Flow Measurement and Instrumentation 40 (2014) 9–18

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Effects of the number of pulse repetitions and noise on the velocity data from the ultrasonic pulsed Doppler method with different algorithms

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ARTICLE INFO

Article history:
Received 10 December 2013
Received in revised form
11 July 2014
Accepted 19 August 2014
Available online 27 August 2014

Keywords:
Pulsed Doppler method
UVP
Wavelet transform
Number of pulse
Velocity profile

ABSTRACT

The ultrasonic pulsed Doppler technique known as the ultrasonic velocity profile (UVP) method has been widely used in many engineering fields. The analysis algorithms of the UVP, the number of pulse repetitions (N_{pulse}), noise and reflector conditions, etc. all affect the measurement accuracy. N_{pulse} is related to the temporal resolution, thus to improve this resolution it must be set as low as possible. However, it is known that the measurement accuracy of the instantaneous velocity becomes worse with decreasing values of N_{pulse}. In this study, UVP analysis algorithms including the fast Fourier transform (FFT), autocorrelation, and the wavelet transform (WT) were compared via simulations and experiments using varying values of N_{pulse} and the signal-to-noise ratio (SNR). We show that there is an appropriate N_{pulse} for each algorithm that depends on the SNR; specifically, the value of N_{pulse} increases with decreasing SNR. The difference between the algorithms for the velocity data was small under low noise conditions. However, a FFT with a Gaussian interpolation produced the best result under noisy conditions. In contrast the WT was relatively unaffected by noise. Therefore, a WT is the preferred choice for measuring velocity distributions if high sampling measurement is not required.

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1. Introduction

The ultrasonic pulsed Doppler method was originally developed for use in medical fields [1]. The technique makes it possible to measure velocity profiles in specific parts of the body. Takeda [2] was the first to apply this technique to an engineering field, where it is referred to as the ultrasonic velocity profile (UVP) method. This method is applicable for opaque fluids and metal pipes without intrusions in the flow field, and it can measure one-dimensional velocity profiles along an ultrasonic beam line. Hence, the UVP has been utilized in many engineering fields, applied for purposes such as flow rate measurement [3], Taylor–Couette flows [4], two-phase bubbly flows [5], and additional applications [6].

In this technique, the ultrasonic pulses are emitted by an ultrasonic transducer, and then the echo signals reflected from moving particles are received at the transducer. The particle positions are obtained from the time interval between the pulse emission and the receipt of the echo signal. The echo signal includes the Doppler frequency, f_d, which depends on the velocity. However, it is difficult to calculate f_d directly from an echo signal because f_d is much smaller than the basic frequency of the ultrasonic pulse, f_0. Therefore, multiple echo signals are usually used for detecting the velocity based on the Doppler phase shift during the pulse interval. In order to calculate f_d from the multiple echo signals, several analysis methods, including frequency domain processing and time domain processing have been proposed [7]. Fast Fourier transforms (FFT) are widely used for frequency domain processing. The frequency resolution of f_d becomes worse with decreasing numbers of pulse repetitions, N_{pulse}. Thus, it is difficult to improve the temporal resolution with too few N_{pulse}. The wavelet transform (WT) is a general technique for signal analysis, and has been used for analyzing Doppler signals within the medical field [8–10]. Furthermore, there have been recent attempts to use the WT for the pulsed Doppler method [11,12]. However, this technique is not widely used in real systems because the analysis method is more complex and takes more time than the FFT. The autocorrelation method [13] is a time domain process that calculates the phase shift during the pulses. If the ultrasonic echo signal does not include noise, the velocity can be precisely obtained from two consecutive echo signals. However, noise cannot be neglected in real measurements. With increasing distance from the transducer, the echo signal becomes lower, and the signal-to-noise ratio (SNR) becomes worse. Therefore, more than two pulses are normally used for obtaining a velocity profile.

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http://dx.doi.org/10.1016/j.flowmeasinst.2014.08.009
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It is empirically known that with increasing N_{pulse}, the accuracy of the velocity improves although the measurement time increases. The color Doppler method that is widely used in medical fields can obtain cross-sectional images and velocity components with real-time measurements [14]. This method employs a phased array technique and requires multiple echo signals in each measurement line. Hence, a high-speed velocity measurement is required; an autocorrelation method with an N_{pulse} of around 10 is normally used. On the other hand, a highly accurate velocity measurement is required to obtain a quantitative velocity distribution from the UVP measurement in engineering fields. The N_{pulse} normally used in an UVP measurement is higher than that for medical purposes, ranging from 2^5 to 2^7 pulses. With increasing N_{pulse}, the temporal resolution becomes worse and faster velocity fluctuations cannot be measured. It is therefore important to evaluate the effects of N_{pulse} on the velocity measurement, particularly for use in turbulent flow measurements.

There are many factors affecting the measurement accuracy, including the value of N_{pulse}, the calculation algorithms for f_d from multiple echo signals, noise, measurement volume, and reflector conditions. These factors are of wide concern, and many investigations into their effects have been carried out. Ueda and Ozawa [15] analyzed ultrasonic echoes scattered from a random medium, and reported the backscattering coefficient. Embree et al. [16] discussed the accuracy of the pulsed Doppler method as affected by Rayleigh scattering and bandwidth. The influence of the transducer bandwidth is summarized by Jensen [14]. Gill [17] investigated the accuracy of a continuous wave system as affected by system error and analyzed the Doppler shift arising from the scattering nonuniformity. Foster [18] showed that by using the autocorrelation method, better results were obtained with a smaller measurement volume. However, these investigations are mainly applicable for blood flow measurements. For UVP measurements, it is important to understand the repeatability of velocity fluctuations that are faster than blood flow pulsations in order to evaluate the standard deviation of the velocity. Furthermore, the SNR changes significantly within the measurement area more than it does in blood flow measurements, because the UVP measurement distance is normally long. However, studies of the effect of the number of pulse repetitions on the velocity fluctuations have not been carried out for UVP measurements in engineering fields. Hence, N_{pulse} is empirically derived in the measurement.

