A Method of Weak Signal Detection Based on Subband ANC and Normalized Energy Spectrum

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***Abstract*—In order to improve the weak signal detection performance of Unmanned Underwater Vehicle (UUV), depressing its self-generated noise and fully using the differences of incidence in space domain and differences in frequency domain (spectral patterns and spectral level) between signal and noise are two key issues. In practice, there are many measures besides ANC (adaptive noise cancellation) to enhance the SNR of output of element. In this paper, a method of weak signal detection was proposed, where in order to improve the performance of ANC we selected multi-channel references to enhance the performance of coherence, and non-uniform subband processing to increase the performance of convergence speed in each output of element; in space domain processing, normalized energy spectrum and beam forming in frequency domain was used. The results of simulation and lake experiments proved the validity of the method.**

***Index Terms*—weak signal detection, beam-forming, adaptive noise cancellation; normalized energy spectrum.**

I. Introduction

The far target detection of unmanned underwater vehicle (UUV) flank in passive mode is weak signal detection under complex environment, in which the broadband noise has the property of non-station, color in space and time domain[1,2], it mainly include mechanical noise, propulsion system noise and hydrodynamic noise, etc.. It can be proved that the great SNR of the output in each element, the better performance in detection after beam-forming.

The self-generated noise is the main factors in all noise sources which affects the performance of flank in weak signal detection. Adaptive noise cancellation is always used, whose effect is determined mainly by correlation between the desired and reference signals. Since the complex of self-generated noise multi-channel ANC method was proposed in [3], for self-generated noise with a non-white distribution, the ability to increase the convergence speed of various LMS algorithms is limited. Subband ANC has the better characteristics of convergence and more flexibility [4], but, the convergence performance of uniform subband decomposition will be deteriorated if a great energy component is in the border of sub-band.

Methods of beam-forming and detection in space domain mainly include conventional beam-forming, frequency domain beam-forming and MVDR, where broadband signals are often decomposed into narrow-band for matching in space domain. The key points in conventional beam-forming method are to achieve accurate delay of broadband signals [3]; MVDR base on the minimum variance distortion response, where the optimization weights of array elements output are adaptive with the input data. The virtue of this method is that the peaks of space spectrum could reflect its energy distributions [5], in order to enhance its detection performance, many improved methods were presented, but large amount of computation in practice is its shortage [6,7]. Energy detection is implemented in time domain by comparing the broadband output in given incidence with the energy threshold under the given false alarm probability. In fact, the detection performance is mainly laid on the differences degree used in space, time and frequency domain between target and noise signal. For broadband noise and signal, in some frequency bins, in which there is large SNR but small energy, when the full band energy is calculated, contributions of these parts is covered by large energy but small SNR parts, it's not benefit for the weak signal detection.

In this paper, we used non-uniform subband decomposition based on DFTSD to improve the performance of ANC, where subband width was given by the distribution of self-generated noise PSD. In fully use of the differences between target signal and environment noise, wideband frequency domain beam-forming was used, and in the energy calculation of given incidence, the method of normalized energy spectrum was proposed which fully utilize the difference of spectral shapes between them. The results of simulation and lake experiments showed that the method significantly reduced the side lobes of beam-forming and improved the performance of detection.

II. System Structure and Theory of Multi-Channel Non-Uniform Subband ANC

A. System structure

The main detection system of UUV flank was showed in Fig.1, which has three parts processing in series. To each output of element, the ANC processing was used firstly, where multi-channel reference signal was acquired by differencing [2], and non-uniform subband was implemented by DFTSD [3]. After ANC, the frequency domain beam-forming and detection were carried in space domain.

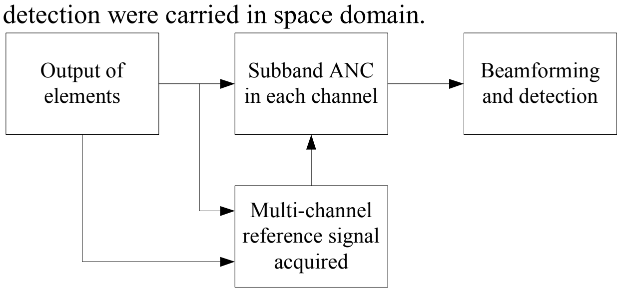

Fig.1 system structure

B. theory of multi-channel non-uniform subband ANC

Thinking about the complex of UUV noise filed, the multi-channel reference signal were obtained by accurate delay and differencing between the outputs of adjacent hydrophones which can decrease the effects of target signal in references. ANC was implemented in non-uniform subband and width of subband was acquired by the PSD distribution of noise. In avoiding the aliasing in-band after decimating in subband, DFT based subband decomposition method (DFTSD [5]) was used. So, we have the system structure of ANC as Fig. 2, which is an example of only one hydrophone noise cancellation and the assumption that noise sources is a wide stationary process.

