Time Delay Estimation in Underwater Positioning for Pattern Time Delay Shift Coding

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Abstract—**Based on the pattern time delay shift coding regime, a structure of positive and negative frequency modulation calling pulses of underwater ultra-short base line acoustic positioning system is given, and the second correlation method of time delay estimation is proposed in this paper. As the second correlation method improves the detectable signal-to-noise ratio of calling end to certain extent, it could accumulate the multipath reflections in the underwater channel on the energy including the direct wave effectively in the complex environment, so as to finish the peak detection accurately and to improve the accuracy of time delay estimation. At last, the sea trial results show that the second correlation method could suppress the multipath interference from interface reflections under different signal-to-noise (SNR) ratio efficiently.**

Keywords- second correlation; pattern time delay shift coding; underwater acoustic positioning

I. INTRODUCTION

As the target tracking and positioning technique developing, research on time delay estimation is emerged. The accuracy of time delay estimation is one of the decisive factors of underwater positioning system. According to the different demands, there are several methods of time delay estimation, including correlation estimation method, parameter estimation method, high order statistics method etc [1,2]. The correlation estimation method is widely used because of its simple algorithm. However, the time resolution of the correlation is inversely proportional to the signal bandwidth, therefore wideband transmitting signal is needed for the high accuracy of time delay estimation.

Underwater acoustic signal is propagated in multipath channels, and the received signal becomes a combination structure of many interface reflecting interferences besides the direct wave, so that the correlation peak of direct wave could be resolved difficultly [3]. To obtain an accurate time delay estimation of direct wave, it is important to detect correct peak of direct wave in underwater positioning system. Based on the pattern time delay shift coding system, the second correlation method is described for the time delay estimation of underwater acoustic positioning in this paper. This paper is organized as follows. Section II describes the pattern time delay shift coding scheme. Section III shows the improved second correlation method in details. In Section IV, the practical field trial results are given. Concluding remarks are given in Section V.

II. PATTERN TIME DELAY SHIFT CODING SCHEME

The underwater acoustic communication based on the pattern time delay shift coding scheme encodes the digital information in the time delay shift values of the pattern rather than modulates on the carrier wave form and different value represents different information as shown in Fig.1 [4]. The duration of every pattern is T_p and the encoding time window for information coding is T_c, so the duration of a symbol is $T_0=T_p+T_c$. If a symbol takes n bits digital information, the quantization unit of the time delay shift is $\Delta\tau=T_c/(2n\text{-}1)$.

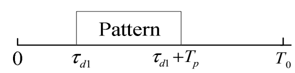


Figure 1. Pattern time delay shift coding scheme

Fig. 1 shows the sketch map of pattern time delay shift coding scheme. $\tau_d=k\Delta\tau$ is the time delay shift value, where k=0, 1, ... , 2n-1. The linear frequency modulation (LFM) signal is selected as the pattern wave whose slope is positive:

$$s_P(t)=\begin{cases}\cos(2\pi f_L t+\pi\beta t^2), t\in[0,T_P]\\ 0 \qquad\qquad\qquad\qquad ,otherwise\end{cases} \tag{1}$$

where f_L is the original frequency of the pattern signal whose slope is $\beta=w_p/T_p$ where w_p is frequency band. Similarly, the form of negative slope modulation pattern pulse can be deduced too. The pattern time delay shift coding scheme usually decodes the digital information by cross correlation to estimate the time delay shift at the receiver.

The depth information of transponder in the ultra-short baseline positioning system is obtained from the pressure sensor. Based on the pattern time delay shift coding system, the depth information is sent to the call end by the time delay shift coding during the acknowledge cycle. As shown in Fig.2, the reply signal consists of three parts, which are synchronous continuous wave (CW), positive linear frequency modulation pulse signal (PLFM), negative linear frequency modulation pulse signal (NLFM). The time delay between PLFM and NLFM represents the depth information of transponder in the system.

