SIGNAL PROCESSING AND SIMULATION FOR ACOUSTIC DOPPLER CURRENT PROFILE

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Abstract- Acoustic Doppler Current Profile (ADCP) is a non-invasive, non-destructive system for measuring the current velocity. Due to the well and secure characteristics of ultrasound, it is suitable for underwater measurement. Comparing to the traditional measuring method, ADCP can be applied to high velocity and wide range measurement. The principle of ADCP is based on the Doppler effect, which the frequency shift is caused by the moving observer. This paper simulated continuous sine signal (narrowband) and pulse signal (broadband) as the received signal, and auto-correlation algorithm (AC algorithm) was used to compute the Doppler shift. The analysis results show that this algorithm can compute the Doppler shift accurately from narrowband signal. This paper also conducted an experiment to confirms AC algorithm being suitable for narrowband signals.

Index Terms- ADCP, Quadrature demodulation, Auto-correlation, Narrowband signal.

I. INTRODUCTION

Current velocity measurement is an important task in various hydro-related engineering. Even in non-engineering field, this task is also necessary for evaluating the watershed eco environment. Most of the traditional devices for current velocity measurement are contact-type method, it means the device only can measure the velocity at the depth where the device located. Thus, it is hard and dangerous for high velocity and wide range current.

Acoustic Doppler current profile (ADCP) is a non-invasive and non-destructive measuring system, and has been developed for several years [1] [2]. ADCP used one transducer for ultrasound transmitting and receiving. Based on the principle of Doppler effect, which the frequency is caused by the moving observer, the current velocity can be derived by computing the Doppler shift. Moreover, the velocity of each depth cell can be implemented by dividing the corresponding time section in received signal.

In this paper, we simulated two kinds of received signal under ideal conditions: continuous sine signal (narrowband) and pulse signal (broadband). The auto-correlation algorithm [3] [4] was utilized to compute the Doppler shift. The comparison will focus on the analysis results of different signal length, different pulses number, narrowband and broadband signals. More details of the simulation and analysis method are described in section 2. This paper also conducted an experiment to prove the AC algorithm being suitable for the narrowband signals, which are mentioned in section 3.

II. METHODOLOGY

A. Principle of Doppler effect

The relative motion between sound source and observer, caused the frequency that observer received is different from the sound source transmitted, this phenomenon is called Doppler effect. The relationship between received frequency f and transmitted frequency f_0 is given by:

$$f = \left(\frac{c \pm v_r}{c \mp v_s}\right) f_0 \qquad (1)$$

where c is the sound speed in the medium; v_r is the velocity of observer relative to the medium; v_s is the velocity of source relative to the medium.

Applied this concept to the ADCP. The whole process for the transmitted signal hitting the particles in water, then reflecting to the received transducer, will undergo two Doppler effects. The schematic is shown Fig. 1.

According to the above description, the Doppler shift $f_d = f_r - f_0$ can be expressed as [3]：

$$f_d = 2 f_0 \cdot v \cos(\theta) / c \qquad (2)$$

where θ is the angle between transducer and horizontal.

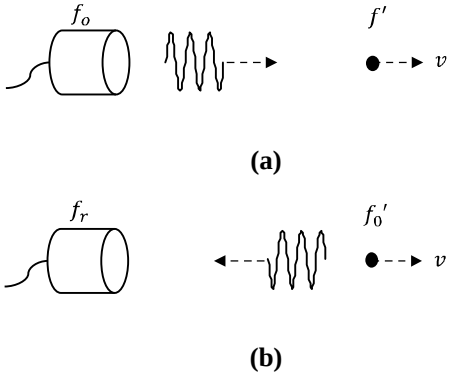


Fig. 1. (a) First Doppler effect. (b) Second Doppler effect.

B. Quadrature demodulation

In order to obtain the information of Doppler shift, the received signal should be quadrature demodulated [5] before frequency computation.

Suppose the received signal $f(t)$ is:

$$f(t) = A_m \cos(\omega_c t + \omega_d t + \theta) \quad (3)$$

where A_m is the amplitude of received signal; ω_c is the frequency of transmitted signal; ω_d is the Doppler shift; θ is the initial phase. The flow chart of quadrature demodulation is shown in Fig. 2.

