A Study on Blanket Noise Jamming to LFM Pulse Compression Radar

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***Abstract*—A blanket noise jamming method based on sawtooth wave frequency shift is proposed in this paper. The characteristic of the jamming signal is analyzed in detail in frequency domain. Due to the frequency modulation, the modulated signal is dis-matched with the matched filter and the output signal's pulse width spreads. The periodic sawtooth wave determines the bandwidth of the jamming signal and the pseudo-random sequence is used to create dense noise signals. After processed by the matched filter, the jamming signal forms a rectangular blanket covering span. The amplitude of the jamming signal's main peak varies slightly and effectively raises the radar detection threshold. The simulation results validate the correctness and effectiveness of the proposed method. When the chirp rate of the LFM signal is large, the proposed method behaves better than the pseudo-random sequence modulation method and other non-coherent noise jamming methods.**

Keywords- blanket jamming, sawtooth wave, DRFM, LFM, frequency shift

I. INTRODUCTION

The radar has been an important military weapon since they are invented. Through coherent processing of the target echo, the radars can provide the range, velocity, angle information of the target [1,2]. The powerful capability of radar threats the battlefield target heavily. Thus many countermeasure techniques are proposed against the radar.

Generally, the passive jamming method, such as chaff jamming, is widely used to jam the radar. The passive jamming does not need special electronic systems but uses objects of strong reflecting property to reflect the radar signal. The target echo is hidden from the radar under the cover of chaff. Bai et al [3] proposed the method of an array of rotating reflectors to deduce unfocused blank jamming along the azimuth direction. Xu et al [4] analyzed the matched filter result of the incident wave reflected by the phase-switched screen and deduce the conclusion that the energy of the wave will reside into the sideband rather than the original frequency band. Thus the target under such screen can be stealth under the light of radar signal.

The active jamming is conducted by special electronic systems and aims at creating deception jamming effect or blanket jamming effect. Due to the reason that the modern radars adopt coherent processing techniques, the jammer based on digital radio frequency memory (DRFM) is the popular jamming method because it achieves some processing gain. Lv et al [5] analyzed frequency shift blanket jamming method and simulated jamming effect when random frequency shift LFM signals are fed with the matched filter. Deception jamming method saves the jamming power and can induce multiple false targets according to the modulation procedure. But the target echo is still involved in the jamming signal can the radar may adopt some anti-jamming techniques to detect the real target. Blanket jamming method, which needs more jamming power, can raise the detection threshold and submerge the target echo. In order to obtain the radar processing gain, smart noise jamming method based on multiplication modulation is analyzed and the jamming effect is presented in [6].

In this paper, a blanket noise jamming method based on frequency shift is proposed. By improving the pseudo-random sequence (PRS) modulation method, the sawtooth wave is used to spread the covering distance and change the amplitude property of PRS modulated signals. The improved method has larger covering distance and the amplitude envelope is more similar a rectangular pulse. The targets located on the covering distance can be effectively protected.

II. JAMMING SIGNAL MODEL

A. *Sawtooth wave frequency modulation.*

Taking advantage of the time-frequency coupling property of LFM signal, the frequency shift LFM signal can be used to form noise jamming effect or deception jamming effect according to the modulation coefficient. Cui et al [7] analyzes the mis-matched LFM jamming signal and indicates that the matched filter result is the signal which covers some distance and has a rectangle-like envelope. The time-frequency relationship of the LFM signal and jamming signal after passing through the matched filter is shown in Fig.1.

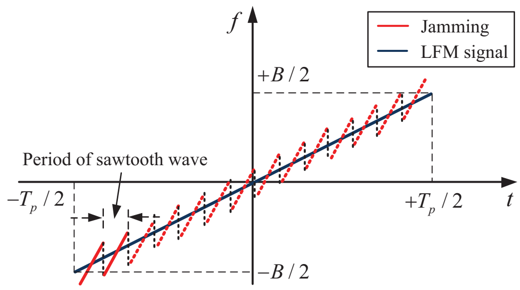


Fig. 1. Time-frequency property of the radar signal and jamming signal.

