Propeller feature extraction of UUVs study based on CEEMD combined with symmetric correlation

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Abstract. In this paper, in view of the characteristic that UUV radiation noise is low and easily interfered by strong noise, the complementary Ensemble Empirical Mode Decomposition (CEEMD) combined with symmetric correlation processing is proposed, which can improve the extraction performance of UUV's propeller features. First, the CEEMD decomposition combined with symmetric correlation processing was used to reduce the radiated noise of the target, then the signals after the noise reduction were demodulated and computed to obtain the DEMON spectrum, and finally features such as the rotational speed of the UUV's propeller were extracted from the DEMON spectrum. The Sea trials signal processing results prove that the method has better noise suppression performance under low SNR conditions, and can clearly and comprehensively extract the DEMON information of the radiated noise, and then accurately extract the propeller features of the UUV. Compared to conventional demodulation techniques, this technique has a greater ability to suppress noise and does not require manual selection of the modulated frequency band.

1 Introductory

UUVs in the course of navigation will radiate noise to the water, the main components of the radiation noise for mechanical noise, hydrodynamic noise and propeller noise. UUV propeller beat to its noise radiation has obvious amplitude modulation [1], can be demodulated from the high-frequency components of UUV radiation noise DEMON (Detection of Envelope Modulation On Noise) spectroscopy is a technique to analyze the modulation component of a propeller at low frequencies, i.e., the harmonic clusters in a DEMON spectrum are rich in characteristic information such as spindle speed, number of blades, target speed and target type. UUV's navigational status and is an important basis for target classification identification.

For modulated signal detection under low SNR conditions, domestic scholars have studied the use of modern signal processing methods to extract DEMON spectra [2], such as

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high-order statistics [3-4] and time-frequency analysis [5-6] and singular value analysis, these methods have improved the extraction performance of modulation characteristics, but most of these methods are used in the signal detection of large targets such as ships. For UUVs with smaller size and lower radiation noise, it is difficult for the above methods to achieve good detection results. Usually, the radiated noise of UUV is weak signal, easily interfered by the noise of large targets such as ships, or submerged in the noise of the marine environment, and the signal with low signal-to-noise ratio is obtained in the receiving device. In this case, the calculated DEMON spectrum often has the disadvantages of inconspicuous line spectra, many interfering line spectra, and poor noise suppression ability, so it is difficult to accurately extract the propeller characteristics of UUV from the DEMON spectrum.

In this paper, CEEMD decomposition combined with symmetric correlation processing algorithm is used for joint denoising and then extracting the radiated noise modulation features of UUV, and the actual UUV radiated noise processing results prove that under low SNR conditions, the method has better noise suppression performance and can clearly and comprehensively extract the DEMON information of radiated noise, and then extract the propeller features of UUV from the DEMON spectrum.

2 Traditional propeller feature extraction method

The traditional modulation feature extraction process is shown in Figure 1,and the basic steps are: firstly, select the frequency band of interest for band-pass filtering of underwater target radiated noise, square the filtered signal or absolute value operation, i.e., demodulation of the envelope of the noise signal, then downsampling of the envelope signal, and finally spectral analysis to extract the modulation characteristics of the underwater target radiated noise [7]. However, the actual underwater target radiated noise often has non-uniform characteristics [8], the modulation depth and intensity in different frequency bands are obviously different, and with different navigational conditions, it is impossible to automatically filter out the frequency bands with concentrated modulation information; on the other hand, if the envelope of the noise signal is demodulated in the full pass band, the effect is often not very satisfactory.

Fig. 1. Block diagram of the DEMON spectrum calculation process.

3 CEEMD combined with symmetric correlation processing for propeller feature extraction

3.1 Complementary approaches to decomposition of the overall empirical model

Empirical Mode Decomposition (EMD) has the function of adaptive frequency band delineation, with orthogonality, completeness and adaptivity, and its physical meaning is clear, which is suitable for processing non-stationary nonlinear signals [9]. However, when EMD method is used to process the signal containing intermittent, there are mode mixing and energy leakage phenomena, making the physical meaning of Intrinsic Mode Function (IMF) unclear. In this regard, the paper [10] proposes a complementary total empirical mode decomposition (CEEMD) on the basis of EEMD (Ensemble Empirical Mode Decomposition) [11], which takes advantage of the uniform distribution of white noise power spectral density to add positive and negative pairs of white noise to the original signal several times. The scale has continuity, and then the influence of auxiliary noise is eliminated with fewer average times, finally making the decomposition process noise-resistant. The method not only solves the problems of modal overlap and energy leakage of EMD method well, but also has a high computational efficiency.

