

STUDY ON THE DEVELOPMENT OF NOVEL VELOCITY PROFILE MEASURING METHOD USING ULTRASOUND TIME-DOMAIN CROSS-CORRELATION

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ABSTRACT

This paper presents a velocity profile measurement by a novel method using pulsed ultrasound. The method is called ultrasound time-domain correlation method (UTDC) and is based on the cross-correlation between two consecutive echoes of ultrasonic pulses to detect the velocity. The UTDC has two advantages over a conventional ultrasound pulsed Doppler method. First, the method has higher time and spatial resolutions than the pulse Doppler method. Second, the system does not have a limitation in maximum measurable velocity and range, which are limited by Nyquist's sampling theorem. In the paper, the velocity profile measurement in turbulent pipe flow using the UTDC is performed.

1. INTRODUCTION

This paper presents that the application of the ultrasound time-domain correlation method (UTDC) [1, 2] to the velocity profile measurement in a turbulent pipe flow. We applied this method to the steady turbulent flow in a pipe, and have obtained the ensemble averaged velocity profile and have not obtained the higher statistical momentum.

The ultrasound flow measurement system has been used in many industrial and scientific fields, because they are non-intrusive and usable in opaque materials, including solids in flow condition. The time-of-flight ultrasound flow-meter using a pair of ultrasound transducers [3, 4] is especially widely used in industry for flows in large pipes. This method can be used for longer without maintenance than orifice flow-meter and venturi nozzle. In addition, this method offers the advantage that it can be applied to pipes with no modification. However, they require a profile factor to assume the velocity profile of a flow or the calibration one between the real flow-rate from the measured one.

The ultrasound Doppler method is a technique, which utilizes the Doppler shift frequency f_D from the scatterers suspended in a working fluid to obtain the velocity of the scatterer v

$$v = c \frac{f_D}{2f_0} \quad (1)$$

where c is the sound velocity in the working fluid and f_0 is the central frequency of the transmitted ultrasound. Since Satomura[5] discovered the ultrasound Doppler shift from blood, this method has been applied in many types of blood flow-meters in biomedical engineering.

The system can be classified into two categories by its measurement principle. One is the continuous wave Doppler method. Its advantage is the limitless measurable velocity. However, it is impossible to detect the position of scatterers by this method. The other is the pulse Doppler method, by which it is possible to obtain both the position and the velocity

information of scatterers. The defect of this system is in the limitation of the measurable velocity due to Nyquist's sampling theorem, which is expressed by

$$v_{max} = c \frac{f_{prf}}{4f_0} \quad (2)$$

where v_{max} is the maximum measurable velocity, and f_{prf} is the pulse repetition frequency. One of the measuring instruments based on the pulse Doppler method, the ultrasound velocity profile monitor (UVP)[6] has been developed at Paul Scherrer Institut (PSI) for both the engineering and academic demand. Although the spatial and time resolution are poor compared with the laser Doppler velocimetry (LDV), the ultrasound pulse Doppler technique has an advantage of the measurement of instantaneous velocity profiles. As a consequence, in the measurement of flow-rate by the UVP, it is that the calibration is not necessary, since the flow-rate can be directly obtained by the integration of measured velocity profile. However, the UVP system cannot be applied to the high speed flow in large pipes because of the measuring limitation due to Nyquist's sampling theorem. The UTDC uses the repetition of ultrasound pulses, but uses different procedure to detect velocity data from the pulse ultrasound Doppler method. In order to detect the velocity profile, the UTDC utilize the cross-correlation function between two echoes from two pulses is calculated. Therefore there is no limitation in the maximum measurable velocity due to Nyquist's sampling theorem and the method has advantages, which the pulse Doppler method has. Additionally it has a better time resolution than the pulse Doppler.

