Homogeneously Distributed Multiple False Targets Jamming Using Frequency Diverse Array

Hui Wang*, Shunsheng Zhang*, Wen-Qin Wang†, Haoliang Guan*, Huihui Ding*
*Research Institute of Electronic Science and Technology, University of Electronic Science and Technology of China
†School of Communication and Information Engineering, University of Electronic Science and Technology of China
Email: cswh147@sina.com

***Abstract*—a novel radar jamming method using frequency diverse array (FDA) is proposed, which is a new technology to encounter pulse compression radar, where the jamming signals generated directly by the FDA do not rely on the radar transmit full signals and its parameters are obtained using the reconnaissance system, so that real-time jamming can be achieved. Compared to the traditional delay-based jammer, our proposed jamming method can easily generate a lot of false targets that are evenly distributed around the true target, and the number of false targets depends on array elements, which implies that many false targets can be generated easily. Simulation results verify the effectiveness of the proposed approach.**

I. INTRODUCTION

Traditional phased-array (PA) is widely used in both military and civil applications. Their ability of adaptive beamforming and flexible beam scanning can largely benefit detection and estimation tasks [1]. PA is playing a more and more important role in modern air defense systems. So how to effectively jam PA and protect our facilities from being detected is becoming a concerned topic in the national military community. At present, jamming techniques to PA can be mainly divided into two categories: Passive jamming and active jamming. Passive jamming is implemented by reducing significance of object target while generating false targets with the help of camouflages or reflectors with large reflecting angles. Active jamming can be divided into noise jamming and deception jamming. Deceptive jammer transmit signals with the same characteristics as those transmitted from enemies, so that false targets can be present. Noise jamming uses noise signal to suppress radar signal, making object target hard to be detected, thus weaken the ability of enemy's electronic device and system [2-3].

Recently, frequency diverse array (FDA) has attracted extensive attention of scholars, which was initially introduced in [4-7] and later the basic characteristic of FDA was investigated [4-10]. By analyzing the echoes from the target of a fixed distance and angle, we have discovered from the antenna pattern that can be represented as a train of peaks with an interval of $1/\Delta f$ that can affect the width of the main lobe after range compression. This special property is extremely useful to jam radar.

Conventional false target deception jamming mainly adopts direct delay, but its deficiency is highly obvious: Above all, fake targets often appear behind real targets, and it is easy to be recognize and eliminated by radar counter-jamming system; Furthermore, it needs to get the full waveform of radar signal instantaneously, which is extraordinary difficult, because there is a mutual movement between radar and jammer in the actual battlefield environment. Our proposed jamming method using FDA signal can easily overcome these shortcomings well. The novelty of our approach lies in the following three points: First, the jamming signals are generated directly by the FDA and the frequency modulation rate and carrier frequency parameter information using reconnaissance equipment to obtain, which ensures the practicability of the jammer. Next, multiple false targets produced using FDA jamming are uniformly distributed both in front of and behind the true target, and by increasing array elements, the number of false targets can be increased, provided that we want to ensure that the difference between the frequency increment and the signal bandwidth can not be too large. Last, the jamming method can not only interfere with the conventional mechanical radar (CMR), but also has better jamming effect to the phased array radar, and our proposed jamming method perform better than delay based jamming in interfering both phased array radar and mechanical radar. This article assumes that the radar to be jammed transmit a linear chirp and the parameters of the jammer are obtained using the reconnaissance system.

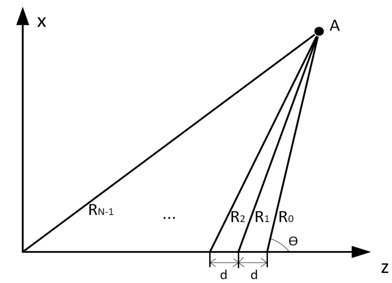

Fig. 1. Linear array of N equally spaced elements.

II. PRINCIPLE OF FDA RADAR JAMMING

For simplicity and without loss of generality, we assume that there is a uniform linear array containing N elements with spacing d and the carrier frequency of each element increases linearly with a frequency increment Δf, which is shown in Fig. 1. All elements are assumed to be in phase coherence and where the signal transmitted by the kth element can be expressed by

$$s_k\left(t\right) = rect\left(\frac{t}{T_p}\right)\exp\left(j2\pi f_k t\right)\exp\left(j\pi\gamma t^2\right) \tag{1}$$

