Interference Analysis and Simulation of Active Jamming for Two Phase Code PD Radar Fuze

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Abstract. Two-phase coding technology is a commonly used radar anti-jamming technology. The paper analyzes a pulse Doppler (PD) radar radar with two-phase encoding. Firstly, the characteristics of the two-phase coded signal are analyzed, and its good anti-interference performance is demonstrated. Then, the working principle of the PD radar fuse is analyzed as the principle of the simulation experiment. In order to investigate the anti-jamming performance of the PD radar fuse with two-phase coding technology, the paper used the radio frequency (RF) suppression interference and the dense false target interference to simulate the interference of the fuse. The simulation results are good, reflecting that the two-phase coded PD radar fuse has certain anti-jamming ability to suppress interference, but it has poor anti-jamming performance for the repeater-type deception jamming.

1. Introduction

Radar fuze is one of the main fuze devices on weapons and equipment for rocket weaponry. Its role is to give appropriate detonation signals for the location to maximize the lethality of the projectile in order to achieve the tactical or strategic purpose of the war. Radar fuses detect the distance and velocity information of a target by transmitting radio waves. It is one of the most commonly used fuze devices on the modern battlefield.

With the development of science and technology, the electromagnetic environment of modern warfare is becoming more and more complex. Compared with World War I and World War II, the Kosovo War and the Afghan War launched by the United States are called informatized warfare, information on the battlefield is changing rapidly, and electromagnetic pulses and electromagnetic interference fill the entire battlefield. Surroundings. In terms of electromagnetic interference, the U.S. "shortstop" jamming machine and Russia's "SPR-2" jamming machine represent the main stream of modern electronic warfare equations [1]. In terms of anti-jamming, commonly used anti-jamming technologies include frequency conversion, variable period, phase encoding, etc.[2].

2. Two-phase coded signal

The two-phase coded signal can generally be expressed as [3]:

$$u(t) = \sum_{n=1}^{N} u_n(t)e^{j\theta_n}e^{j\omega_0 t} = \sum_{n=1}^{N} u[t-(n-1)t_p]e^{j\theta_n}e^{j\omega_0 t} \tag{1}$$

In the equation: $u(t)$ represents the waveform of the sub-pulse, t_p is the pulse width of the sub-pulse, and θ_n is 0 or π. For convenience, the coefficient $c_n = e^{j\theta_n}$ is introduced, the value of c_n is only ± 1, and $\{c_n\}$ is used to represent the two-phase encoded signal.

Commonly used two-phase encoding is Barker code, M code, L code [4], this paper uses the M code as a research object.

The M code, also known as the maximum length sequence (MLS) code, is a pseudo-random code. The reason why it is called pseudo-random code is that its symbol {+1, -1} appears similar to the flip-coin sequence. M-sequences usually have two types, periodic and non-periodic.

2.1. Period M sequence two-phase coded signal
The complex envelope of a two-phase encoded signal of a periodic M sequence can be expressed as:

$$U(t) = \sum_{k=-\infty}^{\infty} c_k u(t-kt_p) = u_1(t) \otimes u_2(t) \tag{2}$$

$$u_1(t) = u(t) = \begin{cases} 1 & 0 \le t \le t_p \\ 0 & others \end{cases} \tag{3}$$

$$u_2 = \sum_{k=-\infty}^{\infty} c_k \delta(t-kt_p) \tag{4}$$

If Nt_p is a period, equation (4) can be converted to:

$$u_2 = \begin{cases} \sum_{k=0}^{N-1} c_k \delta(t-kt_p) & 0 \le t \le Nt_p \\ u_3(t \pm Nt_p) & others \end{cases} \tag{5}$$