2. ULTRASOUND TIME-DOMAIN CORRELATION METHOD

2.1 Principles

Figure 1 shows the concept of UTDC. An ultrasound transducer is set at the angle of with respect to the flow direction. An echo signal is reflected from position 1, when an ultrasound pulse is transmitted at the time of $t = t_0$. The elapsed time between the pulse emission and its reception is $t = t_1$. If another ultrasonic pulse is emitted at the time of $t = t_0 + T$, the echo signal from the same scatterer is from position 2. If the elapsed time of second ultrasonic pulse is $t = t_2$, the distance that the scatterer moved towards the axial direction of the ultrasound beam path, is obtained and the velocity of the scatterer can be obtained from the following equation

$$v = \frac{(t_1 - t_2)c}{2T \cos \theta} \quad (3)$$

where T is equal to $1/f_{prf}$ and $(t_1 - t_2)$ is denoted by τ , the Eq.(3) can be described as

$$v = c\tau \frac{f_{prf}}{2 \cos \theta} \quad (4)$$

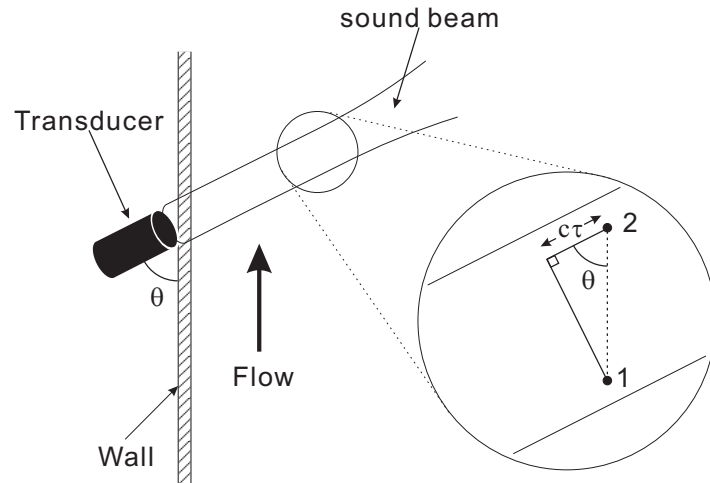


Fig.1 Relationship between a transducer, a flow field and scatterers

In the real measurement, the ultrasonic echo is reflected by the scatterers within the ultrasonic pulse as illustrated in Fig. 2. An echo signal E_1 is due to the scatterers in volume 1 (V_1). At time T ($= 1 / \text{fprf}$) seconds later, scatterers in V_1 moves to V_2 . Then the echo signal E_2 can be obtained. V_1 and V_2 include the same region in the ultrasound path which is illustrated as shaded area in Fig.2. Therefore a set of echo signals which have similar shapes can exist in somewhere between E_1 and E_2 . If the time shift is known, the velocity of the scatterers included in volume 1 can be obtained using Eq.(4).

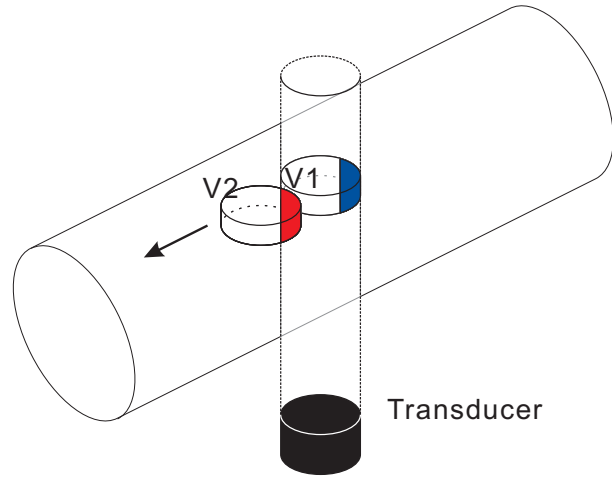


Fig.2 Real image of UTDC

The time shift is obtained by calculating a cross-correlation function $R(s)$ between E_1 and E_2 (see Fig. 2), which is expressed as

$$R(s) = \frac{\int E_1(t)E_2(t+s)dt}{\sqrt{\int E_1(t)^2 dt \int E_2(t+s)^2 dt}} \quad (5)$$

The digitized cross-correlation factor $R(s)$ is represented by

$$R(s) = \frac{\sum_{i=1}^N E_1(i)E_2(i+s)}{\sqrt{\sum_{i=1}^N E_1(i)^2 \sum_{i=1}^N E_2(i+s)^2}} \quad (6)$$

The valuable s is selected so that $R(s)$ reaches the maximum, and is set to s . Using the determined value of τ , the scatterer velocity can be obtained from Eq.(4).

3. CORRELATION INTERPOLATION

Because the echo signal is sampled at discrete times, the correlation function can be also calculated at discrete time delays and the maximum value of the correlation factor exists at between two points. To predict the maximum value, the maximum discrete correlation and its two neighboring points should be found and fitted by any interpolating functions.