From the viewpoint of ray theory, the received combination is a superposition of underwater acoustic signals arriving at the calling end along the different paths. Its impulse function is

$$h(t) = \sum_{i=1}^{M} A_i \delta(t - \tau_i) \quad (2)$$

where A_i, τ_i are the amplitude and the time delay of the ith eigen ray, and M is the number of eigen rays. Assuming the intercepted PLFM signal model is

$$x_P(n) = \sum_{i=1}^{M} A_i s_P(n - \tau_i) + n(n) \quad (3)$$

where $s_p(n)$ is a narrow band signal satisfied with the conditions of flat frequency spectrum and τ is the time delay and $n(n)$ represents additive white noise. As shown in Fig.3, a cross-correlation operation of the received signal with the replica of transmitted signal is

$$\begin{aligned} R_{P1}(\tau) &= E[x_P(n)s_P(n+\tau)] \\ &= E\{[\sum_{i=1}^{M} A_i s_P(n-\tau_i) + n(n)]s_P(n+\tau)\} \quad (4) \\ &= \sum_{i=1}^{M} A_i R_{PP}(\tau - \tau_i) + R_{Pn}(\tau) \end{aligned}$$

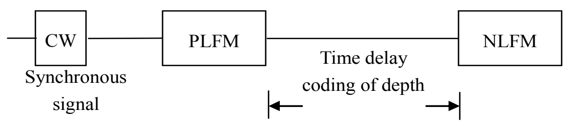


Figure 2. The constitution of the reply signal

Similarly, the received NLFM signal model is

$$x_N(n) = \sum_{i=1}^{M} A_i s_N(n - \tau_i) + n(n) \quad (5)$$

The cross-correlation of received signal with the replica of transmitted signal is

$$R_{N1}(\tau) = \sum_{i=1}^{M} A_i R_{NN}(\tau - \tau_i) + R_{Nn}(\tau) \quad (6)$$

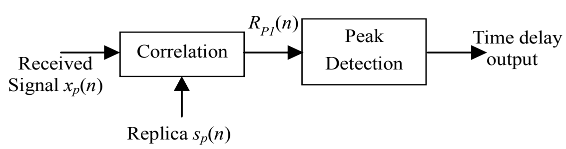


Figure 3. The first correlation operation of the received signal with its replica

Assuming that the noise is ideal Gaussian white noise, so the signal and noise are uncorrelated, then $R_{Pn}(\tau)=R_{Nn}(\tau)=0$. According to the property of cross-correlation functions, $R_{PP}(\tau)$ or $R_{NN}(\tau)$ has maximum correlation peak at $t=D$, namely the peak point of a cross-correlation function corresponding to the time delay point. To sum up, the signal-to-noise ratio is increased after a correlation operation. However the actual noise could not be ideal Gaussian white noise and the signal observation time could not be infinite too, so $R_{Pn}(\tau)$ and $R_{Nn}(\tau)$ are not strictly to be 0. At the same time, as the distance between the mother ship and the transponder increasing, the signal-to-noise ratio of the receiving signal will continue to reduce so that correlation peak will submerge in the background noise. Moreover, in a complicated environment, multiple correlation peaks will appear because of different interface reflections. It is difficult to determine the accurate position of the direct wave correlation peak. The above two problems will largely affect the accuracy of the time delay estimation, and even result in getting a wrong time delay estimation. At the same time, the result will directly influence the calculation of transponder positioning depth.

