A NEW ALGORITHM FOR LOW VELOCITY MEASUREMENT BY UVP

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ABSTRACT

UVP (Ultrasonic Velocity Profiler) is a great tool in the experimental fluid dynamics because it can measure an instantaneous velocity profile. In this study, we suggest a new UVP algorithm, which is called as “Phase difference method”, for low velocity measurement and compare it with two exiting algorithms. Furthermore, we perform the two verification experiments with a measurement system based on the new algorithm, in order to confirm the validity and the utility of the algorithm.

Keywords: UVP, Algorithm, Velocity profile measurement, low velocity measurement

INTRODUCTION

UVP (Ultrasonic Velocity Profiler), which uses ultrasonic pulses, is available to opaque fluids and measures instantaneous velocity profile along a measurement line. These are great advantages to HWA and optical methods such as PIV. There are two fundamental algorithms for UVP. The conventional one is “Pulse Doppler method”. This algorithm is versatile and used widely now. The other one is “Correlation method”, which has been devised in order to measure high-speed flow. These method, however, have threshold for low velocity. In this study, we suggest a new algorithm for low speed flow measurement, mm/s order, such as in a natural convection, and investigate performance of the algorithm.

COMMON PRINCIPLE OF UVP

An ultrasonic pulse emitted from an ultrasonic transducer is reflected by the particles suspended in fluid and is received by the same transducer. Positional information is given by the time of flight from emission to reception of the ultrasonic pulse, and velocity information is obtained by analyzing received echo signal. If a number of the particles is enough, ultrasonic pulse are reflected everywhere on the passing line of the pulse. Thus, UVP can measure an instantaneous velocity profile along the line.

EXITING ALGORITHMS OF UVP

A resolution of measurable velocity is a critical factor for the low velocity measurement. This section describes exiting UVP algorithms and how to be determined the resolution in both algorithms.

1. Pulse Doppler method

Fig.1 shows the sampling process of ultrasonic echo in Pulse Doppler method, where the black squares and the black circles express the transducer and particles respectively. The sampling process is expressed as follows; ①an ultrasonic pulse is emitted from the transducer, ②a part of pulse reflects at a particle and the other passes through, ③the “echo” from the particle reaches the transducer, and is translated into the electric signal, ④it is sampled with index i, that is d_i, where i means temporal index. If sound speed is known, i can be translated into positional index because positional information is given by time of flight of ultrasonic pulse. This sampling is repeated plural times. In this way, the data set to calculate an instantaneous velocity profile is d_{ij}, where j is pulse repetitional index. Fig.2 shows two examples of sampled data, d_{ij}. If the particle is moving faster, the echo wave becomes shorter

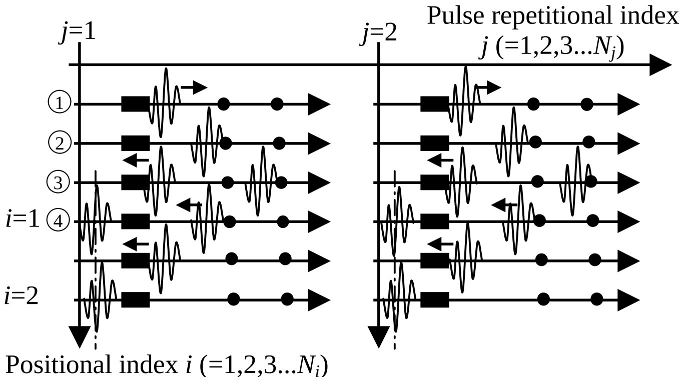
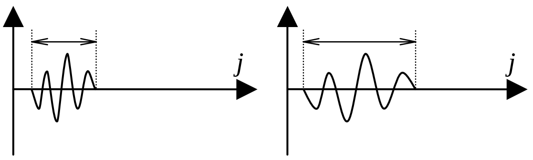


Fig.1 Sampling process for Pulse Doppler method



(a) higher veloctiy (b) lower veloctiy

Fig.2 Examples of sampled data

(Fig.2(a)), and if later, it becomes longer (Fig.2(b)). That is, velocity corresponds to the frequency of the echo. Velocity is determined from the frequency whose power is the largest in the frequency spectrum. On digital process, the frequency is selected as a discrete value. Therefore, the minimum measurable velocity is determined by the frequency resolution.

