UNDERWATER ACOUSTIC TRANSIENT NOISE MEASUREMENT BASED ON CCWEEMDAN AND POWER-LAW DETECTOR

Jiangqiao Li[a], Yue Pan[a], Li Huangfu[a], Xiaoliang Zhang[a]
[a]Fengxian east road No.1, Haidian district, Beijing China, 100094
Fax Nr: +8601059515800; Email: lijiangqiao11@163.com

Abstract: *Acoustic transient noise measurement is important to detect and analyse the sound source. According to traits of underwater acoustic transient signal, a new measurement method of underwater acoustic transient noise based on complete complementary wavelet ensemble empirical mode decomposition with adaptive noise （CCWEEMDAN） and Power-Law was proposed in the paper. Firstly, a new noise-assisted signal decomposition algorithm named CCWEEMDAN was presented based on CEEMD. Then, the CCWEEMDAN method was employed to decompose the noise containing transient signal into the Intrinsic Mode Function (IMF) domain, other noise was suppressed by adaptive ensemble empirical mode decomposition, this method achieved better spectral separation of modes and with fewer screening iterations and extremely low computational cost. In addition, in order to acquire the starting point and lagging edge of transients signal, Power-Law detector was applied to detect the certain order of Intrinsic Mode Function containing short-term burst signal. The Monte Carlo simulation examples of typical underwater transient signal and sea trial data processing results show that the detector which based on CCWEEMDAN and Power-Law can effectively suppress the background interference without a priori knowledge, extract transient signal with the SNR gain higher than the conventional Power-Law detectors, and reduce false alarm probability in a certain extent.*

Key words: *underwater acoustic countermeasure; underwater acoustic transient signals detecting; CCWEEMDAN; Power-Law detector*

1. INTRODUCTION

Ocean acoustic survey is not only the basis of the research on physical knowledge of underwater acoustic channel, but also provides a basis for the design of sonar equipment. Explosive sound source is the most commonly used signal source in ocean acoustic survey, and a typical transient signal of blast wave signal. The first task is to detect the explosion wave in the process of ocean surveying acoustic data. The purpose of this paper is to study the transient signal automatic detection method to improve the efficiency and quality of ocean underwater acoustic survey data processing.

Transient signals are characterized by short duration, fast waveform decay rate and strong instabilities in the frequency domain, it is very difficult to design a high robustness transient signal detector, especially in the underwater complex and changing background environment. Transient signals have time-varying characteristics. The main method of detection of transient signal is time-frequency analysis method, such as the time projection to the time-frequency joint domain on the analysis, the main means are short-time Fourier transform (STFT), Gabor linear transformation, Wigner-Ville bilinear distribution WVD), wavelet transform (Wavelet Transform), etc. [1]Aiming at the detection of underwater transient signals, many scholars have conducted in-depth research and achieved good results. Stefannia [2] proposed a detector based on transient signal of higher order moment with the anti-Gaussian noise characteristics of the high-order moment. Boashash [3] analyses the detection performance of a transient signal detector based on a Wigner-Ville time-frequency distribution and a detector based on a higher order spectrum. WANG Zhen et al. [4] proposed that the optimal detector is Mx (Nuttall's "Maximum" Detector) detector based on the detailed analysis and comparison of the performance of six detectors. However, the assumption of the detector is that the duration and average power of the signal are known, which is contrary to the fact that the duration of the transient signal, the signal waveform structure, the background noise spectrum, and the relative spectral density function are unknown. So the optimal detector can’t be found [5]. In view of the actual application scenario, Nuttall et al. Proposed a DFT-based nonparametric transient signal detector: power-law detector, which is better for the detection of transient signals generated by unknown physical processes [6].

Based on the above research, this paper proposes a method to detect the underwater transient signal based on the completely complementary wavelet noise assisted lumped empirical mode decomposition and power-law detector. The method provides a self-adaptive and strong anti-noise ability, it is suitable for low signal to noise ratio environment and has a small amount of computing. And this method has passed the dual verification of simulation data and lake trial data.

