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Characteristics Analysis of HFM Signal over Underwater Acoustic Channels

Yuan Fei, Wang Wen-Jun, Cheng En*
Key Laboratory of Underwater Acoustic Communication and Marine Information Technology (Xiamen University), Ministry of Education, P.R.C
*Corresponding author, e-mail: chengen@xmu.edu.cn

Abstract

For pulse compression characteristics and not easily affected by noise, linear frequency modulation signal are widely used in underwater acoustic communication. This paper analyzes the characteristics of hyperbolic frequency modulation signal over underwater acoustic channels. Compared with linear frequency modulation signal, hyperbolic frequency modulation has the same performance of strong anti-noise and anti-multipath, what's more, hyperbolic frequency modulation signal is better resist the influence of doppler. And discussed the influence of doppler on signal, simulation results show that the hyperbolic frequency modulation signal detection rate is better than linear frequency modulation signal in the doppler environment.

Keywords: *LFM, HFM, Doppler, underwater acoustic channels*

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1. Introduction

Ultrasound formed as hyperbolic modulation frequency (HFM) is successfully used in echolocation by some animals. And HFM signal had been used in many application such as synchronization, echo location, medical engineering and so on [1-3]. In this paper, analysis of the LFM was given as a contrast to discuss the characteristic about the HFM signal over underwater acoustic channel.

2. HFM signal characteristics

HFM signal is different from frequency linear change over time of LFM signal, it's a special non-linear frequency modulation signal, frequency modulation regularity for hyperbolic functions. HFM signal can be expressed as:

$$c(t) = \cos[2\pi \frac{\ln(kt + 1/f_1)}{k}] \quad (1)$$

Where k is the signal slope: $k = (f_1 - f_2)/(T \times f_1 \times f_2)$, f_1 is starting frequency, f_2 is end frequency. If $f_1 < f_2$, signal represents HFM up sweep signal, on the contrary, signal is HFM down sweep signal. The signal instantaneous frequency is

$$f_i(t) = \frac{1}{kt + 1/f_1} \quad (2)$$

Instantaneous frequency is in the interval [f_1 f_2] over time to change in the hyperbolic form.

HFM is a doppler invariant signal, assume the transceiver end opposite speed is v, speed of sound is c, the doppler factor is $\Delta = 1 + v/c$. The instantaneous frequency of HFM signal becomes

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$$f_r(t) = \frac{1}{2\pi}\frac{d\varphi_r(t)}{dt} = \frac{\Delta}{k\Delta t + 1/f_1} \tag{3}$$

The phase is $\varphi_r(t) = 2\pi \times \ln(k\Delta t + 1/f_1)/k$,make delay $\Delta t = -v/(f_1 \times k \times \Delta \times c)$,so $f_r(t-\Delta t) = f_i(t)$.

This prove that while HFM signal have frequency shifted, there is a length of delay Δt , so that the frequency-shifted signal with the original signal matching.