First, the received signal multiplied by two orthogonal signal to obtain $x_1(t)$ and $x_2(t)$, expressed as (4) and (5):

$$x_1(t) = f(t) \cdot \sin(\omega_c t)$$
$$= \frac{1}{2} A_m \left[\sin(2\omega_c t + \omega_d t + \theta) + \sin(\omega_d t + \theta)\right] \quad (4)$$

$$x_2(t) = f(t) \cdot \cos(\omega_c t)$$
$$= \frac{1}{2} A_m \left[\cos(2\omega_c t + \omega_d t + \theta) - \cos(\omega_d t + \theta)\right] \quad (5)$$

Then use a low-pass filter to filter the high frequency part, we got the baseband signal $I(t)$ and $Q(t)$, expressed as (6) and (7), which only contained the information of Doppler shift.

$$I(t) = -\frac{1}{2} A_m \sin(\omega_d t + \theta) \quad (6)$$

$$Q(t) = \frac{1}{2} A_m \cos(\omega_d t + \theta) \quad (7)$$

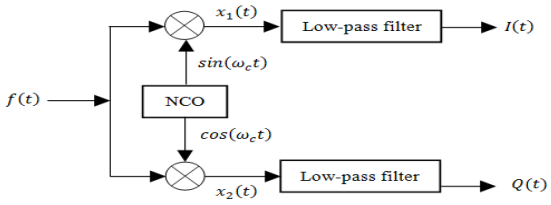


Fig. 2. Flow chart of quadrature demodulation.

C. Auto-correlation algorithm

The auto-correlation algorithm [3] [4] was utilized to the evaluate the frequency shift form received signal. From the previous subsection, we already obtained the baseband signal of received signal. Suppose the baseband signal in complex form is:

$$x(t) = I(t) + jQ(t)$$

From the definition of auto-correlation function $R(\tau)$:

$$R(\tau) = \frac{1}{T - |\tau|} \int_0^{T-|\tau|} x(t+\tau) x^*(t)\, dt$$

$$\phi = \tan^{-1}\left[\frac{\mathrm{Im}\{R(\tau)\}}{\mathrm{Re}\{R(\tau)\}}\right] \quad (10)$$

$\emptyset(\tau)$ is the complex correlation phase. Thus, the Doppler shift f_d can be expressed as $f_d = \emptyset(\tau)/2\pi\tau$ [3], which is in independent of initial phase and amplitude. Combine section A and section B, the whole analysis procedure is shown in Fig. 3.

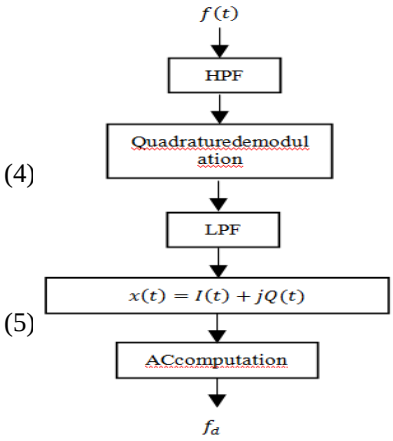


Fig. 3. Analysis procedure.

III. SIMULATIONS

The simulated signals we constructed include continuous sine signal and pulse signal. The difference between these two kinds is their bandwidth. Both of these two signals, the center frequency f_0 were set as 1 MHz, and the sampling frequency f_s were 50 MHz. Two different length of signals, 4 cm and 20 cm, were also built in this paper. That's because we assumed the measuring vertical depth was 25 cm, the angle between transducer and normal line was 30°. Neglect the near field region, there had 20 cm left along the transmitting direction. After constructing the pure simulated signals, Gaussian white noise with different SNR (-20 dB~20 dB) were added to it.

D. Continuous sine signal

The equation for continuous sine signal is shown in (11). f_d is the input Doppler shift, which is from 500 Hz to 3000 Hz.Fig. 4 shows a case whose signal length is 4 cm, SNR is 0 dB.