After frequency shift, the modulated signal is still an LFM signal but with different chirp rate when compared with the radar signal. The chirp rate may become larger or smaller according to the waveform of sawtooth. The frequency modulated LFM can be written as:

$$s_m(t) = \mathrm{rect}(\frac{t}{T_p}) \cdot \exp(j\pi(k+k_m)t^2) \quad (1)$$

where $\mathrm{rect}(\cdot)$ yields a value of 1 when $t \le T_p/2$. k stands for the chirp rate of the LFM signal and k_m is the additional linear variable frequency created by sawtooth wave. According to Cui [7], the matched filter result of modulated signal is

$$I_{\mathrm{m}}(t) \approx \sqrt{k_m} \cdot \mathrm{rect}(\frac{t}{T_p} \cdot \frac{k}{k_m}) \cdot \exp(-j\pi t \cdot \frac{k^2}{k_m}) \quad (2)$$

From (2) we see that the pulse width of the output signal is $|k/k_m|$ times of the radar signal's pulse width T_p. If the period of the sawtooth wave is equivalent or larger than the pulse width of the LFM signal, the matched filter's output signal is in the formation shown in (2). After modulated by the sawtooth wave, the LFM signal's variation property between the frequency and time is changed. The time-frequency relationship is still linear but with a different chirp rate. So the coherence between the jamming signal and the matched filter is wrecked.

This mis-matched signal is not directly used to jam the radar because its amplitude property is quite obvious. The sawtooth wave can be repeated during the radar signal, that is to say, the modulated signal is a periodic signal. So the spectral property of the sawtooth wave is discrete. The bandwidth the jamming signal occupies is still determined by the sawtooth wave. Assume that the frequency expression of sawtooth wave is $M_0(f)$, then the spectrum of the periodic wave can be

$$M(f) = M_0(f) \cdot f_s \cdot \sum_{n=-\infty}^{+\infty} \delta(f - n \cdot f_s) \quad (3)$$

where f_s indicates the repetition frequency of the sawtooth wave, which determines the interval of the spectral line.

B. Jamming signal.

According to the modulation characteristic, we konw that the spread spectral width after PRS modulation is

$$bw = 1/T_c \quad (4)$$

where T_c is the code width of PRS. The amplitude of the spectrum is 0 when $f = 1/T_c$. The corresponding range location is

$$d = \frac{c}{T_c \cdot 2k} \quad (5)$$

That's to say, if the range distance between the jammer and the target equals to the value shown in (5), the jammer may fails to protect the target because the jamming amplitude in this position is very small. Also the failing of protection may occur in the location which is the integer multiple of d. To overcome this shortcoming, the PRS modulated signal is further conducted sawtooth wave frequency modulation. So the formation of the jamming signal can be written as

$$s_j(t) = s_m(t) \cdot p(t) \quad (6)$$

where $p(t)$ is the pseudo-random sequence. Meanwhile, the expression of (6) in frequency domain is

$$S_j(f) = M_0(f) \cdot f_s \cdot \sum_{n=-\infty}^{+\infty} \delta(f - n \cdot f_s) \otimes P(f) \quad (7)$$

where $\otimes$ indicates the convolution process. $P(f)$ is the Fourier transformation result of PRS, of which the result is shown in Fig. 2.

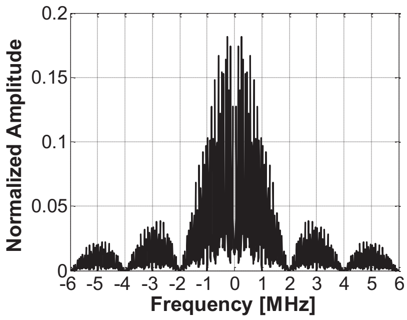


Fig. 2. The spectrum of PRS.