2. TRANSIENT SIGNAL DETECTORS BASED ON CEEMD AND

POWER-LAW

2.1 POWER-LAW TRANSIENT SIGNAL DETECTOR

The US Navy Underwater Warfare Centre proposed Power-Law Transient Signal Detector for the first time, Nuttall believed that, the problem of detection of transient signals in the Gaussian background can be simplified as "the problem of detecting any M-point signal in the DFT sequence of N-point observation data", in this case, the form of the transient signal, the spectral structure and the intensity are unknown, and M is the spectral component of the transient signal. The basic assumptions of the Power-Law transient signal detector are: assuming that H0 represents the absence of a signal, the amplitude of the DFT sequence of the time domain signal, Gaussian white noise, obeys the exponential distribution of the independent identically distributed; assuming that H1 represents the presence of a transient signal, the amplitude squared of the DFT sequence of the time domain signal is no longer subject to the exponential distribution of the same distribution. The two cases are as follows:

$$
\begin{aligned}
\mathrm{H}_0 &: f(X) = \sum_{k=1}^{N} \frac{1}{\mu_0} e^{\frac{X_k}{\mu_0}} \\
\mathrm{H}_1 &: f(X) = \sum_{k \notin S} \frac{1}{\mu_0} e^{\frac{X_k}{\mu_0}} \sum_{k \in S} \frac{1}{\mu_1} e^{\frac{X_k}{\mu_1}}
\end{aligned} \tag{1}
$$

In the above formula, $\{X(t)\}$ is the square of the DFT sequence of the observed data, N is the number of DFT points, and $\mu(\cdot)$ is the step function, S is the subset of the transient signal of size M. The probability distribution function of the transient signal under the assumption of H1 depends on the signal itself, thus the following nonparametric power-law detection method is proposed:

$$T(x) = \sum_{k=1}^{N} X_k^{v}(k) \tag{2}$$

Among them, v is the detection threshold, it is proved that there is a better detection results when the value range of v is 1.5 <p <3 [6], when the detector to obtain better detection results, usually take 2.5. The test statistic is the square sum of the amplitudes of the DFT sequence, and a better detection performance with less computation can be realized, without any prior knowledge about the signal.

The energy of the real transient signal is usually concentrated on one or several bands, and Wang and P. Willett [10], respectively, modify the expression. They add two adjacent frequency points and three frequency points, and then get two new power-law detection expression.

$$T_{f2}(U) = \sum_{k=2}^{N} U_{2j}^{P} = \sum_{k=2}^{N} (x_{j-1} + x_{j+1})^{p} \tag{3}$$

$$
\begin{aligned}
T_{f3}(U) &= \sum_{k=3}^{N} U_{3j}^{P} \\
&= \sum_{k=3}^{N} (x_{j-2} + x_{j-1} + x_{j+1})^{p}
\end{aligned}
\tag{4}
$$

Well, the constant false alarm detector expression corresponding to the coloured noise background is:

$$
T_{fc2}(U) = \sum_{k=2}^{N} \left(\frac{U_{kL}}{\frac{1}{L-1} \sum_{i}^{L-1} U_{ki}} \right)^{p} \tag{5}
$$

As a result of the use of frequency domain continuity (Contiguity), the new detector performance is better than the original detector.

2.2 COMPLEMENTARY OVERALL EMPIRICAL MODE DECOMPOSITION METHOD

In general, the reception bandwidth of the receiver is greater than the frequency band of the transient signal, the effect of narrow-band processing method of the transient signal is better than that of the data processing from the entire frequency band. In other words, we can filter the received signal by filtering to obtain a higher SNR of the signal, but frequency and bandwidth of the underwater acoustic transient signal can’t be estimated. The conventional filter is based on the spectrum, and the frequency components outside the pass band of the filter are completely filtered. Therefore, this paper proposes a filtering method different from the traditional band-pass filter. In Hilbert-Huang transform, the core theory is that the intrinsic mode function (IMF) is derived from the data by their characteristic time scales, the he maximum frequency components in each local time scale are decomposed first, and the local frequencies in the same IMF are not necessarily equal. The resulting signal may be a narrowband signal, and there may be a wideband signal of a larger frequency range, that is, the central frequency and bandwidth of the equivalent filter can be based on the characteristics of the signal to achieve adaptive adjustment. In this paper, a signal pre-processing method based on HHT theory for fully complementary wavelet noise assisted lumped empirical mode decomposition is proposed. The adaptive noise reduction of the signal is realized by decomposing the received signal, and the local instantaneous energy is realized from the modal domain Noise reduction.

