Anti-jamming Filtering for DRFM Repeat Jammer Based on Stretch Processing

Gang Lu, Deguo Zeng, Bin Tang
School of Electronic Engineering
University of Electronic Science and Technology of China
Chengdu, China
e-mail: aeneas999@hotmail.com

***Abstract*—This paper addresses issues about the rejection of false jammer targets in the presence of digital radio frequency memory (DRFM) repeat jammer. An anti-jamming filtering technique is proposed that it can eliminate this type of jamming signal. By using a stretch processing with a particular selected reference signal, the presented method can fully separate the echoes being reflected from the true targets and the signals being re-transmitted by a jammer in frequency domain. Therefore, utilizing the nonoverlapping properties of the received signals, filters or suchlike techniques can be used to reject the undesired jamming signals. Particularly, this method does not require estimation of jamming signal parameters and does not involve a great computation burden. Simulations are given to show the validity of the introduced approach.**

Keywords- anti-jamming; DRFM repeat jammer; ECCM; stretch processing

I. INTRODUCTION

A DRFM repeat jamming is highly correlated with a real radar echo and probably overlaps with the target signal in both time and frequency domain due to its intercepting, sampling, storing and retransmitting the radiation signal of the victim radar [1]-[3]. Thus, the jamming is easy to be received by the radar receiver and processed as the real one. Different from a blanket jamming, this repeat jamming signal can obtain radar processing gain, i.e., it can utilize the jammer transmission power effectively. In practice, the radiate amplitude of the jammer is slightly higher than the echo, for instance, about 1.2 to 1.5 times as the latter. Consequently, the jamming has a significant greater probability of being detected as a target than the real one, and that makes the real target free from risks and the jamming objective is then achieved.

Owing to the foregoing reasons, DRFM repeat jammer has been used widely in Electronic Counter Measures (ECM), which makes radar perform the target detection and parameter estimation inaccurately. Some of its features have been analyzed elaborately in [4]-[8]. An effective electronic counter-countermeasures (ECCM) is presented in [9]-[11]. This method is based on the concept of pulse diversity which indicates the radar, at each pulse repetition interval (PRI), transmits varied waveform following a specific code. Such method is not applicable unless the changing of transmission waveform is permitted. Moreover, the capability of pulse transformation limits the performance of jamming rejection.

The objective of jamming rejection is among received signals to accept those that are desired and to reject those that are undesired. In practice, most rejection approaches utilize the nonoverlapping properties of received signals, mainly in the frequency domain, the time domain or the time-frequency domain. Nevertheless, the DRFM repeat jamming signal usually overlaps with the desired target signal in both time and frequency domain. Even though the (partial) nonoverlapping in the time-frequency domain can be achieved, the corresponding transforming and filtering involve a great computation burden due to the 2-D signal processing.

In this paper, we present a rejection approach by which the jamming signal can be fully separated from the true target echo and then be eliminated. This method is based on the technique of the stretch processing which is conventional used as a pulse compression means in wideband radar systems. With a particular selected reference signal, it utilizes the nonoverlapping property of the beat signals in frequency domain and filters the jamming signals ultimately. Different from the pulse diversity-based method, this approach does not demand varying transmission waveforms. Additionally, the jamming signals can be filtered directly in time/frequency domain without time-frequency processing so that the computation burden is reduced too.

The rest of the paper is organized as follows. Section II presents the principle of stretch processing. In section III, the adapted stretch processing focused on jammer rejection is first derived, and then the anti-jamming method is given. The rejection performances are evaluated using numerical simulations in section IV. Finally, section V concludes the paper.