The PRS is a periodic signal essentially and its length is determined by the structure of the shift-register which creates the sequence. So $P(f)$ is also composed of discrete spectral line, of which the amplitude is affected by the sinc function [8]. The spectrum of the jamming signal is the superposition of the frequency shifted spectrum shown in Fig. 2. Through the superposition, the jamming signal's spectrum amplitude envelope is designed to be more like the rectangular shape.

C. Matched filter result.

The matched filter result of the LFM signal with the Doppler frequency is

$$I_d(t) = (1 - \left|\frac{t}{T_p}\right|)(1 - \frac{|f_d|}{B}) \cdot \sin(k \cdot T_p(1 - \left|\frac{t}{T_p}\right|)(t + \frac{f_d}{k})) \quad (8)$$

From (8) it can be seen that the Doppler frequency f_d causes the time of the output peak to move forward or backward. The discrete spectral line (7) can be treated as the multiple Doppler frequencies. Thus the matched filter result of the jamming signal consists of multiple peaks appearing at different locations. The peak's amplitude is modulated by sinc function and the sawtooth wave's property.

$$I(t) = \sum_{n=-L}^{L} \sum_{l=-P}^{+P} A_n \cdot A_l \cdot I(t - \frac{n \cdot f_s \cdot c}{2k} - \frac{l / PT_c}{2k}) \tag{9}$$

where A_n is the amplitude of sawtooth wave's spectral line. A_l is the amplitude of PRS's spectral line and its expression is

$$A_l = \frac{\sqrt{P+1}}{P} \cdot \frac{\sin(\pi f T_c)}{\pi f T_c} \cdot \sum_{\substack{l=-\infty \\ l \neq 0}}^{+\infty} \delta(f - \frac{l}{PT_c}) \tag{10}$$

In our design, the code width of the PRS approximates to the period of sawtooth wave. The frequency span of f_s is used to spread the bandwidth of PRS and increase the covering span of the jamming signal. The frequency distance between two adjacent spectral lines is

$$f_l = \frac{1}{PT_c} \tag{11}$$

The corresponding range distance is

$$f_l = \frac{1}{PT_c} \cdot \frac{c}{2k} \tag{12}$$

To most LFM radar, the distance in (12) is smaller than the range resolution when P is quite large.

III. SIMULATION RESULTS

In this section, we present the jamming effect when the jamming signal together with the target echo is received by the radar receiver. The parameters of the simulation are as below: the bandwidth and the pulse width of LFM signal are 100 MHz and 100 us, respectively.

When the duration time of the sawtooth wave is equivalent to the pulse width of the radar signal, the matched filter result of the modulated LFM signal is not in the formation of sinc function but a rectangular wave, as shown in Fig. 3. The amplitude of the modulated signal is normalized by the ideal LFM signal. The pulse width of the output signal spreads and the amplitude decreases. If this modulated signal is directly used to jam the radar, its property is very clear and the radar may adopt some anti-jamming method to eliminate the jamming. So we intend to adjust the time-frequency property of the modulated signal and make it be more similar to a noise signal.

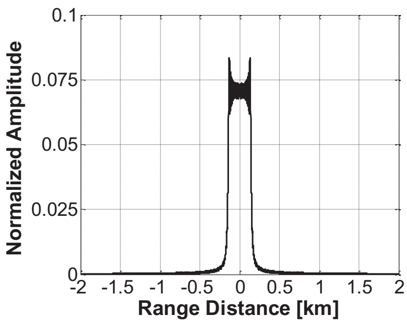
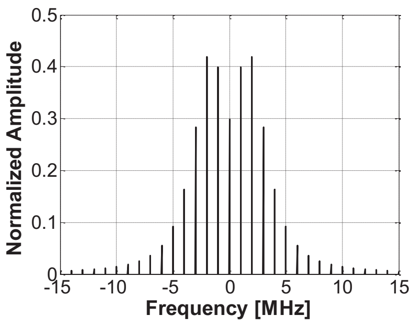
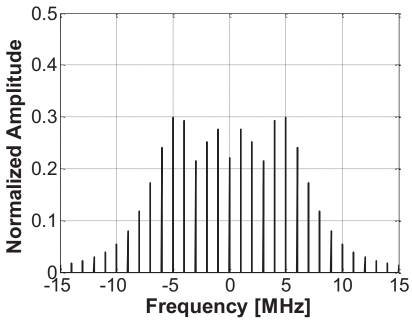