Hilbert-Huang Transform (HHT), the core theory is empirical mode decomposition (EMD). EMD decomposition of the signal is decomposed into a limited number of IMF (Intrinsic Mode Function). Each order IMF contains different frequency components, representing different harmonic oscillatory functions, and performing a Hilbert transform on each IMF signal to obtain the instantaneous frequency representing a particular physical meaning, resulting in an accurate expression of the frequency change.

Empirical Mode Decomposition (EMD) has adaptive band division function, which has the characteristics of orthogonality, completeness and self-adaptability. Its physical meaning is clear and suitable for dealing with non-stationary nonlinear signals. [7]

However, there are modal aliasing and energy leakage phenomena when the EMD method is used to deal with the intermittent signal, so that the physical meaning of the IMF is unclear.

And so, an new complementary entire empirical model decomposition (CEEMD) is proposed based on EEMD (Ensemble Empirical Mode Decomposition) [9] in Ref. 8. CEEMD adds positive and negative white noise to the original signal multiple times with the characteristics of white noise power spectral density uniform distribution, so that the signal has continuity on different scales And then use the complementary properties of the white noise of the positive and negative polarities to eliminate the influence of the auxiliary noise with less average number of times, and finally make the decomposition process anti-noise characteristic. Nevertheless, CEEMD still has the problem of high number of iterations and low computational efficiency in practical application. Therefore, this paper uses the CCWEEMDAN method proposed in Ref. 10 to decompose the signal to reduce the number of iterations and improve the computational efficiency.

CCWEEMDAN includes the following steps:

The definition operator $E_j(\cdot)$ is the operator of the j-order modal of the given signal by EMD. The operator $M(\cdot)$ is defined as the residual signal after calculating the first order modal of the EMD. The operator $W_j(\cdot)$ is the operator of the given j-th wavelet decomposition by wavelet and the operator of the j-th detail signal, Gaussian white noise is $\omega_k(k = 1,2,\dots,K)$, K is the total number of times, K is even number.

1) The target data $x_0(t)$ is added to the same noise as the K / 2 amplitude and the noise of 180 ° different from the phase angle , respectively, the specific noise is obtained by wavelet decomposition, then you can construct two new mixed signal:

$$x_{k0+}(t) = x_0(t) + \beta_1 W_1(\omega_k(t)),\ \ k = 1,2,\dots,K/2 \tag{5}$$

$$x_{k0-}(t) = x_0(t) - \beta_1 W_1(\omega_k(t)),\ \ k = 1,2,\dots,K/2 \tag{6}$$

2) The new data $x_{k0+}(t)$ and $x_{k0-}(t)$ are respectively subjected to EMD decomposition, then the corresponding K / 2 residual components are obtained. The first order residual components can be obtained after the aggregation of the residual components. The EMD decomposition method is given in Ref. 7.

$$r_1(t) = \frac{1}{K}\sum_{i=1}^{K/2}\left(M(x_{i0+}(t)) + M(x_{i0-}(t))\right) \tag{7}$$

