Feature extraction of target echo based on wavelet energy spectrum

ZHOU Bo
Department of Basic Science, Dalian Navy Academy, Dalian 116018, China
*Corresponding author's e-mail: mjliu@dlactech.com

Abstract—The characteristics of target echo are related to many complicated factors, such as transmission waveform, the structure, attitude and motion state of the target and multi-channels transmission of ocean channel. The characteristics of target echo in different time-frequency spaces are discussed. The echo is recognized by the combination of different characteristic spaces such as energy, frequency band, entropy, kurtosis and variance of the wavelet energy spectrum. Firstly, the wavelet energy spectrum in time domain by using the continuous wavelet transformation, then the energy spectrum entropy describing quantitatively signals varying with time was calculated along the time axis, and their time-wavelet energy spectrum were different. The data processing shows that segmented spectrum center, spectral bandwidth can classify different types of underwater echoes to some extent.

1. Introduction
Detection of target echo is the basis of target classification recognition. In general, the rise and fall of target echoes are critical to target information. In a pulse cycle, when the target appears, it is generally impossible to predict. The width of the echo signal is also difficult to determine in advance. Therefore, how to obtain the exact position of the target echo is of great importance. Linear Frequency Modulated (LFM) signals are commonly used in underwater target detection recognition. Its corresponding target echo has the mixed characteristics of time and frequency. Therefore, the extraction of time-frequency characteristic parameters is an effective method [1,2].

The spectrum of the signal reflects the change of signal energy with frequency. Common spectral decomposition methods include Short-time Fourier Transform(STFT), Wigner-ville distribution method(WVD), Hilbert-Huang transform(HHT), and wavelet transform(WT). However, in the case of low signal-to-noise ratio, the time-frequency distribution obtained by WVD is not ideal due to cross-term interference, which is not conducive to the accurate detection of signal parameters. STFT does not have the problem of crossover items, but it uses a fixed time-frequency window for different frequency components, and can not adapt to change of the time resolution and frequency resolution. The HHT obtains different modal components of the signal by repeatedly extracting the average value of the upper and lower envelope, and then obtains the instantaneous frequency of the signal through the Hilbert transform, but there is a boundary effect in the envelope extraction process[1,2].

WT has multi-resolution characteristics by adjusting scale parameters, higher time resolution can be obtained for high-frequency components, higher frequency resolution can be obtained for low frequency components. Physiological studies have shown that the cochlear basement membrane, which plays a key role in hearing, acts as a set of constant-Q (quality factor) band-pass filters based on membrane vibration[3 -4]. Wavelet transform uses band-pass filters with constant-Q, which is
consistent with the processing characteristics of sonars for auditory information. It can be seen that using wavelet transform can simulate the feelings of the sonar listening process. Since the wavelet spectrum represents the local time-frequency energy of the signal, if the echo signal can be regarded as a mutation signal regard to the reverberation and noise signal, the mutation location of the echo signal can be tracked using the wavelet spectrum energy characteristics by extracting the front and back edges of the echo signal.

2. Features of Echo Signal extracted by Wavelet Transform

2.1. Definition and characteristics of wavelet transform

The Wavelet transform is the inner product of the mother wavelet function $\psi(t)$ and the signal to be analyzed at different scales $a$:

$$WT_x(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^*(\frac{t-\tau}{a}) dt, \quad a > 0$$

Its frequency domain is expressed as:

$$WT_x(a, \tau) = \frac{\sqrt{a}}{2\pi} \int_{-\infty}^{\infty} X(\omega)\psi^*(a\omega)e^{+j\omega\tau} d\omega$$

The Fourier transform of $x(t)$ and $\psi(t)$ are $X(\omega)$ and $\Psi(\omega)$ respectively in (2). Proper selection of base wavelet, making it has a finite support in the time domain and concentrated in the frequency domain. Then the WT has the ability to characterize the local characteristics of the signal in the time and frequency domains. Therefore, it is helpful to detect the transient of the echo signal.

The energy change properties of the wavelet transform are:

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{a^2} |WT_x(a, \tau)|^2 d\tau da = C_\psi \int_{-\infty}^{\infty} |x(t)|^2 dt$$

Formula(3) describes the energy relationship between the wavelet transform of the signal and the original signal, that is, the integral of the square of the wavelet transform is proportional to the energy of the signal.

$$E_x = \int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |w_x(a, \tau)|^2 \frac{d\tau da}{a^2} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(a, \tau) d\tau da$$

The energy density function $E(a, \tau)$ in the wavelet domain is called the wavelet energy spectrum.

The distribution along the time axis $E(\tau) = \int_{-\infty}^{\infty} E(a, \tau) da$ is called wavelet time-energy spectrum. The distribution along the scale axis $E(a) = \int_{-\infty}^{\infty} C_\psi a^2 E(a, \tau) d\tau$ is called the wavelet scale-energy spectrum.

2.2 Echo detection based on wavelet spectrum

Spectral centroid describes the subjective feelings of the listeners sound. If the echo sounds deep and balanced, strong and powerful, such echoes often contain more low-frequency content, and the spectral centroid is relatively low; On the contrary, if the echo sounds compact and light, bring listeners a sense of urgency, the frequency components are mostly concentrated at high frequencies and the spectral centroid is relatively high. Therefore, the Spectrogram centroid (abbreviation SC) can
be used as a characteristic parameter to distinguish the target. The spectral centroid is the center of the frequency component\cite{6,7}. The formula is as follows:

\[
SC = \frac{\sum_{n=1}^{N} f(n)E(n)}{\sum_{n=1}^{N} E(n)} = \sum_{n=1}^{N} f(n)P(E(n))
\] (5)

\(x(n)\ (n = 1,2,\cdots,N)\) is the discrete time signal received, \(E(n)\) is the energy of the corresponding spectrum of the wavelet transform, \(f(n)\) is the corresponding frequency point after the wavelet transform, and \(N\) is the sampling point.

