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Blind Source Separation of the Fractional Fourier Domain in Reverberation Background

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Abstract: To resolve the problem that reverberation signal usually seriously affect active sonar's detection performance, Blind Source Separation method of the Fractional Fourier Domain is adopted in this study. First, the Fractional Fourier Transform is used to enhance the signal-to-reverberation ratio. And then the separation condition is analyzed and target echo is separated from the received signal by using the Blind Source Separation method. At last, the highlight characteristic of the underwater target is extracted. Simulation and experiment data processing affirm the effectiveness of the proposed method.

Key words: Blind source separation of the fractional fourier domain, underwater target detection, reverberation

INTRODUCTION

Underwater target echo is a kind of physical process which comes from targets when incident sound wave excites the targets, so the echo contains a lot of messages with characteristics of targets. These messages are the base of active sonar to detect and recognize the underwater targets. Reverberation signal is caused by emission signal which is formed by sound waves' scattering superposition at inhomogeneous medium when sound wave propagates in the sea. The frequency band of reverberation is similar to the frequency band of transmit signal which is a kind of non-stationary colored noise. Reverberation is the key interference factor of active sonar's target detection and it makes sharp decrease of working performance of sonar. Sonar processing machine extract characteristics of targets by process the echo signal in order to classify and recognize targets. Highlight structure of targets is one of the most characteristics of underwater targets which is usually researched and which is especially suitable to analyze military targets of big size. It is a key problem to extract and recognize these highlights.

In 1980, the Fractional Fourier Transform was first specified and a more rigorous analysis of the technique was given later (Namias, 1980; Tao *et al*., 2004). The relationship between the conventional Fourier transform and the Fractional Fourier transform can be demonstrated like this: the conventional Fourier transform can be seen as the signal is rotated counterclockwise $\pi/2$ radian from time axis to frequency axis while the Fractional Fourier transform can seen as the signal is rotated counterclockwise α radian from time axis to u axis. Because the Fractional Fourier transform is linear transform and can be computed by Fourier transform, its computation can be simplified. Further more, as conventional Fourier transform is suitable to analyze stationary signal, FRFT can decompose signals into mutual orthogonal chirp signals, so it is suitable to analyze time-variant and non-stationary signals, especially chirp signals. When active sonars transmit chirp signals, the target echo signal and reverberation are different in fractional domain, so target echo signal can be detected under reverberation background.

Compared with traditional signal processing methods, Blind Source Separation (BSS) technique is a kind of signal processing method which can separate source signals from the observed signals without prior knowledge of signal sources and the channel as long as the source signals are mutually independent or uncorrelated. Considering of these advantages, Blind Source Separation method of the Fractional Fourier Domain is adopted in this study to separate the target echo from observed signals, good simulation results and experimental data analysis are got to realize the highlight characteristic extraction of targets under reverberation background.

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ANALYSIS OF TARGET ECHO AND REVERBERATION BASED ON FRACTIONAL FOURIER DOMAIN

The basic Fractional Fourier transform definition of function f (t) is expressed by:

$$F^p(u) = \int_{-\infty}^{\infty} f(t) K_\alpha(t,u)\,dt \tag{1}$$

In Eq. 1, $\alpha = p\pi/2$, p is the order of Fractional Fourier transform K_α (t, u), is the kernel of the transform which is expressed by:

$$K_\alpha(t,u) = \begin{cases} \sqrt{(1-j\cot\alpha)/2\pi}\, e^{j\frac{t^2+u^2}{2}\cot\alpha - jtu\csc\alpha}, & \alpha \neq n\pi \\ \delta(t-u), & \alpha = 2n\pi \\ \delta(t+u), & \alpha = (2n\pm 1)\pi \end{cases} \tag{2}$$

Form Eq. 1 and 2, it can be seen that the signal is represented as sums of some chirp signals. When the active sonar transmit signal as a chirp signal form, different α is scanned. When α is matched with the parameters of transmit signals, the signal has the most energy concentration at u axis. Target echo has energy concentration in FRFT domain while reverberation has not energy concentration in FRFT domain, so that reverberation is restrained in FRFT domain. According to the concept of highlight model (Tang, 1994), the echo signals of active sonar are simulated as follows.