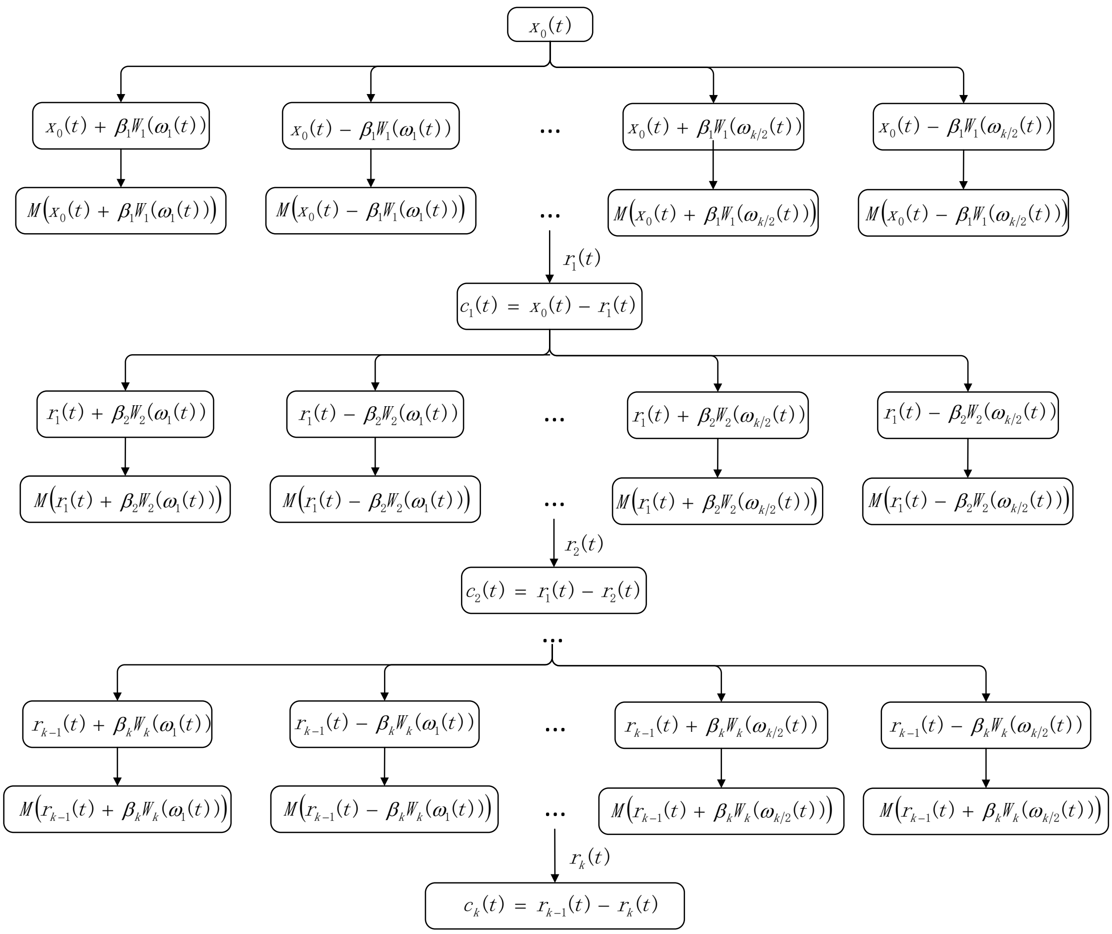
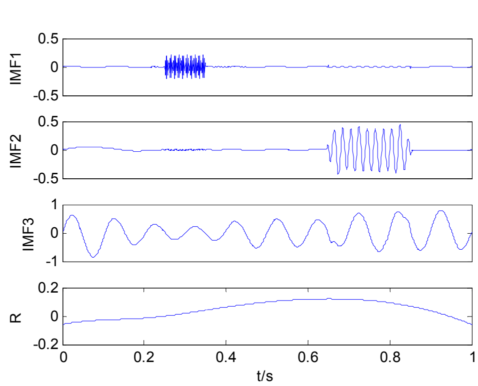


Fig 1 The flow chart of CCWEEMDAN



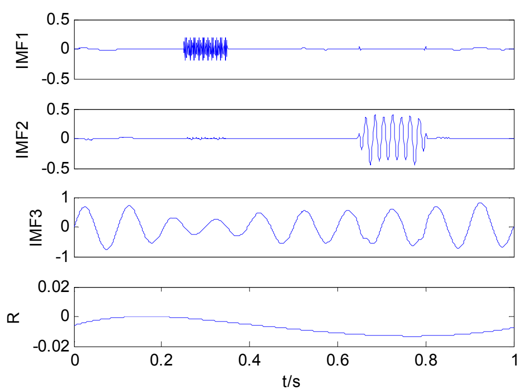


Figure2 CEEMD results *Figure3 CCWEEMDAN results*

3) Calculate the first order IMF component $c_1(t)$ obtained by the signal decomposition:

$$c_1(t) = x_0(t) - r_1(t) \tag{8}$$

4) The K / 2 group specific noise signal is superimposed with the first order residual component $r_1(t)$ to obtain:

$$r_{k1+}(t) = r_1(t) + \beta_2 W_2\big(\omega_k(t)\big),\ \ k = 1,2, \dots, K/2 \tag{9}$$

$$r_{k1-}(t) = r_1(t) - \beta_2 W_2\big(\omega_k(t)\big),\ \ k = 1,2, \dots, K/2 \tag{10}$$

5) The second-order residual component $r_2(t)$ is obtained by decomposing the mixed signal $r_{k1+}(t)$、$r_{k1-}(t)$:

$$r_2(t) = \frac{1}{K}\sum_{i=1}^{K/2}\Big(M\big(r_{i1+}(t)\big) + M\big(r_{i1-}(t)\big)\Big) \tag{11}$$

6) Calculate the second order IMF component $c_2(t)$

$$c_2(t) = r_1(t) - r_2(t) \tag{12}$$

7) The second-order IMF component $c_2(t)$ is used as the original signal, and the specific auxiliary noise is added and decomposed according to Step 5 and Step 6 until the signal can no longer be decomposed.

The above steps are expressed in flow chart as Figure 1.

2.3 POWER-LAW BASED ON CCWEEMDAN TRANSIENT SIGNAL DETECTION

The DFT-based Power-Law Transient Signal Detector essentially utilizes the frequency domain aggregation characteristics of the signal, and the traditional Power-Law detector has poor detection results when the signal-to-noise ratio of the transient signal is low. In the actual ocean test data processing, in order to improve the detection capability of the week underwater acoustic transient signal, this paper uses the CCWEEMDAN decomposition method to denoise the received signal and then detects the wave arrival point of the transient signal. Based on CCWEEMDAN, the Power-Law transient signal detector utilizes the binary adaptive filtering characteristic of modal decomposition. The noise components in the signal are decomposed into low-order IMF. Compared with the energy detection in the whole band, the IMF obtained by CCWEEMDAN adaptive decomposition can better reflect the local characteristics of the transient signal, to a certain extent, a higher signal-to-noise ratio is obtained than the full-band signal processing in the IMF containing the transient signal. The complementary lumped empirical mode decomposition overcomes the traditional algebraic problem of empirical mode decomposition, and inherits the excellent properties of EMD decomposition while using the low computational complexity of wavelet decomposition and has high computational efficiency. The main steps of Power-Law detection based on CCWEEMDAN decomposition are as follows:

1) Decomposing the sampled signal by CCWEEMDAN
2) Removing the IMF component with strong noise, reconstructing the remaining IMF components to obtain the reconstructed signal of noise reduction;

3) Using the Power-Law constant false alarm detector without pre-whitening determined in the formula (5) to detect the reconstruction of the signal.

3. SIMULATION EXPERIMENT

The results of the Navy Underwater Warfare Centre (NUWC) show that typical underwater transient signals can be modelled by superposition exponential decay sinusoidal signal according to the physical mechanism of the acoustic transient signal The model of the transient signal adopted in this paper is the sum of the exponential decay sinusoidal curves at three different starting moments. The expression is:

$$s(t)=\sum_{k=1}^{K}A_k e^{-\lambda_k(t-\tau_k)}\cos(2\pi f_k(t-\tau_k)+\phi_k) \tag{13}$$

Where $k=3$, A_k、 τ_k respectively, represent the amplitude coefficient and delay corresponding to kth component, sampling frequency $fs=20480$, the frequency of each component is $f_1=3\text{kHz}$,$f_2=7\text{kHz}$,$f_3=4\text{kHz}$, λ_k is the amplitude attenuation factor which control each component amplitude attenuation speed, the values are 700, 600 and 400, respectively. ϕ_k is the initial phase, the value is φ_1 = 0.5, φ_2 = 0.7, φ_3 = 0.9, respectively. The initial moment of the transient signal is 0.025s, as shown in Fig.5.