III. SECOND CORRELATION

Due to the problems of time delay estimation based on the first correlation, a new time delay estimation method is proposed which is based on the second correlation technique. After finishing the first correlation, the second correlation of $R_{P1}(\tau)$ with $R_{N1}(\tau)$ is further conducted. Because the second correlation operation is a time function, so taking n replaces τ, namely

$$\begin{aligned} R_{PN}(\tau) &= E[R_{P1}(n)R_{N1}(n+\tau)] \\ &= E\{[\sum_{i=1}^{M} A_i R_{PP}(n-\tau_i) + R_{Pn}(n)] * \quad (7) \\ &\quad [\sum_{j=1}^{M} A_j R_{NN}(n+\tau-\tau_j) + R_{Nn}(n+\tau)]\} \end{aligned}$$

As previously introduced, the cross-correlation of the signal with noise can be approximate to be 0. Similarly, if the noise is unrelated Gaussian white noise, $E[R_{Pn}(n)R_{Nn}(n+\tau)]$ can be approximate to 0 too. Assuming that the second correlation result between PLFM and NLFM is $R_{PPNN}(\tau) = E[R_{PP}(n)R_{NN}(n+\tau)]$. Equation (7) can be simplified as

$$\begin{aligned} R_{PN}(\tau) &= \sum_{i=1}^{M} A_i \{\sum_{j=1}^{M} A_j E[R_{PP}(n-\tau_i)R_{NN}(n+\tau-\tau_j)]\} \\ &= \sum_{i=j}^{M} A_i^2 R_{PPNN}(\tau) + \sum_{i\neq j}^{M} A_i A_j R_{PPNN}(\tau+\tau_i-\tau_j) \end{aligned} \quad (8)$$

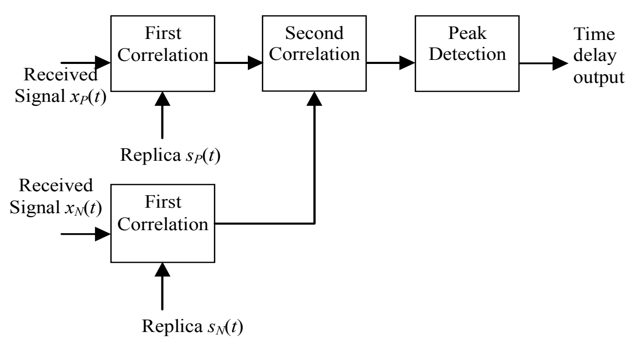


Figure 4. Implementation of the second correlation operation of the received signal with its replica

It is seen that the first term in (8) is the second correlation peak to accumulate the multipath reflections on the energy. The first term is obviously greater than the second term from multiplication cross between different reflections. The specific flow diagram is shown in Fig.4. According to the property of the cross-correlation function, $R_{PN}(\tau\text{-}D)$ has a maximum at τ=D. So the time delay estimation will be obtained if only finding a point in abscissa axis corresponding to the maximum correlation peak of $R_{PN}(\tau\text{-}D)$. The superiority of the second cross-correlation method is that the time delay could be estimated in a lower signal-to-noise ratio environment and in the complex multipath channels compared to the first cross-correlation method. As it is approximate to rake reception technology, this method can further distinguish subtle multipath signals in time, and accumulate these discriminated multipath signals of interface reflection respectively on the energy to composite a correlation peak.

IV. Simulation and Trial Results

We make the channel impulse response by summing the discrete multi-paths by ray tracing with diffusive multi-paths. In order to change the signal-to-noise ratio of the received signal, the Gaussian white noise with different power spectral density is added in the simulation waveform. Its center frequency of the responder's transmitted signal is 14 kHz. The bandwidth of positive or negative frequency modulation pulses is 8 kHz, and the sampling frequency of underwater acoustic ultra-short baseline positioning system is 72 kHz. The simulation channel impulse response is given in Fig.5, which includes three propagation paths. The delay time of the second and the third paths are 1ms and 2ms respectively, and their magnitudes are -0.8 and 0.5 after normalized.