In this study, the effects of the frequency analysis algorithms and N_{pulse} on the velocity data with changing SNRs are investigated for use in engineering fields, comparing between the FFT, autocorrelation, and WT methods by means of simulations using pseudo Doppler signals and experiments.

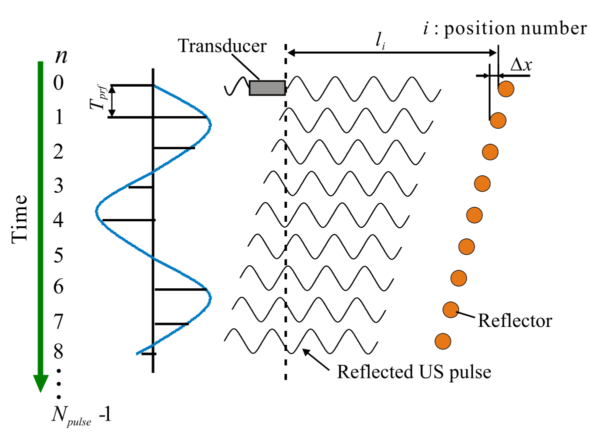

Fig. 1. Detection of the Doppler frequency.

2. Pulsed Doppler method and frequency analysis

Fig. 1 shows a schematic of the pulsed Doppler method. In this method, an instantaneous velocity profile is obtained along the ultrasonic beam line. The measurement position can be detected based on the round-trip time from each echo signal. Ultrasonic pulses are emitted at the ultrasonic transducer with a pulse repetition frequency of f_{prf}, and then the echo signal is received at the sensor. The variable $t_{n,i}$ represents the delay time of the echo signal at a position i in the nth pulse, and is expressed as follows:

$$t_{n,i} = nT_{prf} + \frac{2l_i}{c} \tag{1}$$

where c is the sound speed in the medium, T_{prf} is the time interval of the pulse repetition and $T_{prf}=1/f_{prf}$. The echo signal reflected from a moving target, $s(t)$, is expressed using an amplitude of A, a basic ultrasonic frequency of f_0, and a Doppler frequency of f_d as follows:

$$\begin{aligned} s(t) &= \sum A_{n,i} \cos 2\pi f_0 \left(t - t_{n,i} + \frac{2n\Delta x}{c} \right) \\ &\approx \sum A_{n,i} \cos 2\pi \{ f_0 (t - t_{n,i}) + f_{d,i} n T_{prf} \} \end{aligned} \tag{2}$$

Here the target moves Δx during T_{prf}. In the pulsed Doppler method, the phase shift of the echo signal caused by moving targets is detected to obtain the velocity for each measured position. In order to detect the phase shift, at least two ultrasonic pulses are required.

Fig. 2 presents a block diagram of the measurement system. An ultrasonic pulser/receiver, P/R, emits ultrasonic pulses, and the echo signals are sampled by a high-speed digitizer. The echo signals are multiplied by the cosine and sine components, and a low-pass filter is applied to the signals to eliminate the carrier wave components of f_0.

$$\begin{aligned} z_i(t) &= \{2s(t)e^{j2\pi f_0 t}\}_{LowPass} = x_I(t) + jx_Q(t) \\ &= \sum A_{n,i} \cos 2\pi (f_{d,i} n T_{prf} - f_0 t_{n,i}) - j \sum A_{n,i} \sin 2\pi (f_{d,i} n T_{prf} - f_0 t_{n,i}) \end{aligned} \tag{3}$$

This procedure is called quadrature phase demodulation and it allows the detection of the flow direction. The above procedures are sampled at $t_{n,i}=nT_{prf}+\tau_i$, then

$$\begin{aligned} z_i[n] &= x_I(t_{n,i}) + jx_Q(t_{n,i}) \\ &= x_{I,i}[n] + jx_{Q,i}[n] \\ &= A_{n,i} \cos(2\pi f_{d,i} n T_{prf} - \varphi_i) - jA_{n,i} \sin(2\pi f_{d,i} n T_{prf} - \varphi_i) \end{aligned} \tag{4}$$

is obtained, where φ_i is the initial phase of the in-phase signals x_I and the quadrature-phase signals x_Q, signals. Hence, to apply a

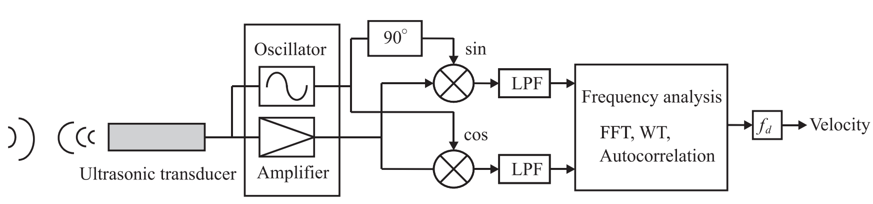

Fig. 2. Block diagram of the measurement system.

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