3.2 Definition of the symmetric correlation function

The methods for offsetting noise in the signal are correlation methods, such as the ESPRIT [12] method, MUSIC method, Pisarenko method, etc., the correlation method is more sensitive to noise; there are also higher-order accumulation methods [13], such as the BMU method, the wavelet transformation method, DFT method, 1.5-dimensional spectral method, etc., the wavelet transformation method will produce certain errors; although the 1.5-dimensional energy The spectral analysis method can remove the uncoupled frequency component to some extent and strengthen the fundamental frequency component at the same time, but the noise reduction effect is still unsatisfactory and computationally expensive for the mixed uncorrelated additive random noise in the UUV radiated noise. This method is based on the special case of Wigner-Ville Distribution (WVD), which can preserve the modulation characteristics of the original information at zero frequency and has a good noise suppression effect [3].

Symmetric correlation is defined as, assuming that given a harmonic real signal:

$$s(t) = A\cos(\omega_0 t + \varphi) \tag{1}$$

where A is the amplitude, ω is the angular frequency, and φ is the phase, all three of which are constants. The analytical form of the signal $s(t)$ is:

$$s(t) = \frac{A}{2}[e^{j(\omega_0 t+\varphi} + e^{-j(\omega_0 t+\varphi})] \tag{2}$$

when $s(t) = \sum_{n=1}^{M} A_n \cos(\omega_n t + \varphi_n)$.

$$W_s(t,0) = \pi \sum_{n=1}^{M} A_n^2 \cos(2\omega t + 2\varphi_n) \tag{3}$$

It can be seen that when $\omega = 0$, the SVD transformation of the periodic real signal is still a harmonic signal, and the cross term at zero frequency contains all the information of the original signal, it should be noted that the frequency of the signal obtained after the transformation and the initial phase become twice as much as the original signal, then the symmetric correlation function of the real signal $s(t)$ is defined as follows.

$$W_s(t) = \frac{1}{2T}\int_{-T}^{T} s(t+\tau/2)s(t-\tau/2)d\tau \tag{4}$$

The power spectrum of the symmetric correlation function $W_s(t)$ is called the symmetric power spectrum:

$$P_{ws}(t) = \int_{-\infty}^{\infty} W_s(t)e^{-j\omega}dt \tag{5}$$

where ω is the angular frequency of the signal.

3.3 Noise reduction mechanism of symmetric correlation functions

Set a noise-bearing harmonic signal as $x(t)=\sum_{n=1}^{M} A_n \cos(\omega_n t+\varphi_n)+n(t)$, where the fundamental frequency of the signal is ω_0 , the corresponding period is T , the mean value of the additive noise $n(t)$ is 0, the variance is σ^2 and the period of the signal is not associated with random noise. The symmetric correlation function is defined by

$$
\begin{aligned}
W_x(t) &= \frac{1}{T}\int_{-T/2}^{T/2} x(t+\tau/2)x(t-\tau/2)d\tau \\
&= \frac{1}{T}\int_{-T/2}^{T/2} [s(t+\tau/2)+n(t+\tau/2)]\times \\
&\quad [s(t-\tau/2)+n(t-\tau/2)]d\tau \\
&= \frac{1}{T}\int_{-T/2}^{T/2} [s(t+\tau/2)s(t-\tau/2)+n(t+\tau/2)s(t-\tau/2) \\
&\quad + s(t+\tau/2)n(t-\tau/2)+n(t+\tau/2)s(t-\tau/2)]d\tau \\
&= \frac{1}{T}\int_{-T/2}^{T/2} s(t+\tau/2)s(t-\tau/2)d\tau+\frac{1}{T}\mathrm{n}^2 \\
&= W_s(t)+\frac{1}{T}\mathrm{n}^2
\end{aligned}
\tag{6}
$$

From the above formula, the intensity of random noise in the signal is inversely proportional to the observation time, i.e., the longer the signal, the closer the sequence is to the symmetric correlation process, and the smaller the noise pollution in the periodic signal, thus showing the unique noise suppression ability.

