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Countermeasures for range false target jamming based on quasi-Karhunen-Loève translate basis dictionary learning method

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Abstract: [**Objectives**] Waveform diversity technology is an effective anti-jamming measure against range false target jamming. However, in an environment of strong-energy jamming, the high sidelobe caused by the jamming signal mismatch will still affect the detection performance of the radar. To this end, a dictionary learning method is proposed in order to better suppress and eliminate high-power jamming. [**Methods**] First, initialization dictionaries corresponding to the target and jamming signals are established. Second, the initialization dictionaries and selected atoms are used to generate autocorrelation matrix templates, and the matching coefficients are obtained using the non-homogeneous linear mean square estimation. Next, approximate quasi-Karhunen-Loève transform (Q-KLT) bases corresponding to the target and jamming signals are constructed with templates and matching coefficients respectively. Finally, a convex optimization algorithm is used to separate and recover the target and jamming signals. [**Results**] The simulation results show that the proposed method can effectively counter the jamming of one or multiple range false targets at a 30 dB jamming-to-signal ratio. [**Conclusions**] Compared with the traditional waveform diversity technology, the proposed method still maintains good anti-jamming performance in high jamming-to-signal ratio environments and can be used by shipboard radar to counter range false target jamming.

Key words: anti-jamming of range false target; waveform diversity; dictionary learning; quasi-Karhunen-Loève transform

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0 Introduction

Shipboard radar, a detection device for locating and tracking sea-surface or aerial targets, is the key object jammed by the enemy [1-2]. In recent years, electronic countermeasures have gradually matured with the development of shipboard radar. Specifically, the most distinctive is the digital radio frequency memory (DRFM) technology that develops rapidly, providing effective support for jamming methods [3]. As deceptive jamming signals generated by the DRFM technology are of high coherence with radar transmitted signals, radar can hardly obtain the distance or velocity information of targets correctly. As a result, such deceptive jamming becomes the greatest threat to shipboard radar [4].

For this reason, taking the lead in introducing the waveform diversity technology to radar anti-jamming, Soumekh [5] suppressed deceptive jamming by matched-filtering clipping through phase perturbation or frequency modulation slope variation of linear frequency modulation (LFM) signals at differ-

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ent pulse repetition frequencies. On the basis of the waveform diversity technology, Akhtar [6] proposed a method of orthogonal-pulse block coding to counter active deceptive jamming. In this method, four orthogonally coded signals with specific structures are designed for continuous transmission in a pulse repeat interval (PRI), and jamming signal mismatch is then achieved by matched filtering to suppress jamming. Lu [7] proposed a waveform design algorithm based on priori knowledge of electronic jamming in a radar environmental knowledge base to counter new-system jamming. In recent years, with the development of the waveform diversity technology, radar waveforms, such as interpulse frequency-agile signals, coded signals, time-varying orthogonal frequency divisi on LFM (OFD-LFM) signals, and chaotic-sequence based radar orthogonal signals, have been used for anti-jamming research [8-11]. However, under strong-energy jamming, mismatching of jamming signals passing through matched filters will produce high-range sidelobe jamming. Therefore, the technical methods used in the above references fail to guarantee normal detection of real targets by radar under high-power jamming.

On the basis of the waveform diversity technology and with the waveforms of agile phase perturbation LFM (PPLFM) signals as radar transmitted waveforms, this paper proposed a method of countering range false target jamming based on non-homogeneous linear mean-square estimation (NLMSE) templates [12] matching quasi-Karhunen-Loève transform (Q-KLT) bases, thereby enabling the radar to counter strong-energy DRFM based deceptive jamming. The basic idea is as follows: First, initialization dictionaries of target and jamming signals are constructed within one range gate by using radar-signal correlation functions containing range-dimensional information. Then, atoms of maximum correlation coefficients with diagonal vectors of radar-echo autocorrelation matrixes are selected from the dictionaries. The selected atoms and the initialization dictionaries are used to generate autocorrelation matrix templates. NLMSE is employed to calculate the linear combination coefficients of various templates, namely the matching coefficients. After that, approximate autocorrelation matrixes of target and jamming signals are obtained by calculating templates and matching coefficients. These matrixes are decomposed by eigenvalues to attain approximate Q-KLT bases corresponding to the target and jamming signals respectively. Finally, a convex optimization algorithm is employed to separate the target and jamming signals. In this way, high-power range false target jamming and range sidelobe jamming are suppressed.