Where $rect\left(\frac{t}{T_p}\right) = \begin{cases} 1, |t| \le \frac{T_p}{2} \\ 0, |t| > \frac{T_p}{2} \end{cases}$ is the impulse function, T_p is the pulse duration, $\gamma = \frac{B}{T_p}$ is the frequency modulation rate, B is the signal bandwidth, $f_k = f_0 + k\Delta f, k = 0, 1, \cdots, N-1$. Consider a far field point target at angle θ, range R_0, the echo pattern $p\left(f, t, R_0, \theta\right)$ can be written as

$$\begin{aligned} p\left(f, t, R_0, \theta\right) &= \sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{t - \frac{R_k}{\lambda_k}}{T_p}\right)\exp\left(j\omega\right) \\ &= \sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{t - \frac{R_k}{\lambda_k}}{T_p}\right)\exp\left\{j\left(\varphi_0 + \omega_k\right)\right\} \\ &\approx \sum_{k=0}^{N-1} \frac{1}{R_0} rect\left(\frac{t - \frac{R_k}{\lambda_k}}{T_p}\right)\exp\left\{j\left(\varphi_0 + \omega_k\right)\right\} \end{aligned} \tag{2}$$

Where $R_k = R_0 + kd\sin\theta, \lambda_0 = c/f_0$,
$\omega = 2\pi\left(\frac{\gamma}{2}t^2 + f_k t - \frac{R_k}{\lambda_k}\right)$, $\varphi_0 = 2\pi\left(f_0 t - \frac{R_0}{\lambda_0}\right) + \pi\gamma t^2$,

$$\omega_k = 2\pi\left(\frac{\gamma}{2}t^2 + k\Delta f t - k\frac{\Delta f R_0}{c} - k\frac{d\sin\theta}{\lambda_0} - k^2\frac{\Delta f d\sin\theta}{c}\right)$$

and the approximation is made due to the fact that .Although, in general terms, a closed form of the pattern in (2) cannot be written, a closed approximation exists when $\left(N-1\right)\Delta f/c \ll 1/\lambda_0$, which is true as long as $(N-1)\Delta f \ll f_0$, In this case the term $k^2\Delta f d\sin\theta/c$ in (2) becomes negligible [14], and the pattern can be written as

$$\begin{aligned} p\left(f, t, R_0, \theta\right) &\approx \sum_{k=0}^{N-1} \frac{1}{R_0} rect\left(\frac{t}{T_p}\right)\exp\left(j\varphi_0\right) \\ &\quad \times \exp\left\{j2\pi k\left(\Delta f t - \frac{\Delta f R_0}{c} - \frac{d\sin\theta}{\lambda_0}\right)\right\} \\ &\approx rect\left(\frac{t}{T_p}\right)\frac{\exp\left\{j\left(\varphi_c + \pi\left(N-1\right)\frac{d\sin\theta}{\lambda_0}\right)\right\}}{R_0} \\ &\quad \times \frac{\sin\left[\pi N\left(\Delta f t - \frac{\Delta f R_0}{c} - d\sin\theta\right)\right]}{\sin\left[\pi\left(\Delta f t - \frac{\Delta f R_0}{c} - \frac{d\sin\theta}{\lambda_0}\right)\right]} \end{aligned} \tag{3}$$

Where $\varphi_c = 2\pi f_c\left(t - \frac{R_0}{c}\right) + \pi\gamma t^2$, $f_c = \frac{1}{N}\sum_{k=0}^{N-1} f_k = f_0 + \frac{N-1}{2}\Delta f$, $d = \frac{\lambda_0}{2}$, then we can exploit the property of FDA to jam conventional mechanical radar and modern phased-array radar. The jamming signal is exactly the same as the FDA signal.

In order to facilitate the analysis and make comparison, two hypotheses were presented in this section. At the same time, we assume that the parameters of jammer are obtained by the reconnaissance system and the radar to be jammed transmit a linear chirp. The geometry relationship of airborne radar and the jammer is shown In Fig.2. The airborne radar platform flies along an ideal orbit line at an altitude of h with a constant velocity v. P is the target location. θ is the beam width.

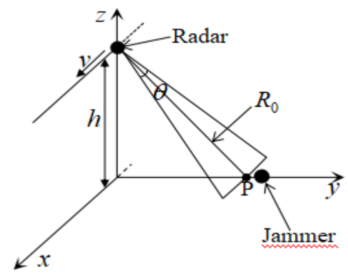

Fig. 2. the jammer geometric model.