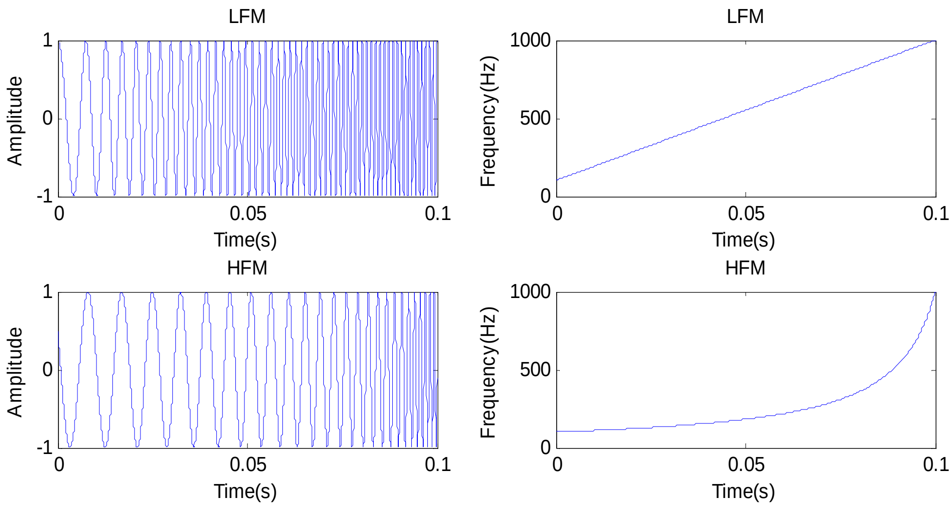

Figure 1. Time domain of up sweep signal

3. The characteristics of HFM signal in underwater acoustic channels

3.1. White Gaussian noise

As we all know, LFM signal has a strong resistance to white Gaussian noise, because of its self-correlation [4, 5] characteristics. And HFM signal also having a good self-correlation characteristic. As can be seen from Figure 2, the contrast effect between HFM signal and LFM signal is basically the same, the self-correlation peak of output matching signal is evident at higher SNR, and side lobe is clean. At low SNR, side lobe energy become large, but the signal self-correlation peak is still evident. It shows that white Gaussian noise only influence the side lobe of the output matching signal, self-correlation peak is still evident.

3.2. Multipath

The influence of multipath are very serious in underwater acoustic communication [6], it causes amplitude attenuation and inter-symbol interference. Signal which pass through multipath channel may be expressed as [7]

$$y(t) = a_0 c(t) + \sum_{i=1}^{N-1} a_i c(t - \tau_i) \tag{6}$$

The first component is the signal of first arrive at the receiving end, the other N-1 components that amplitude attenuation a_i , delay τ_i .

Figure 3 shows underwater acoustic line and impulse response of multipath simulation channel, transmission signal pass through simulation channel will become multipath delay signals. Figure 4 shows with the influence of multipath [8], the matching output effect of HFM signal and LFM signal is basically the same. Therefore HFM signal and LFM signal have almost the same anti-multipath capability.

