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Echo analysis of objects on the seafloor

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Abstract: Echoes from elastic objects on the seafloor comprise two kinds of acoustic components as well as bottom reverberation. One is elastic scattering echoes, and the other is geometric echoes. These echoes are called highlights, which can be used for identification of objects. Because time delay among highlights from small objects is very short, neither the wavelets resolved highlights structure nor suppressed bottom reverberation according to research. In order to obtain highlights structure and decay reverberation, the Hilbert Huang Transform(HHT), which is a new idea for analyzing nonlinear and nonstationary is applied in the paper. The HHT can describe the data from the instantaneous frequency and energy rather than the global frequency and energy defined by the Fourier spectral analysis, and the adjustable window Fourier spectral analysis defined by the wavelet. The results from both extensive simulations and real data show that the HHT has the highest resolution in time and frequency domain, and may prove to be a vital method for identification of objects on the sea floor.

1 Introduction

Time-frequency and temporal analysis methods have been widely applied in anti-mine sonar signal processing. Conventional techniques for data analysis, such as Fourier Transform (FT) and Short-Time Fourier Transform (STFT) [1], seek to represent the temporal characteristics of the signal by spectral components in the frequency domain or time-frequency domain. But when it comes to nonstationary and nonlinear signals, apply of the two time-frequency methods is limited because of an assumption that the original signals satisfy the stationarity condition or local stationarity condition. The methods for nonstationary and nonlinear signals including Winger-Ville Distribution (WVD) [2] and Wavelet Transform (WT) [3] provide solutions to balance the resolution of both time and frequency while the Fourier Transform uses a globe time window and the STFT has to select an unchangeable time window. However, WT is very useful for data analyze and compression, the temporal location and frequency scale cannot be determined with arbitrary precision simultaneously by WT [4].

A problem of anti-mine sonar signal processing need to be solved, the strong bottom reverberation. The low signal-reverberation ratio is caused by powerful wave absorption in sea bottom. Extraction echo signal from reverberation often failed for the identity of echo and reverberation in frequency spectrum. Usually the reverberation signals are nonstationary and nonlinear signals. For these difficulties, conventional signal processing methods are hard to capture echo effectively. Therefore a new method which can highlight the local characteristic time scale of the nonstationary and nonlinear signals, be independent from selected basis function and have higher resolution is demanded to overcome the drawbacks of conventional methods. This study seeks to use Hilbert-Huang Transform (HHT) as a new method to challenge the problem.

Highlight Model has been used wildly in the study of Anti-mine sonar signal processing. Highlight is showed in a signal as the form of impulses adding together. It often failed to reveal geometry highlights because they depend on the location and shape of a target, but it is more feasible to separate elastic highlight from echo than to geometry elastic highlight in time-frequency domain using a Time-frequency and temporal analysis method. This ideal of elastic character identification has sparked new methods using Time-frequency analysis method [5] [6]. This study seeks to apply HHT, a new Time-frequency analysis method. With an aid of HHT, results from the analyses show that HHT provide a better resolution ability of disparate amount geometry and elastic highlight.

2 Methodology

The HHT was developed by Huang et al with a purpose that decomposes nonstationary signals in to server intrinsic mode functions (IMF) [7]. The IMF refers to a series that have meaningful

instantaneous frequency and satisfies two requirements: Its number of extrema and number of zero crossings must either be equal or differ by one and the mean value of the envelopes defined by the local maxima and minima is zero. The instantaneous frequency is defined as:

$$f_i(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \qquad (1)$$

To arbitrary narrow band time-series $x(t)$, In order to use this unique definition of instantaneous frequency,

If want to obtain its meaningful frequency, its analytical function should be given as:

$$z(t) = x(t) + jy(t) = a(t)e^{i\theta(t)} \qquad (2)$$

Where the $y(t)$ is Hubert Transform of $x(t)$ and is estimated as:

$$y(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}d\tau = x(t) * \frac{1}{\pi t} \qquad (3)$$

Then the instantaneous amplitude and instantaneous phase of analytical signal are estimated as:

$$a(t) = [x^2(t) + y^2(t)]^{1/2} \qquad (4)$$

$$\theta(t) = \arctan\left(\frac{y(t)}{x(t)}\right) \qquad (5)$$

For obtaining meaningful instantaneous frequency, it is necessary to decompose $z(t)$ into series of monocomponent functions advised by Cohen [8]. These functions are defined as IMF in the theory of HHT. It is demanded to reduce an arbitrary data set into IMF components from which an instantaneous frequency value can be assigned to each IMF component [9]. Huang had developed empirical mode decomposition (EMD) to extract the IMFs from arbitrary narrow band time-series $x(t)$ as follows.