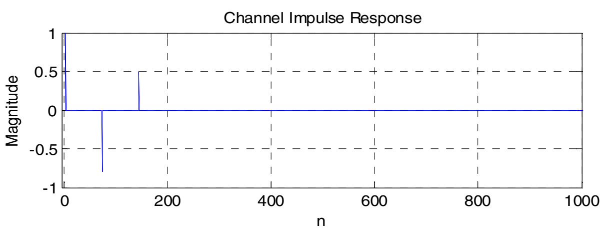
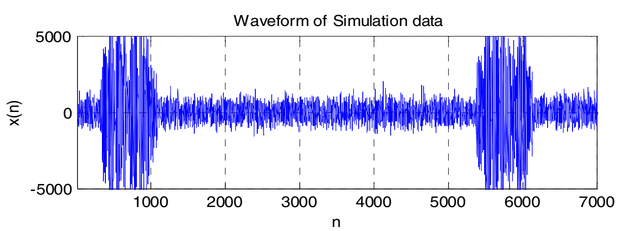


Figure 5. Simulation channel impulse response



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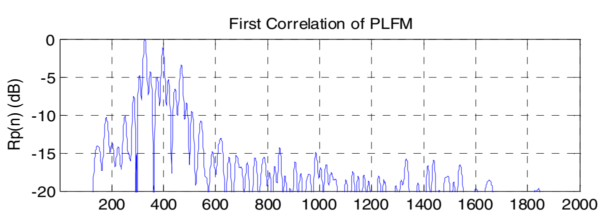

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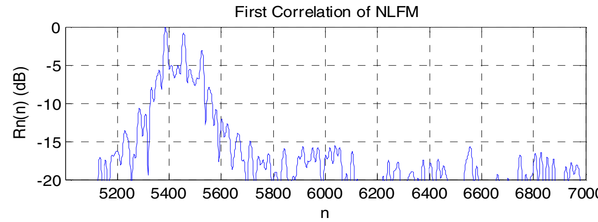

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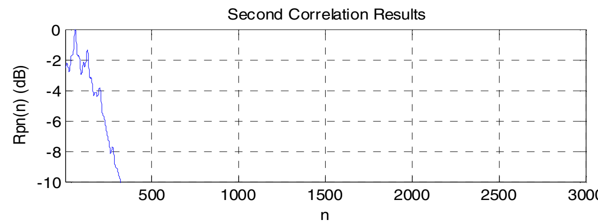
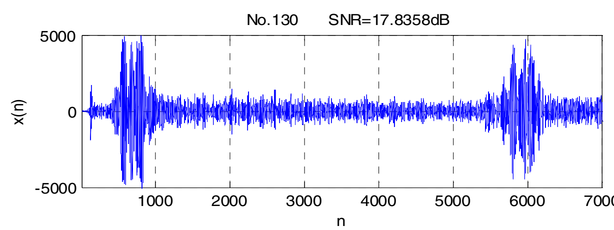


(d)

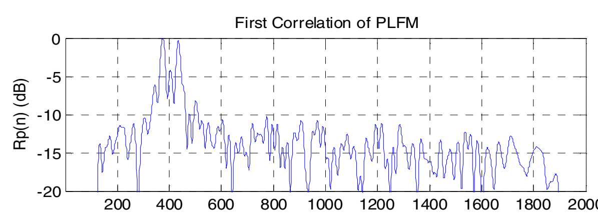
Figure 6. The simulation data waveform, its first and second correlation results

In Fig.6(a), the simulated waveform is given, in which the delay time interval of three propagation paths is 1ms. The fore and after pluses are positive and negative frequency modulation linear frequency modulation pulse signals. The correlation results with their replicas of positive or negative frequency modulation pulses are shown in Fig.6(b) and Fig.6(c) respectively. In each figure, there are three correlation peaks nearby the 400th and 5400th sampling points corresponding to the delay time structure of simulating multi-paths, and the second correlation result is given in Fig.6(d). It is obvious that the peak could be resolved easily with the second correlation.

To verify the above algorithm, a sea trial was conducted in Pearl River estuary, Guangdong, China. The sea depth in trial field is about 40m. In this procedure, a small craft hanging a responder sailed from the near to the distant.



