Effects of analysis algorithms and number of repetition pulses on velocity data by using ultrasonic Doppler method

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An ultrasonic velocity profile (UVP) method is mainly based on the pulse Doppler method. In order to improve the time resolution, number of pulse repetition, \( N_{\text{pulse}} \), must be reduced. However, the appropriate \( N_{\text{pulse}} \) changes with algorithms of the frequency analysis and signal-noise-ratio (SNR). In this study, appropriate algorithms of the frequency analysis and \( N_{\text{pulse}} \) were investigated with changing of the SNR by simulation and experiments. As a result, \( N_{\text{pulse}} \) could be set at the lowest by using autocorrelation method if the SNR was high. With decreasing of the SNR, results calculated by FFT became better. Furthermore, wavelet transform (WT) was hard to be affected by noises, and it is one of choice for measuring flow field if on-time measurement isn't required.

Keywords: Autocorrelation, FFT, Wavelet transform, Doppler method, UVP

1 INTRODUCTION

An ultrasonic velocity profile (UVP) method is mainly based on the pulse Doppler method although a cross-correlation method has been proposed [1,2]. Echo signals reflected from moving particles include Doppler frequency, \( f_d \), depending on the velocity. However it is difficult to obtain \( f_d \) directly from an echo signal because the \( f_d \) is much smaller than the basic frequency of the ultrasonic, \( f_0 \). Therefore multiple echo signals are usually used for the calculation. If fast Fourier transform (FFT) is used for analyzing the echo signals, factorial of 2 time repetitions are required. Frequency resolution of the \( f_d \) becomes worth with decreasing the number of repetition pulse, \( N_{\text{pulse}} \). Therefore, fewer \( N_{\text{pulse}} \) for improving the time resolution is difficult. The autocorrelation method [3] calculates the phase change at least 2 pulses, but several number of echo signals are required in real situation because of noises and an assumption of the calculation. Wavelet transform (WT) is one of the frequency analysis methods. Some attempts using WT for the Doppler method was carried out in medical field [4, 5]. However, effect of noises on the measurement data has not been investigated. In this study, effects of the frequency analysis algorithms and \( N_{\text{pulse}} \) on the velocity data with changing of signal-noise-ration (SNR) are investigated compared with the FFT, autocorrelation and WT methods.

2 PULSE DOPPLER METHOD

2.1 Principle

Schematic of the ultrasonic Doppler method is shown in Fig.1. The ultrasonic transducer emits a pulse with basic frequency of \( f_0 \). If the pulse reflects on a reflector, the echo signal \( z(t) \) is expressed as

\[
z(t) = A \cos 2\pi(f_0 + f_d)t,
\]

where \( A \) is amplitude of the signal. Multiple ultrasonic pulses are emitted and received for obtaining the velocity in each measurement position. Time delay, \( t_{h,j} \) in pulse of \( h \) and measurement position of \( i \) can be expressed as

\[
t_{h,j} = hT_{\text{prf}} + \frac{2l}{c}.
\]

Here, time of the first pulse emission is referred to as 0. Where \( T_{\text{prf}} \) is interval time of the pulse emissions, and expressed as \( T_{\text{prf}}=1/f_{\text{prf}} \) using pulse repetition frequency, \( f_{\text{prf}} \). Echo signal, \( s_{h,i}(t) \), can be shown as

\[
s_{h,i}(t) = A_{h,i} \cos 2\pi(f_0 + f_d)\left(t - t_{h,i} + \frac{2\Delta x h}{c}\right) \approx A_{h,i} \cos 2\pi f_0\left(t - t_{h,i}\right) + f_d hT_{\text{prf}}
\]

Here, the reflector moves \( \Delta x \) during \( T_{\text{prf}} \). Velocities in each measurement position can be obtained from calculating the phase change of the consecutive echo signals.

Figure 2 represents block diagram of the measurement system. Echo signals are received at a pulser/receiver, and the signals are digitized by a

Figure 1 Schematic of detecting the Doppler frequency
high-speed digitizer. Quadrature detection is applied to the signals, and it makes possible improve the SNR and detect the direction of the moving reflector. Above procedures are sampled at \( t_{n,i} = nT_{prf} + \tau_i \), \( x_c[n] \) and \( x_s[n] \) are obtained as follow:

\[
\begin{align*}
z(t) &= \{ s(t) \cdot e^{j2\pi f_d t} \}_{t=t_{n,i}} = x_c[n] - jx_s[n] \\
x_c[n] &= A_j \cos(2\pi f_{prf} n T_{prf} - \phi) \\
x_s[n] &= A_j \sin(2\pi f_{prf} n T_{prf} - \phi)
\end{align*}
\]

