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A Line Spectrum Extraction Method based on Sonar Array Beam Pattern

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ABSTRACT

The conventional method of extraction of target line spectrum based on target tracking beam data of sonar array signal. In the presence of multiple target, there are line spectrum interference between targets signal, especially In the low frequency region. It brought difficulties to extraction the target line spectrum correctly. Based on the linear array sonar, this paper analyzes multi-target line spectrum energy distribution in frequency domain and spatial domain. A multi-beam line spectrum model is given under the condition of multi-target array signal. Based on the model, this paper proposes a target line-spectrum extraction method based on multi-beam data. The method transfer array data to multi-beam frequency domain data by frequency domain beamforming. The line spectrum detection is made considering the conditions of frequency domain and spatial domain at the same time. Experimental results based on simulation data have verified the correctness and effectiveness of the proposed method.

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(See . http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf .)

1. INTRODUCTION

There is a rich line spectrum in underwater target radiated noise [1], which is an important basis for underwater target detection and feature extraction. Under the condition of actual sea, the target noise feature extracted from sonar array beam data is susceptible to be polluted by other target noise. The interference target sometimes leads to decreased of processing performance of extraction of target line spectrum, including degradation of the detection probability or extract to interfere line spectrum. In recent years, many scholars have carried out the research of line spectrum extraction in interference environment, including the application of focus beam-forming[2,3] and deconvolution[4,5] etc. In fact, the sonar array data includes information of time frequency and space domain. Using a combination of spatial information and frequency information, we can effectively improve the performance of detection of target line spectrum, and reduce interference line spectrum caused by other target. Based on the sonar beam pattern, this paper proposes a method of extracting the target line spectrum, which make judgment in the frequency and space domains at the same time.

2. LINEAR ARRAY MULTI TARGET INTERFERENCE MODEL

2.1 Directivity Function of Linear Array

Uniform linear array is a common sonar formation. The principle of linear array beam forming is as follows: Assuming the number of linear array sensors is N. The sensor spacing is d. Receiving sensitivity of each sensor are the same. Target signal incident angle is θ_0 . As shown in Figure 1.

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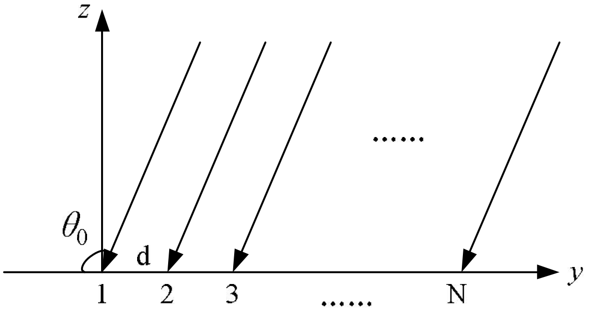


Figure 1- Uniform linear array reception signal model

Suppose the received signal of array sensor 1 is $x_1(t) = s(t) + n_1(t)$. Taking array sensor 1 as a reference sensor, then the received signal of array sensor i is

$$x_i(t) = s(t - \tau_i(\theta_0)) + n_i(t) \tag{2-1}$$

where $\tau_i(\theta_0) = (i-1)d\cos\theta_0 / c$

Forming the beam at incident angle θ using received signal array data, we can obtain the beam data $y(t,\theta)$.

$$y(t,\theta) = \sum_{i=1}^{N} x_i(t + \tau_i(\theta)) + \sum_{i=1}^{N} n'_i(t) \tag{2-2}$$

where $n'_i(t)$ is obtained from $n_i(t)$ after delay. If the incident signal single-frequency signal $s(t) = A\cos(\omega t)$, then the normalized directivity function is

$$R(\theta) = \left| \frac{\sin(\frac{N\pi d}{\lambda}(\cos\theta - \cos\theta_0))}{N\sin(\frac{\pi d}{\lambda}(\cos\theta - \cos\theta_0))} \right| \tag{2-3}$$

The $R(\theta)$ is a like -sinc function. When $\theta = \theta_0$, $R(\theta)$ has the biggest value 1. $R(\theta)$ has different main lobe width and side lobe width with different frequencies. Let b denote $\cos\theta$, where $b \in [-1,1]$. Then $R(\theta)$ can be expressed as

$$R(\theta) = \left| \frac{\sin(\frac{N\pi d}{\lambda}(b - b_0))}{N\sin(\frac{\pi d}{\lambda}(b - b_0))} \right| \tag{2-4}$$