First all the local extrema of $x(t)$ are identify and connected by cubic splines to produce the upper envelope, and lower envelope. The mean of these two envelopes is designated as $m_{10}(t)$ .The different between is estimated as:

$$h_{10}(t) = x(t) - m_{10}(t) \qquad (6)$$

If the $h_{10}(t)$ does not satisfy the two conditions of a IMF, to $h_{10}(t)$ the first procedure should be repeated until $h_{1i}(t)$ which satisfies requirements is obtained. $h_{1i}(t)$ is defined as the first IMF:

$$imf_1(t) = h_{1i}(t) \qquad (7)$$

Then remove imf_1 from original signal $x(t)$

$$r_1(t) = x(t) - imf_1(t) \qquad (8)$$

The first procedure, Eq.(6),(7), should be repeated if $r_1(t)$ contains longer-period components, and other IMFs are estimated as:

$$r_1 - imf_2 = r_2, r_2 - imf_3 = r_3 \cdots, r_{n-1} - imf_n = r_n \qquad (9)$$

Finally $x(t)$ is decomposed as:

$$x(t) = \sum_{i=1}^{n} imf_i(t) + r_n(t) \qquad (10)$$

Where $r_n(t)$ is a residue which is a monotonic function or has a too low frequency and is considered as tend.
All the IMFs can be given as :

$$imf_i(t) = a_i(t)\exp(i\theta_i(t)) = a_i(t)\exp\left(j\int \omega_i(t)dt\right) \qquad (11)$$

Then $x(t)$ can be decomposed as:

$$x(t) = \mathrm{Re}\left(\sum_{i=1}^{n} a_i(t)\exp\left(j\int \omega_i(t)dt\right)\right) \qquad (12)$$

This Eq.(12) shows that frequency, time and amplitude can be represented in a three-dimensional plot. Frequency-time distribution of the amplitude is designated as the Hilbert amplitude spectrum $H(w,t)$ .To measure the total amplitude contribution from each instantaneous frequency value, the Hilbert marginal spectrum is estimated as:

$$h(\omega) = \int_{-\infty}^{+\infty} H(\omega, t)dt \qquad (13)$$

3 Results

3.1 Analysis of simulated anti-mine sonar signal based on Highlight Model

Every highlight can be considered as a sound source, scattering the wave signal transmitted by the anti-mine sonar. So the system function of a highlight can be defined as:

$$H_m(w) = A_m(w)e^{jw\tau_m}e^{j\varphi_m} \qquad (14)$$

In which A is amplitude, τ is time delay and φ is phase-angle jump.

The scattering waves contributed by all the highlights are added together, and then the final system function is estimated as:

$$H(w) = \sum_{m=1}^{N} A_m(w)e^{jw\tau_m}e^{j\varphi_m} \qquad (15)$$

If we simulate with a linear frequency modulated (LFM) transmitted signal:

$$s(t) = A\cos(2\pi f_0 t + \pi k t^2) \qquad -\frac{T}{2} \le t \le \frac{T}{2} \qquad (16)$$

