2	37.0
$L_{a,\,max}$ [mm]	131.8	65.8
$L_{w,\,min}$ [mm]	57.2	28.4
$L_{w,\,max}$ [mm]	149.0	74.4
ξ_a [mm]	57.6	31.8
ξ_w [mm]	91.8	46.1

2.2 Pulsed Doppler method

The emitter was driven by a pulser/receiver (JPR-600C, Japan Probe Co., Ltd), and the echo signal received from R1 and R2 was amplified by preamplifiers (PR-60BP, Japan Probe Co., Ltd) which include band-pass filter function to improve the signal to noise ratio (SNR), and it is recorded on a memory of PC. The signal was demodulated by quadrature phase demodulation [4], and the autocorrelation method was adopted to compute a Doppler frequency (f_D). The receiver direction velocity (V_R) was obtained using Eq. (2) where c is sound speed and f_0 is the basic frequency of ultrasound.

$$V_R = \frac{c f_D}{2 f_0} \qquad (2)$$

3. Feasibility test

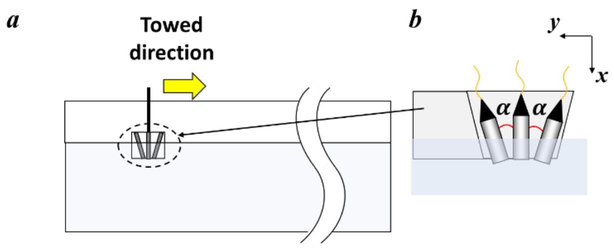

Figure 2: Schematic of experiment apparatus (a) a towing tank facility and (b) a transducer holder.

Two feasibility tests were carried out; one was to evaluate the measurable distance by α and the other was to assess the measurement of velocity vector. For these tests, a towing tank facility was utilized with a transducer holder as shown in Figure 3(a) and (b), respectively. Tracer particles were mixed in water (HP 20SS, Mitsubishi Chemical), and their density and diameter are 1010 kg/m^3 and 50–120 μm, respectively. The water temperature was 21°C.

3.2 Feasibility test for measurable distance

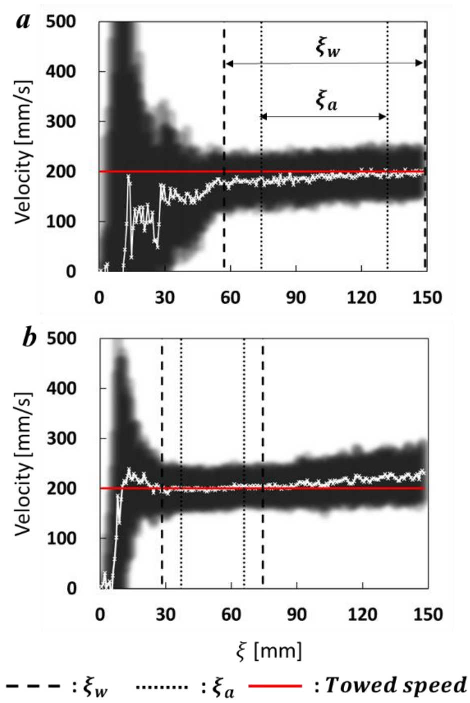

Figure 3: Time-averaged velocity (a) α = 5° and (b) α = 10°. Black region implies standard deviation.

In the feasibility test for the measurable distance, the transducer holder was submerged horizontal to the water surface as shown in Figure 3(b) and towed as 200 mm/s. The ultrasound (4 cycles) was emitted with f_0 of 4 MHz and f_{PRF} (pulse repetition frequency) of 1 kHz, and the number of pulse repetitions in a velocity profile was 25. The fifty velocity profiles were averaged (Figure 4). In the ξ_a and the ξ_w, the measured velocity is converged well to the towed speed for each α, while it shows higher residuals in the outside of the ξ_a and the ξ_w than that in the ξ_a and the ξ_w.

$$E_R = \frac{\left| V - \overline{V_y} \right|}{V} \times 100\ [\%] \qquad (3)$$

To evaluate this result, error rate (E_R) was computed using Eq . (3), and the spatio-temporal average E_R for each α is summarized in Table 2. As the average E_R for each α is equal within the ξ_a and the ξ_w, it can be said that the ξ_w is also adopted using the TX4-5-8-40. In addition, the E_R is below in 6%, thus the measurable distance is constructed well for each α.