2. Correlation method

Fig.3 shows the sampling process of ultrasonic echo for Correlation method. The sampling process is described as follows; ①an ultrasonic pulse is emitted from the transducer, ②a part of ultrasonic pulse reflects and the other passes through, ③the echo from the transducer reaches the transducer, and is translated into the electric signal, ④it is sampled with positional index *i*, and additionally sampled with index *k* between each *i*, where *k* is sampling index. Thus, the Correlation method needs higher sampling rate than Pulse Doppler method. This sampling is repeated at least two or generally more times. There is a time delay between two waves, which has the same positional index *i*. It corresponds to moving distance of the particle, and then, the velocity can be obtained by calculating the time delay. In other words, the velocity is determined from the time delay at which correlation coefficient is the largest in correlation function. As well as Pulse Doppler method, the minimum measurable velocity is limited because of discrete value, in this method time delay.

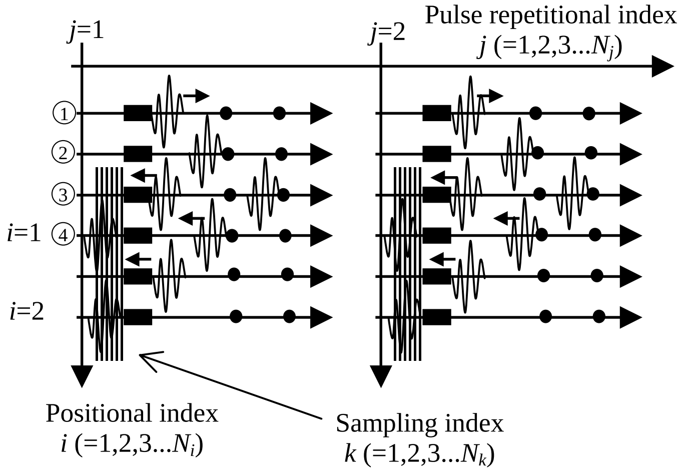


Fig.3 Sampling process for Correlation method

NEW ALGORITHM FOR LOW VELOCITY

1. Theoretical concept of new algorithm

A primal concept is similar to Correlation method. Namely, measurement data set of echo is described as $d_{ij}(k)$ as shown in Fig3. In the new algorithm, however, velocity is not obtained from time delay, but from phase difference between two waves. The theoretical calculating process is described as following. First, echo data $d_{ij}(k)$ is decomposed by using Fourier Transform,

$$C_{ij}(s) = \mathbf{Re}\left[\frac{1}{N_k}\sum_{k=0}^{N_k-1} d_{ij}(k)(W_{N_k})^{kS}\right] \qquad (1)$$

$$S_{ij}(s) = \mathbf{Im}\left[\frac{1}{N_k}\sum_{k=0}^{N_k-1} d_{ij}(k)(W_{N_k})^{kS}\right] \qquad (2)$$

where N_k is sampling number about index *k* and *s* is the Fourier index, defined as,

$$f_s = sf_1, \qquad f_1 = \frac{1}{N_k t_{sa}}$$

where t_{sa} is sampling time interval about *k*. $C_{ij}(s)$ is the cosine component and $S_{ij}(s)$ is the sin component of the original echo signal. $\theta_{ij}(s)$, an initial phase of the decomposed wave with frequency f_s, is obtained as the ratio of $C_{ij}(s)$ and $S_{ij}(s)$ as,

$$\theta_{ij}(s) = \tan\frac{S_{ij}(s)}{C_{ij}(s)}. \qquad (3)$$

$\theta_{ij}(s)$ gives initial position of the decomposed wave as,

$$x_{ij}(s) = \frac{\theta_{ij}(s)}{2\pi}\lambda(s) \qquad (4)$$

where $\lambda(s)$ is wavelength of decomposed wave with frequency f_s, and is determined as follows.

$$\lambda(s) = \frac{c}{f_s} = \frac{N_k t_{sa} c}{s} \qquad (5)$$

The moving distance $dx_{ij}(s)$ is defined as positional difference between *j-1* and *j* as follows.

$$\begin{aligned} dx_{ij}(s) &\equiv x_{ij}(s) - x_{ij-1}(s) \\ &= \frac{\theta_{ij}(s) - \theta_{ij-1}(s)}{2\pi}\lambda(s) \end{aligned} \qquad (6)$$

If form of two waves, *j-1* and *j*, is quite same, the positional difference of all decomposed waves must be constant. Namely, $dx_{ij}(s)$ does not depend on *s*, and becomes constant.

$$dx_{ij}(s) = \text{const.} \equiv dx_{ij} \qquad (7)$$

dx_{ij} corresponds to the moving distance of particle. The velocity is calculated as following equation,

$$u_{ij} = \frac{1}{2}\frac{dx_{ij}}{t_j}$$

where t_j is time interval of ultrasonic emitting. We call this new algorithm "Phase difference method". In ideal system, u_{ij} does not depend on *s*, and then velocity can be calculated from just representative frequency f_r. Thus, Fourier index *s* is rewritten as s_r in Eq.(1)-(7). Namely, if f_r is determined at the beginning of the calculating process, the computational amount can be reduced drastically. The base frequency of an ultrasonic pulse should be selected as f_r because it is less sensitive to noise than any other frequency components.

