Calculation and Analysis of FCR Burn-Through Range with Noise Jamming

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Abstract Burn-through range is the important basis to evaluate the antinoise jamming capability of fire control radar (FCR). In order to calculate and analyze FCR burn-through range in noise jamming conditions, a calculation of burn-through range is thus modeled. The model puts into consideration the influences on calculation of burn-through range exerted by pulse accumulation and imperfect jamming signal and adoption of technological measures as fixed multipoint frequency hopping, random digit code frequency hopping, and pulse compression. In the operations with scenarios, the model makes a calculation of FCR burn-through range. The calculation result can be used to analyze FCR antinoise jamming capability and to guide the research on relative antijamming technologies and tactical measures.

Keywords Fire control radar · Noise jamming · Burn-through range Calculation

1 Introduction

Noise jamming is a kind of electronic jamming with randomly changing frequency, amplitude, and phase. Similar to the internal noise of radar receiver, it is a basic jamming pattern of suppression jamming [1, 2]. The detection of target by fire control radar (FCR) is based on a certain probability with regard to noise. When the external noise enters radar receiver, the noise-to-signal ratio of the receiver will be increased. Thus, the radar is difficult to detect the target [3]. The burn-through range is the significant item to reflect the combat capability of FCR in noise jamming conditions. The quantitative calculation of burn-through range is of good reference for analyzing FCR antijamming capability and researching proper antijamming technologies and tactical measures.

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2 Calculation Model of Burn-Through Range with Noise Jamming

When suffering from the noise jamming released from jammer, the noise-to-signal ratio obtained by radar is [4] as follows:

$$\frac{P_{rj}}{P_{rs}} = \frac{P_j G_j}{P_t G_t} \cdot \frac{4\pi\gamma_j}{\sigma} \cdot \frac{G_t'}{G_t} \cdot \frac{R_t^4}{R_j^2} \cdot \frac{\Delta f_r}{\Delta f_j} \tag{1}$$

in which P_j is transmitting power of jammer, G_j is gain in main lobe direction of jammer antenna, γ_j is polarization coefficient of jamming signal toward radar antenna, usu. $\gamma_j = 0.5$, R_j is distance between jammer and radar, Δf_j is bandwidth of jammer, P_t is transmitting power of radar, G_t is gain in the main lobe direction of radar antenna, σ is radar cross-section, R_t is distance between target and radar, Δf_r is bandwidth of radar receiver, and G_t' is radar antenna gain in jammer direction. The approximate calculation formula of G_t' is as follows [4]:

$$G_t' = \begin{cases} G_t & 0 \le |\theta| < \theta_{0.5}/2 \\ K(\theta_{0.5}/\theta)^2 G_t & \theta_{0.5}/2 \le |\theta| < 90^\circ \\ K(\theta_{0.5}/90)^2 G_t & 90^\circ \le |\theta| < 180^\circ \end{cases} \tag{2}$$

in which θ is included angle between radar main lobe direction and jammer direction, $\theta_{0.5}$ is lobe width of radar antenna, and K is a constant ranging from 0.04 to 0.1. To the antenna with high gain and strong directivity, K takes larger value; to the antenna with small gain and wide beam, K takes smaller value. The FCR is of high gain and strong directivity, and K thus takes larger value ranging from 0.07 to 0.1.

If the jamming is effective, the noise-to-signal ratio should be greater than or equal to suppression coefficient K_j, i.e.,

$$\frac{P_{rj}}{P_{rs}} = \frac{P_j G_j}{P_t G_t} \cdot \frac{4\pi\gamma_j}{\sigma} \cdot \frac{G_t'}{G_t} \cdot \frac{R_t^4}{R_j^2} \cdot \frac{\Delta f_r}{\Delta f_j} \ge K_j \tag{3}$$

Suppression coefficient refers to the ratio of the minimum jamming signal obtained by radar receiver input terminal to radar echo signal power when radar detection probability decreases to 0.1, i.e.,

$$K_j = P_j / P_r |_{P_d = 0.1} \tag{4}$$

Obviously, suppression coefficient is a comprehensive function involving jamming signal modulation pattern, jamming signal quality, receiver response characteristics, signal processing mode, etc. Reference Book No. 5 makes analysis of the value range of suppression coefficients in terms of radar with PPI and range scope as terminal devices and radar in automatic working state. Reference Book No. 6 points out that the value of jamming suppression coefficient is usually 3 dB in terms of conventional pulse radar, frequency agility radar, and frequency diversity radar. It should be noted that the above value is merely a coarsely estimated value. Reference Book No. 7 makes a calculation of noise jamming suppression coefficient in various modulation modes. Reference Book No. 8 points out that when false alarm probability P_{fa} ranges from 10^{-3} to 10^{-9} and detection probability P_d ranges from 0.1 to 0.9, the calculation result can be accurate to less than 0.2 dB by using the following formula:

$$S/J = \lg(A + 0.12AB + 1.7B) \tag{5}$$

in which $A = \ln\left(0.62/P_{fa}\right)$, $B = \ln[P_d/(1 - P_d)]$. FCR usually adopts constant false alarm detection technology. When the false alarm probability is determined, calculate the signal-to-noise ratio when detection probability P_d is 0.1, then take the reciprocal of signal-to-noise ratio, thus obtain suppression coefficient.