II. STRETCH PROCESSING PRINCIPLE

Consider the transmission signal given by

$$S_T(t) = \mathrm{rect}(\frac{t}{T_p})e^{j2\pi[f_0 t + \mu t^2/2]}, \tag{1}$$

where f_0 is the carrier frequency, μ is the chirp rate, T_p is the pulse duration, and $\mathrm{rect}(\cdot)$ is defined as

$$\mathrm{rect}(\frac{t}{T_p}) = \begin{cases} 1 & |t| \le T_p/2 \\ 0 & \text{others} \end{cases}.$$

If we ignore the amplitude gain, the received signal can be expressed as

$$S_R(t) = \mathrm{rect}(\frac{t-\tau}{T_p})e^{j2\pi[f_0(t-\tau)+\mu(t-\tau)^2/2]}, \qquad (2)$$

where τ denotes the time-delay of echo. The local reference signal is assumed as

$$S_L(t) = e^{j2\pi(f_0 t+\mu t^2/2)}, \qquad (3)$$

where we assume that this signal last out the whole period of observing widow. Then, $S_R^*(t)$ and $S_L(t)$ can be used to produce the beat signal, i.e.,

$$\begin{aligned} & S_R^*(t)\cdot S_L(t) \\ &= \mathrm{rect}(\frac{t-\tau}{T_p})e^{-j2\pi[f_0(t-\tau)+\mu(t-\tau)^2/2]+j2\pi(f_0 t+\mu t^2/2)} \\ &= \mathrm{rect}(\frac{t-\tau}{T_p})e^{j2\pi(\mu\tau t+f_0\tau-\mu\tau^2/2)} \end{aligned} \qquad (4)$$

Hence, the signal phase is

$$\varphi = 2\pi(\mu\tau t + f_0\tau - \mu\tau^2/2). \qquad (5)$$

Consequently, the instantaneous frequency can be calculated by the first derivation of the signal phase, therefore

$$f_I = \mu\tau. \qquad (6)$$

Substituting $\mu=B/T_p$ and $\tau=2R/C$ to (6) and rearranging yield the range solution, that is

$$R = \frac{T_p C}{2B} f_I, \qquad (7)$$

where B is the signal band wide, R is the target range, and C is the light velocity.

III. DRFM Repeat Jammer Rejection

In the conventional stretch process, (3) is chosen as the local reference signal to calculate the range solution. In this approach, however, jamming rejection is focused. Thus, the conventional stretch processing needs adaption to the new conditions.

A. Adapted Stretch Processing

We define the received signal at slow-time l as

$$S_R(t,l) = \alpha(l)S_l[t-\tau(l)], \qquad (8)$$

where t denotes the fast-time, $\alpha(l)$ and $\tau(l)$ denote the signal amplitude and time-delay, respectively. The signal $S_l(t)$ is given by

$$S_l(t) = \mathrm{rect}(\frac{t}{T_p})e^{j2\pi[(f_0+f_{d,l})t+\mu t^2/2]}, \qquad (9)$$

where $f_{d,l}$ denotes the Doppler frequency shift at slow-time l. Accordingly, the received signal at slow-time l+1 is

$$S_R(t,l+1) = \alpha(l+1)S_{l+1}[t-\tau(l+1)]. \qquad (10)$$

Here, we choose $S_R(t,l)$ as the reference signal so that the product is given by

$$\begin{aligned} & S_R^*(t,l+1)S_R(t,l) \\ &= \alpha(l)\alpha(l+1)\mathrm{rect}[\frac{t-\tau(l)}{T_p}]\mathrm{rect}[\frac{t-\tau(l+1)}{T_p}] \\ &\bullet e^{j2\pi\{[\tau(l+1)-\tau(l)]\mu t-(f_{d,l+1}-f_{d,l})t\}} \\ &\bullet e^{j2\pi\{f_0[\tau(l+1)-\tau(l)]+[f_{d,l+1}\tau(l+1)-f_{d,l}\tau(l)]-[\tau^2(l+1)-\tau^2(l)]\mu/2\}}. \end{aligned} \qquad (11)$$