3.4 CEEMD decomposition combined with symmetric correlation processing

The CEEMD decomposition technique can decompose the signal into several inherent modal components with clear physical meaning according to the inherent modal characteristics of the signal to be decomposed to achieve adaptive division of the frequency band, and at the same time has the features of orthogonality, completeness and adaptivity The CEEMD decomposition is now combined with symmetric correlation processing to perform noise reduction on the UUV radiated noise signal and then extract the modulation features of the signal, the basic flow of which is shown in Figure 2.

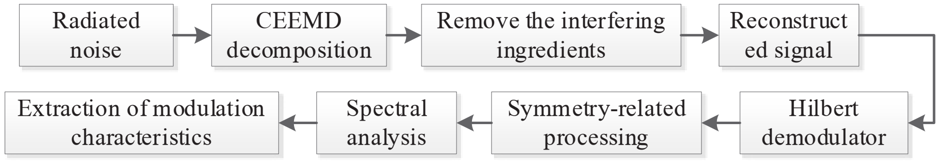

Fig. 2. Block diagram of the new method of DEMON spectrum extraction.

The radiated noise signal sequence of the UUV is $x(n)$, n=$0,1,...,N-1$, the sampling rate of the signal is fs , the data length $N \geq fs$.

(1)Firstly, the original signal AA is standardized and pre-processed:

$$x_1(n) = \frac{x(n) - E\left[x(n)\right]}{std\left[x(n)\right]}\sqrt{2} \tag{7}$$

where $E\left[x(n)\right]$ is the mean value of $x(n)$, $std\left[x(n)\right]$ is the standard deviation of $x(n)$.

(2) CEEMD decomposition of $x_1(n)$ as an input signal to obtain a number of IMF components.

(3) A correlation method is used to remove the interference modes as a quantitative description of the correlation between each of them and the original signal, and the correlation coefficient reflects the richness of the modulation information contained therein. The correlation coefficient is calculated as follows:

$$R_{I,x_1} = \frac{\sum_{i=0}^{N-1} x_1(i) IMF(i)}{\sqrt{\sum_{i=0}^{N-1} \left|x_1(i)\right|^2 \bullet \left|IMF(i)\right|^2}} \tag{8}$$

The range of the correlation coefficient is $[0,1]$, its physical meaning is clear, when $R_{I,x_1} = 0$, it means that the IMF of this order is not related to the original signal, only when the original signal is exactly the same as the IMF is established, the larger the value of R_{I,x_1} it means that the correlation between IMF and original signal is stronger, that is, the information components in IMF are more similar to the original signal. When R_{I,x_1} is lower than the set threshold value, the IMF is judged to be an interference component.

(4) Several of the interference components are removed to obtain the reconstructed signal.

(5) The reconstructed signal $IMF_s(n)$ is symmetrically correlated to remove the noise mixed in the signal to obtain $\overline{IMF_s(n)}$.

(6) According to the Hilbert transform formula, perform the Hilbert transform on $\overline{IMF_s(n)}$ o obtain the new sequence $H_{IMF_s}(n)$.

(7) Constructing analytical signals:

$$\begin{aligned} z(n) &= \overline{IMF_s(n)} + jH_{IMF_s}(n) \\ &= A(\mathrm{n})\ e^{\mathrm{j}\phi(\mathrm{n})} \end{aligned} \tag{9}$$

where: modulation amplitude function is

$$A_n(n) = \sqrt{\overline{IMF_s(n)}^2 + \left[H_{IMF_s}(n)\right]^2} \tag{10}$$

phase function is

$$\phi(n) = \arctan \frac{H_{IMF_s}(n)}{\overline{IMF_s(n)}} \tag{11}$$

(8) Power analysis of the amplitude function and extraction of modulation information from the power spectrum.

4 Sea trials validation

The algorithm proposed in this paper is applied to the propeller feature extraction of the measured target at sea to verify its anti-noise effect. The verification test is carried out in the East China Sea with a water depth of 80 m. The hydrophone array is used to collect the target radiated noise, the distance between the receiving end and the UUV is about 1800 m, and the sampling rate of the signal is 48 kHz. 20 s are used to process the target radiated noise using the method proposed in this paper. The radiated noise from the ship severely interferes with the detection of UUVs.