Concerning the particle image velocimetry (PIV), in which the cross-correlation function is used for detecting the movement of scatterers crowd, the solution of light scattering by a small particle is known as Airy function which can be assumed as Gaussian function. From these reasons, Gaussian function is well used as the interpolating function to

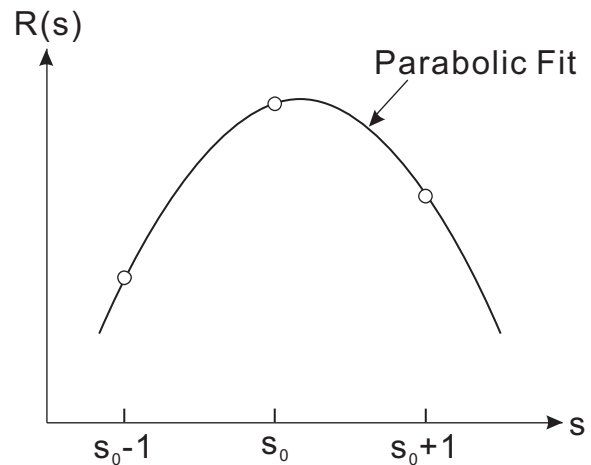


Fig.3 Interpolation of the correlation function

obtain the movement in PIV.

Because the solution of the time evaluation of acoustic scattering is unknown, we used the parabolic function to interpolate the correlation function. This is illustrated in Fig. 3.

4. EXPERIMENTAL APPARATUS

The schematic diagram of the experimental apparatus is shown in Fig. 4, which consisted of a test section and a measurement system.

A working fluid was tap water. Micro particles of nylon powder were suspended in the water to be used as scatterers of ultrasonic pulses. The average diameter of the particle was about $80\mu\text{m}$, and the specific density was 1.02. The test pipe is made of Plexiglas, and has an inner diameter of $D=50\text{mm}$, an outer diameter of 60mm and a length of 4800mm .

Water flowed downward into the vertical circular test section from the upper entrance through bell-mouth nozzle and tripping ring to reduce entrance length. The water flow rate was controlled by a needle valve and measured by an orifice flow meter, both of which were located at the bottom part of the apparatus.

Figure 5 shows the measurement section. The wall thickness at the measuring position was 1mm . An ultrasonic transducer was set on the outer surface at the contact angle of 45° toward the liquid main flow direction, and was fixed at $80D$ far from the inlet of the test pipe. The gap between the transducer and the wall surface was filled with water to prevent the reflection of ultrasonic pulses on the wall. Experiments were performed at $Re=12000$, which was based on the bulk velocity and the pipe diameter.

Figure 6 shows the setup of the measuring system, which consisted of an ultrasound pulser/receiver DPR-35+ (JSR Co. Ltd.), an ultrasound transducer (Imasonic S.A.), and a digital oscilloscope LC-574A (Lecroy Corp.).