Then, the instantaneous frequency f_I is

$$f_I = \mu[\tau(l+1)-\tau(l)] - (f_{d,l+1} - f_{d,l}). \qquad (12)$$

B. Stretch Processing Modeling in Anti-jamming Approach

Suppose the uncontaminated target echoes at slow-time l is

$$S_R(t,l) = \sum_m \alpha_m(l)S_{T,l}[t-\tau_m(l)], \qquad (13)$$

where the subscript T denotes the target, $\alpha_m(l)$ and $\tau_m(l)$ denote the target amplitude and time-delay, respectively. If we assume that the victim radar is jammed by the false targets at slow-time l+1, the contaminated received signals can be expressed as following

$$\begin{aligned} & S_R(t,l+1) \\ &= \sum_m \alpha_m(l+1)S_{T,l+1}[t-\tau_m(l+1)] \\ &+ \sum_n \beta_n(l+1)S_{J,l+1}[t-\tau_n(l+1)], \end{aligned} \qquad (14)$$

where the subscript J denotes the jammer, $\beta_n(l)$ and $\tau_n(l)$ denote the false target amplitude and time-delay, respectively. It is clear that the received signals contain both true and false targets. When the adapted stretch processing is applied to the signals, the product is given by

$$\begin{aligned}&S_R^*(t,l+1)S_R(t,l)\\&=\sum_m \alpha_m(l+1)S_{T,l+1}^*[t-\tau_m(l+1)]\bullet\sum_m \alpha_m(l)S_{T,l}[t-\tau_m(l)]\\&+\sum_n \beta_n(l+1)S_{J,l+1}^*[t-\tau_n(l+1)]\bullet\sum_m \alpha_m(l)S_{T,l}[t-\tau_m(l)].\end{aligned} \quad (15)$$

If m=1, …, M and n=1, …, N, the above equation can be expanded as

$$\begin{aligned}&S_R^*(t,l+1)S_R(t,l)\\&=\sum_{i=1}^{M}\sum_{k=1}^{M}\alpha_i(l+1)\alpha_k(l)\mathrm{rect}[\frac{t-\tau_i(l+1)}{T_p}]\mathrm{rect}[\frac{t-\tau_k(l)}{T_p}]\\&\bullet e^{j2\pi\{(f_0+f_{d,l,k})[t-\tau_k(l)]-(f_0+f_{d,l+1,i})[t-\tau_i(l+1)]+\mu\{[t-\tau_k(l)]^2-[t-\tau_i(l+1)]^2\}/2\}}\\&+\sum_{q=1}^{N}\sum_{k=1}^{M}\beta_q(l+1)\alpha_k(l)\mathrm{rect}[\frac{t-\tau_q(l+1)}{T_p}]\mathrm{rect}[\frac{t-\tau_k(l)}{T_p}]\\&\bullet e^{j2\pi\{(f_0+f_{d,l,k})[t-\tau_k(l)]-(f_0+f_{d,l+1,q})[t-\tau_q(l+1)]+\mu\{[t-\tau_k(l)]^2-[t-\tau_q(l+1)]^2\}/2\}}.\end{aligned} \quad (16)$$

As shown in (16), the expression can be divided into two parts. The first part is the product of the conjugate target signals at current slow-time and the target signals at previous slow-time. Contrarily, the second part is the product of the conjugate jamming signals at current slow-time and the target signals at previous slow-time.

For the first part, it is composed of two categories of product and the corresponding instantaneous frequency is

$$f_I=\mu[\tau_i(l+1)-\tau_k(l)]-(f_{d,l+1,i}-f_{d,l,k}),\ i,k=1,...,M. \quad (17)$$

First, if i=k=m, namely, the beat signals are produced only by same targets at different slow-times, f_I can be given as following

$$f_I=\mu[\tau_m(l+1)-\tau_m(l)]-(f_{d,l+1,m}-f_{d,l,m}),\ m=1,...,M. \quad (18)$$

In (18), the contributions from the listed terms are minor because the variations between two proximate slow-times in time-delay and Doppler frequency of target are both limited to a specific range under the condition of high pulse repetition frequency (PRF). Formally, (18) can be transformed as