The main lobe of the directivity function is $b \in [b_0 - \frac{c}{Nfd}, b_0 + \frac{c}{Nfd}]$. The main lobe width is $\frac{2c}{Nfd}$. With the increasing of f , the main lobe width will become narrow and the target resolution capability will become stronger. However , in order to avoid grating lobe of the directivity function, the parameters need to fulfill the following condition.

$$f \le \frac{c}{2d}$$

Suppose N=32, d=2m, f=375Hz, b0=0.5, the directivity function $R(\theta)$ is shown as Figure 2.

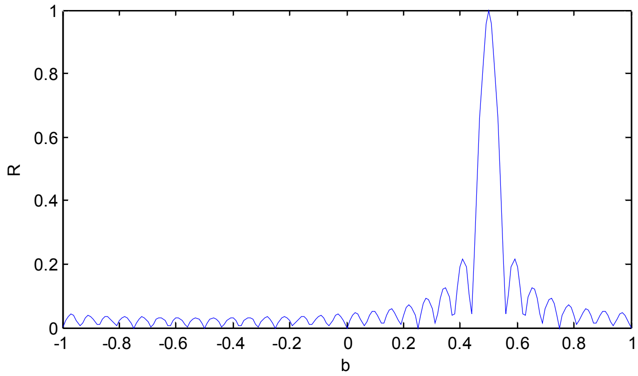


Figure 2-Schematic diagram of directivity function

2.2 Multiple Narrow Band Target Analysis

Based on the conventional beam forming of linear array, we discuss the expression form of directivity function of multiple narrowband target. Assuming that each sensor's background noise is uncorrelated white Gauss noise, the target number is N, the incident angle of the kth target signal is θ_k ($k=1,2,\cdots,M$). The narrowband signal is approximated by the single frequency signal. The received signal of sensor 1 is

$$x_1(t)=\sum_{k=1}^{M}s_k(t)+n_1(t)=\sum_{k=1}^{M}A_k\cos(\omega_k t+\phi_k)+n_1(t) \tag{2-5}$$

where ϕ_k is the initial phase of the kth target signal, and ω_k is the center frequency of the kth target signal .

The time delay of the kth target signal to sensor i is

$$\tau_i(\theta_k)=-(i-1)\frac{d}{c}\cos\theta_k \qquad i=1,2,\cdots,N\ ;\ k=1,2,\cdots,M \tag{2-6}$$

Then the received signal of sensor i is

$$x_i(t)=\sum_{k=1}^{M}s_k(t-\tau_i(\theta_k))+n_i(t)=\sum_{k=1}^{M}A_k\cos\omega_k(t+(i-1)\frac{d}{c}\cos\theta_k+\phi_k)+n_i(t) \tag{2-7}$$

Where $n_i(t)$ is the white Gauss noise of sensor i.

The conventional beam output at θ is

$$\begin{aligned}y(t,\theta)&=\sum_{i=1}^{N}x_i(t+\tau_i(\theta))\\&=\sum_{i=1}^{N}\sum_{k=1}^{M}A_k\cos[\omega_k(t+(i-1)\frac{d}{c}(\cos\theta_k-\cos\theta)+\phi_k)]+\sum_{i=1}^{N}n_i(t-(i-1)\frac{d}{c}\cos\theta)\end{aligned} \tag{2-8}$$

Let

$$\varphi_k=\omega_k\frac{d}{c}(\cos\theta_k-\cos\theta)$$
$$n(t)=\sum_{i=1}^{N}n_i(t-(i-1)\frac{d}{c}\cos\theta)$$

then

$$\begin{aligned} y(t,\theta) &= \sum_{i=1}^{N}\sum_{k=1}^{M} A_k \cos[\omega_k t + (i-1)\varphi_k + \phi_k)] + n(t) \\ &= \sum_{k=1}^{M} A_k \cos[\omega_k t + \frac{N-1}{2}\varphi_k + \phi_k)]\frac{\sin(M\varphi_k/2)}{\sin(\varphi_k/2)} + n(t) \end{aligned} \tag{2-9}$$

Let us suppose that N is 2, the proof process is similar when N>2.