Simulation 1: There is only one geometrical highlight in echo signal. Simulated signal is a chirp signal, of which pulse width is 1200 sec, frequency band is form 0.05-0.1 Hz, sampling frequency fs = 1 Hz, signal-to-reverberation ratio SRR = 0 dB.

Figure 1 is the simulated echo signal in time domain, Fig. 2 is the simulated echo signal in frequency domain and Fig. 3 is the fractional fourier transform of the simulated echo signal. It can be seen that under reverberation background, the target signal can't be distinguished with reverberation either in time domain or in frequency domain while in fractional Fourier domain, the target echo is represented as sinc function form which confirms that FRFT can restrain reverberation.

Simulation 2: There are two geometrical highlights contained in echo signal. Simulated signals are chirp signals, both of which pulse width is 1200 sec, frequency band is form 0.05-0.1 Hz, sampling frequency fs = 1 Hz, time delay of the two signals is 400 sec, signal-to-reverberation ratio SRR = 10 dB.

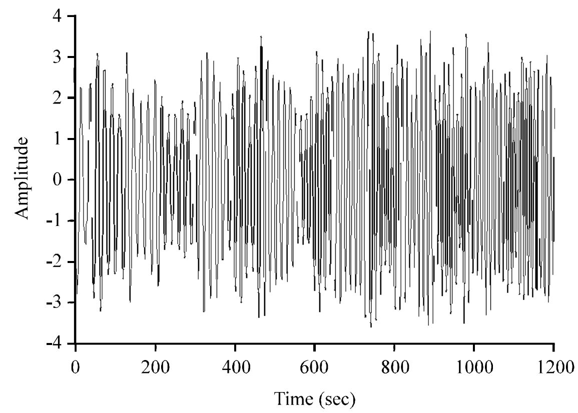

Fig. 1: Echo signal 1 in time domain

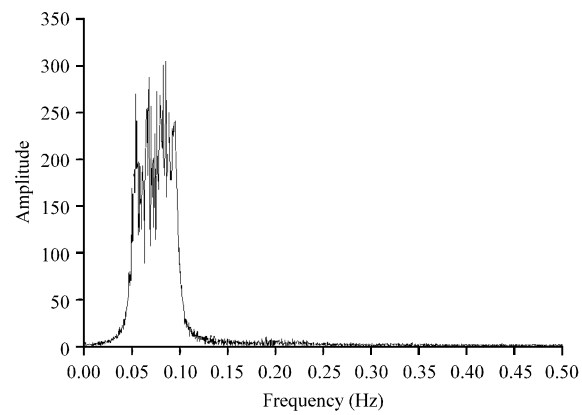

Fig. 2: Echo signal 1 in frequency domain

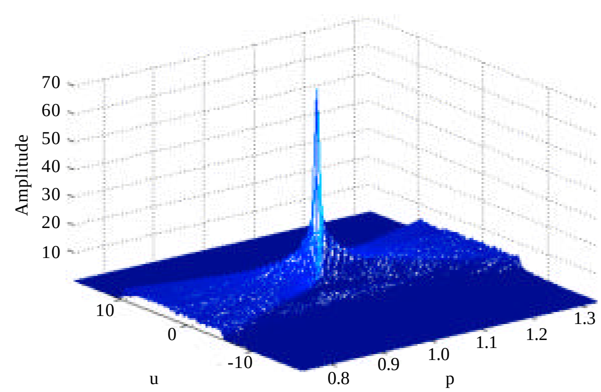

Fig. 3: Fractional fourier transform of signal 1

Figure 4 is the simulated echo signal 2 in time domain, Fig. 5 is the simulated echo signal 2 in frequency domain and Fig. 6 is the fractional fourier transform of the simulated echo signal. It can be seen that under reverberation background, the two geometrical highlights can't be distinguished either in time domain or in