$$f_I=\mu\frac{2v}{Cf_{\mathrm{PRF}}}-\frac{2a}{Cf_{\mathrm{PRF}}}, \quad (19)$$

where f_{PRF} is the PRF, v and a are the mean values of target velocity and acceleration, respectively. The second term on the right side of this expression can be neglected completely because $a<<Cf_{\mathrm{PRF}}$. Hence, f_I is determined mainly by the first term, i.e., $2\mu v/(Cf_{\mathrm{PRF}})$. It seemed that we can calculate certain definite f_I through this. Nevertheless, in practice, the time-delay difference between two proximate slow-time of the same target is tiny and generally less than one sampling point. Thus f_I is bounded in a very low frequency normally near zero. Second, if $i\neq k$, i.e., the beat signals are produced by different targets, f_I is given as (17) (except for $i\neq k$). The partial strength of these corss-terms is attenuated by the factor rect(·). Furthermore, the residuals lead to certain high frequencies if $|\tau_i(l+1)-\tau_k(l)|>|\tau_m(l+1)-\tau_m(l)|$ is met. In practice, $|\tau_i(l+1)-\tau_k(l)|>|\tau_m(l+1)-\tau_m(l)|$ is almost satisfied. Otherwise, even if no jammer is present, radar can not discriminate ith and kth target in nature (except super-resolution technique is applied) and just treat them as a single one.

For the second part, it is produced by the target signals at slow-time l and the conjugate jamming signals at slow-time l+1. The corresponding instantaneous frequencies are expressed below

$$f_I=\mu[\tau_q(l+1)-\tau_k(l)]-(f_{d,l+1,q}-f_{d,l,k}),\ q,k=1,...,M. \quad (20)$$

Typically, the deception jamming signals are employed to resemble the true target echoes reasonably but positioned at different ranges. If the jamming signal overlaps echo exactly, the target signal power will be enhanced. That is not consistent with the objective of jamming. Accordingly, $|\tau_q(l+1)-\tau_k(l)|>|\tau_m(l+1)-\tau_m(l)|$ is achieved, namely the corresponding f_I is located in relative high values. Moreover, since rect(·) always attenuate external data, jamming power is also attenuated.

C. Jamming Signal Rejection

As described in last section, the instantaneous frequencies of targets are confined around zero and the others that are undesired are located in relative high values due to the stretch processing. Meanwhile, the function rect(·) attenuate the undesired signal power too. Then, a low-pass filter or mask template in frequency domain can be designed to reject the jamming and cross-terms. In theory, the jamming and the target signals are capable of being so close that they can not be separated completely by filtering or suchlike techniques. In practice, because the jamming objective is to deceive radar into treating with the false targets, the jamming and the target signals are to separate at last or the jamming objective can not be achieved. If the time-delay between them beyond a certain threshold with which a filter or a mask template in frequency domain can reject the undesired signals, the jamming terms and the involved cross-terms will be eliminated by filtering-like techniques.

A jamming rejection method is proposed and the system block diagram is shown in Fig. 1. Clearly, the received signal, which is composed of the true target echoes and jamming signals, is conjugated first. Next, it multiplies with the reference signals, i.e., the uncontaminated echoes at last slow-time, to shift the target echoes around near zero frequency and position the jamming signals at relative high frequency. Through a low-pass filter (or mask template in frequency domain), the jamming signals and the undesired cross-terms can be eliminated. And then, a signal recovering processing is applied to recover the true target signals in their original form. The output can act as reference signal for the next slow-time.

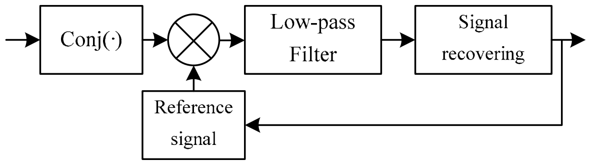

Figure 1. System block diagram of stretch-based anti-jamming filtering.

IV. SIMULATIONS

The purpose of this section is to provide simple simulations to demonstrate the main idea introduced in this paper. The pulse compression pike-to-pike ratio of jammer before and after rejection (PPRJ) is used to test the anti-jamming efficiency. Since the PPRJ does not take into account of the loss of target power, we also use the pulse compression pike-to-pike ratio of target before and after rejection (PPRT) for comparison.