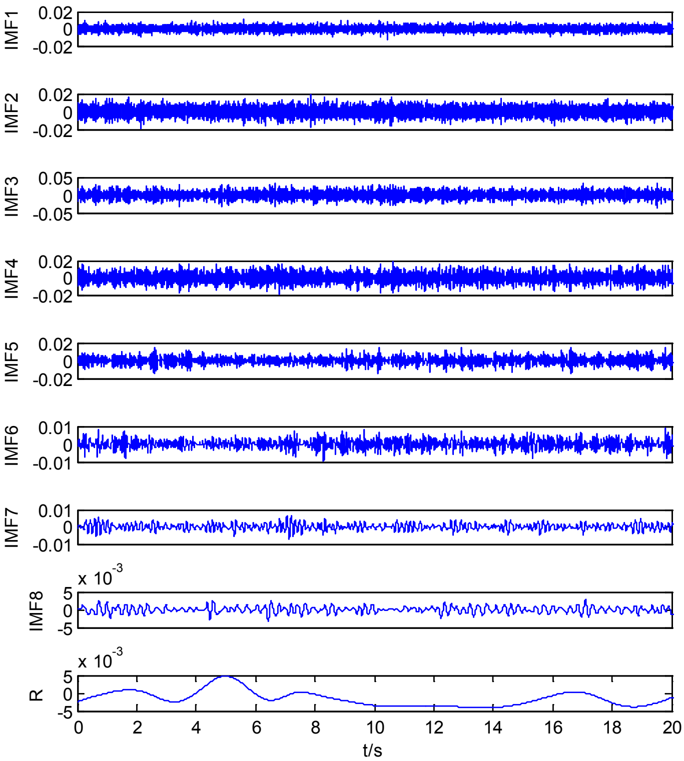

Fig. 3. CEEMD decomposition results of UUV radiation noise.

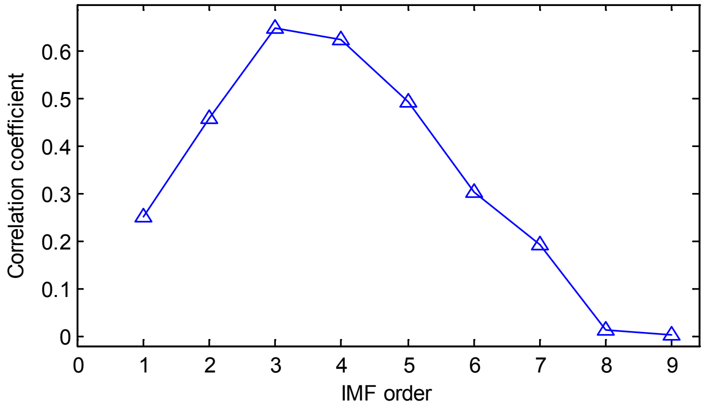

Fig. 4. Correlation of each order IMF with the original signal.

Fig. 3 shows the CEEMD decomposition results of the received signal, and the decomposition yields the 8th order IMF and the remaining components, and the correlation coefficients between each order IMF component and the original signal are shown in Fig. 4. In this test, the correlation threshold is set at 0.35, and only the correlation between the 2nd to 4th order IMF components and the original signal exceeds the preset threshold in the figure, so only the 2nd to 4th order IMF is reconstructed, and then the reconstructed signal is demodulated and feature extracted. Figure 5 shows the DEMON spectrum obtained from the demodulation and spectral analysis of the received signal directly by the traditional method, a set of harmonics can be obtained from the DEMON spectrum: 6.18Hz, 12.35Hz, 18.53Hz, 23.35Hz, 30.72Hz. The propeller shaft frequency is 6.18Hz, which corresponds to a propeller speed of 370.8 rpm.

However, there are two noise sources at the same time in the observed position, and the DEMON spectrum obtained by the traditional method has only one set of harmonics, which only reflects the characteristics of one target, obviously this set of harmonics belongs to the characteristics of the vessel with higher noise source level and faster speed, that is to say, the traditional method does not detect the UUV with weaker signal. for comparison, the received signal is processed by the new algorithm proposed in this paper. The results obtained are shown in Figure 6. Observation of the DEMON spectrum shows that the results of the new method are richer than those of the traditional method in the low-frequency band (1-7 Hz) and also in the high-frequency band (7-35 Hz) at the same time. The maximum convention number of these harmonics is 1.37Hz, from which we can obtain the propeller shaft frequency of 1.37Hz, which corresponds to the propeller speed of 82.2 RPM. Verify that this speed is the same as the actual speed of the UUV.