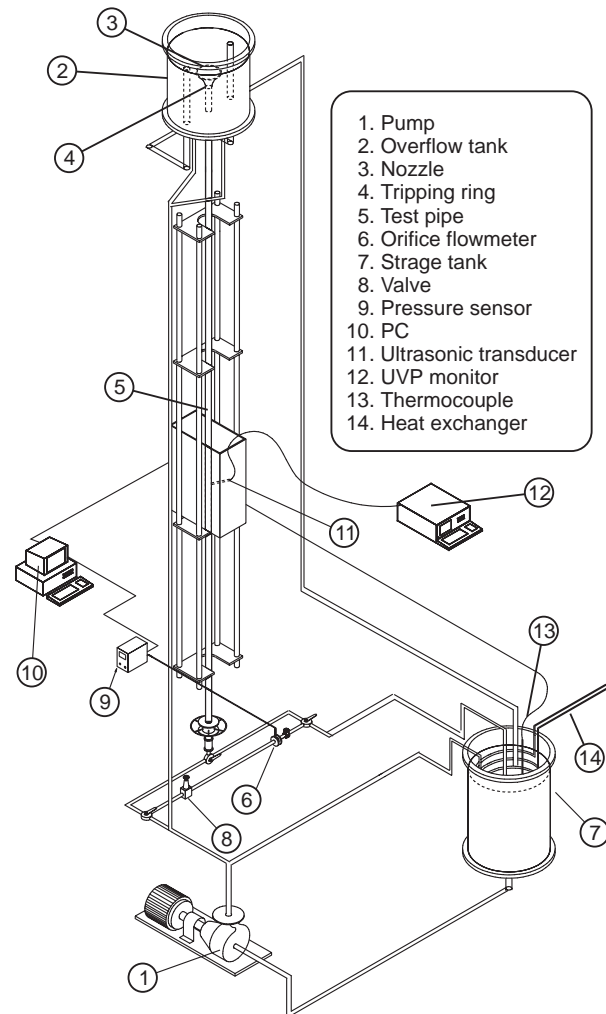


Fig.4 Experimental apparatus

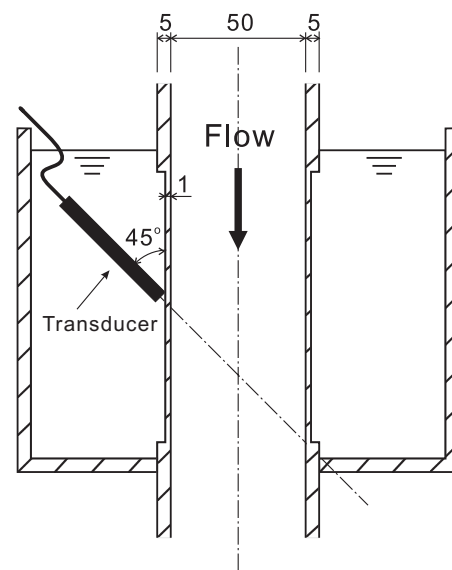


Fig.5 Test section

The center frequency of the ultrasound pulse emitted from the transducer was 4MHz, because the ultrasonic transducer was designed for center frequency of 4MHz. After the pulse emission, the transducer was changed to receiver mode. The LC-574A has the 8-bit A/D converter, whose maximum sampling rate is 4GS/s. The RF and the position signals were tapped from the pulser/receiver. The RF signal were digitized at 100MS/s in the experiment and placed into the memory of the LC-574A. The RF echo was triggered by the pulse repetition frequency at the pulse emission. The pulse repetition frequency f_{prf} is 2000Hz.

5. RESULTS AND DISCUSSION

Figure 7 shows an example of consecutive ultrasound echoes with respect to the elapsed time from the emission of the ultrasound pulse. Because of the deference of acoustic impedance between the working fluids and the scatterers, the echo from scatterers can be divided from electrical noise by setting the threshold, which is shown in Fig.7. When the three sets of signals are compared, it is observed that every signal has similar wave form in a region.

By separating signals into windows and comparing the windows with those for the following signal, the correlation factor can be calculated. The window length was set to 100 samples, and the sampling rate was 100 MSamples/s.

Figure 8 shows the ensemble averaged velocity profile and the data valid rate with respect to the distance from the pipe wall. The circle plots are the average of 26000 instantaneous velocity profiles. The data valid rate is shown as the blue bar. From the figure, the data valid rate is very low, and the mean velocity at each point is the average of approximately 2000 data.

Figure 9 shows the non-dimensional velocity profiles. In Fig.9 the circle is the present result, the blue curve is the DNS data by Eggels et al. and the red curve is the LDV measurement by Durst et al.. The figure shows that the present data is in agreement with the LDV data and the logarithmic low. But the present data is little bit scatter, because the data valid rate is very low.

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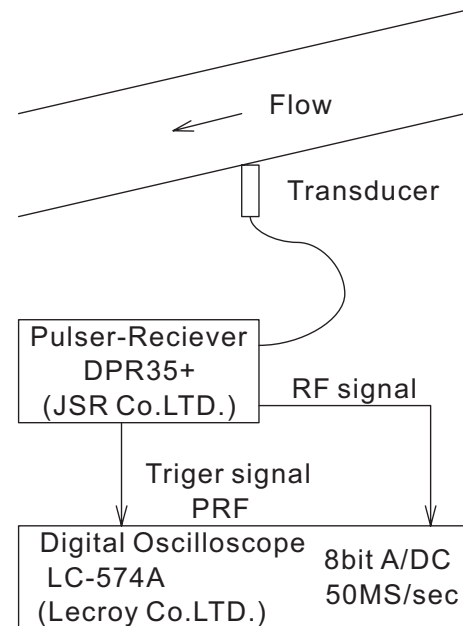