Let $y_k(t,\theta) = A_k \cos[\omega_k t + \phi_k + (M-1)\frac{\varphi_k}{2}]\frac{\sin(M\varphi_k/2)}{\sin(\varphi_k/2)}$, we can obtain

$$\begin{aligned} P(\theta) &= E[\int (y_1(t,\theta) + y_2(t,\theta) + n(t))^2 dt] \\ &= P_1(\theta) + P_2(\theta) + E[\int n^2(t)dt] \\ &+ 2E[\int (y_1(t,\theta) + y_2(t,\theta))n(t)dt] + 2E[\int y_1(t,\theta)y_2(t,\theta)dt] \end{aligned} \tag{2-10}$$

where

$$E[\int n^2(t)dt] = \int E[n^2(t)]dt = \sigma^2 T$$

where σ^2 is noise power, T is integral time

Arbitrary two single frequency signals, their initial phase are random. In the sense of Statistics, equation 1 is true.

$$E[\int y_1(t,\theta)y_2(t,\theta)dt] = \int E[y_1(t,\theta)y_2(t,\theta)]dt = 0$$

so we can obtain

$$P(\theta) = P_1(\theta) + P_2(\theta) + \sigma^2 T \tag{2-11}$$

where $\sigma^2 T$ is constant, which does not affect the shape of the function.

3. LINE SPECTRUM EXTRACTION BASED ON BEAM PATTERN

When array beamforming, the frequency spectrum of each phase superimposed to obtain the energy distribution in the frequency components of each azimuth on. Use the formula (2-11), beam energy diagram of each frequency can be reconstructed by one or more single target beam energy patterns. Secondary treatment of multi beam power spectrum is carried out, the reconstruction parameters can be whether the interference judgment on the beam line Interference suppression of interference signals in the vicinity of the signal Extraction of line spectrum feature belongs to the target itself.

Beam pattern reconstruction is needed to calculate the directivity function of the linear array. Using the function,

$$P(\theta) = \left| \frac{\sin(\frac{N\pi d}{\lambda}(\cos\theta - \cos\theta_0))}{N\sin(\frac{\pi d}{\lambda}(\cos\theta - \cos\theta_0))} \right|^2 \tag{3-1}$$

The function is related to the element spacing, element number, the signal frequency and the incident angle of the signal.

The beam reconstruction processing procedure is as follows: (1) Analyze the power spectrum of the tracking beam signal; (2) Detect the line spectrum from target power spectrum data and estimate the line spectrum frequency; (3) According to the frequency of line spectrum, calculate the beam energy of each angle at the frequency point; (4) Search for the maximum value and the corresponding incidence angle from the beam pattern, and calculate the beam pattern by the parameters of frequency, incidence angle, etc.; (5) Subtract the beam generated by the target from the total beam pattern, and determine whether the residual beam component can be divided further. go to step (4) until the error of the original beam pattern and the composite beam pattern is stable.

The method is verified by simulation experiment with two target A and B. The incident direction of the target A and B is 40 degrees and 100 degrees respectively. Target A signal contains two spectral lines at 120Hz and 150Hz. Target B signal contains two spectral lines at 120Hz and 300Hz. The array is a uniform 24 sensors linear array with spacing at 2m. Signal sampling rate is 6kHz. Beamforming for array signals, tracking 40 degree and 100 degree direction signal can be obtained A and B tracking beam. Power spectrum analysis of tracking beam data for target A and B is shown in Figure.3.