In the equation: $u_3(t) = \sum_{k=0}^{N-1} c_k \delta(t-kt_p) \quad 0 \le t \le Nt_p$. Fig. 1 shows the signal model for n = 3 and N=7.
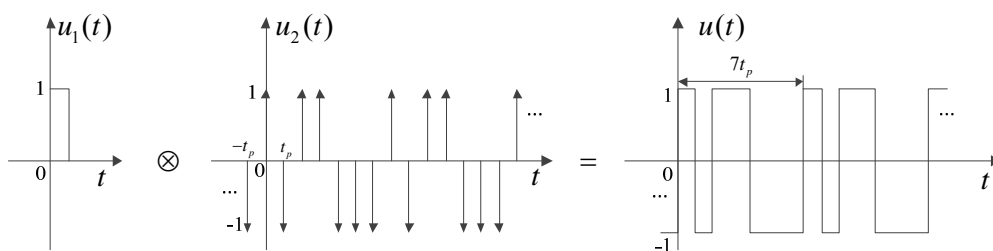

Figure 1. Periodic M-sequence signal model

The ambiguity function of the M sequence signal can be derived as:

$$\chi(\tau,\xi) = \int_{-\infty}^{\infty} u(t)u^*(t+\tau)e^{j2\pi\xi t}dt = \sum_{m=-(N-1)}^{N-1} \chi_1(\tau-mt_p,\xi)\chi_2(mt_p,\xi) \tag{6}$$

In the equation: $\underset{\tau}{\otimes}$ denotes the convolution of τ, $\chi_1(\tau,\xi)$ is the ambiguity function of a simple rectangular pulse signal, $\chi_2(\tau,\xi)$ represents the ambiguity function of the shock signal. Their expression equation can be written as:

$$\chi_1(\tau,\xi) = \begin{cases} e^{j2\pi\xi\tau} \dfrac{t_p-|\tau|}{t_p} \dfrac{\sin\pi\xi(t_p-|\tau|)}{\pi\xi(t_p-|\tau|)} & |\tau| \le t_p \\ 0 & |\tau| > t_p \end{cases} \tag{7}$$

$$\chi_2(mt_p,\xi) = \sum_{k=0}^{N-1} C_k C_{k+|m|} e^{j2\pi k\xi\tau} \qquad -(N-1) \le |m| \le N-1 \tag{8}$$

In the equation: $C_k = a_k e^{j\theta_k}$, a_k, θ_k denotes the amplitude and phase of the k-th symbol.

The periodic M sequence two-phase code has a steep main lobe and uniformly distributed side lobes, and the ratio of the main side lobes is equal to the number of pulses in a single cycle of the M sequence, so it has a good distance characteristic.

2.2. Aperiodic M sequence two-phase coded signal

Aperiodic M-sequence two-phase coded signals are mainly used in two-phase code pulse compression. The ambiguity function of aperiodic M-sequence two-phase coded signals can be expressed as:

$$\chi(\tau,\xi) = \sum_{m=-(N-1)}^{N-1} \chi_1(\tau-mt_p,\xi)\chi_2(mt_p,\xi) \tag{9}$$

In the equation: $\chi_1(\tau,\xi)$ is the ambiguity function of simple rectangular pulse signal, and its expression is the same as equation (7). $\chi_2(\tau,\xi)$ is as follows:

$$\chi_2(mt_p,\xi) = \begin{cases} \displaystyle\sum_{k=0}^{N-1-m} C_k C_{k+m} e^{j2\pi k\xi t_p} & 0 \le m \le N-1 \\ \displaystyle\sum_{k=-m}^{N-1} C_k C_{k+m} e^{j2\pi k\xi t_p} & -(N-1) \le m \le 0 \end{cases} \tag{10}$$

With respect to the periodic M sequence, the ratio of the main side lobes of the aperiodic M sequence waveform is much lower. When the code length N of the aperiodic M sequence is long enough, the ratio of the main side lobe can reach $\sqrt{N}$, but whether it is a periodic M sequence or a non-periodic M sequence, the distribution of the ambiguity function of the two is the same.