When Expression No. (3) takes the equal sign, R_t in this case is termed burn-through range, and is also called self-defense range. It can be represented by R_O, whose value is as follows:

$$R_O = \left(\frac{P_t G_t}{P_j G_j} \cdot \frac{\sigma}{4\pi\gamma_j} \cdot \frac{G_t}{G_t'} \cdot \frac{\Delta f_j}{\Delta f_r} \cdot R_j^2 \cdot K_j\right)^{1/4} \tag{6}$$

When target range is greater than or equal to R_O, FCR cannot detect the target; when less than R_O, FCR is capable of detecting the target.

3 Correction of Calculation Model in Several Cases

3.1 Correction in Case of Pulse Accumulation

Expression No. (6) is a calculation model on a basis of one target echo. When FCR actually detects the target, it makes the useful radar echoes from target added together. Reference Book No. 8 indicates that the radar operator observes cathode-ray tube display and acquires the accumulation improvement factor which is thought to be equal to $\sqrt{n}$ (n is the accumulated echo number) in early radars, which is actually obtained according to incorrect theory and poorly performed display. In consideration of pulse accumulation, the relationship among radar detection probability, false alarm probability, and signal-to-noise ratio can be expressed in the following experiential formula:

$$(S/J)_n = -5\lg n + \left(6.2 + \frac{4.54}{\sqrt{n - 0.44}}\right) \cdot \lg(A + 0.12AB + 1.7B) \tag{7}$$

It should be noted that the result of Expression No. (7) is in unit of dB. The echo number n accumulated by radar can be calculated by the following formula:

$$n = \frac{\theta_{0.5} f_p}{\theta_s} \tag{8}$$

in which $\theta_{0.5}$ is radar antenna lobe width, f_p is pulse repetition frequency, and θ_s为 is antenna scanning speed.

3.2 Correction in Case of Imperfect Jamming Signal

With regard to Expression Nos. (5) and (7), the jamming signal input to radar receiver is Gaussian noise. In terms of information theory, the optimum jamming waveform is characteristic of maximum entropy, i.e., the waveform with maximum uncertainty. With certain average power, Gaussian noise has maximum entropy in any random waveform. Therefore, the ideal optimum jamming waveform is Gaussian noise. The amplitude of Gaussian noise distribution random variable covers the infinity, which cannot be realized in the actual equipment [3]. Expression Nos. (3) and (5) put forward the noise quality factor which is used to evaluate the quality of actual jamming signal. The noise quality factor means the ratio of P_{j0} needed by ideal jamming signal to P_j needed by actual jamming signal with the same suppression effect, i.e.,

$$\eta = \frac{P_{j0}}{P_j} \tag{9}$$

With the known jamming power needed by Gaussian noise multiplied by noise quality factor, one can get the power needed by actual effective jamming. Expression No. (6) may be corrected as follows:

$$R_O = \left(\frac{P_t G_t}{P_j G_j} \cdot \frac{\sigma}{4\pi\gamma_j} \cdot \frac{G_t}{G_t'} \cdot \frac{\Delta f_j}{\Delta f_r} \cdot R_j^2 \cdot \frac{K_j}{\eta}\right)^{1/4} \tag{10}$$

Yet, the probability density of actual jamming signal is difficult to be analyzed by use of mathematical formula. Thus, the noise quality factor is often determined by use of experimental method. Usually, noise quality factor $\ll 1$ [5]. The testing results of jammers which are in service or being developed indicate that the noise quality factor of actual jamming signal has a loss of 17 dB [3] compared with ideal Gaussian noise, i.e., $\eta = 0.02$.