(a)



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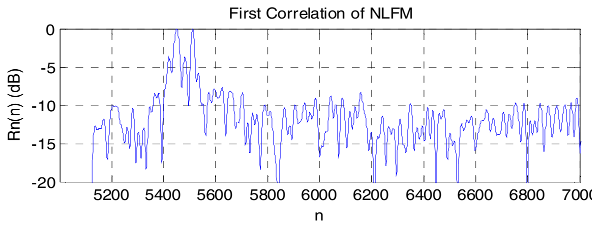

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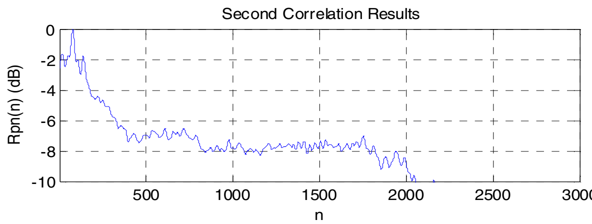
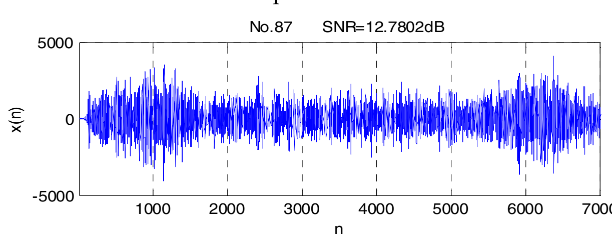


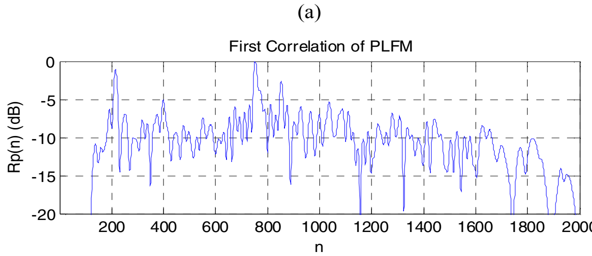
(d)

Figure 7. When 600 m apart from the mother ship, data waveform, its first and second correlation results

The received signal of ultra-short baseline positioning system is shown in Fig.7 when the small craft is about 600 m away from the mother ship. In Fig.7(a), the waveform of the received signal is given, in which the fore and after pluses are positive and negative frequency modulation linear frequency modulation pulse signals, and it is apparent that the waveform retains high signal-to-noise ratio. The correlation results with their replicas of positive or negative frequency modulation pulses are shown in Fig.7(b) and Fig.7(c) respectively. In each figure, there are two correlation peaks nearby the 400th and 5400th sampling points, and it is measured that one of them could be brought by the reflected echoes of sea surface. But it is difficult to choose the correct correlation peak of the direct wave so as to obtain the accurate time delay estimation. At the same time, the second correlation result is given in Fig.7(d), and it is clear to obtain a single correlation peak after accumulating energy of the multipath echoes, thus the intervals between the two pluses could be inferred accurately.



(a)



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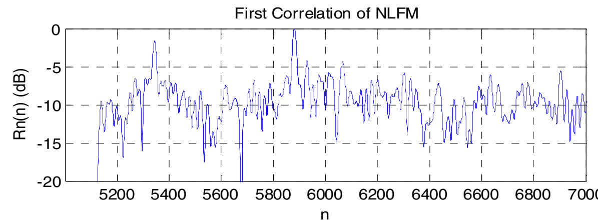