Comparing the DEMON spectra calculated by the traditional method and the new method, the latter has fewer interfering components, richer line spectrum of the target, and more complete spectral structure, which is conducive to the extraction of physical parameters such as propeller speed, and effectively detects another weak target, i.e., UUV, which is mixed in the strong signal. Therefore, it can be said that the new method is more effective in suppressing the noise and can effectively improve the propeller feature extraction ability of UUV.

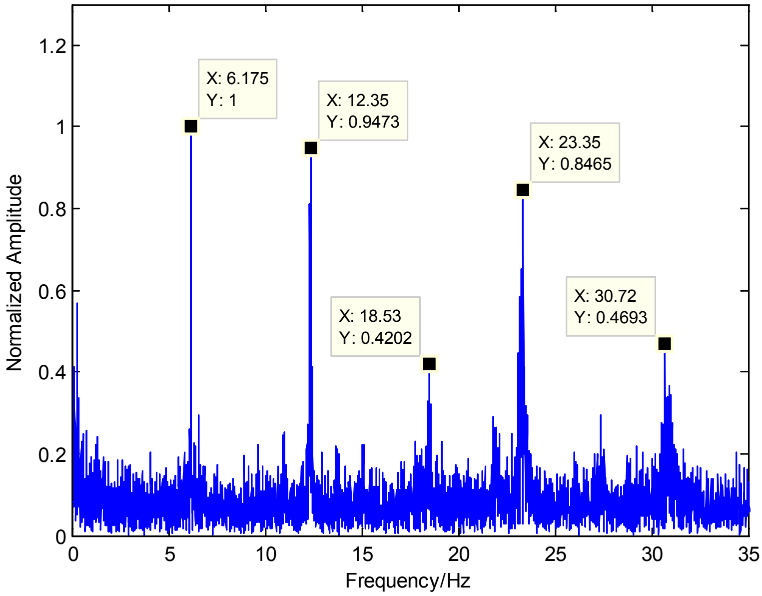

Fig. 5. DEMON spectra obtained by demodulation of UUV radiation noise by conventional methods.

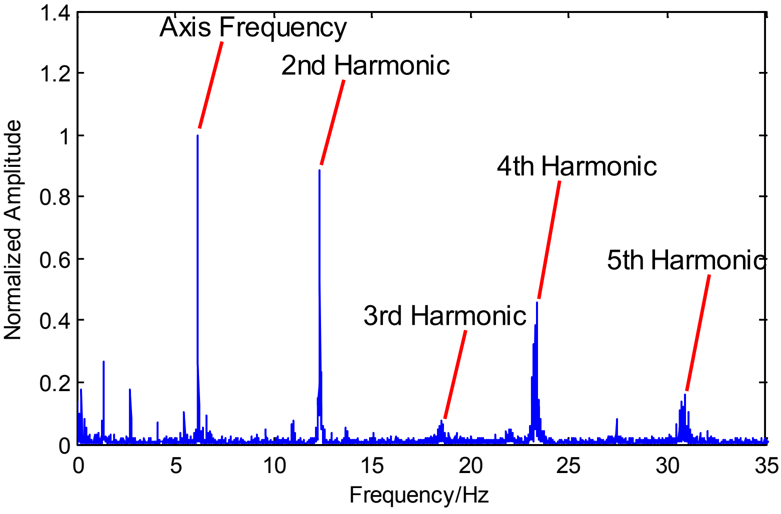

Fig. 6. DEMON spectrum obtained by the new method for UUV radiation noise demodulation.