1 Signal model

PPLFM waveforms are those of the N pulse signals subjected to different phase perturbations and transmitted by the radar within one coherent process interval (CPI). Specifically, the signal transmitted in the n-th PRI is expressed as follows:

$$S_n(t) = \exp\left(\mathrm{j}\pi k t^2 + \mathrm{j}\theta_n(t)\right), \quad n = 1,2,\cdots,N \tag{1}$$

where $k = B/T$ is the frequency modulation slope of an LFM signal (in which B is signal bandwidth and T is signal time width); t is time; $\theta_n(t)$ is a random signal, namely

$$\theta_n(t) = \sum_{q=1}^{Q} \theta_n(q)\left[U(t - q t_{\mathrm{p}}) - U(t - (q-1) t_{\mathrm{p}})\right] \tag{2}$$

Specifically, the signal is divided into $Q=T/t_{\mathrm{p}}$ sub-pulses (t_{p} is the time width of the sub-pulses); $U(t)$ is a step function; $\theta_n(q)$ is the phase code of the q-th sub-pulse of the n-th PPLFM signal ($\theta_n(q)\in[-\pi, \pi]$).

The output of a radar received signal after matched filtering is given by

$$y_n(t) = \sigma_{\mathrm{T}} \cdot A_n(t - \tau_{\mathrm{T}}) + \sigma_{\mathrm{J}} \cdot C_n(t - \tau_{\mathrm{J}}) + W_n(t) \tag{3}$$

where $\boldsymbol{A}_n(t)=\boldsymbol{S}_n(t)\otimes\boldsymbol{S}_n(t)$ is the autocorrelation function of the PPLFM signal $S_n(t)$ in the n-th PRI; $\boldsymbol{C}_n(t) = \boldsymbol{S}_n(t)\otimes\boldsymbol{J}(t)$ is the cross-correlation function between the PPLFM signal in the n-th PRI and a jamming signal $\boldsymbol{J}(t)$; σ_{T} and σ_{J} are amplitudes of the target and jamming signals, respectively; τ_{T} and τ_{J} are time delays of the target and jamming signals, respectively; $\boldsymbol{W}_n(t)$ is a Gaussian noise signal.

2 Anti-jamming method based on dictionary learning

The number of periods of the jamming signals lagging behind the radar transmitted signals is estimated, and this number is used as priori information for the anti-jamming method. The number of periods is estimated by spike detection. According to the difference between target echoes and jamming signals in their phases of interpulse initial phase agile waveforms, this detection method estimates the phase difference of compressed spikes of adjacent periodic signals by wavelet transform and then determines the number of lag periods. Fig. 1 is the flow chart. The specific steps of spike detection are as follows:

Specific interpulse initial phase agile waveforms are transmitted by the radar in a CPI. The initial phase of the first agile waveform is set to $\varphi_1=\phi$ (ϕ is a parameter), while the initial phases of other waveforms are all set to $\varphi_n = 0$. Suppose that the number of jamming lag periods is 3, then the initial phase of the agile waveform emitted by the jammer is $\varphi_4 = \phi$. After that, the phase residuals of the first and the fourth waveforms after pulse compression are calculated as $\theta_1 = \phi$ and $\theta_4 = -\phi$, respectively. Finally, the phase differences between the first pulse-compressed signal spike and the subsequent $N-1$ pulse-compressed signal spikes are estimated successively. The phase difference obtained in the third estimation is $\hat{\theta}_{1,4} = 2\phi$, while that obtained in other estimations is $\hat{\theta}_{1,n} = \phi$ ($n \neq 4$). Thus, the number of periods of jamming signals lagging behind transmitted signals is determined to be 3.