2.3. Two-phase coded modulation signal

As shown in Fig. 2, the pulse signal generator of the radar fuse generates a pulse train with a pulse width of t_p and a pulse repetition period (PRT) of T_r. The pulse train is modulated by modulator with

a pseudo-random binary code signal to form the transmitted signal. The transmitted signal encounters the ground reflecting back to form an echo signal. The echo signal is related to the previous transmitted pulse signal. Only reaching a certain degree of correlation, the echo is considered valid. This method effectively avoids the interference of other clutter and interference signals.
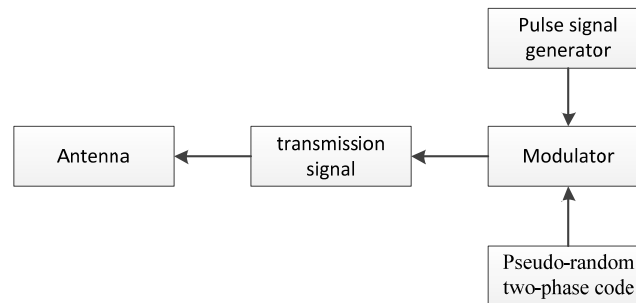

Figure 2. Pulse modulation block diagram

Fig. 3 shows a periodic M sequence two-phase code modulated pulse signal. It can be seen from the figure that the two-phase code sequence modulates the positive pulse train into positive and negative pulse trains, and the phase of the pulse train is synchronized with the phase of the two-phase code sequence.
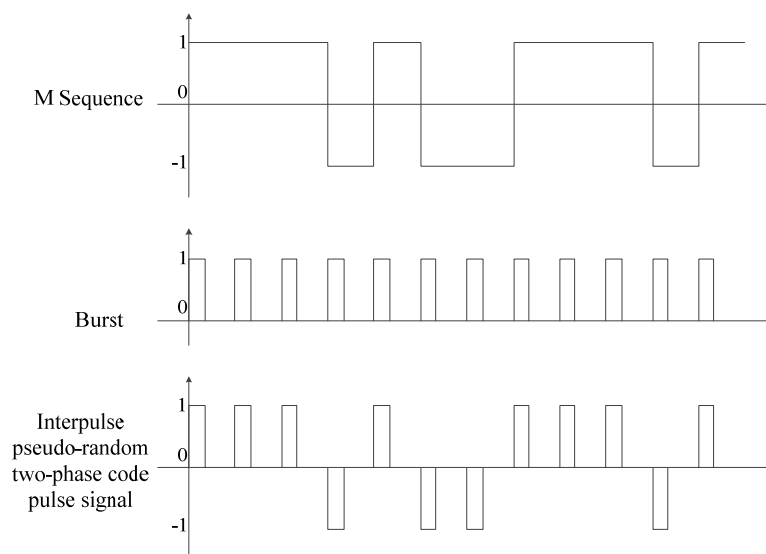

Figure 3. Two-phase code sequence modulation signal

3. PD radar fuze

3.1. Principle of PD radar fuze

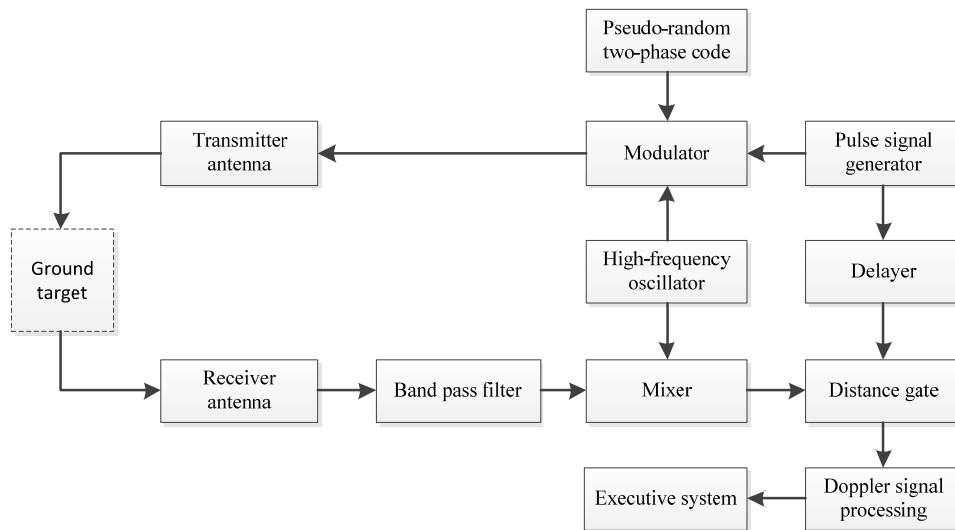Fig. 4 shows the block diagram of the PD radar fuse [5].