The phase range determines theoretical maximum limit of measurable velocity. This method cannot give the correct result when the componential wave moves beyond its wavelength $\lambda(s)$. Following equation must be fulfilled,

$$dx_{ij} < \lambda(s)$$

as assigning Eq.(2) and Eq(1) to this equation,

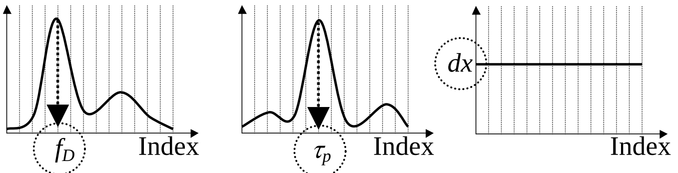
$$\Rightarrow 2u_{ij}t_j < \lambda(s)$$

$$\Rightarrow u_{ij} f_s < \frac{c}{2t_j}. \qquad (8)$$

Because representative frequency f_r is used to calculate the velocity, f_r substitutes for f_s in Eq.(8). Ultimately, maximum limit of measurable velocity is determined as follows.

$$u_{ij} f_r < \frac{c}{2t_j}.$$

On the other hand, the minimum limit of measurable velocity is not determined theoretically. As refers to above, in Pulse Doppler method and Correlation method, it is determined by discrete value f_D and τ_p whose value is largest in frequency spectrum and correlation function respectively, as shown in Fig.4(a) and (b). In this new algorithm, however, discrete value is not used. dx_{ij} is calculated from $\theta ij(s_r)$, a ratio of cosine and sin component, and it does not depend on frequency index and varies continuously, as shown in Fig.4(c). If we determine the minimum limit forcedly, it becomes resolution of quantization in a system. For instance, when we use 8-bit double–precision floating point variables, this limit becomes $4.9*10^{-324}$. In actual measurement, the measurement deviation is far larger. Because Phase difference method has no theoretical limit of measurable minimum velocity unlike exiting algorithm, it is available and suitable for low velocity measurement.



(a) Pulse Doppler method (b) Correlation method (c) Phase difference method

Fig.4 Value of determining velocity in each algorithms

2. Setup of UVP system

The setup of UVP system that we specify in this study and its measurement conditions are shown in Table 1. A basic frequency of pulse emitted from a transducer is 4 MHz, and then a representative frequency f_r in calculating process is 4 MHz as well. A sampling interval t_{sa} is 2 ns and a burst repetition interval t_j is 75 μs. When the analog signal of an echo is quantized into the digital signal, $d_{ij}(k)$, a quantization error is caused. As using this parameter, it becomes about 0.12 mm/s. this error depends on the sampling resolution of ADC, and it can be reduced by using higher-performance one. Numbers of each index N_i, N_j and N_k are 67, 5 and 550 respectively. Namely, 67 measurement points are on the measurement line, the velocity is calculated from 550-sampled echo, and the average of repeating 5 times gives an instantaneous velocity profile. By these parameters, the measurement conditions are determined as described in Table 1. These depend on sound speed c, and Table 1 show the case of water, c = 1480 m/s.

Table 1 The specification an performance of UVP built on new algorithm

Setup parameters	
Base frequency of pulse	4 [MHz]
Number of positional index i : N_i	67
Number of pulse repetitional index j : N_j	5
Number of sampling index k : N_k	550
Sampling interval: t_{sa}	2 [ns]
Burst repetition interval: t_j	75 [μs]
Measurement conditions*	
Start of the measurement section	0 [mm]
End of the measurement section	53.80 [mm]
Positional resolution	0.803 [mm]
Temporal resolution	0.2 [s]
Measurable maxmum velocity	2713 [mm/s]

* in the case of using water, c = 1480 [m/s]

VERIFICATION EXPERIMENTS

As discussed above, a possibility of the low velocity measurement with a new algorithm is indicated theoretically. But, there is no guarantee that the algorithm can apply to the realistic low velocity measurement, because of various error factors. It is necessary to confirm validity and the utility of the algorithm for low velocity measurement, to bring out the problem of measurement and to improve the measurement accuracy through realistic experiments. In this section, two verification experiments are performed.