$$f(t) = \sin\left(2\pi\left(f_c + f_d\right)t\right) \quad (11)$$

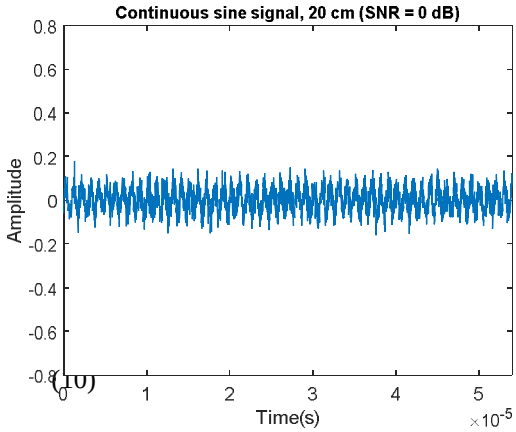


Fig. 4. Continuous sine signal: length = 4 cm; SNR = 0 dB

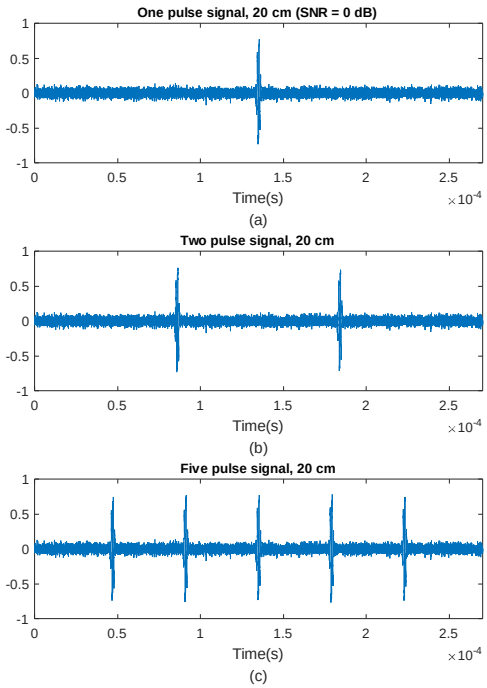


Fig. 5. Pulse signal: length = 4 cm; SNR = 0 dB. (a) One pulse (b) Two pulses (c) Five pulse.

E. Pulse signal

In order to construct a pulse signal (broadband signal), Hanning window was applied on sine signal. The bandwidth of pulse signal was set as 25% relative to the center frequency. In this paper, we compared the analysis results of different length of signals, 4 cm and 20 cm. Moreover, different number of pulses in one signal were also discussed. Fig. 5 show the signals with one pulse, two pulses and five pulses. Their signal lengths were 20 cm and the SNR of one pulse signal was 0 dB.

IV. RESULTS AND DISCUSSIONS

F. Continuous sine signal

Two different length of continuous signals, 4 cm and 20 cm, were compared in this paper. Fig. 6 & 7 show the analysis results of output frequency shift (f_d). Both of the two results

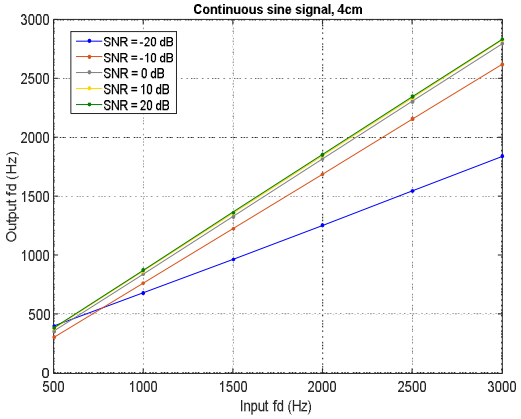


Fig. 6. Results of 4 cm continuous sine signal.

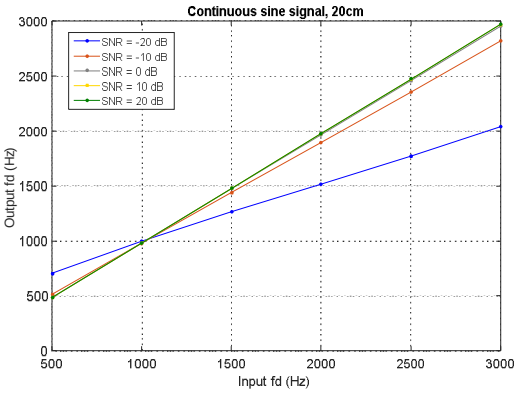


Fig. 7. Results of 20 cm continuous sine signal.

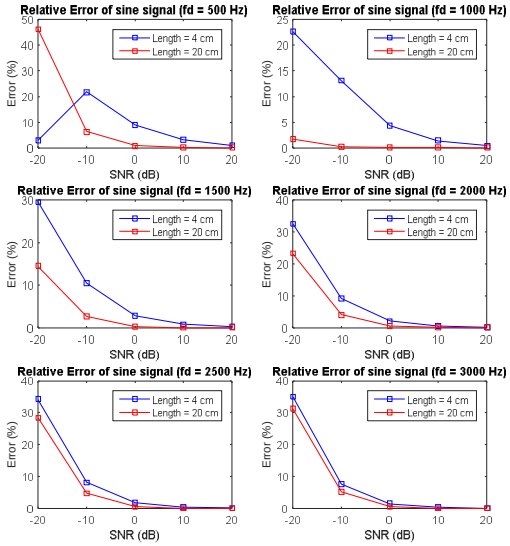


Fig. 8. Relative Error of continuous sine signal for different input frequency an SNR.

indicate that there is an obvious positive relationship between input frequency and output frequency. From Fig. 8, it can more clearly to compare the results of different signal length. The results of different input frequency, all indicate that the longer signal had smaller relative error.