Table 2: Spatio-temporal averaged error rate for each α

	α = 5°	α = 10°
ξ_a	6 %	1 %
ξ_w	6 %	1 %

3.3 Feasibility test for vector measurement

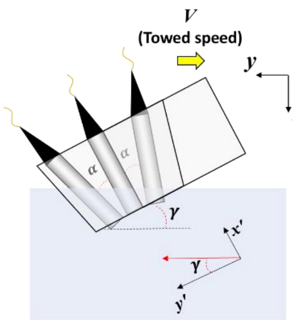

Figure 4: A virtual coordinate by tilting transducer holder.

The transducer holder was tilted with an angle γ to generate two vectors in the towing tank as shown in Figure 4. A virtual coordinate is formed with x' and y' with the γ, and the velocity in the x' and y' can be theoretically estimated by Eq. (4) where V is towed speed. In this test, the γ was 30°.

$$V_{x',\mathrm{theo}} = V\sin\gamma,\ \ V_{y',\mathrm{theo}} = V\cos\gamma \qquad (4)$$

The experimental condition is the same as to previous feasibility test other than f_{PRF} and α. The f_{PRF} was changed to 2 kHz to prevent the aliasing problem, and the α of 5° is adopted in this test. Figure 5 shows the time-averaged $V_{x'}$ and $V_{y'}$ when the γ is 30°. A red line indicates $V_{x',theo}$, and a yellow line means $V_{y',theo}$. It can be clearly recognized that $V_{x'}$ and $V_{y'}$ are converged to the theoretical value in the ξ_a and the ξ_w. To estimate the error of this result, magnitude velocity (V') was obtained and error rate (E_v) was computed using Eq. (5).

$$E_V = \frac{\left| V - V' \right|}{V} \times 100\ [\%],\ V' = \sqrt{V_{x'}^2 + V_{y'}^2} \qquad (5)$$

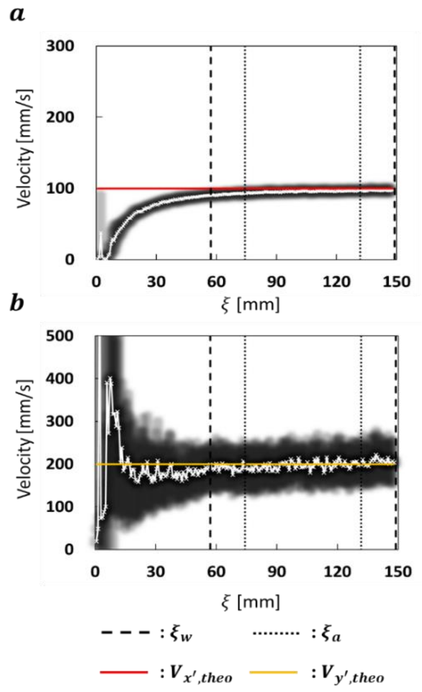

Figure 5: Time-averaged $V_{x'}$ and $V_{y'}$ when γ is 30°, and black region implies standard deviation.

The spatio-temporal averaged E_v are 2% and 1% in the ξ_a and the ξ_w, respectively. Based on this result, it is possible to say that two vectors can be obtained with low errors using the vector-UVP in time-average. Meanwhile, the condition of this experiment can be considered as a steady state flow because the towed speed is constant regardless of measurement time. Nevertheless, the standard deviation of $V_{y',theo}$ is much high, whereas that of $V_{x',theo}$ is converged to zero. This means that the fluctuations of velocity are included in instantaneous velocity profiles, and this is due to the lack of velocity resolution of $V_{y',theo}$. To explain, the velocity resolution of $V_{x'}$ ($\Delta V_{x'}$) and $V_{y'}$ ($\Delta V_{y'}$) can be expressed as Eq. 6 where ΔV_R is the velocity resolution in the beam direction. Although it is difficult to calculate the ΔV_R in the autocorrelation frequency analysis, the resolution is roughly estimated using the denominator of the equation by substituting 5° in α.

$$\Delta V_{x'} = \frac{\Delta V_R}{1+\cos\alpha},\ \Delta V_{y'} = \frac{\Delta V_R}{\sin\alpha} \qquad (6)$$

$$\Delta V_{x'} = 0.5\Delta V_R,\ \Delta V_{y'} = 11.5\Delta V_R \qquad (7)$$

As shown in Eq. (7), the $\Delta V_{y'}$ is 23 times much larger than the $\Delta V_{x'}$. For this reason, the standard deviation of $V_{y'}$ is much higher than that of $V_{x'}$. Therefore, the α should be optimized to minimize the error caused by the lack of velocity resolution considering the measurement distance.