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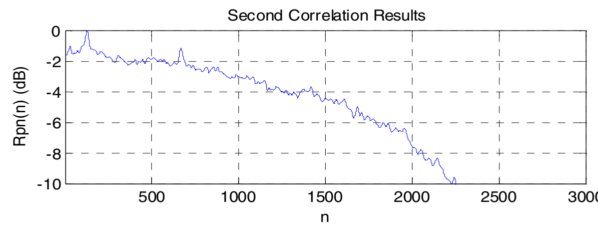
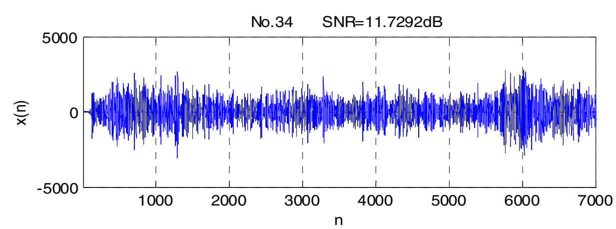


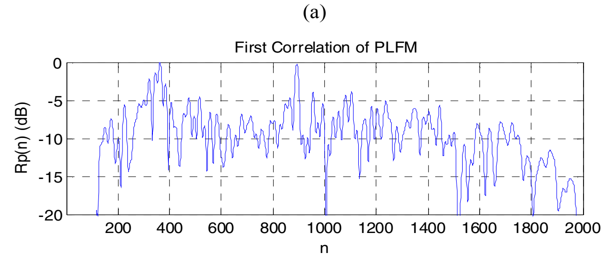
(d)

Figure 8. When 1 km apart from the mother ship, data waveform, its first and second correlation results

As the small craft sailing away, compared to the waveform in Fig.7(a), the signal-to-noise ratio of the received waveform in Fig.8(a) becomes lower obviously. The cross correlation results with their replicas of positive or negative frequency modulation pulses show that the correlation peak of direct wave is lower than the correlation peak of interface reflection in Fig.8(b) and Fig.8(c). In this condition, it is difficult to design a strategy to achieve an accurate peak detection. However, after finishing the second correlation, its peak in Fig.8(d) could be discriminated clearly and easily. When the distance from the transponder to the mother ship is greater than 1 km, it is difficult to discriminate the frequency modulation pulses from the receiving waveform in Fig.9(a). However, the intervals between pattern pulses could be inferred steadily with the second correlation method in Fig.9(d).



(a)



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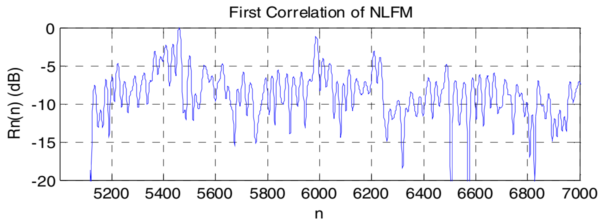

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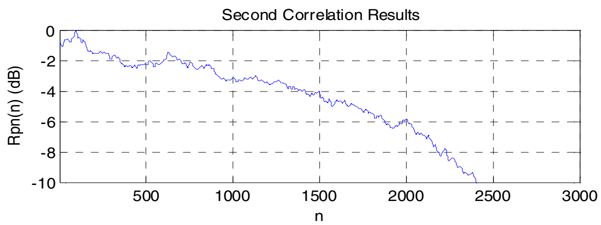

(d)

Figure 9. When greater than 1 km apart from the mother ship, data waveform, its first and second correlation results

V. CONCLUSION

After a responder transmitting, the received signal of an ultra-short baseline positioning system is always processed with the matched filter. However, it is difficult to estimate the time delay of correlation peak in complex environment. Based on pattern time delay shift coding system, the structure of positive and negative frequency modulation pulses is given, and the second correlation is proposed for time delay estimation in this paper. As the second correlation method improves the detectable signal-to-noise ratio by suppressing the background noise to certain extent, it could accumulate the multipath reflections including the direct wave on the energy effectively. The superiority of the second cross-correlation method is that time delay could be estimated in a lower signal-to-noise ratio environment and in the complex multipath channels compared to the first cross-correlation method. At last, the field trial results show that the second correlation could suppress the multipath interference in underwater channel efficiently. Consequently, it is valuable that the second correlation is implemented efficiently and simply.

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