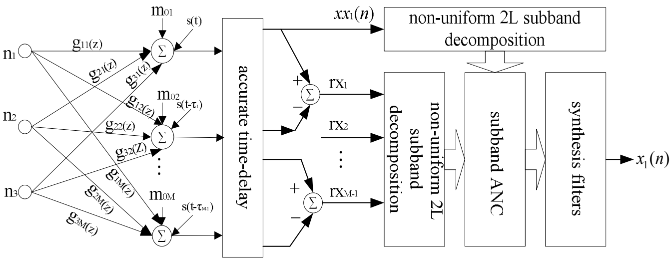

Fig.2 multi-channel subband ANC structure

In Fig.2, n_j is the jth noise source, the m_{0i} means the ith marine environment noise from the hydrophone, the $s_i(n)$ means the ith hydrophone received far field target signal, $g_{ji}(n)$ is the unit impulse response of the jth noise source to the ith hydrophone transmission system.

III. DETECTOR OF NORMALIZED ENERGY SPECTRUM

A. Broadband beamforming in frequency domain

Assume the far-field broadband target and noise signal are in $f_{\min}$-$f_{\max}$ Hz, the incidence of target is θ; the additional noise in space domain is white.

Assume the received array is a linear array consisted of M isotropic array elements, and the output of the *m*th element after ANC is $x_m(t) = s(t-\tau_m) + n_m(t)$, in which τ_m represents the array element's delay relative to the reference array element (select the first element as reference), and $n_m(t)$ is the noise in the output of the *m*th array element, then the output of the array is

$$\boldsymbol{x}(t) = \boldsymbol{s}(t) + \boldsymbol{n}(t) \tag{1}$$

Where

$\boldsymbol{x}(t) = [x_0(t), x_1(t), \cdots, x_{M-1}(t)]^{\mathrm{T}}$, $\boldsymbol{s}(t) = [s_0(t), \cdots; s_{M-1}(t-\tau_{M-1})]^{\mathrm{T}}$, after preprocessing and ADC, the corresponding sequence can be obtained

$$\boldsymbol{x}(n) = \boldsymbol{s}(n) + \boldsymbol{n}(n) \tag{2}$$

Where

$\boldsymbol{x}(n) = [x_0(n), x_1(n), \cdots, x_{M-1}(n)]^{\mathrm{T}}$, $\boldsymbol{n}(n) = [n_0(n), n_1(n), \cdots, n_{M-1}(n)]^{\mathrm{T}}$, and define the Fourier transform of them as

$\boldsymbol{X}(K) = \mathrm{DFT}[\boldsymbol{x}(n)]$, $\boldsymbol{S}(K) = \mathrm{DFT}[\boldsymbol{s}(n)]$, $\boldsymbol{N}(K) = \mathrm{DFT}[\boldsymbol{n}(n)]$.

Assume the array manifold vector of the *K*th bin in frequency domain can be described as

$$\boldsymbol{v}(f_K, \theta) = [1, e^{j2\pi f_K \tau_1}, \cdots e^{j2\pi f_K \tau_{M-1}}]^{\mathrm{T}}$$

Where $c = \lambda_K f_K$, $\tau_i = 2\pi d_i \sin\theta / \lambda_K$, Then

$$\boldsymbol{X}(K) = \boldsymbol{v}(f_K, \theta) S(K) + \boldsymbol{N}(K)$$

Select weighted vector arrays as $\boldsymbol{w}_K = \boldsymbol{v}^{\mathrm{H}}(f_K, \theta)/M$, so the output of beamforming in the *K*th bin is

$$Y(K) = \boldsymbol{w}_{\mathrm{K}} \boldsymbol{X}(K) \tag{3}$$

So the output in entire frequency bins could be denoted as

$$\boldsymbol{Y} = \boldsymbol{w}\boldsymbol{X}$$

and the output can be expressed in time domain as

$$\boldsymbol{y}(n) = \mathrm{IDFT}[\boldsymbol{Y}]$$

$$\text{where } \boldsymbol{X} = \begin{bmatrix} X_0(0) \cdots X_0(N-1) \\ X_1(0) \cdots X_1(N-1) \\ \vdots \quad \vdots \quad \vdots \\ X_{N-1}(0) \cdots X_{N-1}(N-1) \end{bmatrix}, \ \boldsymbol{w} = \begin{bmatrix} \boldsymbol{w}_0 \\ \boldsymbol{w}_1 \\ \vdots \\ \boldsymbol{w}_{N-1} \end{bmatrix}, \ \boldsymbol{Y} = \begin{bmatrix} Y(0) \\ Y(1) \\ \vdots \\ Y(N-1) \end{bmatrix}.$$