3.3 Correction After Adopting Antijamming Measures

3.3.1 Correction After Adopting Fixed Multipoint Frequency Hopping

The frequency hops in a wider range so that radar may work in the frequency which is not being jammed [9]. It is the important antijamming measure of FCR. The faster and wider the frequency hops with stronger randomness, the higher the antijamming capability. If the fixed multipoint frequency hopping is employed, the number (n) of frequency hopping points generally does not exceed 20. As to this kind of frequency agility radar, jammer may use frequency memory. It may transmit the jamming signals at n numbers of frequency points. Thus, the radar will suffer from noise suppression jamming no matter which frequency point it hops to. With regard to fixed multipoint frequency hopping, Expression No. (6) can be corrected as follows:

$$R_O = \left(\frac{P_t G_t}{P_j G_j} \cdot \frac{\sigma}{4\pi\gamma_j} \cdot \frac{G_t}{G_t'} \cdot \frac{\Delta f_j}{\Delta f_r} \cdot R_j^2 \cdot K_j \cdot n \right)^{1/4} \tag{11}$$

3.3.2 Correction After Adopting Random Digit Code Frequency Hopping

With the development of technology, the modern FCR may conduct random digit code frequency hopping in the whole working bandwidth. Since the jammer is unable to get the fixed frequency points of the radar, it generally employs wideband noise barrage jamming. Then, the jamming band needs to cover the whole working band f_r of the radar, i.e.,

$$f_r = \Delta f_j \tag{12}$$

3.3.3 Correction After Adopting Pulse Compression

Pulse compression means the transmitter transmits the wide pulse signal with regularly changing carrier frequency and the receiver compresses the echo signal into narrow pulse signal. Modern FCR usually employs pulse compression technology which means to adopt wide pulse in transmission to enhance transmission average power and ensure distant enough detection range, and to obtain narrow pulse in reception to acquire good range resolution. Thus, it effectively solves the contradiction between detection range and range resolution [10]. With pulse compression technology, when all the other conditions are same, the filtering of wide pulse by matched filter increases the suppression coefficient by B times [11]:

$$B = \frac{\tau_s}{\tau_{sc} \cdot K_o} \tag{13}$$

in which τ_s is pulse signal width of receiver input terminal, τ_{sc} is pulse signal width after pulse compression, and K_o is a coefficient causing rectangular parameters to change when radar pulse is widened that may take the value of 1.5.

4 Application and Analysis of Calculation Model

The following illustrates calculation of burn-through range of FCR on the background of jammer screening fighter bomber to penetrate FCR. The FCR parameters are as follows: P_t = 160 kW, G_t = 36 dB, $\theta_{0.5}$ = 20, Δf_r = 3 MHz. The farthest operating range is 75 km to the target with σ = 10 m^2. f_p = 1500 Hz, θ_s = 900/s, P_{fa} = 10^{-6}. The constant of antenna pattern K takes the value of 0.1. With fixed frequency hopping technology, there are ten frequency hopping points. With random digit code frequency hopping, f_r may vary randomly within 1000 MHz. With pulse compression, the pulse width can compressed from 6 μs into 0.3 μs. Jammer and fighter bomber parameters are as follows: P_j = 1000 kW, R_j = 150 km, σ = 10 m^2, G_j = 20 dB, Δf_j = 6 MHz. The calculation result is shown in Table 1.

Different values pertaining to each parameter may be taken for calculation of burn-through range and a graph of burn-through range changing with included

Table 1 FCR burn-through range with noise jamming

Antijamming measures	$\|\theta\|$ (°)	Burn-through range (km)
No measures	0	2.4
	10	9.8
	30	17.0
	90	29.5
Fixed multipoint frequency hopping	0	4.3
	10	12.2
	30	30.3
	90	52.4
Random digit frequency hopping	0	8.8
	10	35.1
	30	61.2
	90	75
Pulse compression	0	4.8
	10	18.6
	30	32.4
	90	56.4

angle then be drawn. Lack of space forbids further elaboration. According to the above combat background, the following points can be presented from the calculation result:

(1) Without antijamming measures, the maximum burn-through range is 29.5 km which is 39.3% of normal operating range, and the minimum burn-through range is 2.4 km, just 3.2% of normal operating range which basically loses working capability. Thus, FCR is of poor antinoise jamming capability.
(2) With antijamming measures, the antijamming capability is apparently improved. Random digit code frequency hopping achieves optimum antijamming effect. Fixed multipoint frequency hopping and pulse compression share similar effects. If pulse compression ratio and fixed frequency hopping points are increased, the burn-through range will be further lengthened.
(3) The FCR antijamming capability is closely related to the included angle θ between jammer antenna and radar antenna main lobe. When jammer conducts jamming within radar antenna main lobe, the radar's maximum burn-through range does not exceed 9 km which is 12% of normal operating range. The radar is seriously affected. When jammer conducts jamming beyond radar antenna main lobe, radar's burn-through range will be rapidly increased.

5 Conclusion

This paper makes a calculation and analysis of FCR burn-through range with noise jamming. In consideration of pulse accumulation and imperfect jamming signal and adoption of technological measures as fixed multipoint frequency hopping, random digit code frequency hopping, and pulse compression, the calculated result may reflect the actual countering effect, which is of certain reference and application value. Jamming and antijamming will undergo a dynamic development process. While adopting various new jamming patterns, new antijamming systems and technologies, FCR antijamming capability calculation and analysis needs further research.

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