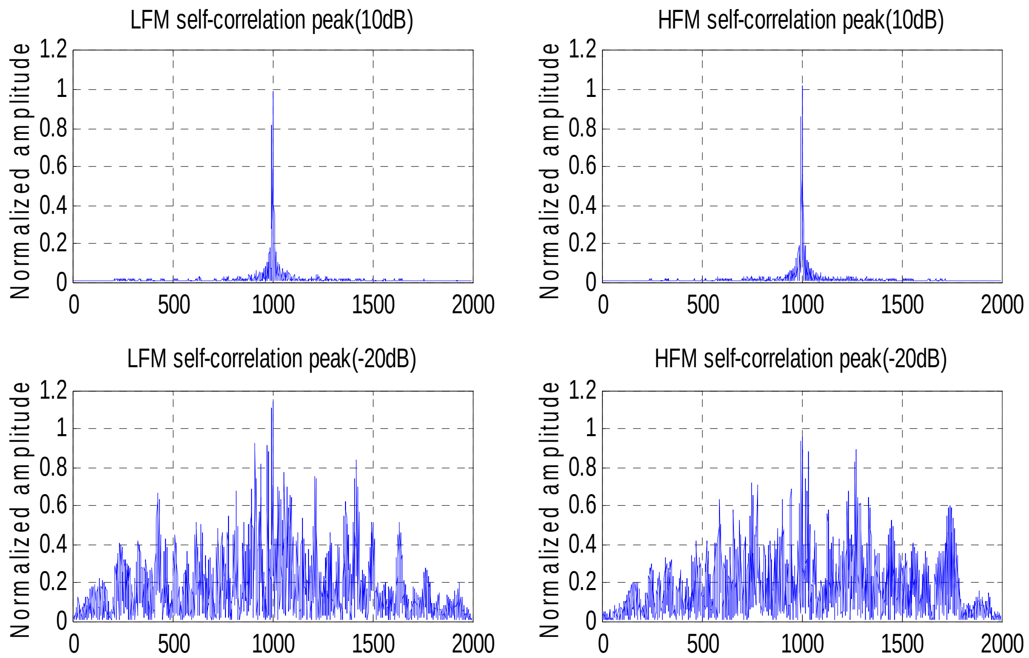

Figure 2. The influence of noise on self-correlation peak

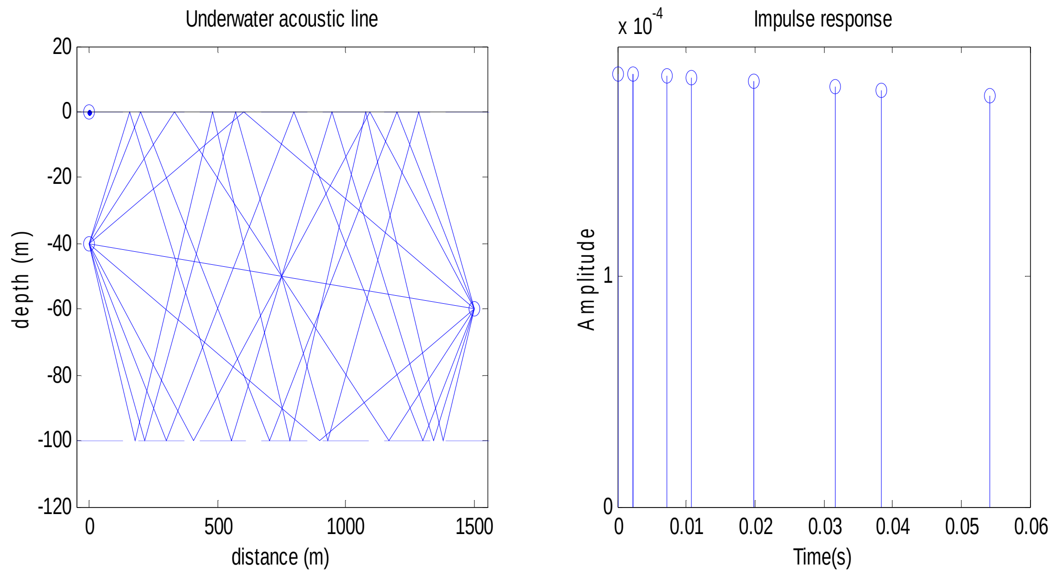

Figure 3. Underwater acoustic Line and impulse response

3.3. Doppler

The influence of doppler on signal is frequency offset and time expansion/compression [9], it changes signal modulation frequency rate and causes signal mismatch with the local correlation signal. If doppler is small, the signal is a narrow-band range, time expansion/ compression has little influence on signal, doppler effects show only the frequency shift. Assume LFM signal has a frequency offset w_d , the expression is

$$c_d(t, w_d) = \cos[(w_0 + w_d)t + ut^2 / 2] \qquad -T/2 < t < T/2 \tag{7}$$