Radar transmitted-signal phase φ_n

$\varphi_1=\phi$	$\varphi_2=0$	$\varphi_3=0$	$\varphi_4=0$	$\varphi_5=0$	…	$\varphi_{N-1}=0$	$\varphi_N=0$

Jamming-signal phase φ_{n-i}

$\varphi_{M-2}=0$	$\varphi_{M-1}=0$	$\varphi_M=0$	$\varphi_1=\phi$	$\varphi_2=0$	…	$\varphi_{N-4}=0$	$\varphi_{N-3}=0$

Phase residual $\theta_n=\varphi_n-\varphi_{n-i}$

$\theta_1=\phi$	$\theta_2=0$	$\theta_3=0$	$\theta_4=-\phi$	$\theta_5=0$	…	$\theta_{N-1}=0$	$\theta_N=0$

Estimated phase difference $\hat{\theta}_{1,n}=\theta_1-\theta_n$

$\hat{\theta}_{1,2}=\phi$	$\hat{\theta}_{1,3}=\phi$	$\hat{\theta}_{1,4}=2\phi$	$\hat{\theta}_{1,5}=\phi$	$\hat{\theta}_{1,6}=\phi$	…	$\hat{\theta}_{1,N}=\phi$	

Fig. 1 Flow chart for estimating the number of jamming lag periods by spike detection

The number of lag periods of a jamming signal is obtained by the above method, and the phase coding sequence of the jamming signal is determined. Initialization dictionaries $\boldsymbol{D}_i$ (i =1, 2) of the target and jamming signals are thereby constructed.

$$\begin{cases} \boldsymbol{D}_1 = \{D_1^p(t) = A_n(t-\tau_\mathrm{p})\} \\ \boldsymbol{D}_2 = \{D_2^p(t) = C_n(t-\tau_\mathrm{p})\} \end{cases}, \ p = 1,2,\cdots,P \tag{4}$$

In the formula, $\tau_\mathrm{p} = 2\,(d_{\min} + p\cdot d)/C$ is the time delay of a signal. Specifically, d represents the range of the minimum resolution, and the width scope of a radar range gate is $[d_{\min},\ d_{\max}]$; C represents the speed of light. $P = (d_{\max}-d_{\min})/d$ is the number of determinable atoms in an initialization dictionary.

Atoms in the initialization dictionaries $\boldsymbol{D}_i$ (i =1, 2) are transformed into diagonal vectors of autocorrelation matrixes to obtain dictionaries $\boldsymbol{G}_i$ (i =1, 2). On this basis, autocorrelation matrix templates are generated and matching coefficients are calculated. Moreover, approximate Q-KLT bases corresponding to the target and jamming signals are constructed. Then, the basis pursuit (BP) algorithm [13] is employed to separate and reconstruct the target and jamming signals and ultimately suppress range false target jamming.

The specific steps of countering range false target jamming based on Q-KLT bases are as follows:

1) Calculate the autocorrelation matrix $\boldsymbol{R}_y$ and diagonal vector $\boldsymbol{d}_{R_y}$ of a radar received signal $\boldsymbol{y}$. Discrete Fourier transform (DFT) of the radar received signal $\boldsymbol{y}$ yields the signal $\boldsymbol{Y}$. Then, the autocorrelation matrix of the received signal is calculated as follows:

$$\boldsymbol{R}_y = E\left\{\boldsymbol{Y}\boldsymbol{Y}^\mathrm{H}\right\} \tag{5}$$

The diagonal vector is given by

$$\boldsymbol{d}_{R_y} = diag(\boldsymbol{R}_y) = diag\left(\boldsymbol{Y}\boldsymbol{Y}^\mathrm{H}\right) \tag{6}$$

2) Select P atoms with the largest correlation coefficients with the diagonal vector $\boldsymbol{d}_{R_y}$ from the dictionaries $\boldsymbol{G}_i$ (i = 1, 2), and they are $\boldsymbol{g}_i^{k_1}, \boldsymbol{g}_i^{k_2}, \cdots, \boldsymbol{g}_i^{k_m}$ (where k are the labels of atoms g in the dictionaries $\boldsymbol{G}$ and m is the number of the atoms g.