In this simulation, a LFM signal, with pulse width 30μs and bandwidth 10MHz, is employed. Besides, the sampling frequency is 40MSPS, the PRF is 10KHz, the wavelength is 3cm and the target is moving in a velocity of 300m/s. A target echo is received in the presence of a DRFM repeat jammer. The target signal and the repeat signal, with the same signal parameters except a time-delay difference of 10μs, are overlapping in both time and frequency domain. During the process of pulse compression, matched-filtering measure is applied with the hamming window. In the following, the signal-to-noise ratio (SNR) varies from -5 to 20dB and the jamming-to-signal ratio (JSR) varies from 2 to 6dB. The noises are additive, Gaussian and white. Monte Carlo simulation is run 200 times.

It can be shown in Fig. 2 that with the rise of SNR, the PPRJ is also increased. The curves of PPRJ with JSR=2, 4, 6 are close and specifically range from 32.46 to 55.81dB, i.e., the power attenuation of the jammer caused by this method is about 30dB at least. Meanwhile, the PPRJ with higher JSR is greater than the one with lower JSR related to the difference of jammer power. Accordingly, the jammer power enhancement which creates the spacing between the curves is therefore being eliminated.

In Fig. 3, the PPRT versus the different SNR is given. It is clear that all the curves are bunched together as the increase of SNR and they are eventually converged to the vicinity of zero, about 0.07dB in this simulation. In other words, the power loss of the target is extremely small.

Through the presented method exploiting the nonoverlapping properties in frequency domain, it is proved that the jamming signals can be greatly attenuated and the true target signals remain almost unchanged. In simulations, it is interesting to note that with the increase of SNR, the PPRJ rises also, but the PPRT remains unchanged on the whole, i.e., the rejection performance is improved as SNR increased. On the contrary, the JSR has little impact on the rejection performance. In the concrete, no matter whether the JSR is positive or negative, this approach is effective for radar to reject the DRFM repeat jammer. As a result, it is available when the jamming power is lower than the real one.

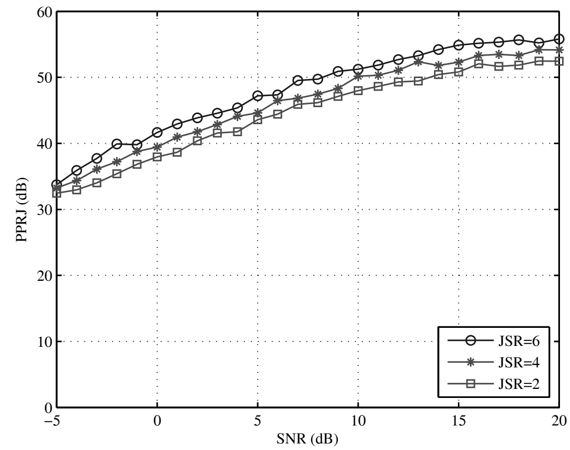

Figure 2. PPRJ curves.

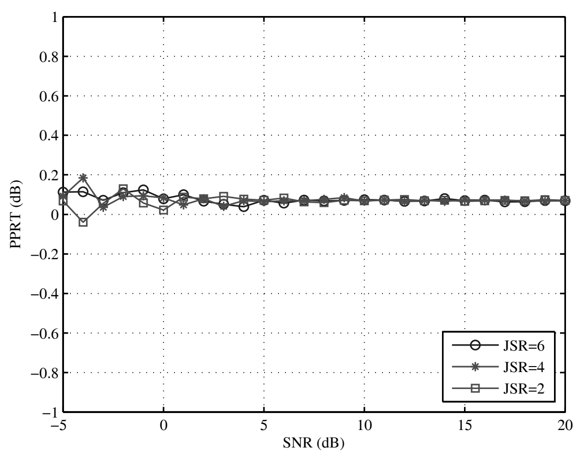

Figure 3. PPRT curves.

V. CONCLUSIONS

In this paper, the issues about rejection of DRFM repeat jammer are addressed, and a stretch-based anti-jamming approach is proposed. Different from conventional stretch process, this method use the signal at previous uncontaminated slow-time as reference signal to shift the target echoes around zero frequency and situate the jamming signals at relative high frequency. Accordingly, a low-pass filter or suchlike techniques can be used to reject the jamming signals and the true target echoes are obtained finally. This approach is jamming-proof for overlaps in the time and/or frequency domain.

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