Spectral centroid bandwidth (abbreviated as SCB) refers to the bandwidth of the energy distribution, reflecting the area of the sound energy set. The expression is as follows

\[
SCB = \frac{\sum_{n=1}^{N}|SC - f(n)|E(n)}{\sum_{n=1}^{N} E(n)}
\] (6)

### 3. Simulation experiment

The LFM signal used in the simulation experiment contains two LFM components, which are called component 1 and component 2. The simulated signal parameters are set to: time width 20ms; Starting frequency 5000 Hz; Cut-off frequency 7000 Hz; Sampling rate 44.1 Khz, adding noise with a variance of 0.9. The echo signal is \(x(t)\), and the discrete sampling value is \(x(n), \quad n = 1,2,\cdots,N\). First, normalization:

\[
u(n) = \frac{x(n)}{\max\{x(n)\}}
\] (7)

Figure 1 is the normalized signal with a sampling frequency of 44.1 KHz. It is difficult to locate the leading- and trailing-edge of the echo because of the strong noise. The soft threshold method is used to remove the additive noise and the threshold is determined by the Soft threshold:

\[
\hat{t}_{j,k} = \begin{cases} 
  t_{j,k} - \lambda \text{sgn}(t_{j,k}) & |t_{j,k}| \geq \lambda \\
  0, & |t_{j,k}| < \lambda 
\end{cases}
\] (8)

Where \(t_{j,k}\) is the original wavelet coefficient before threshold processing, \(\lambda\) is the soft threshold, the sgn (.\) is a symbolic function, and \(\hat{t}_{j,k}\) is the coefficient after threshold processing.

Daubechies wavelet is used to de-noising (dB5). The scalogram is obtained by using three-layer wavelet decomposition, and the envelope of scalogram can be reconstructed with the low frequency coefficient of the third layer to extract the front and rear edges of the echo signal.
Figure 1. the spectrum of the signals received by active sonar.
(a) the normalization signal (b) Wavelet spectrum of a component 1
(c) Time domain distribution of time-wavelet spectrum

Table 1. Echoing the timbre characteristics of echo signals

| Signal source                        | No. 1     | No. 2     |
|--------------------------------------|-----------|-----------|
| Wavelet time-energy spectrum mass center(s) | 0.0105    | 0.03602   |
| Wavelet time-energy spectrum radius(s)  | 0.0100    | 0.0097    |
| Echo Front(s)                        | 0.0005    | 0.02632   |
| Back edge of echo(s)                 | 0.0205    | 0.04572   |

Figure 1(a) is the original signal with a sampling frequency of 44.1 KHz. Figure 1(b) shows its wavelet spectrum. It can be seen from the wavelet spectrum that the energy of the signal is concentrated in the LFM signal, the frequency is concentrated in the 5KHz to 7KHz range, and the time is concentrated near the sampling point. This information can also be seen in figures 3 and 4. Figure 1(3) is the discrete wavelet time-energy spectrum, which reflects the envelope change of the received signal that reflects the characteristics of the signal energy with frequency changes.

The curves of standard deviation, bias coefficient, peak coefficient, and entropy change with time, combined with the two-dimensional characteristics of peak and entropy, locate the position where the echo signal occurs.

4. Conclusion
The characteristics of echoes extracted from the wavelet time-energy spectrum and the frequency-energy spectrum, the spectral center and spectral center bandwidth parameters can be distinguished. On the basis of wavelet time-energy spectrum, the location of echo signal is determined by combining
the two-dimensional characteristics of peak and entropy. And the spectral energy distribution of the target is more concentrated and more stable than that of reverberation and noise. The frequency of the target's harmonics is more than that of reverberation and noise, so the echoes of target will be distinguished.

References

[1] Wang Na, Chen Ke’an, “Regression model of timbre attribute for underwater noise and its application to target recognition,” Acta Physica Sinica, vol. 59 (4), pp. 2873-2881, 2010.
[2] Cao Hongli, Fang Shiliang, “Boats and ships radiated noise loudness and the timbre feature pattern,” University of Southeast Journal (Natural Science Edition), vol. 43, pp. 241-246, 2013.
[3] Li Qing, Wang Qi-shen, “Wavelet spectrum and its application to LFM signal detection,” Chinese Journal of Quantum Electronics, vol. 22 (5), pp. 685-689, 2005.
[4] Zhang Qiao-ge, Liu Zhi-gang, Chen Gang, “Frequency Detection of Transient Oscillation Signal Using Morlet Wavelet Based on Spectral Kurtosis Method,” Proceedings of the Chinese Society of Universities for Electric Power System and Its Automation, vol. 25 (5), pp. 1-6, 2013.
[5] Li Xiukun, Li Tingting, Xia Zhi, “Feature extraction and fusion based on the characteristics of underwater targets,” Journal of Harbin Engineering University, vol. 31 (7), pp. 903-908, 2010.
[6] Wang Na, Chen Ke, “Application of Sub-band Spectral Centroid Features to Recognizing Underwater Targets,” Acta Armamentarii, vol. 30 (2), pp. 144-149, 2009.
[7] Shu Xianglan, Sun Rongguang, Ma Xin, “Echo detection of LFM signal under strong reverberation background,” Telecommunication Engineering, vol. 56 (1), pp. 82-87, 2016.