B. The Normalized Energy Spectrum Detector

Hypothesis

$$\mathrm{H}_0 : \boldsymbol{X}(K) = \boldsymbol{N}(K) \qquad K = 0,1 \cdots N-1$$

$$\mathrm{H}_1 : \boldsymbol{X}(K) = \boldsymbol{v}(f_K, \theta) \boldsymbol{S}(K) + \boldsymbol{N}(K) \quad K = 0,1 \cdots N-1$$

Due to $X_m(K)$ obey the Gaussian distribution, for a particular incident direction, the weights are constant, so $Y(K)$ also obeys the Gaussian distribution. In practice, the numbers processed in each time are much larger, different frequency components could be thought none relevant, So $\boldsymbol{Y}$ is a Gaussian vector, and the joint complex Gaussian probability density function can be expressed as

$$p(Y) = (\prod_{K=0}^{N-1} \frac{1}{\pi \sigma_{YK}^2}) \exp[-\sum_{K=0}^{N-1} \frac{|Y(K)|^2}{\sigma_{YK}^2}] \tag{4}$$

Where

$\sigma_{YK}^2 = \mathrm{E}[Y(K) Y^*(K)] = \boldsymbol{w}_{\mathrm{K}} \mathrm{E}[\boldsymbol{X}(K) \boldsymbol{X}^{\mathrm{H}}(K)] \boldsymbol{w}_K^{\mathrm{H}} = S_s(K) + S_{n'}(K)$

$S_s(K) = E[S(K) S^{\mathrm{H}}(K)]$, $S_{n'}(K) = \boldsymbol{w}_K \mathrm{E}[N(K) N^{\mathrm{H}}(K)] \boldsymbol{w}_K^{\mathrm{H}}$.

Under the two hypothesis, the probability density function of $\boldsymbol{Y}$ is

$$p(\boldsymbol{Y} | \mathrm{H}_0) = A \exp[-\sum_{K=0}^{N-1} \frac{|Y(K)|^2}{S_{n'}(K)}]$$

$$p(\boldsymbol{Y} | \mathrm{H}_1) = B \exp[-\sum_{K=0}^{N-1} \frac{|Y(K)|^2}{[S_s(K) + S_{n'}(K)]}]$$

Where A and B are constants, and irrespective with $Y(K)$. So the log-likelihood ratio is

$$\lambda(\boldsymbol{X}) = \ln(\frac{B}{A}) + \sum_{K=0}^{N-1} |Y(K)|^2 \frac{S_s(K)}{S_{n'}(\mathrm{K})[S_{n'}(K) + S_s(K)]}$$

Ignore these constant, so the optimal test statistic is

$$T_{op}(\boldsymbol{X}) = \sum_{K=0}^{N-1} |\boldsymbol{w}_{\mathrm{K}} \boldsymbol{X}(K)|^2 \frac{S_s(K)}{S_{n'}(\mathrm{K})[S_{n'}(K)+S_s(K)]}$$
$$= \sum_{K=0}^{N-1} |\boldsymbol{w}_{\mathrm{K}} \boldsymbol{X}(K)|^2 H_w(K) H_{mmse}(K) \tag{5}$$

In (5), $H_w(K)=1/S_{n'}(\mathrm{K})$ represents the noise whitening, $H_{mmse}(K)=S_s(K)/[S_{n'}(K)+S_s(K)]$ is Wiener filter for target signal.