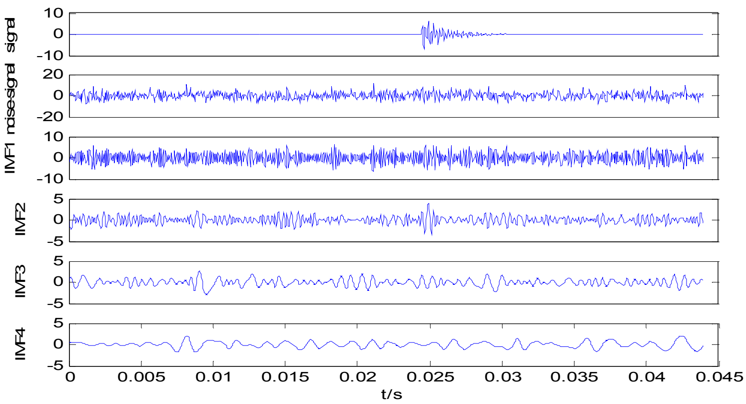


Fig 4 The transient signal, noisy signal and IMF component

Fig.4 shows a number of the order of the IMF component of the signal-to-noise ratio of -16dB transient signal by CEEMD decomposition, with Gaussian white noise added to the signal, and the value of the Power - Law constant virtual alarm detector is 2.5. It can be seen from the comparison of the test results in Fig. 5 that the traditional Power-law detection method can't detect the arrival point of the transient signal when the signal-to-noise ratio is -16dB. The method proposed in this paper can improve the signal to noise ratio- Accurately detect the start time of the transient signal is 0.025s, at this time the detection statistics is much larger than other moments.

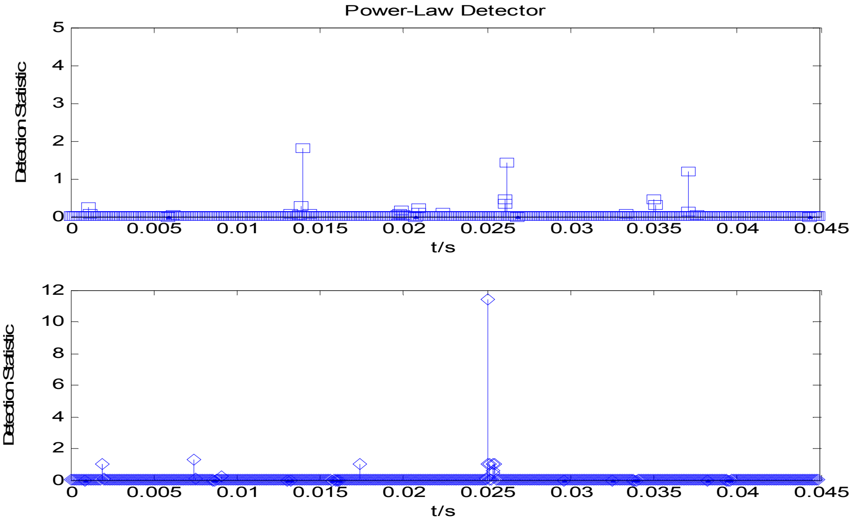


Fig 5 Performance comparison of two CFAR detectors when SNR=-14dB

4. SEA TRIAL DATA PROCESSING AND PERFORMANCE ANALYSIS

In order to verify the actual detection performance of CEEMD-based Power-Law detector, the data of transient signal with the sea trial data is processed by the traditional Power-Law detection and the detection method proposed in this paper. The result is shown in Fig.7 and Fig.8.

As shown in Fig.6, it's the time-domain waveform of the transient signal recorded at sea. The signal length is 2.5s, the signal sampling frequency is 2048Hz, and the wave arrival time of the transient signal is about 1.80s. It is difficult to accurately judge the occurrence of the signal from the time domain plot. This paper gets a number of IMF after using the CEEMD decomposition method to decompose the signal, of which the first five order IMFs as shown in Fig.6 There are obvious waves to pulse in IMF1 and IMF2 in 1.80s, while the noise energy has also been greatly weakened. The IMF2 is subjected to transient signal detection using the method presented in this paper to obtain the result shown in Fig. 7. The peak value of the detection statistics in the figure is consistent with the arrival time of the actual signal. In contrast, the traditional Power-Law detector also detects the transient signal at the same time, but at other times the interference component is stronger, is not conducive to the determination of the threshold, from the statistical results, the false alarm probability is higher.