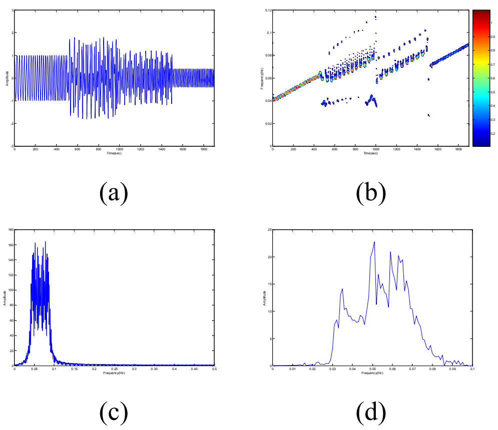
The received echo will be estimated as:

$$U(t) = \sum_{i=1}^{n}\left\{A_m\cos\left[2\pi f_{0m}(t-\tau_m) + \pi k_m(t-\tau_m)^2 + \varphi_m\right]\right\} + A_e\cos\left[2\pi f_e(t-\tau_e) + \pi k_e(t-\tau_e)^2 + \varphi_e\right] \qquad (17)$$

In equation A_e is amplitude of elastic highlights; f_e is characteristic frequency; τ_e is time delay; φ_e is phase-angle jump; f_0 is carrier of LFM signal, k is slope and T is bandwidth.

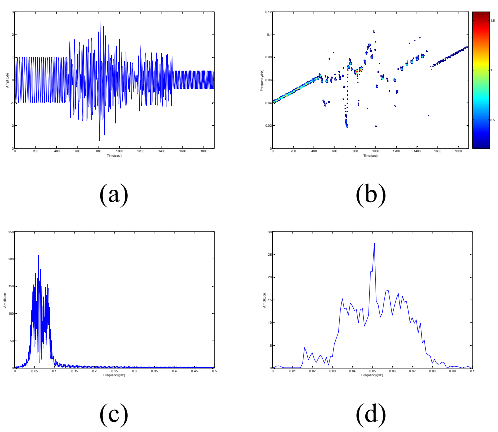
Three simulated signals were produced. The first one includes three geometry highlights and no elastic highlight (fig.1);The second one is produced by three geometry highlights and one elastic highlight (fig.2); the last one is constructed by adding experimental reverberation to the second one, with its signal-reverberation ratio is 1dB (fig.3).

As a compare, we decompose the Fourier spectrum of simulated echo without reverberation background using a Discrete Wavelet Transform (DWT) in order to reveal elastic highlight disturb in the wavelet spectrum (fig.4).



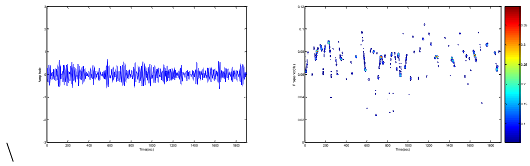
(a) (b) (c) (d)

Fig.1 (a) simulated echo without elastic highlight. (b) Hilbert amplitude spectrum of simulated echo without elastic highlight. (c) Fourier spectrum of simulated echo without elastic highlight. (d) Hilbert marginal spectrum of simulated echo without elastic highlight.

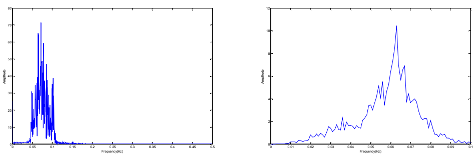


(a) (b) (c) (d)

Fig.2 (a) simulated echo with elastic highlight. (b) Hilbert amplitude spectrum of simulated echo with elastic highlight. (c) Fourier spectrum of simulated echo with elastic highlight. (d) Hilbert marginal spectrum of simulated echo with elastic highlight.

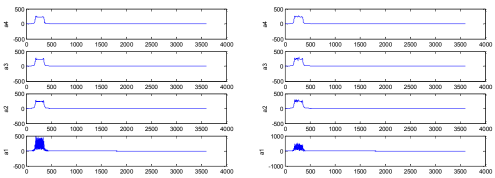


(a) (b)



(c) (d)

Fig.3 (a) simulated echo with reverberation background. (b) Hilbert amplitude spectrum of simulated echo with reverberation background. (c) Fourier spectrum of simulated echo with reverberation background. (d) Hilbert marginal spectrum of simulated echo with reverberation background.



(a) (b)

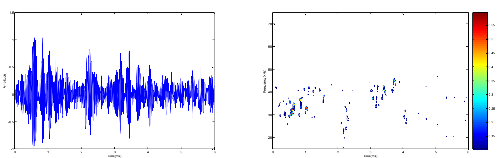
Fig.4 (a) discrete wavelet spectrum of Fourier spectrum without elastic highlight. (b) discrete wavelet spectrum of Fourier spectrum with one elastic highlight.