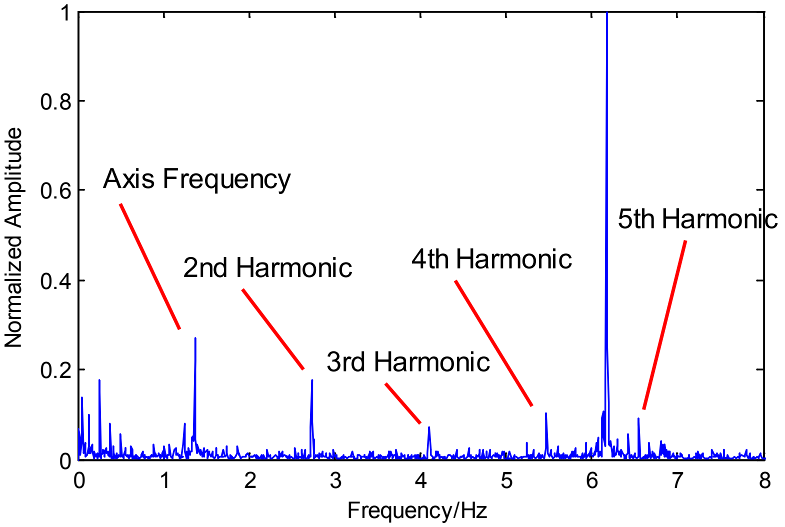

Fig. 7. DEMON spectrum obtained by the new method for demodulation of UUV radiation noise.

5 Conclusion

The sea trials signal processing results demonstrate that in the presence of strong target interference, i.e., low SNR conditions, the new method proposed in this paper can detect the modulated signal of the UUV's propeller from the complex background noise and exhibits a strong noise suppression capability. Based on CEEMD and symmetry-correlation noise reduction techniques, the suppression of interference noise is better, the target line-spectral components are significantly enhanced, and the calculated DEMON spectral harmonics are rich and the line-spectral structure is clear, which can clearly and comprehensively extract the DEMON information of the radiated noise and create favorable conditions for the accurate extraction of physical features such as the propeller speed.

References

1. Shi Guangzhi, Hu Junchuan, Cheng Yusheng. Extraction of frequency domain features of ship radiation noise based on multi-resolution analysis[J]. Journal of Qingdao University: Natural Science Edition. 2003, 4: pp. 44-48.
2. Cheng Yusheng, Wang Yichuan, et al. DEMON analysis of ship noise signals based on modern signal processing techniques[J]. Acoustics Technology, 2006, 25(1) : 71 -74.
3. Fan Yang Yu, Sun Jin Cai, Li Ping An. Extraction of ship radiation noise features based on high-order spectra[J]. Journal of Acoustics, 1999, 24(6): 611-616.
4. Wang Jianwen, Wang Zhiwei, Liu Ning, et al. High-order spectral-based signal feature extraction of targets in water [C]. Changsha: Proceedings of the 12th Symposium on Underwater Noise from Ships, 2009: 427-432.
5. Wang Jing, Yuan Lianxi, Sun Shaowu. Wavelet transform for shipboard radiation noise modulation information detection[J]. Journal of Harbin Engineering University, 2004, 25(1):53-57.
6. Yang Rijie, Li Hong, Zhao Junwei, et al. A method for extracting modulation spectra from radiated noise [J]. Applied Acoustics, 2000, 19(1):27-31.
7. Wu Guoqing. Two ways of extracting propeller recognition features[J]. Journal of Acoustics. 1993, 5.
8. Tian Tan. Underwater positioning and navigation technology [M]. Beijing: National Defense Industry Press, 2007: 124-132 pp.
9. Huang N E, Shen Z, Long S R, et al. The Empirical Mode Decomposition and the Hilbert Spectrum for Non-linear and Non-stationary Time Series Analysis[J]. Proc. R. Soc. Lond. A, 1998(454): 903-995.
10. Yeh Jiarong, Shieh Jiannshing, Huang Norden E. Complementary Ensemble Empirical Mode Decomposition: A Novel Noise Enhanced Data Analysis Method [J]. Advances in Adaptive Data Analysis,2010,2(2): 135-156.
11. Wu Z H, Huang N E. Ensemble empirical mode decomposition: a noise-assisted data analysis method[J]. Advances in Adaptive Data Analysis,2009,1(1): 1-41.
12. Fan Yang-Yu, Tao Bao-Qi, Xiong Ke, Chen Ren-Wen, Shang Jiu-Hao. Harmonic signal reconstruction based on symmetric correlation function method[J]. Signal Processing. 2001, 10.
13. Fan Yang-Yu, Sun Jin-Cai, Li Ping-An, Xu Jiadong. High-order spectral-based ship target recognition[J]. Pattern recognition and artificial intelligence, 1999, 6.