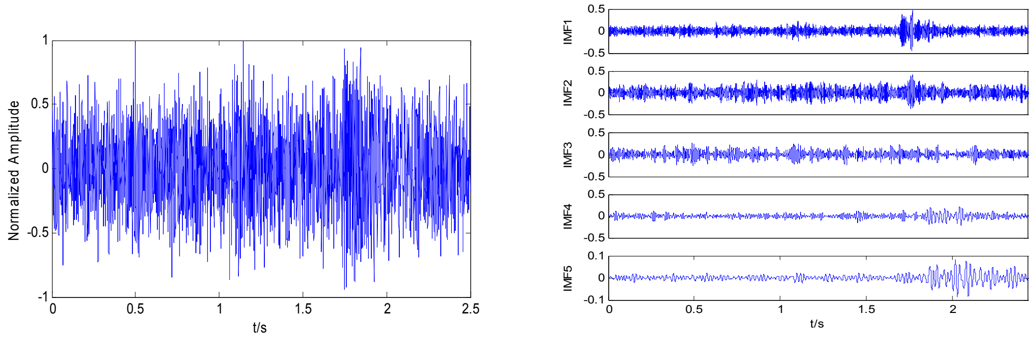


Fig 6 The waveform of underwater transient signal and its IMF component

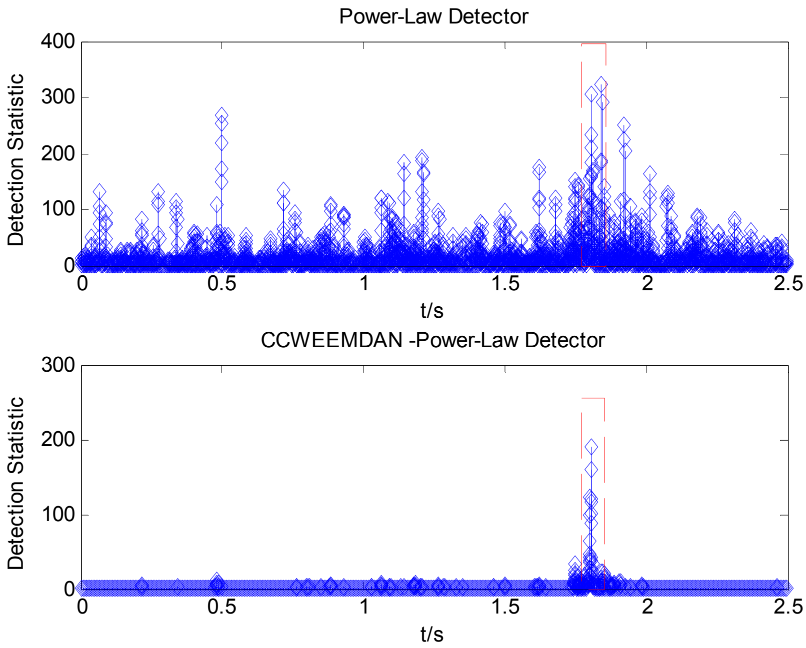


Fig 7 Performance comparison of two CFAR detectors

5. CONCLUSION

In this paper, based on the analysis of Power-Law transient detector, this paper proposes a new CEEMD-Power-Law transient signal detector based on CEEMD method, for the low signal-to-noise ratio, short duration and suddenness of underwater acoustic transient signal. State signal detector.

The simulation and maritime record data processing results show that the proposed method can effectively suppress the background interference and improve the signal-to-noise ratio of the transient signal. It can effectively detect the arrival point of the transient signal without the prior knowledge of the signal. The detection result is obviously superior to the traditional Power-Law detection method.

The algorithm proposed in this paper has greatly reduced the computation of CEEMD process, which provides the possibility for engineering application.

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