A. Multiple False Targets Jamming Used On CMR

First, assuming the conventional mechanical radar signal is

$$s_m(t) = rect\left(\frac{t}{T_p}\right)\exp\left\{j2\pi\left(f_0 t + \frac{\gamma}{2}t^2\right)\right\} \tag{4}$$

The matched filter response of traditional mechanical radar is

$$h_m\left(t\right) = s_m^*\left(t_0 - t\right) \tag{5}$$

Where t_0 is delay of the filter and in general, we assume it is equal to 0. When FDA jamming signal passes through the linear filter, the output is

$$\begin{aligned} y_{mj}\left(t\right) &= p\left(f, t, R_0, \theta\right) * h_m\left(t\right) \\ &= \int_{-\infty}^{+\infty}\sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{\tau}{T_p}\right) rect\left(\frac{t-\tau}{T_p}\right) \\ &\quad \times \exp\left\{j2\pi\left(f_k\tau - \frac{R_k}{\lambda_k}\right) + j\pi\gamma\tau^2\right\} \\ &\quad \times \exp\left\{j2\pi\left(f_0\left(t-\tau\right) - \frac{\gamma}{2}\left(t-\tau\right)^2\right)\right\} d\tau \\ &= \sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{t}{2T_p}\right)\frac{\sin\left\{\pi\phi\left(T_p - |t|\right)\right\}}{\pi\phi} \\ &\quad \times \exp\left\{j2\pi\left(f_0 t + \frac{k\Delta f}{2}t - \frac{R_k}{\lambda_k}\right)\right\} \end{aligned} \tag{6}$$

Where $\phi = k\Delta f + \gamma t$, the first exponential term is caused by the positions of different elements and different frequency increment and indicates the phase; while $\frac{\sin\{\pi\phi(T_p - |t|)\}}{\pi\phi}$ is the compression result of a chirp. Then the amplitude response of the output $y_{mj}\left(t\right)$ can be derived as

$$|y_{mj}(t)| = \sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{t}{2T_p}\right)\frac{\sin\left\{\pi\phi\left(T_p - |t|\right)\right\}}{\pi\phi} \tag{7}$$

Where $\phi = k\Delta f + \gamma t$, the main lobe width of $\frac{\sin\{\pi\phi(T_p - |t|)\}}{\pi\phi}$ depends on the product of kth element and the frequency increment. At the same time, the bandwidth also has an impact on it. The number of peak is determined by the number of array elements.

B. Multiple False Targets Jamming Used On PA radar

Because the expressions of FDA radar and phased-array radar are distinguished only by frequency increment. Therefore the phased array signal model can be expressed as

$$s_p(t) = \sum_{k=0}^{N-1} \frac{1}{R_k} rect\left(\frac{t}{T_p}\right) \times \exp\left\{j2\pi\left(f_0 t - \frac{R_k}{\lambda_k} + \frac{\gamma}{2}t^2\right)\right\} \tag{8}$$

Assuming the matched filter response of phased array radar is

$$h_p(t) = s_p^*(-t) \tag{9}$$

Then pulse compression can be conduced as

$$\begin{aligned} y_{pj}(t) &= p(f,t,R_0,\theta) * h_p(t) \\ &= \int_{-\infty}^{+\infty} \sum_{k=0}^{N-1}\sum_{k=0}^{N-1} \frac{1}{R_k^2} rect\left(\frac{\tau}{T_p}\right) rect\left(\frac{t-\tau}{T_p}\right) \\ &\times \exp\left\{j2\pi\left(f_0(t-\tau) + \frac{R_k}{\lambda_k} - \frac{\gamma}{2}(t-\tau)^2\right)\right\} \\ &\times \exp\left\{j2\pi\left(f_k\tau - \frac{R_k}{\lambda_k} + \frac{\gamma}{2}\tau^2\right)\right\} d\tau \\ &= \sum_{k=0}^{N-1}\sum_{k=0}^{N-1} \frac{1}{R_k^2} rect\left(\frac{t}{2T_p}\right) \frac{\sin\{\pi\phi(T_p - |t|)\}}{\pi\phi} \\ &\times \exp\left\{j2\pi\left(f_0 t + \frac{k\Delta f}{2}t\right)\right\} \end{aligned} \tag{10}$$

It can be seen from the formula (10): Phase of the exponential term is independent of the distance. The number and location of the main peaks should be related to the frequency increment Δf and the number of the array elements N. In practical applications, we must ensure that the frequency increment Δf is not much greater than the signal bandwidth B, otherwise, multiple false targets will not occur.