4. Application of developed vector-UVP

As a demonstration of the developed vector-UVP, we measured the Reynolds stress in a turbulent pipe flow. A schematic diagram of experimental equipment is shown in Figure 6(a). A bent hose is connected with the inlet of a pipe as shown in Figure 6(b), and this led to asymmetric flow in the pipe. The pipe has a 50 mm inner diameter (D) and 2000 mm length (L), and the transducers and high-speed camera were installed at $L/2$. Same as to feasibility tests, HP 20SS was mixed in the water. The bulk velocity (U_{bulk}) is 1 m/s, and the Reynolds number defined as $Re = U_{bulk}D/\nu$ where ν is a kinematic viscosity is 50,000.

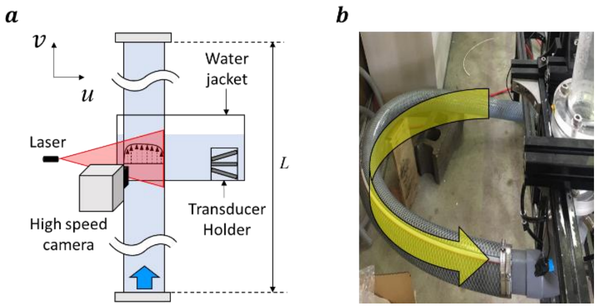

Figure 6: Experimental equipment for the measurement of Reynolds stress in a pipe flow. (a) A schematic diagram of experimental set-up. (b) A bent hose at pipe inlet. A yellow arrow indicates flow direction in the bent hose.

About measurement conditions, images of pipe flow were obtained by the camera with 1,500 fps to compare the vector-UVP and the PIV result. The ultrasounds were emitted f_0 of 4 MHz with f_{PRF} of 2 kHz. The spatial resolution is 0.74 mm, and 27 repetitions were included in a velocity profile. 500 velocity profiles were used to compute the mean velocity and the Reynolds stress, and they are shown in Figure. 7. For the time-averaged magnitude velocity (Figure 7(a)), there are small differences between the PIV and the vector-UVP up to the diameter of 24 mm, however, the velocity distributions of the two measurement systems are almost the same as each other. The magnitude velocity at a diameter of 2 mm includes erroneous data in the vector-UVP result due to the multiple reflections. As explained previously, velocity profiles by vector-UVP and PIV shows asymmetric velocity distribution because of the bent hose connected with the pipe inlet as explained previously. Generally, the Reynolds stress can be obtained from velocity profiles on multiple measurement lines of UVP, not a vector-UVP, by assuming the $\overline{u}$ becomes zero [5]. However, it is likely that the $\overline{u}$ is not zero in this asymmetric flow, and then the Reynolds stress cannot be estimated using the UVP. As two vectors in the flow field can be obtained by developed vector-UVP, the Reynolds stress can be gained in any flow condition by using the vector-UVP. To talk about the measurement result of Reynolds stress, small differences exist between the two measurement results, but they are closely agreed to each other except for the multiple reflection points. The Reynolds stress means turbulent fluctuations in fluid momentum, and instantaneous velocity profiles are required to acquire the stress. Since the Reynolds stress obtained by the PIV and the vector-UVP are consistent, the instantaneous velocities measured by the vector-UVP are statistically valid.

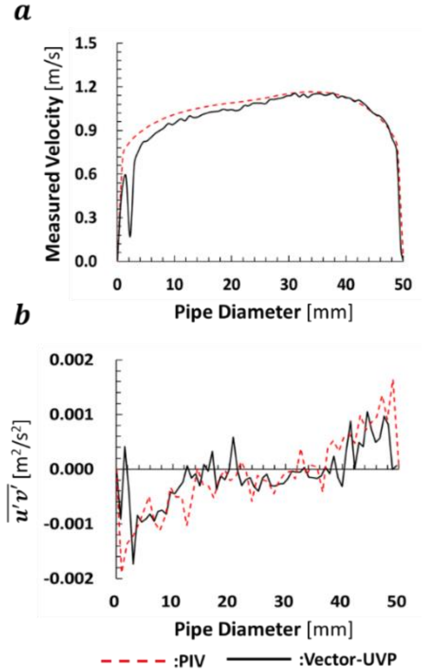

Figure 7: A comparison of vector-UVP and PIV results. (a) Time-averaged magnitude velocity and (b) Reynolds stress.

5. Summary

The new vector-UVP system using conventional transducers was successfully developed in this study. According to the angle of the receiver, the measurable distance is determined, and it was confirmed that the velocity error is below 2% in the measurable distance. In this system, the optimal angle of the receiver should be adopted considering the measurement distance because nonnegligible error can be included with the low angle which causes the lack of velocity resolution. The applicability of developed vector-UVP was examined by measuring the Renoylds stress in the turbulent pipe flow, and it shows a good agreement to the PIV result.

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