Figure 4. Functional block diagram of PD radar fuze

The PD radar fuse receives the target reflection signal during the transmission of the RF pulse and operates by using the frequency difference between the echo signal and the transmission signal. The fuse transmitter operates in a pulsed state and therefore has high peak power and low average power. Since the PD radar fuse operates on the Doppler principle, a wideband filter is not required. In addition, the PD radar fuse uses the Doppler frequency to determine the radial velocity of the target relative to the fuse, and its operating principle is the same as that of an ordinary PD radar. PD radar fuzes generally have the following characteristics:

1. Has a sufficiently high pulse repetition frequency (PRF) that there is no speed ambiguity in either the clutter or the observation target.

2. Be able to realize Doppler filtering of single spectral line of pulse train spectrum.

3. Due to the high PRF, there will be distance blurring.

The condition for radar fuses without distance ambiguity is: $\dfrac{c}{2PRF} > r$ r is the radial distance

between the radar fuse and the ground target. The condition without velocity ambiguity is: $\dfrac{\lambda PRF}{2} > v$

v is the radial velocity of radar fuses and ground targets. Therefore, distance ambiguity and velocity ambiguity are contradictory. In general, PD radar fuses use high PRF to avoid velocity ambiguity. In order to solve the distance ambiguity, radar fuses adopt two-phase coding technology.

4. Active interference analysis and simulation

According to the analysis of Section 2, it can be seen that the phase-encoded signal has good anti-interference performance. But what exactly is the anti-jamming performance? We need to give a result through simulation experiments. The paper selects two types of active interference, one is active suppression interference-radio frequency noise interference, and the other is active deception interference-intensive false-target interference. The conclusion is given through the analysis and simulation of the interference.

4.1. Doppler Effect

4.1.1. Analysis of RF noise interference. Radio frequency noise suppression interference is a typical way to suppress interference. It uses white noise or Gaussian noise to directly amplify and transmit [6]. In general, this type of interference is difficult to achieve high power, but with the development of

interference technology, high-power RF noise jammers have emerged. The advantage of RF noise is that the interference principle is simple, and theoretically it has a good masking effect. It is a good method of interference.

The mathematical expression of RF noise suppression interference is:

$$J_N(t) = A_n(t)\cos(\omega_o t + \varphi_n) \tag{11}$$

In the equation: $A_n(t)$ is the amplitude of the envelope, subjects to the Rayleigh distribution. φ_n is the phase process, obeys the uniform distribution of $[0, 2\pi]$, and they are independent. The power spectrum of RF noise usually uses the same rectangular power spectrum as the receiver bandwidth, expressed as:

$$P_{J_N}(\omega) = \begin{cases} \dfrac{N_0}{2} & |\omega \pm \omega_0| \le \pi\Delta F \\ 0 & others \end{cases} \tag{12}$$

In the equation: $\dfrac{N_0}{2}$ is a noise bilateral power spectral density, ΔF is the RF noise bandwidth, therefore, the power of RF noise is:

$$P_{J_N} = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\frac{N_0}{2}d\omega = N_0\Delta F \tag{13}$$

The echo signal of the fuze can be expressed as:

$$S_r(t) = A_r\cos((\omega_o + \omega_d)t + \varphi_r)[P_{\frac{\tau_0}{2}}(t - \tau_t) \otimes \sum_{-\infty}^{+\infty}\delta(t - NT_r)] \tag{14}$$

In the equation: $\tau_t = \dfrac{2(R_0 - v_r t)}{c}$ is the delay time, R_0 is the initial distance of the fuze, v_r is the decreasing speed, A_r is the amplitude of the echo pulse, φ_r is the echo phase, and ω_d is the Doppler angle frequency. The power of the echo can be derived from the above equation:

$$P_r = \lim_{T\to\infty}\frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}}S_r^2(t)dt = \frac{A_r^2\tau_0}{2T_r} \tag{15}$$