3) Select the atoms corresponding to $\boldsymbol{g}_i^{k_1}, \boldsymbol{g}_i^{k_2}, \cdots, \boldsymbol{g}_i^{k_m}$ from the initialization dictionary $\boldsymbol{D}_i$ (i = 1, 2), and according to the autocorrelation matrixes $\boldsymbol{R}_i^{k_m} = \boldsymbol{d}_{R_y}\left(\boldsymbol{d}_{R_y}\right)^\mathrm{H}$, generate templates $\boldsymbol{R}_i^{k_1}, \boldsymbol{R}_i^{k_2}, \cdots, \boldsymbol{R}_i^{k_m}$.

4) Calculate matching coefficients a_i^0, a_i^1, a_i^2, $\cdots$, a_i^m of the templates by the NLMSE method to minimize Formula (7).

$$E = \left[\boldsymbol{d}_{R_y} - \left(a_i^0 + \sum_{m=1}^{N} a_i^m \boldsymbol{g}_i^{k_m}\right)\right]\left[\boldsymbol{d}_{R_y} - \left(a_i^0 + \sum_{m=1}^{N} a_i^m \boldsymbol{g}_i^{k_m}\right)\right]^\mathrm{T} \tag{7}$$

5) Calculate approximate autocorrelation matrixes $\hat{\boldsymbol{R}}_i\,(i = 1,2)$ of the target and jamming signals.

$$\hat{\boldsymbol{R}}_i = a_i^0 + \sum_{m=1}^{N} a_i^m \boldsymbol{R}_i^{k_m} \tag{8}$$

6) By eigenvalue decomposition of $\hat{\boldsymbol{R}}_i$, calculate approximate Q-KLT bases $\boldsymbol{U}_i^\mathrm{H}$ (i = 1, 2) corresponding to the target and jamming signals.

7) Finally, obtain a union dictionary $\boldsymbol{U}_\mathrm{unit}^\mathrm{H} = [\boldsymbol{U}_1^\mathrm{H}, \boldsymbol{U}_2^\mathrm{H}]$ composed of the approximate Q-KLT bases corresponding to the target and jamming signals. Solve the following convex optimization problem by the BP algorithm to obtain an optimal solution, namely to separate the target and jamming signals. The sparse estimate is given by

$$\hat{\boldsymbol{a}} = \underset{a}{\mathrm{argmin}}\|a\|_1$$
$$\text{s.t. } \|\boldsymbol{y} - \boldsymbol{U}_\mathrm{unit}a\| \leqslant \varepsilon \tag{9}$$

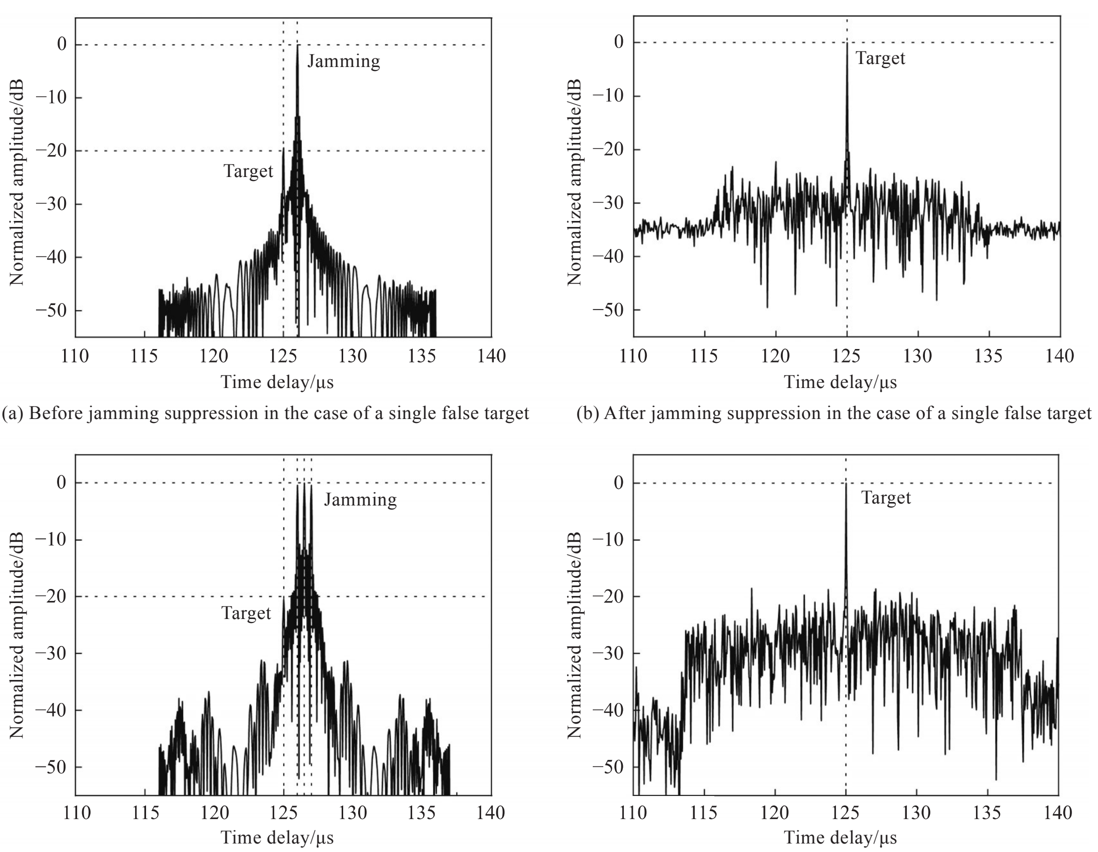
where a is a sparse coefficient under the union dictionary $\boldsymbol{U}_\mathrm{unit}^\mathrm{H}$ and ε is a minimum boundary value.