III. SIMULATION ANALYSIS

In this part, we assume that the parameters of the jammer measured by the reconnaissance system are the same as that of the other radar system. Homogeneously Distributed Multiple False Targets Jamming are simulated and verified with parameters shown in TABLE. I:

TABLE I
SIMULATION PARAMETERS

Parameter name	Parameter value
Carrier frequency	$1GHz$
Bandwidth	$100MHz$
Pulse width	$20us$
Reference range	$3km$
Frequency increment	$300KHz$
Angle	0°
Speed light	$3\times10^8 m/s$

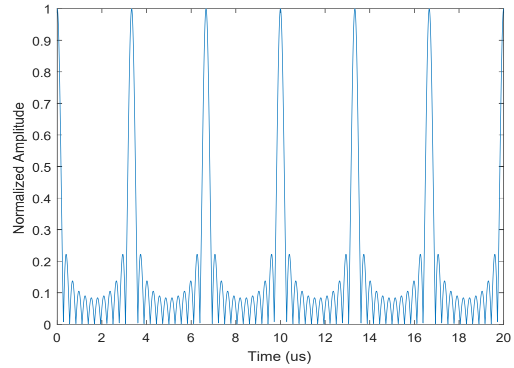

Fig. 3. jamming signal (12 elements)

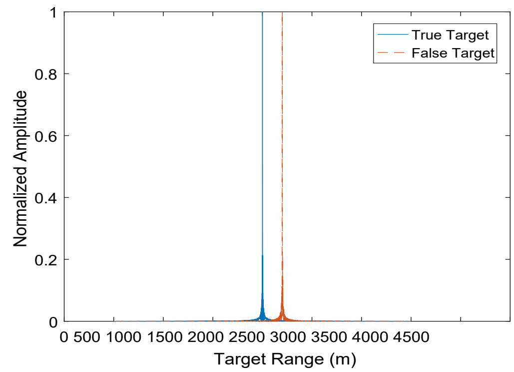

Fig. 4. Direct delay jamming

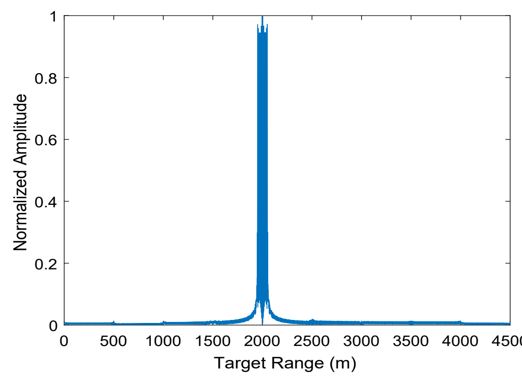

Fig. 5. Pulse compression result of the mechanical radar (12 elements)

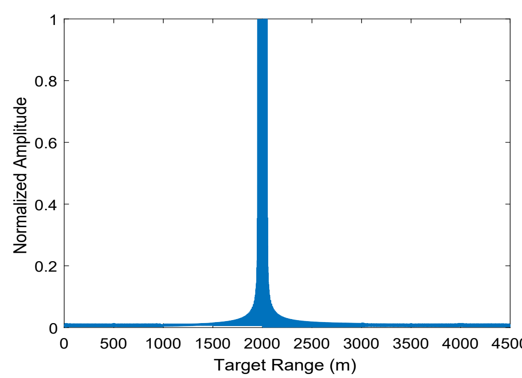

Fig. 6. Pulse compression result of the phased array radar (12 elements)

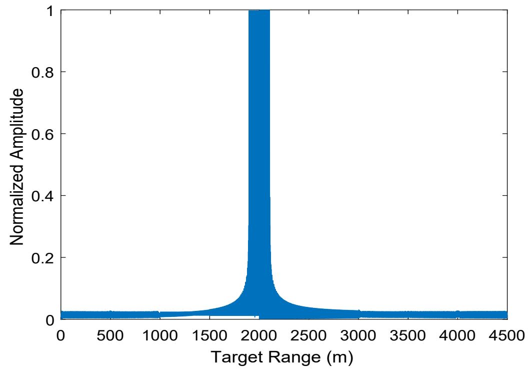

Fig. 7. Pulse compression result of the phased array radar (24 elements)

The jamming signal generated by the FDA is show in Fig.3, which is a periodic signal with an interval of $1/\Delta f$, which proves that the theory depicted in previous section is correct. Because the jamming signal only need to receive part of the radar transmitting signal, it can interfere with the radar in real time, which is extremely important for Modern Warfare. According to the Fig.4, it can be clearly seen that the direct delay jamming forms a false target which is behind the true target, and this result is applicable to the phased array radar is also suitable for CMR. The result of pulse compression of the signal received by CMR with FDA jamming (The number of array elements of FDA is 12) is shown in Fig.5, and the pulse compression result of the phased array received signal is shown in Fig.6. The result corresponding to received signal jammed by FDA with 24 elements of pulse compression of phased array radar is shown in Fig.7.