Combined with formula (13), the input signal to interference ratio of the fuse unit is:

$$\frac{S}{N} = \frac{P_r}{P_{J_N}} = \frac{A_r^2\tau_0}{2N_0\Delta F T_r} \tag{16}$$

4.1.2. RF noise interference simulation. Simulation description as follows: Fig. 5 shows the relationship between the SIR (signal to interference ratio) and echo correlation. Through the comparison of pictures, we can know that with the decline in the SIR ratio, the correlation between echo and range-gate is weaker.
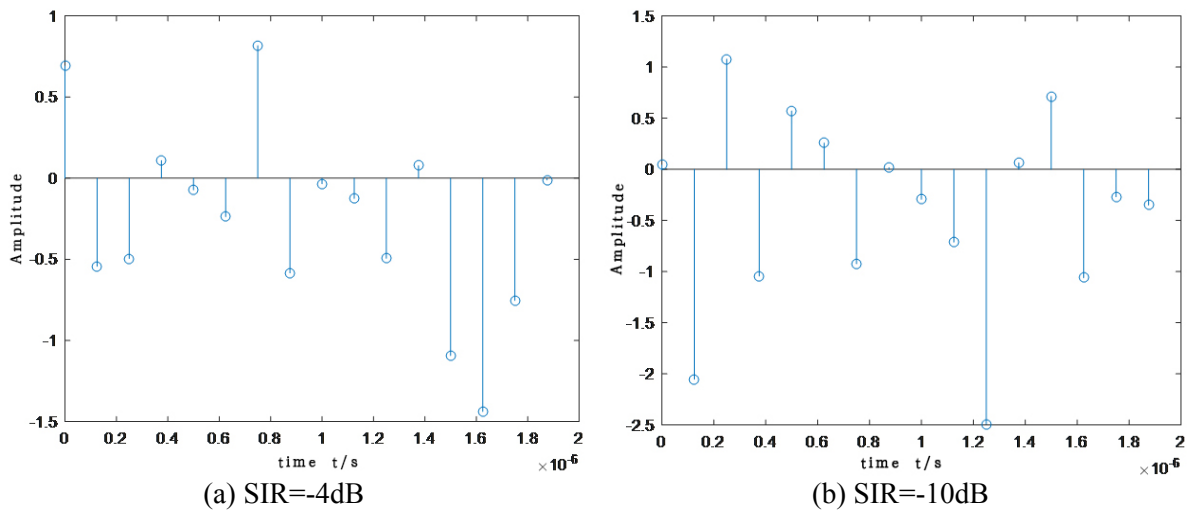
(a) SIR=-4dB (b) SIR=-10dB

Figure 5. The relationship between SIR and echo correlation
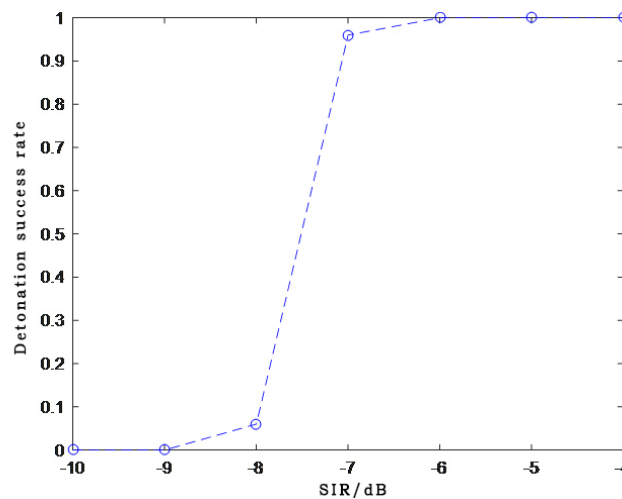

Figure 6. The relationship between the SIR and the probability of giving detonation signal

In the simulation experiment, SIR changed from -10dB to -4dB, and simulated 500 times after each change of experimental conditions. Fig. 6 shows the relationship between SIR and the probability of detonation signal. When the threshold is 90%, the SIR must be greater than -7dB, and the radar fuse can reliably give the detonation signal. This is because the radar fuse uses the amplitude and phase of the echo signal to determine the height of the target. When the interference power is large enough, the echo signal will be submerged, and it is difficult for the terminal of the radar fuse to extract effective information, causing misjudgment and reducing the correlation.