\( \phi \) is the differential phase between the initial phase. Applying frequency analysis to the signals, Doppler frequency in each position, \( f_{d,i} \), can be obtained, and velocities are calculated as follow:

\[
v_i = \frac{c f_{d,i}}{2 f_0}.
\]

2.2 Frequency analysis

FFT and autocorrelation method [3] is usually used for calculating the Doppler frequency from Eq.(4). A time-frequency window with fixed length which depends on the \( N_{pulse} \) is used for calculating the FFT analysis. Therefore, the time-resolution and frequency-resolution are incompatible. If we want to reduce the time-resolution, the \( N_{pulse} \) must be reduced. Which means the frequency-resolution becomes worth although an interpolation method is usually applied between the discrete spectrums. Hence, the \( N_{pulse} \) must be set at higher value appropriately, and time-resolution has limitation to be reduced. In this study, a threshold is used for eliminating the uncertain data. If the maximum value of power spectrum density (PSD) is higher than the threshold, the data is considered as effective. Otherwise, the data is recorded as invalid data.

Autocorrelation method utilizes the autocorrelation function to obtain the phase change between two consecutive echo signals, and expressed as

\[
R_1(\tau) = \int z_i(t) \times z_i(t+\tau) dt.
\]

Substituting \( \tau = T_{prf} \) into Eq.(6),

\[
R_1(T_{prf}) = \int z_i(t) \times z_i(t+T_{prf}) dt = R_{ss}(T_{prf}) + jR_{ss}(T_{prf})
\]

Doppler frequency \( f_{d,i} \) can be expressed as

\[
f_{d,i} = \frac{1}{2\pi T_{prf}} \tan^{-1} \left( \frac{R_{ss}(T_{prf})}{R_{ss}(T_{prf})} \right).
\]

Velocity is obtained theoretically from 2 echo signals, and it is high time-resolution. However, this includes an assumption that either velocity component of going away from the transducer or toward the transducer is 0. In addition, ultrasonic has wide spectrum, and it includes noises. Several times repetition is required to obtain velocity accurately.

WT uses flexible time-frequency window. Mother wavelet changes with scaling parameter. If the frequency is high, the time-resolution becomes better. In this study, Gabor was used for the mother wavelet.

3 SIMULATION USING PSEUDO DOPPLER SIGNALS

3.1 Simulation method

Time series of velocity data was measured by using laser Doppler velocimetry (LDV) at a position in a horizontal duct. Pseudo Doppler signal was calculated by the frequency modulation of the LDV data. In order to simulate the noises, white noises with SNR of 20dB and 5dB was added to the signal. Velocities were obtained by applying the Doppler analysis on the signals, and compared with the LDV data (true velocity).

3.2 Simulation results

Time series of velocity data are compared with true velocity (measured by LDV) and analyzed velocities as shown in Figure 3. Figure 3(a) is the case of \( N_{pulse}=4 \), and (b) is the case of \( N_{pulse}=16 \). Results calculated from with and without noises are shown in each case. If there are no noises, the smaller \( N_{pulse} \) is, the better results are obtained. With decreasing of the \( N_{pulse} \), high-frequency velocity fluctuations could be analyzed. This is because of time resolution. With increasing of \( N_{pulse} \), the time resolution becomes worth, and the velocity data is averaged during the longer time. Therefore, it can be said that the \( N_{pulse} \) must be set at the lowest if the signal doesn’t include noises.

However, if noises exist in the signal, the results changed. In case of \( N_{pulse}=4 \), the analyzed velocity has larger fluctuation than the true velocity. In this case, it is expected that the velocity standard
deviation is overestimated. On the other hand, the difference of velocity between without and with noises is small in the case of $N_{\text{pulse}} = 16$. In this case, the velocity standard deviation is underestimated.