When the power spectrum of signal and noise are very similar and whitening is not consideration, suboptimal test statistic (basic method) can be obtained

$$T(\boldsymbol{X}) = \sum_{K=0}^{N-1} |\boldsymbol{w}_{\mathrm{K}} \boldsymbol{X}(K)|^2 = \sum_{K=0}^{N-1} |Y(K)|^2 \tag{6}$$

In the low SNR, $S_{n'}(K)$ approximates the power spectrum of the input signal, and $S_{n'}(K) = \boldsymbol{w}_K \mathrm{E}[N(K)N^{\mathrm{H}}(K)]\boldsymbol{w}_K^{\mathrm{H}}$ can be approximated by

$$[S_{n'}(\mathrm{K})]^{\frac{1}{2}} \approx \frac{1}{M} \sum_{m=1}^{M} |X_m(K)| \tag{7}$$

So the improved test statistics is obtained

$$T(\boldsymbol{X},\theta) = \sum_{K=0}^{N-1} \left| \boldsymbol{w}_{\mathrm{K}} \frac{\boldsymbol{X}(K)}{\sum_{m=1}^{M} |X_m(K)|} \right|^2 \tag{8}$$

Taking into account the real sequence input and the frequency ranges in $f_{\min} - f_{\max}$, then the scope of the cumulative performed is only on $K=[N_1 \quad N_2]$, where $N_1 = \left\lfloor \frac{f_{\min}}{f_s} N \right\rfloor$, $N_2 = \left\lfloor \frac{f_{\max}}{f_s} N \right\rfloor$. So in the incidence θ, the spectrum normalized test statistic (output energy after beam-forming) is

$$T(\boldsymbol{X},\theta) = \sum_{K=N_1}^{N_2} \left| \boldsymbol{w}_{\mathrm{K}} \frac{\boldsymbol{X}(K)}{\sum_{m=1}^{M} |X_m(K)|} \right|^2 \tag{9}$$

And use FBEAM to denote this test statistics.

If $T(\boldsymbol{X},\ \theta) > \gamma(\theta)$, H_1 is true, the target is found; If $T(\boldsymbol{X},\ \theta) < \gamma(\theta)$, H_0 is true, target is not found. Here $\gamma(\theta)$ is a threshold for given false alarm probability in the condition of absent target.

IV. EXPERIMENTS

A. Performance Simulation

Conditions in simulation are uniform linear array, 20 array elements, 0.05meter between adjacent elements, 0° incidence and White noise in space domain; Target signal and noise are band-limited which is in 3kHz-10kHz; In simulation, the Stat. times is 100 and false alarm probability is 0.05; amplitude of array element is weighted by rectangular window.

Figure 3 shows the comparison of detection performance between the basic (BFBEAM was used to denote suboptimal test statistics, formula (6)) and improved test statistics (FBEAM) in 5000 snapshots in the condition that wideband target and noise are both band-limited white noise signal. Figure 4 shows the comparison of detection performance between the basic and improved test statistics in colored noise and target signal with 5000 snapshots.

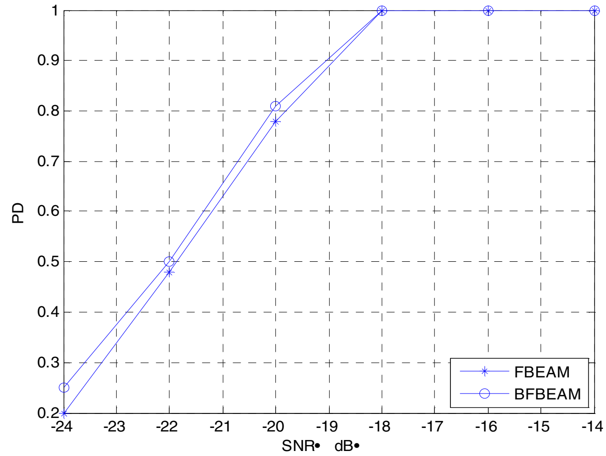

Fig.3 the detection performance under white noise

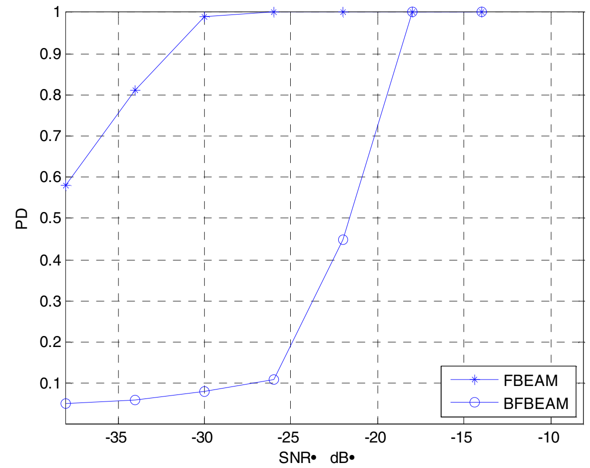

Fig. 4 the detection performance under colored noise

B. Lake Experiments

The self-generated noise and target signal were broadband noise (2 kHz-16 kHz), the linear array was used, after shifting and differencing, 16 channels of reference signal were acquired, then each hydrophone output data was processed by subband ANC, Finally, we have the output of beam-forming. Subband parameters are 2L=12; digital bandwidth $BW1=2\pi/20$; $BW2=2\pi/40$; $BW3=2\pi/8$; $BW4=2\pi/8$; $BW5=2\pi/20$;