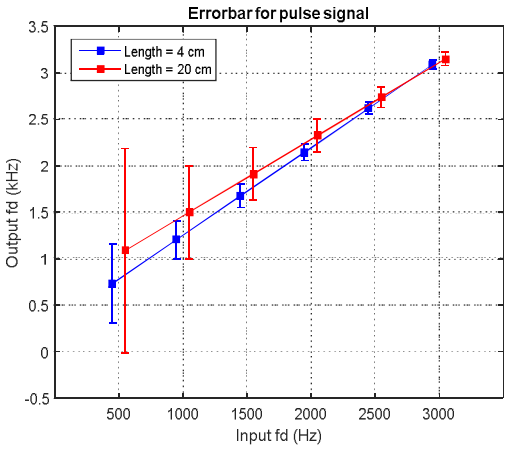


Fig.9. Error bars of different length of pulse signals. SNR = 0 dB for 4-cm signal.

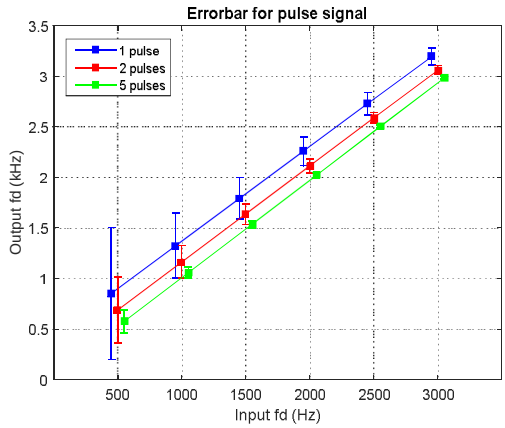


Fig. 10. Error bars of one pulse signal, two pulses signal and five pulses signal.

G. Pulse signal

(1) Comparison of different signal length

Fig. 9 shows the error bars of two different length signals with input frequency from 500 Hz to 3000 Hz, where the SNR = 0 dB for the 4-cm pulse signal. Both of the two signals contained only one pulse in a signal. The results obviously indicate that the error of 4-cm signals are smaller.

(2) Comparison of different pulses number

Error bars of one pulse signal, two pulses signal and five pulses signal are shown in Fig. 10. To focus on the different analysis results caused by number of pulses, the amplitude and signal length of these three signals were identical. The results indicate that the error decrease with increasing number of pulses.

H. Experiments

In order to confirms the auto-correlation algorithm method be suitable for narrowband signal, pulse echo experiments were also conducted in this paper. Fig. 11 shows the pulse echo system. In this system, there has no Doppler shift in the received signal in theory. We transmitted the sine signals with different cycles number, to compare the analysis results. Signals with more cycles number means its bandwidth are narrower. However, the

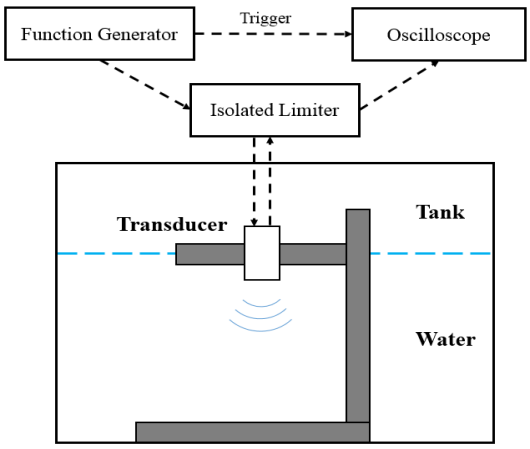


Fig. 11. Pulse echo system

Cycle	Doppler shift (Hz)
1	-4.9615e+05
10	-3.8077e+05
20	7.1648e+03
50	584.2928
100	178.7645
140	109.2397
280	4.0708

Table.1. Results of experiments

maximum cycles number was limited by the vertical distance of the pulse echo system. In our experiments, the vertical distance was 21 cm, maximum cycles number was about 280 cycles. The homemade transducer's center frequency was 1MHz. The analysis results are shown in Table. 1.

CONCLUSIONS

This paper confirms that the Doppler shift can be computed by using auto-correlation algorithm (AC method). From the results of continuous sine signal in section 3.1, show that the longer signal has smaller relative error. More precisely, the signal with narrower bandwidth has better analysis results. When conducting the experiments, we can capture the specific section of received signal, where pulses were contained, to have more accurate results. On the other hand, the experimental results indicate that the signals with more cycles, caused the Doppler shift closer to zero Hz. Compare the results of continuous sine signal and pulse signal, we concluded that the auto-correlation algorithm is more suitable for narrowband signal analysis.

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