1. Measurement of the pseudo-flow model

The model assumed a low velocity flow is constructed, in order to confirm that new algorithm can really measure low velocity with a few mm/s order. Fig.5 shows the experimental setup. In water, six strings as reflectors of the ultrasonic pulse are fixed perpendicularly on the measurement line of an ultrasonic transducer. The transducer is moved by stepping motor controlled by PC. The speed of transducer toward strings is 1 mm/s and away is 4 mm/s. Fig.6 shows the velocity profile, where the horizontal axis is time, the vertical axis is distance from the transducer and gray scale expresses velocity.

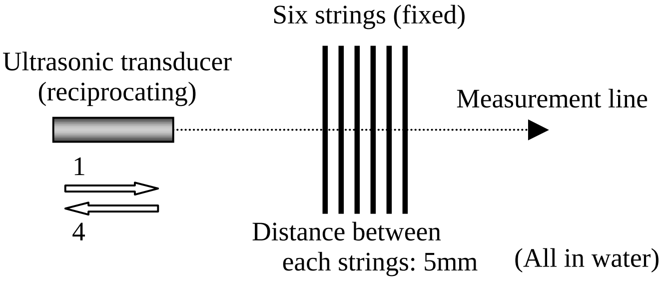


Fig.5 Experimental setup

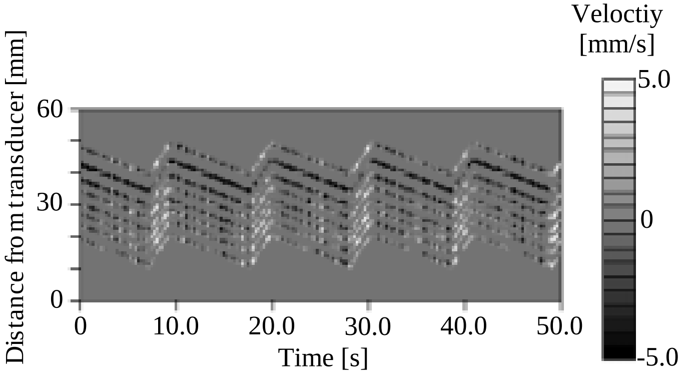


Fig.6 Veloity color map

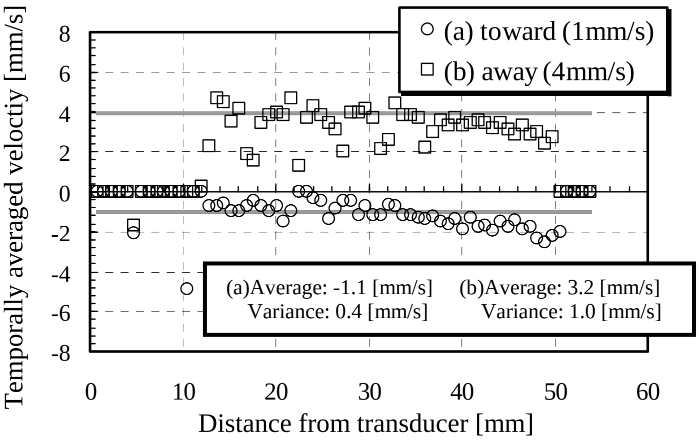


Fig.7 Temporally averaged velocity profile and its positional average and variance

When the transducer moves toward strings, velocity is positive, otherwise negative. In Fig.6, six lines drawn zigzag are identified with six strings. This proves that UVP with new algorithm measure velocity at correct position. Fig.7 shows the averaged velocity, where the horizontal axis is distance from the transducer and the vertical axis is velocity. It is found that measured velocity corresponds to setting value. Consequently, it is confirmed that this new algorithm can measure low velocity.