Fig.6 Block diagram of hard ware system

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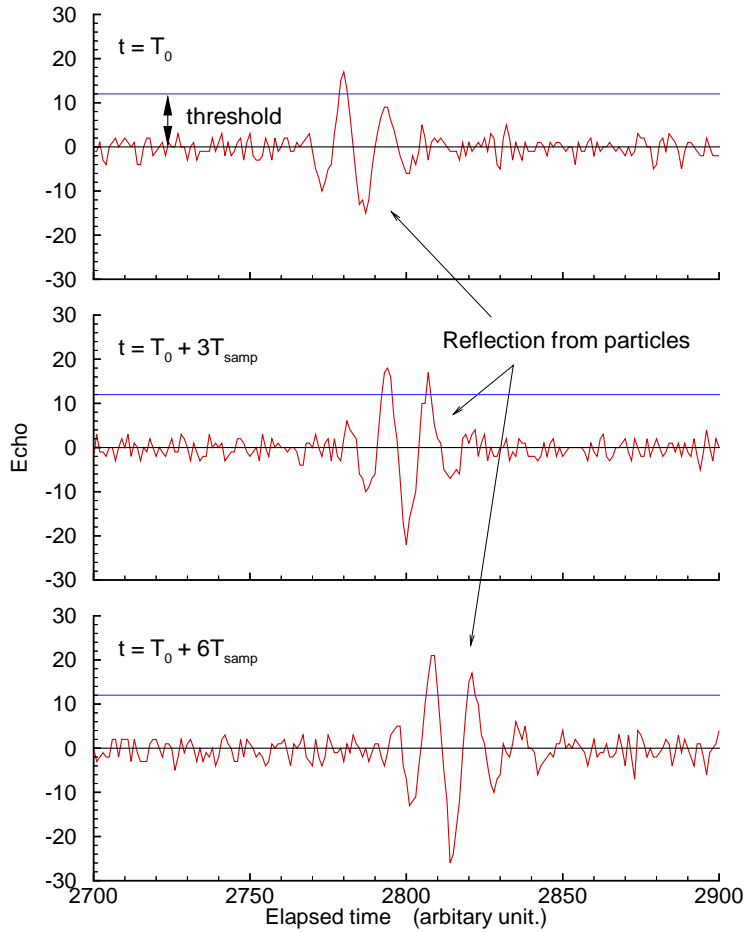


Fig.7 Typical consecutive echoes

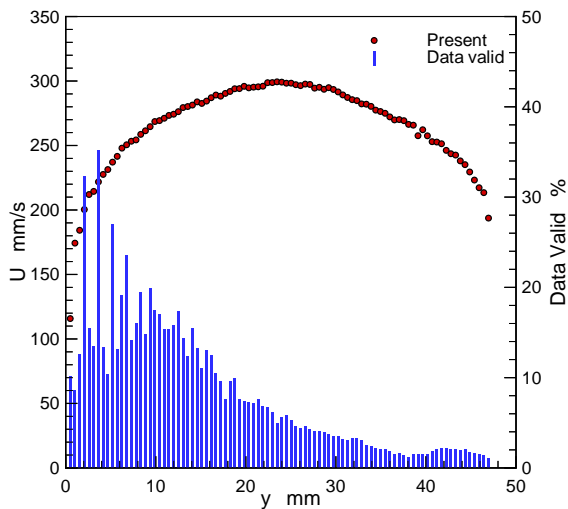


Fig. 8 Ensemble averaged velocity profile and the data valid rate

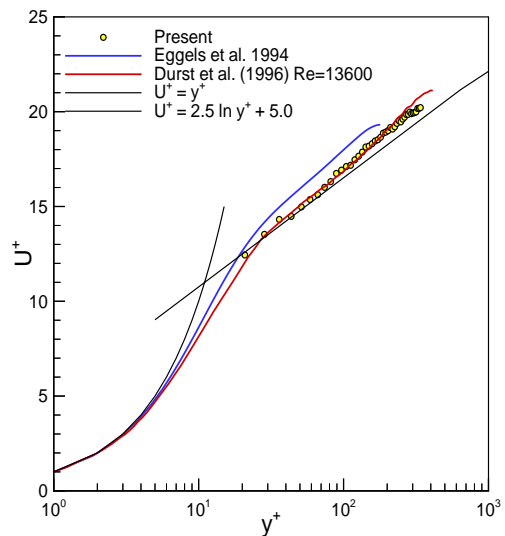


Fig. 9 Ensemble averaged velocity profile and the data valid rate