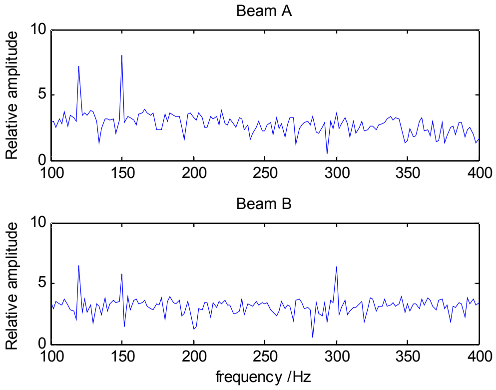
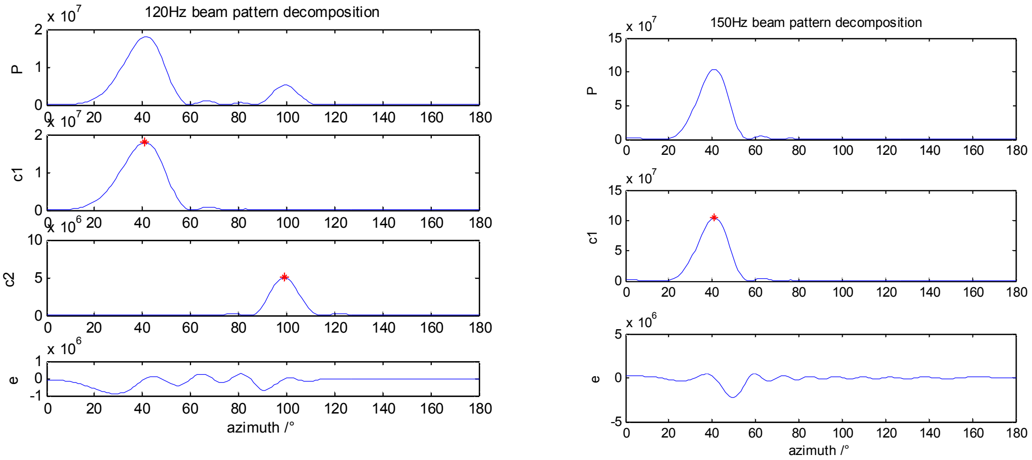


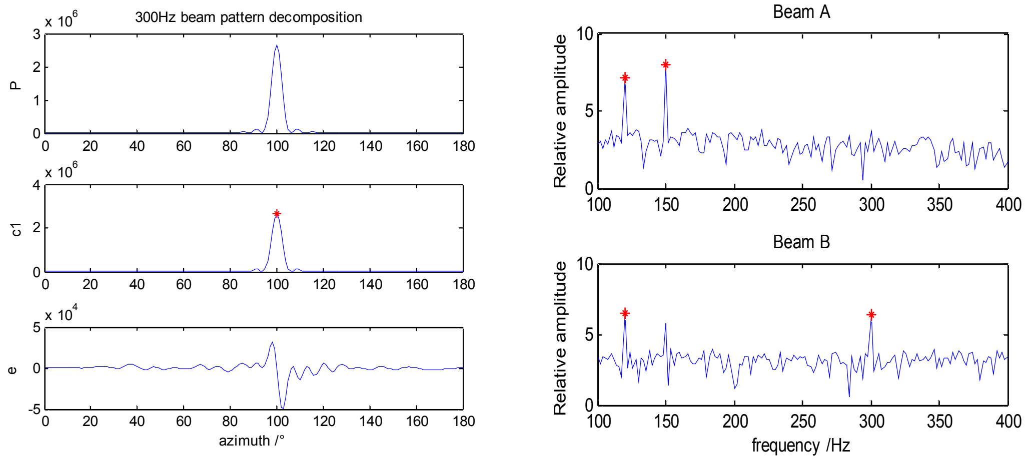
Figure 3-Power spectrum beam A and B

As you can see from FigureX, Target A signal contains two spectral lines at 120Hz and 150Hz. Target B signal contains three spectral lines at 120Hz ,150Hz and 300Hz.

We perform beam decomposition for 120Hz, 150Hz, and 300Hz in beam pattern . The results are shown in Figure 4.



(a) 120Hz beam pattern decomposition (b) 150Hz beam pattern decomposition



(c) 300Hz beam pattern decomposition (d) line spectrum of beam A and B

Figure 4-results of beam pattern decomposition

As you can see from Figure4, the beam pattern at 120Hz can be decomposed into 2 target at 40 degree and 100 degree. the beam pattern at 150Hz is composed of only one target at 40 degree. the beam pattern at 150Hz is composed of only one target at 100 degree. Therefore, the spectral lime of 150Hz in trace beam B is interferences which should be restrained. By beam pattern decomposition processing, we extracted to the target tracking and target tracking A and B spectrum correctly.

4. CONCLUSIONS

This paper propose a method to extract line spectrum based on beam pattern decomposition. Using the spatial distribution and frequency distribution characteristics of beam pattern, the method improve the line spectrum extraction performance by reducing the influence of interference target. Results of simulation have verified the correctness and effectiveness of the method.

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