From the above simulation results, we can clearly get the following conclusions: Firstly, the CMR system using FDA jamming appears multiple false peak, which are evenly distributed around the true target, and they are about the symmetry of the main peak, as shown in Fig.5. Secondly, the phased array radar can also be interfered with the jamming signal, and all the false target peaks are of the same altitude, which is shown in Fig.6. Thirdly, From Fig.6 and Fig.7, it can be seen that the number of false targets can be increased by increasing array elements. Finally, this jamming method not only can interfere with phased array and conventional mechanical radar, but also has better jamming effect than direct delay jamming, as shown in Fig.4, Fig.5 and Fig.6.

IV. Conclusion

Homogeneously distributed multiple false targets jamming method based on FDA was studied in this paper. When this method is used to jam conventional mechanical radar, multiple false targets can be evenly placed around the real target, and consequently, there are a main false peak and multiple symmetrical secondary false peaks due to multiple false targets. At the same time, this approach is also suitable for jamming traditional phased array radar, where multiple false targets are equably distributed in front and at the back of the true target. Simulation results clearly show that the number of false targets increases with the increase of the array elements. Compared with conventional direct delay interference, this jamming approach is extremely effective to interfere with phased array radar and conventional mechanical radar.

V. Acknowledgments

This work was supported by the National Natural Science Foundation of China under grant 61671122.

References

[1] Jingwei Xu, Guisheng Liao, Shengqi Zhu. Receive Beamforming of Frequency Diverse Array Radar Systems. 2014 XXXIth URSI General Assembly and Scientific Symposium(URSI GASS), 2014: 1-4

[2] Jianyin Liu, Zhenhua Liu, Wenzhen Yu. Study on the Jamming of SAR Point Target. Modern Radar, 2006,28(10): 38-41

[3] Zengtai Zhang. Design Discussion of Structurai System for Mobiie 3D Radar. Electro -Mechanical Engineering, 2004,20(5): 11-13

[4] Wenqin Wang, Huaizong Shao, Hui Chen. Frequency Diverse Array Radar: Concept, Principle and Application. Journal of Electronics and Information Technology, 2016,38(4).

[5] P. Antonik, M. C. Wicks, H. D. Griffiths, et al. Range Dependent Beamforming. 2006 International Waveform Diversity and Design Conference, Jan. 2006: 22-27.

[6] P. Antonik, M. C. Wicks, H. D. Griffiths, et al. Range-dependent Beamforming Using Element Level Waveform Diversity. 2016 International Waveform Diversity and Design Conference, January. 2006: 140-144.

[7] Wenqin Wang. Adaptive RF Stealth Beamforming for Frequency Diverse Array Radar. Proceedings of 23rd European Signal Processing Conference, Nice, France, 2015: 1163-1166.

[8] P. Antonik, M. C. Wicks, H. D. Griffiths, et al. Multi-mission Multimode Waveform Diversity. Proceedings of the IEEE Radar Conference, Apr. 2006: 580-582.

[9] P. Antonik, M. C. Wicks, H. D. Griffiths, C. J. Baker. Frequency Diverse Array Radars. Proc. IEEE Radar Conf, April. 2006: 215-217.

[10] Wenqin Wang. Frequency Diverse Array Antenna: New opportunities. IEEE Antennas and Propagation Magazine, 2015, 57(2): 145-152.

[11] Wenqin Wang. Cognitive Frequency Diverse Array Radar with Situational Awareness. IET Radar, Sonar and Navigation, February. 2016, 10(2): 359C369.

[12] Jingjing Huang, Kinfai Tong, Chris Baker. Frequency Diverse Array: Simulation and Design. International Antennas and Propagation Radar conference (RADAR 2009), 2009: 1-4.

[13] Mustafa Secmen, Simsek Demir, Altunkan Hizal, Taylan Eker. Frequency Diverse Array Antenna with Periodic Time Modulated Pattern in Range and Angle, IEEE Radar Conference, 2007: 1070-1072.

[14] SAMMARTINO P F, Baker C J, and Griffiths H D. Frequency diverse MIMO techniques for radar. IEEE Transactions on Aerospace and Electronic Systems, 2013: 201-222.

[15] Wenqin Wang. Moving-target Tracking by Adaptive RF Stealth Radar Using Frequency offsets. IEEE Transactions on Geoscience and Remote Sensing, July. 2017, 54(7): 3764-3773.

[16] Wenqin Wang. Overview of Frequency Diverse Array in radar and navigation applications. IET Radar, Sonar and Navigation, 2015.