4.2. Dense false target interference

4.2.1. Analysis of dense false target interference. Dense false target interference belongs to forwarding fraudulent interference. The difference between dense false target interference and distance fraudulence interference is that the repetition period of dense false target interference pulses is very dense. It increases the probability of searching for interference signals from the range gate by a large number of interference pulses. Therefore, the success rate of dense false target interference is related

to the density, that is, the repetition period of interference pulses. The expression of dense false targets can be written as:

$$J_{NB}(t) = A_{NB} \cos(\omega_o(t - \tau_{NB}) + \varphi_{NB})[P_{\frac{\tau_0}{2}}(t - \tau_{NB}) \otimes \sum_{-\infty}^{+\infty} \delta(t - NT_{rNB})] \qquad (17)$$

In the equation: A_{NB} is the interference amplitude, τ_{NB} is the interference delay, φ_{NB} is the interference phase, and T_{rNB} is the repetition period of dense false target interference pulses, T_{rNB} is much smaller than T_r. From the expressions, it can be seen that the dense false target interference actually means that the jammer first intercepts the transmission signal of the fuse and then forwards it out at different periods. Calculating the effective interference power of interference needs to know two points, one is the power of a single false target, and the other is the detected number. Let $P_{NB}(i)$ be the power of the i-th false target, m is the total number of false targets detected in the 2n unit, and the power of the effective false target interference is:

$$P_{NB} = \frac{\sum_{i=1}^{m} P_{NB}(i)}{2n} = \frac{mP_{NB}(i)}{2n} \qquad (18)$$

4.2.2. Intensive false target simulation. The paper uses repeatered dense false target interference. The jammer first receives the signal sent by the radar fuse, then analyzes the signal, and finally emits an interference pulse sequence similar to the echo but with all amplitudes of 1. The interference signal is superimposed with the echo signal, thus destroying the phase code information of the echo phase code. Fig. 7 shows the simulated interference signal.

Fig. 8(a) shows an ideal echo in one encoding period, and Fig. 8(b) shows an echo superimposed in one encoding period. By comparison, it can be seen that the interference will affect the encoding phase of the echo.

Simulation experiment set SIR to -6dB, do 100 simulations to get simulation data, the data is shown in Fig. 9. In the case of a false target interference superposition, the correlation peaks associated with echoes and distance gates will be significantly smaller than the ideal case, with the best one being only 34% of the ideal value.