3.2 Analysis of anti-mine sonar signal in strong bottom reverberation background

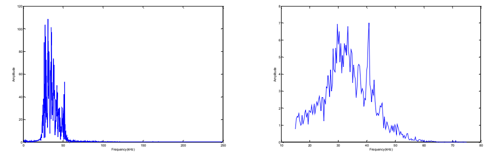
In the experiment, a false target was sunk into a lake and buried in the bottom of the lake. The first signal is the echo of a transmitter parallel to sea level (fig.4).

There is an 10° inclination angle between transmitter and sea level in the second signal (fig.5). The transmitted signal is LFM.

The bottom reverberation signals were recorded before sinking the target, and a reverberation signal's Fourier spectrum is decomposed by Discrete Wavelet Transform (fig.6).

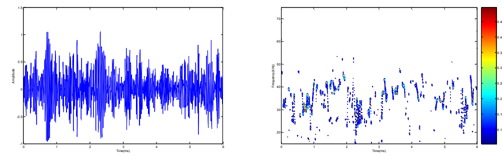


(a) (b)

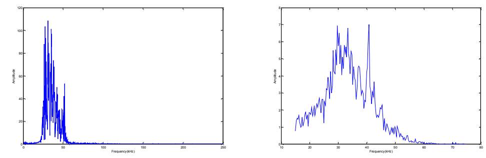


(c) (d)

Fig.5 (a) echo without inclination angle. (b) Hilbert amplitude spectrum of echo without inclination angle. (c) Fourier spectrum of echo without inclination angle. (d) Hilbert marginal spectrum of echo without inclination angle.

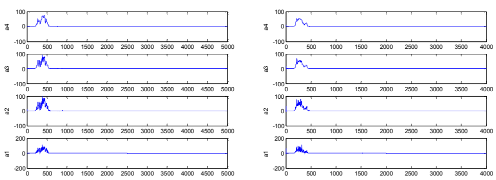


(a) (b)



(c) (d)

Fig.6 (a) echo with inclination angle. (b) Hilbert amplitude spectrum of echo with inclination angle. (c) Fourier spectrum of echo with inclination angle. (d) Hilbert marginal spectrum of echo with inclination angle.



(a) (b)

Fig.7 (a) discrete wavelet spectrum of Fourier spectrum with inclination angle. (b) discrete wavelet spectrum of reverberation's Fourier spectrum. which includes no target's echo.

4 Discussion

Showed by Fig.1, the geometry highlights are clear using HHT, while Fourier spectrum is clutter with strong Gibbs. If the elastic part is simulated in signal (Fig.2), Hilbert marginal spectrum can reveal interference caused by an elastic highlight clearly, however all the geometry highlights and elastic highlight is cover by Gibbs in Fourier spectrum. The simulated reverberation can disturb the Hilbert marginal spectrum a little, but it is not a block to recognize the elastic highlight.

Discrete wavelet spectrum of signal's Fourier spectrum can show elastic highlight decomposing signal (Fig.4). If an elastic highlight contributes, the fourth order moments wavelet detail coefficients will be disturbed according Fig.4. But when the experimental data is decomposed by DWT (Fig.7), the reverberation can not be suppressed for the wavelet detail coefficients of both bottom reverberation signal and target echo signal with a reverberation background are seriously disturbed.

HHT disperse the reverberation in Hilbert amplitude spectrum and the reverberation is suppressed by this process. Even in a low signal-reverberation ratio condition, the superiority of Hilbert marginal spectrum is evident comparing with Fourier spectrum in representing the character of highlights. The comparison with DWT also prove the merit of HHT.

5 Conclusion

This study has represented a method for the extraction of highlight characters of underwater target in a strong reverberation background. The method based on HHT has a better resolution ability to detect elastic highlight than DWT and FT. Characters can be capture by analyze the Hilbert marginal spectrum of the echo, even with a low signal-reverberation ratio. The result supports that further research can work on an amount of samplings to build feature database based on Hilbert marginal spectrum of the target.

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