In order to evaluate the instantaneous velocity difference between true velocity ($v_1$, LDV data) and analyzed velocity $v_2$, root-mean-square of the velocity, $\sigma$, is calculated as follow:

$$\sigma = \sqrt{\frac{1}{N} \sum \left( v_1(t) - v_2(t) \right)^2}$$  \hspace{1cm} (8)

Figure 4 represents change of $\sigma$ with $N_{\text{pulse}}$ in each noise condition. Note that $\sigma$ by WT is constant with $N_{\text{pulse}}$ because the time-frequency window doesn't change. $\sigma$ becomes worth with decreasing of the $N_{\text{pulse}}$ under noise condition. Therefore, optimal values for decreasing the $\sigma$ exist in both autocorrelation and FFT. Furthermore, the optimal analysis method and $N_{\text{pulse}}$ changes with the SNR. Autocorrelation give us a good result under lower noise level (SNR = 20dB). On the other hand, FFT is better under higher noise level (SNR = 5dB). This is because the threshold works well to remove the invalid data. Furthermore, the optimal $N_{\text{pulse}}$ increases with the noises.

In case of WT, it can be confirmed that the effect of noise is relatively small, and the values are almost the same at between the SNR = 5 and 20dB. It can be said that the WT is hard to be affected by noises.

4 EXPERIMENTS

4.1 Experimental method

In order to confirm the optimal analysis method and $N_{\text{pulse}}$ in Doppler method, experiment was carried out at the horizontal duct with 50 mm width and 25 mm height ($H$). Working fluid was tap water kept at 19 to 21 °C, and the Reynolds number was 8,000. Ultrasonic transducer with 4 MHz basic frequency was set at outer surface of the top wall with inclined angle of 45°. The $f_{\text{prf}}$ was set at 4 kHz. During the experiment, multiple echo signals were continuously recorded as much as possible in a data file, and calculation were carried out after the experiment. Therefore, the same wave data were used for the calculation with changing analysis methods and $N_{\text{pulse}}$. Gain of the pulser/receiver was set at 30dB and 20dB. Changing of the gain setting, SNR could be changed. The 30dB was the best for the measurement. Therefore, SNR at 20dB was worth than that at 30dB.

4.2 Experimental results

Figure 5 indicates time-average velocity distributions calculated by autocorrelation method with $N_{\text{pulse}} = 8 \sim 128$ and wavelet analysis at 30dB. The horizontal axis indicates the distance from the wall, $y$, divided by $H$. It is confirmed that there is little difference between them, and average velocity can be obtained accurately from even $N_{\text{pulse}} = 8$ except near wall region. Because ultrasonic has relatively large measurement volume, velocity measurement near the wall where velocity gradient is steep is difficult.

Velocity standard deviations, $u'_{45}$, are strongly affected by the $N_{\text{pulse}}$. It can be seen that $N_{\text{pulse}} = 8$ in
The autocorrelation method couldn't measure it accurately. Even at $N_{\text{pulse}}=16$, the fluctuation can is confirmed at $y/H > 0.4$. With increasing of the $N_{\text{pulse}}$, the $u'^{+45}$ decreases all over the positions. This is reasonable result. The standard deviation calculated by WT takes values between $N_{\text{pulse}}=8$ and 16.

In case of 20dB, the $u'^{+45}$ becomes worth in autocorrelation method. Accuracy of $u'^{+45}$ were low at $N_{\text{pulse}}=32$, and it is confirmed that the $N_{\text{pulse}}$ must be increased with increasing of the noises. The $u'^{+45}$ at $N_{\text{pulse}}=64$ increases with distance from the wall. It means that the accuracy of $u'^{+45}$ becomes worth with the distance. This is because the SNR of ultrasonic echo signal becomes worth with the distance from the transducer. However, it can be confirmed that the WT is hard to be affected by noises. This result is good agreement with the simulation results shown in Figure 4.

Comparing the results under lower SNR by autocorrelation and FFT, the results in autocorrelation are better at the same $N_{\text{pulse}}$. However, if appropriate $N_{\text{pulse}}$ is chosen in FFT, $u'^{+45}$ around $y/H=0.1$ can be obtained more accurately than that in autocorrelation. This tendency is similar with the results by WT. In case of WT, time-frequency window changes with the velocity. Therefore, the WT is more convienient than the FFT. However, the calculation-time takes much longer than the other methods. It means the WT is one of the methods for measuring velocity distributions because the SNR continuously changes with measurement positions, if on-time measurement isn't required.

### 5 SUMMARY

Effects of algorithms and $N_{\text{pulse}}$ on velocity measurement by using pulse Doppler method were investigated by simulation and experiments. $N_{\text{pulse}}$ could be set at the lowest by using autocorrelation method if the SNR was high. With increasing of the SNR, results by FFT became better. However, $N_{\text{pulse}}$ must be chosen appropriately depending on the SNR. WT is relatively hard to be affected by noises. Therefore, WT is one of choice for measuring velocity distributions if on-time measurement isn't required.

### REFERENCES