Through analysis, we can know that the amplitude of the echo has both positive and negative values after two-phase code modulation, as shown in Fig. 3. These positive and negative echo sequences represent the phase information of the two-phase code. Dense interference superimposes echoes by a large number of positive pulses, turning some negative pulses in the echo sequence into positive or zero values. After quantization, these changed pulses become 1-valued pulses. The phase information of the two-phase code originally carried by the echo is destroyed. When the echo is correlated with the original binary code sequence, the correlation will be greatly reduced.
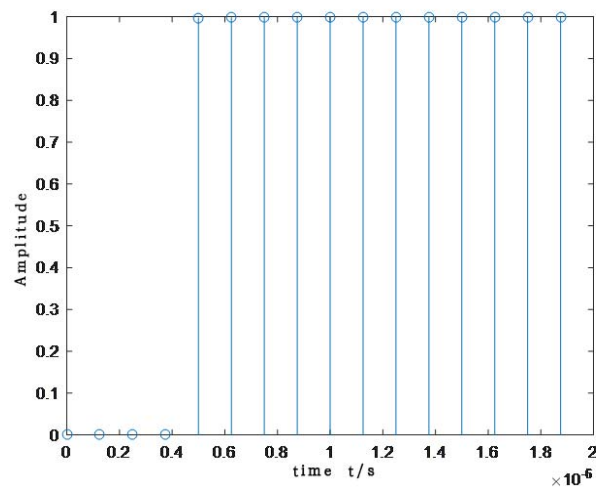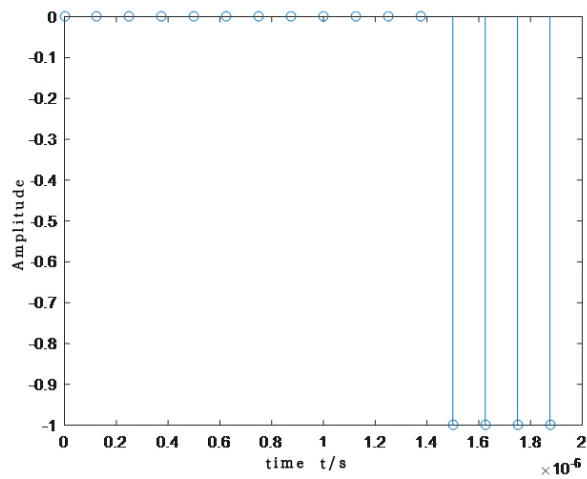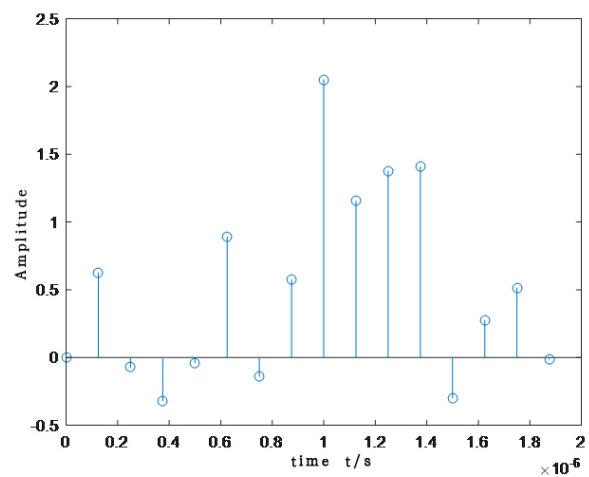
Figure 7. Interference signal simulation diagram

(a) Ideal echo

(b) Echo with interference superposition

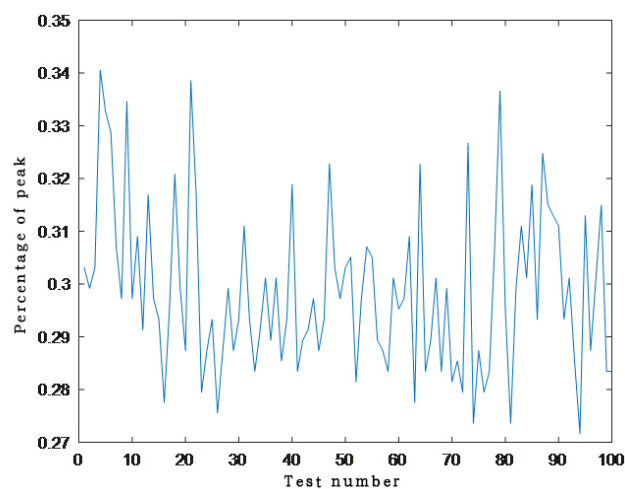**Figure 8.** Comparison between ideal echo and interference echo

Figure 9. Correlation peak data

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5. Conclusion

The paper introduces the principle of two-phase coded signal and PD radar fuse. Two-phase coded signal can improve the anti-interference of PD radar fuze, however, quantitative analysis results are lacked. The paper selects two typical active interferences and simulates the interference of a two-phase coded PD radar radar. We summarized two conclusions through simulation results: one conclusion is that for suppressing jamming, two-phase coded PD radar fuse have certain immunity to interference, but as the jamming power increasing, PD radar radar fuzes will also be affected; another is that for superimposed dense false-target interferences, the anti-interference effect of two-phase coded PD radar fuse is relatively poor, and interference can easily affect the fuzes.

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