Fig. 3. Matched filter result of the mis-match LFM signal (band width of the sawtooth wave is 1 MHz).

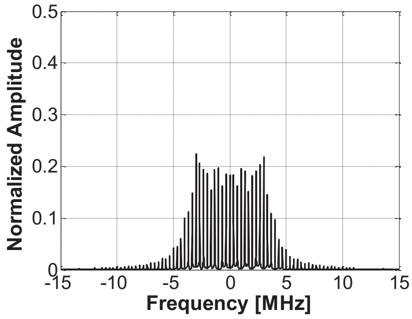
The spectral property of the periodic sawtooth wave is demonstrated in Fig. 4, where we see that the spectrum consists of multiple discrete lines and the bandwidth of the signal is $B_{saw} = k_{saw} \cdot T_{saw}$, where k_{saw} is the chirp rate and T_{saw} is the period of the sawtooth wave. When B_{saw} is large, the amplitude of each spectral line is small, meanwhile the frequency span increases. When the period of the sawtooth wave becomes large, the frequency span of two neighboring lines becomes dense. So the period can be determined according to the code width of PRS. The period shall be nearly to the code width and make the amplitude envelope to be not affected by sinc function.



(a) chirp rate variation is 2%, period is 1 us.



(b) chirp rate variation is 4%, period is 1 us.



(b) chirp rate variation is 4%, period is 3 us.

Fig. 4. Spectrums of sawtooth wave with different parameters.

The matched filter result of the PRS modulated LFM signal is shown in Fig. 5. The amplitude of the output signal is determined by sinc function and the main peak has most jamming power. But the amplitude away from the main peak decreases heavily. To make sure that the main peak of the jamming signal is not too little, the code width of the sequence shall not be very small. In Fig. 5, we see that the amplitude of the jamming signal consists of multiple peaks and the other peaks except for the main peak are with much smaller amplitude. The amplitude characteristic is quite clearly that the minimal value appears frequently.

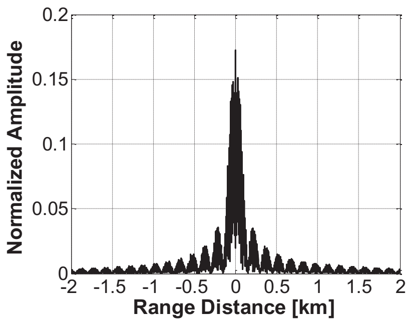
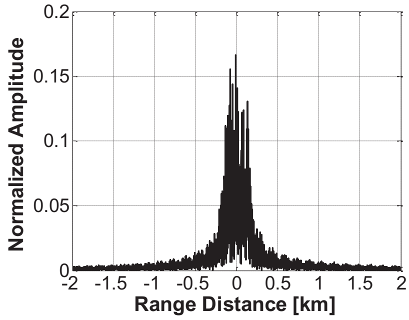
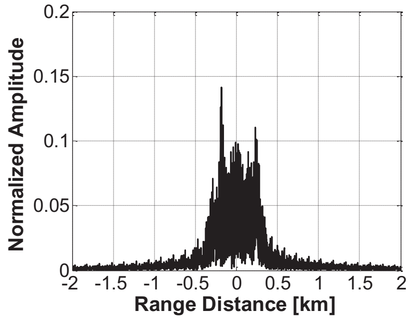


Fig. 5. Matched filter result of PRS(P=31, code width=0.5 us).