3 Simulation

To verify the effectiveness and superiority of the method of countering range false target jamming, this paper simulated the algorithm by Matlab. For LFM signals, the bandwidth and time width were set to B=10 MHz and T=10 μs, respectively; the pulse repetition interval was PRI =200 μs, and the code length of phase coding sequences was 100. The jamming-to-signal and signal-to-noise ratios were respectively set to JSR=20 dB and SNR=10 dB. The assumed time delay of target echoes was 125 μs, and the assumed time delays of the jamming signals were 126, 126.5, and 127 μs, respectively.

A genetic algorithm (GA) was used to optimally design PPLFM signals with low-autocorrelation sidelobes, further reducing range sidelobe jamming. Then, under a single false target and multiple false targets, the method of countering range false target jamming based on NLMSE templates matching Q-KLT bases was adopted to separate the target and jamming signals.

Figs. 2 (a) and 2 (c) illustrate the outputs of fixed LFM signals passing through a matched filter. As can be seen, the gain amplitude of the jamming signals is much higher than that of target echoes. As a result, the radar fails to distinguish the range information of correct targets. Figs. 2 (b) and 2 (d) present the results of the anti-jamming method combining optimally designed PPLFM signals and dictionary learning. From the figures, this method can separate out strong-energy jamming signals effectively to suppress range false target jamming and obtain real target signals.



(a) Before jamming suppression in the case of a single false target

(b) After jamming suppression in the case of a single false target

(c) Before jamming suppression in the case of multiple false targets

(d) After jamming suppression in the case of multiple false targets

Fig. 2 Simulation results of jamming suppression

Fig. 3 displays the results of 100 Monte Carlo simulations. From the figure, the Gini coefficients [14] of projection vectors of the jamming signals increase with the increase in JSR, while those of target signals increase first and then decrease as JSR increases. Moreover, the sparsity of projection vectors of target signals in the case of one false target is better than that in the case of three false targets.

Fig. 4 shows the variation of $PSLR$ after jamming suppression with JSR, obtained by 100 Monte Carlo simulations. From the figure, the peak sidelobe ratio (PSLR) tends to increase before it decreases. These curves are almost the same as the Gini coefficient curves of projection vectors of target signals shown in Fig. 3.