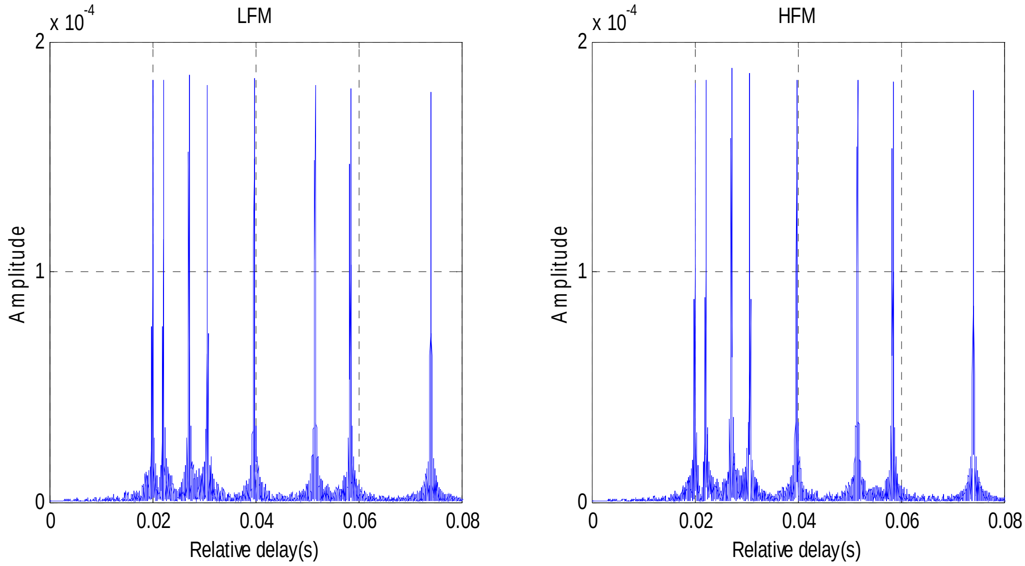

Figure 4. The influence of multipath on self-correlation peak

After pass through the matched filter, the resulting signal is

$$\sqrt{\frac{2u}{\pi}}\frac{\sin\left[\frac{w_d+ut}{2}\left(T-|t|\right)\right]}{w_d+ut}\cos\left(w_0+\frac{w_d}{2}\right)t \qquad -T<t<T \tag{8}$$

That $u=2\pi M$, M for modulation frequency rate of LFM signal. The doppler frequency shift will cause the match output signal's lobes broaden, the peak amplitude attenuation and peak location offset. If set $\varepsilon=w_d/u$, frequency offset cause the amplitude of match output peak reduce ε and the peak position offset εT .