When sawtooth wave frequency modulation signal is added to the PRS modulated LFM signal, the output signal of the matched filter is shown in Fig. 6. According to the frequency property of periodic sawtooth save, the spectrum of the jamming signal is the superposition of the multiple frequency shifted spectrum of PRS sequence. After the superposition, the amplitude property of the sinc function can be reduced. The spectrum's amplitude of the jamming signal is designed to be more like a rectangular pulse. From Fig. 6 we know that the covering span is determined mainly by the bandwidth of the sawtooth wave. When the bandwidth of the sawtooth wave is large, the covering span occupies more range distances. When the bandwidth is small, the covering distance will decrease but have larger amplitude.



(a) chirp rate variation is 2%, period is 3 us.



(b) chirp rate variation is 4%, period is 3 us.

Fig. 6. Matched filter result of the jammign signal.

To test the jamming effect, the target echo and the jamming signal are mixed and processed by the matched filter. The jammer is 150 meters ahead from the target and the location of the jammer is 0 in Fig. 7. Constant false alarm rate (CFAR) detection is used to search for potential target and it is presented by red lines. The averaging cell is 64 and the guard is 4. The false alarm rate is 10^{-5}. We see that the detection threshold around the jammer is raised and target's amplitude is smaller than the threshold, which means that the target cannot be detected by the radar.

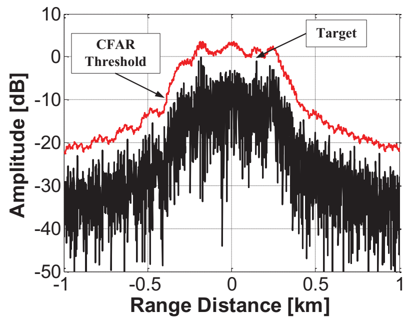


Fig. 7. CFAR detection of the jamming signal.

As a comparison, the PRS modulation method is presented in Fig. 8. The code width of the sequence is 0.5 us, which corresponds to the covering distance of 150 m in the simulation. The target just locates at the minimal value of the jamming signal's amplitude and the detection threshold is lower than target's amplitude, which means that the jammer fails to protect the target.

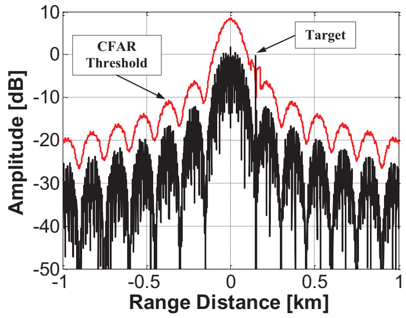


Fig. 8. CFAR detection of the PRS method.

From Fig. 7 and Fig. 8 we know that the proposed method is with wider covering distance and the jamming power mainly concentrate in the main peak. The amplitude property of the jamming signal is not in the formation of sinc function. The amplitude variation of the main peak is quite ease so the real target which located in the main peak will be protected.

In real applications, the bandwidth of the sawtooth wave is used to determine the main covering distance and it shall result in a considerable covering distance which occupies the potential location of the target. As the covering distance increases, the main peak's amplitude decreases and it means that the jammer needs more jamming power.

IV. CONCLUSION

In this paper, a spectrum expansion modulating jamming method is proposed against the LFM pulse compression radar. To overcome the shortcoming that the amplitude of the jamming signal periodically appears minimum value in the PRS phase-modulation method, the periodic sawtooth wave frequency modulation is added to the jamming signal. Through the selection of different modulation coefficients, the major power of the jamming signal focuses in the frequency span as we expect. The amplitude envelope of the jamming signal approximates to the rectangular wave and they can be used to enhance the detection threshold. Although the amplitude of the main peak of the jamming signal is slightly smaller than the PRS method, the proposed method's jamming effect is better when the target is far away from the jammer.

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