2. Measurement of the flow in the rotating cylinder

As a measurement of a realistic flow, we use the flow in a rotation cylinder with 150 mm diameter. This system has theoretical solution of the flow and then often used as a verifier for UVP. Fig.8 shows the experimental setup as looking downward. The cylinder filled with water suspended tracer particles is rotating with stationary angular velocity ω. Just after the beginning of rotating, water starts to move by being pulled, and as time goes by enough, water rotates as rigid body. In this time, velocity measured by UVP should be spatially and temporally constant. This is described as follows. A distance between the measurement line and the central axis on the horizontal section of the cylinder is a, now a = 22 mm. A circumferential velocity v_θ at a certain position on the measurement line is described by using a and θ as shown in Fig.8 and as following equation.

$$v_\theta = \frac{a\omega}{\cos\theta}$$

Because the velocity measured by UVP is the component of the measurement line, theoretically expected velocity u_m becomes,

$$\begin{aligned} u_m &= v_\theta \cos\theta \\ &= a\omega \end{aligned}$$

u_m is constant at any positions on the measurement line.

Table 2 shows ω and u_m in each cases, where negative ω means reverse rotation. Fig.9 shows the results of temporally averaged velocity profile with each condition, where the horizontal axis is the distance from transducer and the vertical axis is averaged velocity with 2000 time steps. It is found that velocity value well corresponds to u_m.

Table 2 Angular velocity ω and expected velocity u_m

	(a)	(b)	(c)	(d)
ω [rad/s]	3.9	-3.9	1.1	-1.1
u_m [mm/s]	86	-86	24	-24

These two averaged velocity profile shown in Fig.7 and Fig.9 indicates possibility for low velocity measurement. But, there is a fluctuation in instantaneous velocity profile. It is thought that this error of measurement is caused by poverty of particles in measurement volume. It is a common problem for any UVP algorithm. Particularly, it is a serious problem for this new algorithm. Because it requires that form of two waves of echo correspond, the deformation of the echo may affect the deformation of velocity directly. So, seeding particles needs to be paid close attention. And there is still room for improvement in the algorithm.

CONCLUDING REMARKS

The new UVP algorithm, Phase different method, is suggested in this study. It has no theoretical limit of measurable minimum velocity unlike exiting algorithm. By this reason, it is available and suitable for low velocity measurement. Two verification experiments confirm its possibility. And these also expose its problem. It is essential that the precision is improved, in order to measure low velocity.

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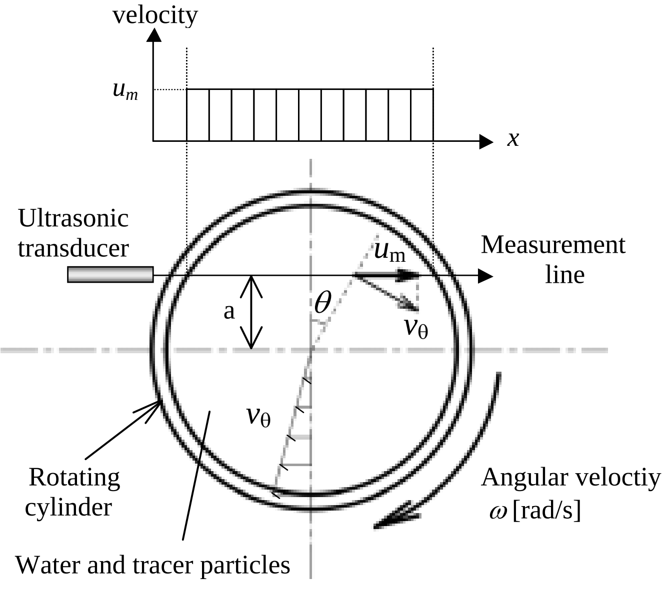

Fig.8 Experimental setup

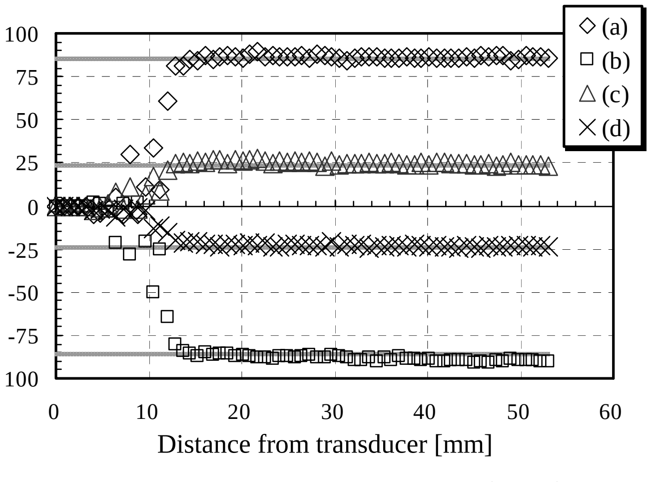

Fig.9 Temporally averaged velocity proifle at four diffirent conditions as shown in Table 2