If Doppler is strong, it not only cause the frequency shift, as well as time expansion / compression. Assume the Doppler cause frequency shift of signal in transmission, that the relative velocity between sending and receiving end is v, speed of sound is c, the doppler factor for $\Delta=1+v/c$. For LFM signal, under the influence of frequency shift and time compressed, the instantaneous frequency become $f_d(t)=f_0\Delta+M't$, $M'=M\times\Delta^2$, symbol time is T/Δ , and signal no longer match with the original signal[10]. HFM signal is different from LFM signal, according to formula (3), HFM signal can effectively resist the influence of doppler.

As can be seen from Figure5, delay time T1 and T2 of LFM signal is not equal, and the modulation frequency rate changes significantly, signal no longer match. Delay time T1 and T2 of HFM signal are equal that prove the modulation frequency rate does not change, HFM signal can find a delay time to match the original signal.

Figure 6 shows signal self-correlation peak have different level of amplitude change and peak position offset, the modulation frequency rate of HFM signal does not change under the influence of doppler, while LFM signal no longer match, so the self-correlation peak of HFM signal changes smaller than LFM signal.

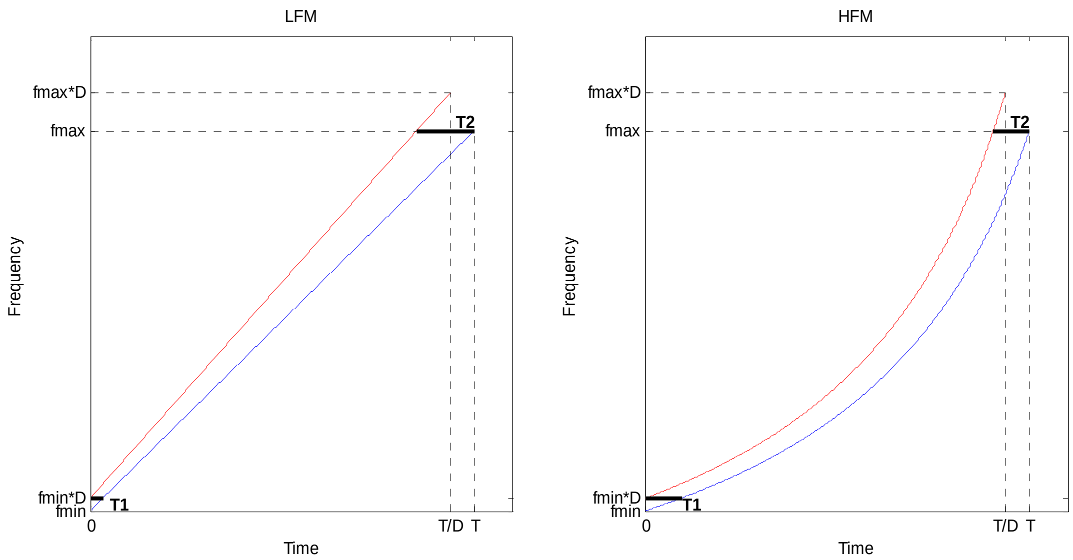

Figure 5. The influence of Doppler on modulation frequency rate

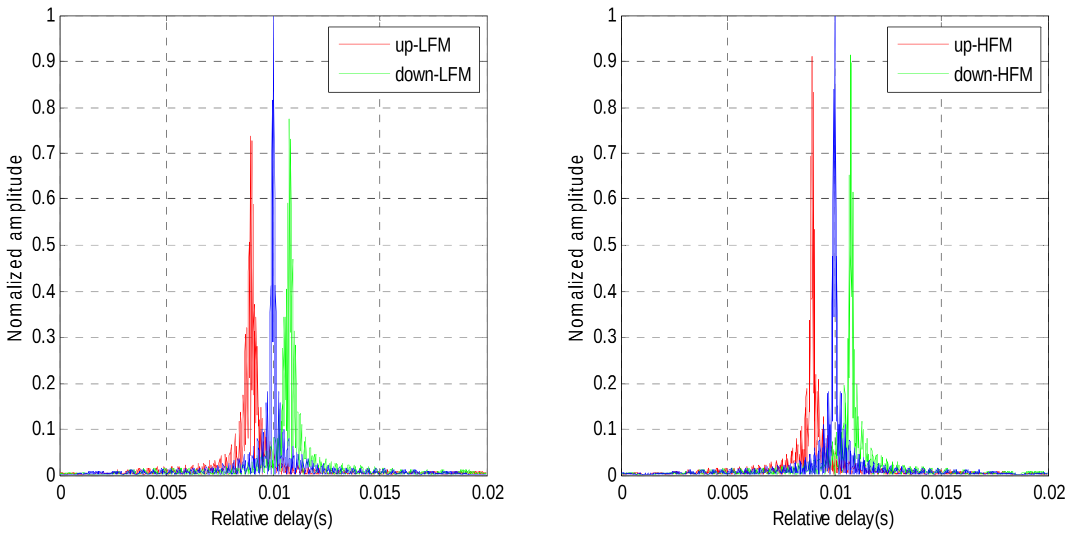

Figure 6. The influence of 30m/s relative velocity on self-correlation peak

Further study the amplitude variation of the self-correlation peak under the influence of Doppler, analyze the changes of self-correlation peak by the influence of time-varying, frequency offset and both caused by Doppler. Figure7 shows HFM signal is capable of strong resistance to the influence of Doppler. Even under the influence of strong doppler, the peak amplitude is still large. However, the peak amplitude of LFM decreased rapidly with doppler enhanced, which seriously affect the signal demodulation judgment.

According to formula (8), shorten symbol time will reduce the change of LFM self-correlation peak caused by frequency shift. For LFM signal, shorten symbol time effectively resist the influence of Doppler, and shorten symbol time has almost no effect of resistance to Doppler for HFM signal.