The comparison between Figs. 3 and 4 indicates

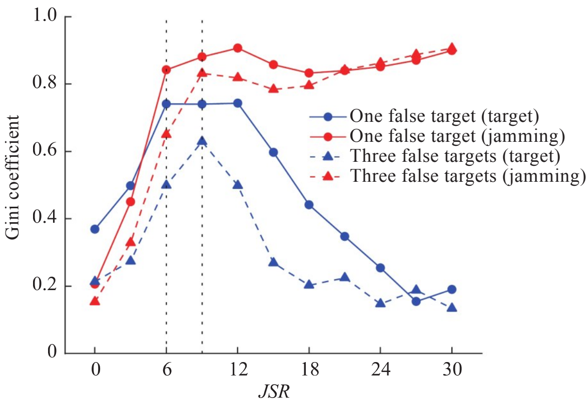


Fig. 3 Variation of Gini coefficient with *JSR*

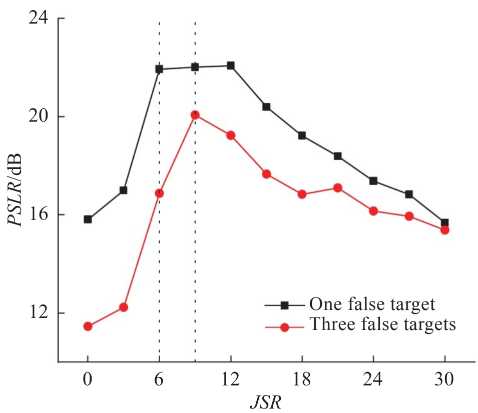


Fig. 4 Variation of *PSLR* value after jamming suppression with *JSR*

that in the case of a low *JSR* and low sparsity of projection vectors of jamming and target signals, the performance of countering range false target jamming is poor (low *PSLR*). As *JSR* rises, the sparsity of projection vectors of jamming and target signals increases, and the anti-jamming performance improves accordingly. With the further increase in *JSR*, the sparsity of projection vectors of jamming signals continues increasing, while that of target signals decreases. As a result, the anti-jamming performance worsens. However, the performance in such a case is still better than that in the case of a low *JSR*. As can be seen, the favorable sparsity of signals under adaptive dictionaries (basis functions) enables the jamming signals to be well separated from target ones so that the *PSLR* after jamming suppression is equivalent to that of a target signal (without jamming) after matched filtering. This means that the anti-jamming performance of the proposed method is affected by the sparsity of signals under Q-KLT bases. The *PSLR* after jamming suppression in the case of one false target is higher than that in the case of three false targets. In the case of *JSR*=30 dB, *PSLR* can still reach more than 15 dB. This further shows the superiority of the proposed method in suppressing high-power range false target jamming.

4 Conclusions

High-power repeater deceptive jamming poses a threat to shipboard radar in complex electromagnetic environments. On the basis of waveform diversity technology, this paper studied a dictionary learning method based on Q-KLT bases for countering high-power range false target jamming to solve this problem. With the Gini coefficient and *PSLR* as indicators, the paper respectively evaluated the sparsity and anti-jamming performance of the proposed method under typical *JSR* conditions by simulation. According to the simulation results, the variation of *PSLR* is almost the same as that of the Gini coefficient of the projection vector of a target signal. This indicates that the sparsity of the target signal under the Q-KLT basis represents the favorable anti-jamming performance of the proposed method. In the case of *JSR*=30 dB, the *PSLR* after jamming suppression is still above 15 dB. This clearly indicates the superiority of this method under strong-energy jamming.

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基于准 Karhunen-Loève 变换基的字典学习抗距离假目标干扰方法

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摘　要:[**目的**] 波形分集技术是一种有效对抗距离假目标干扰的舰载雷达抗干扰的措施,但在强干扰环境下信号失配产生的较高旁瓣依然会影响雷达探测性能。因此,为了能够更好地抑制大功率距离假目标的干扰,提出一种基于字典学习的干扰消除方法。[**方法**] 首先,建立与目标和干扰信号对应的初始化字典;然后,将选取的原子与初始化字典生成自相关矩阵模板,采用非齐次线性均方估计求得匹配系数,再通过模板与匹配系数分别构建目标和干扰对应的近似准 Karhunen-Loèv 变换基;最后,利用凸优化算法实现目标和干扰信号的分离与恢复。[**结果**] 仿真试验结果表明,所提方法可以在干信比 30 dB 时有效对抗一个或多个距离假目标的干扰。[**结论**] 相较于传统雷达波形分集技术,该方法在高干信比环境下依然保持良好的抗干扰性能,可用于舰载雷达对抗大功率距离假目标干扰。

关键词: 抗距离假目标干扰; 波形分集; 字典学习; 准 Karhunen-Loève 变换