$BW6 = 2\pi / 8$; subsample rate are R1=20; R2=40; R3=8; R4=8; R5=20; R6=8. Fig.5 was a typical results of beam pattern in lake experiments, in which 1-the output of typical broad-bandwidth frequency domain beam-forming; 2- the output of typical broad-bandwidth frequency domain beam-forming where multi-channel ANC used; 3- the output of typical broad-bandwidth frequency domain beam-forming, where multi-channel non-uniform subband ANC presented in the paper used.

Statistic 100 times, 4000 snapshots was used and false alarm probability was 0.05. Figure 6 shows the typical detection results of lake experiments in BFBEAM and FBEAM after ANC.

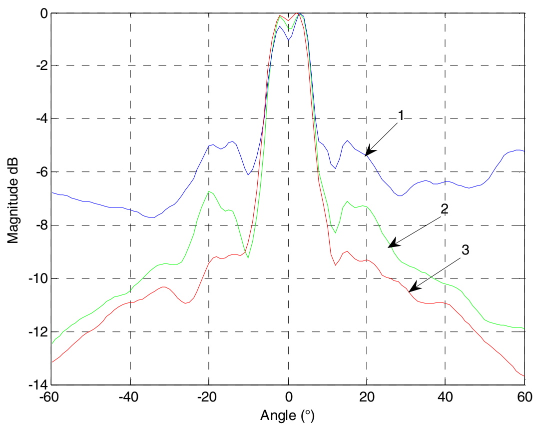

Fig5. Typical beam pattern used different method

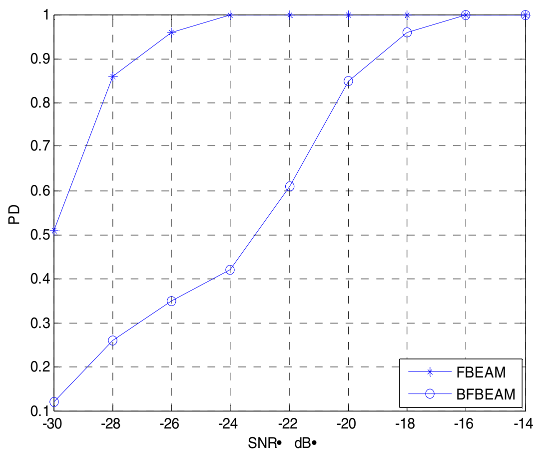

Fig.6 detection performance in lake experiments

C. Analysis of Experimental Results

From the results of simulations and lake experiments, we can obtain, after ANC the sidelobe of beam-forming is lower than without its pre-processing, especially in the multi-channel non-uniform subband ANC used. The typical decreased amount is about 4dB between conventional method and the new ones from the space pattern; in beam forming and detection, when target signal and noise are white noise(Fig.3), the ability of energy detection between the basic method (BFBEAM) and improved method (FBEAM)) is almost the same; for the conditions of white noise in space and time domain, there almost have none difference in spectrum pattern between target and noise signal, the detection is only based on the difference in spectrum level in time domain; in colored noise, the Fig.4, the FBEAM method has a better detection performance than the basic one because it makes full use of the difference between spectrum form and level of target and noise signal. In the lake experiments, the SNR of minimum detection in the same conditions improved about 8dB compare with the basic method.

V. CONCLUSION

It is the key issue in improving the detection performance that the full use of the differences between target signal and noise in statistical properties, time domain, frequency domain, space domain, joint domain, energy and so on. In this paper, we used multi-channel non-uniform subband adaptive noise cancellation to enhance the SNR of output in hydrophone that made a better foundation for farther processing; used normalized energy spectrum in beam-forming, we had fully used the differences of spectrum pattern and level between signal and noise, so detection performance was improved greatly. In addition, the method can also be used to estimate the orientation of targets if the full work regions are scanned.

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