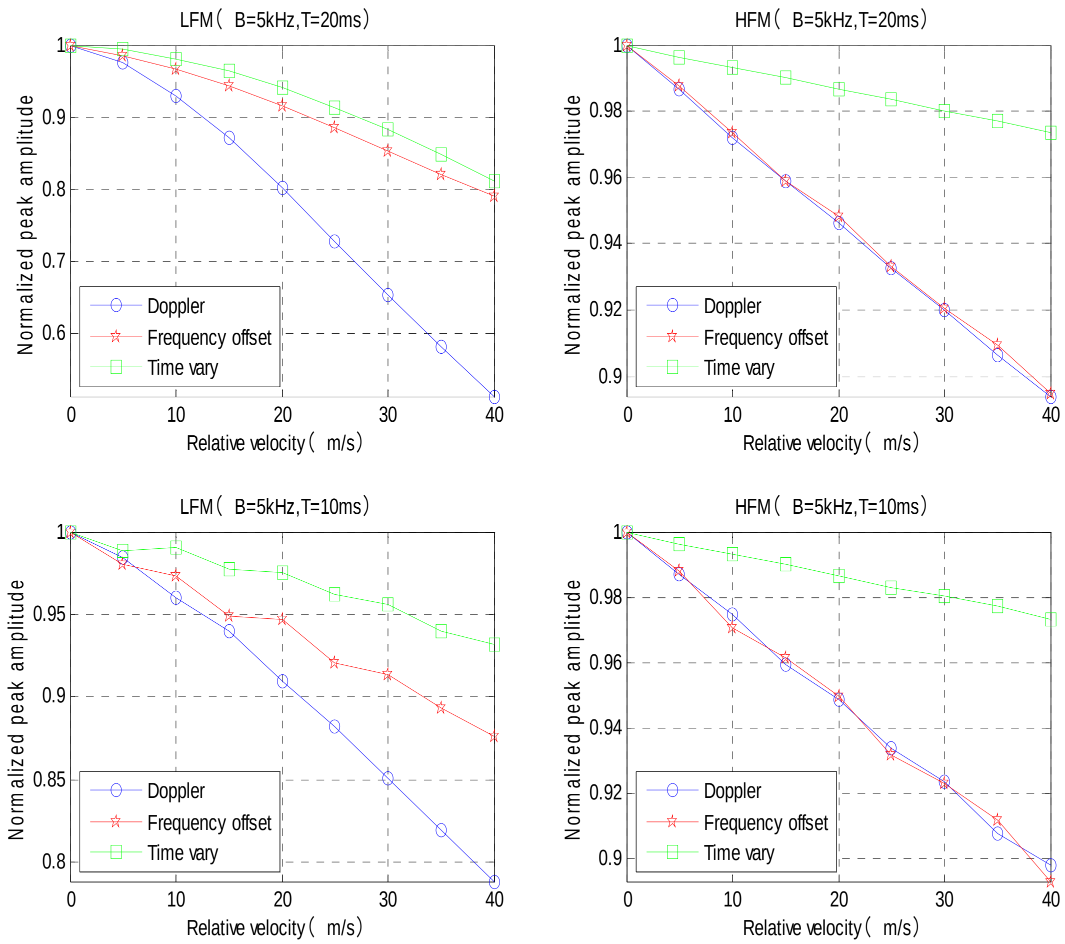

Figure 7. Amplitude of self-correlation peak change with frequency offset

4. Simulation

The system parameters for the simulation are indicated in Table1 and used the BOK system, up sweep signal represent the symbol "1", down sweep signal represent the symbol "0".

Table 1. System simulation parameters

Parameter	value
Signal sweep frequency	15kHz-20kHz
Symbol time	20ms
bandwidth	5kHz
Sampling rate	40kHz
Relative velocity	30m/s

Figure 8 shows the simulation results of detection performance under the influence of Doppler. Between -24dB to -10dB, the HFM signal detection rate is better than LFM signal. The detection rate of HFM signal reaches the maximum at -12dB, LFM signal backward 2dB compared with HFM signal, reaches the maximum at -10dB. It shows that HFM signal detection rate is superior to LFM signal under the influence of Doppler.

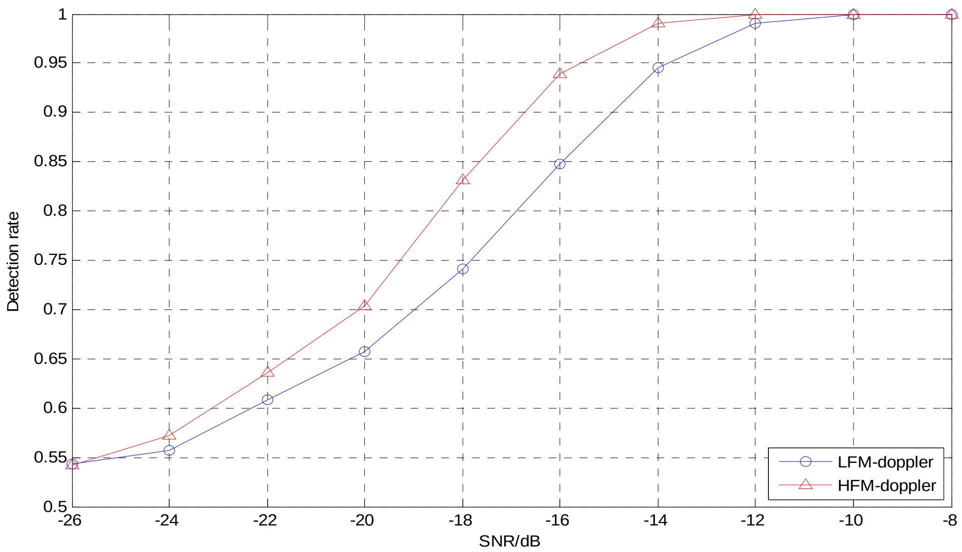

Figure 8. Detection performance curve under the influence of Doppler

Table2 shows that with the influence of Doppler, the minimum value of SNR while detection rate above 95%. By comparing with LFM signal, the performance of HFM signal is better than LFM signal, with the increase of relative velocity, the improvement of HFM performance is more obviously.

Table 2. The minimum value of SNR while detection rate above 95%

Relative velocity \ signal	HFM	LFM
10m/s	-16dB	-15dB
20m/s	-15dB	-14dB
30m/s	-15dB	-13dB
40m/s	-14dB	-11dB

5. Conclusion

In this paper, by comparising the change of HFM signal and LFM signal over underwater acoustic simulation channel, it shows that HFM signal and LFM signal have strong anti-noise and anti-multipath capability, simulation prove that HFM signal is more effectively to resist the influence of doppler. And HFM signal is more suitable for underwater acoustic communication with mobile platform or underwater acoustic channel with strong doppler influence.

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