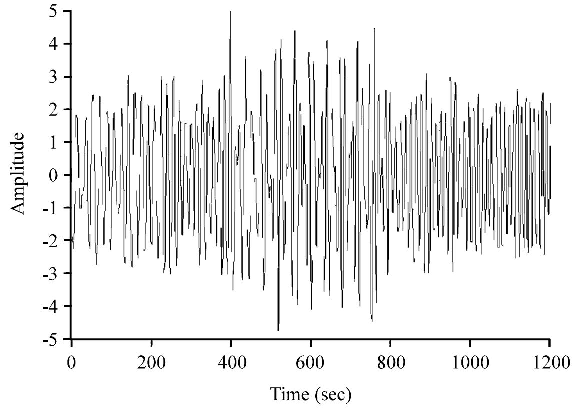

Fig. 4: Echo signal 2 in time domain

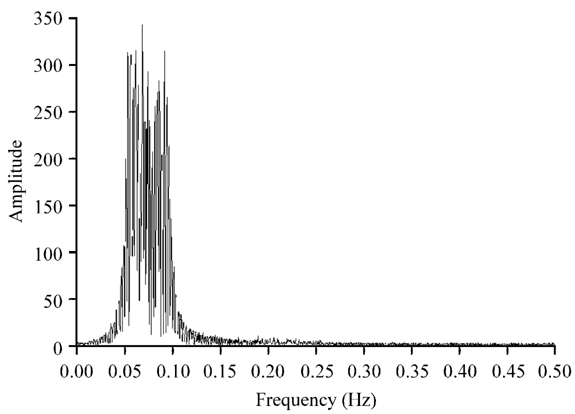

Fig. 5: Echo signal 2 in frequency domain

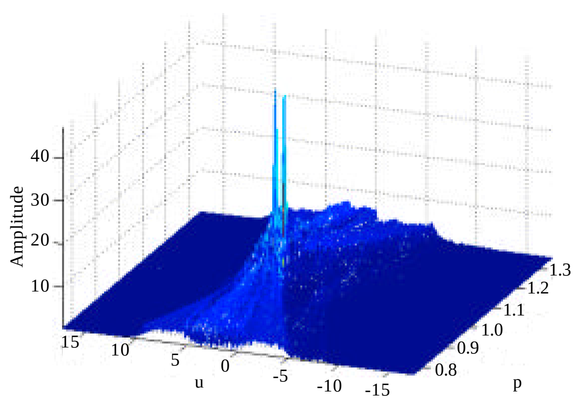

Fig. 6: Fractional fourier transform of signal 2

frequency domain while in fractional Fourier domain, the two highlights are separated which can confirm that highlight message can be extracted by Fractional Fourier transform.

It can be seen from above simulations that FRFT can restrain reverberation and can enhance the signal-to-reverberation ratio.

BLIND SOURCE SEPARATION METHOD BASED ON FRACTIONAL FOURIER DOMAIN

Blind source separation method is a developing technique of array processing and data analysis and its aim is to recover unobserved signals or "sources" from observed mixtures, using only the assumption of mutual independence between the signals (Cardoso, 1998). It is used more and more popular in the field of underwater signal processing (Kim *et al*., 2009; Huang and Gao, 2006; Xu *et al*., 2010). It is important to select proper blind source separation method to analyze signals. Considering of the reverberation signals are non-stationary, Second Order Nonstationary Source (SONS) separation method which is the improved algorithm based on Second Order Blind Identification (SOBI) method is adopted in this study.

The SOBI algorithm is as follows:

- Compute the zero-delay covariance matrix of the observed signal x(t) and make singular value decomposition:

$$R_x(t) = E\{x(t)\, x(t)^T\} = UQU^T \quad (3)$$

Let whitening matrix $B = Q^{-1/2} U^T$ and the whitening signal z (t) = Bx (t)

- To get a matrix W by means of joint diagonalizing the covariance matrix of different time delays to minimize the cost function:

$$\min J(\bar{R}, W) = \sum_{i=1}^{K} \text{off}(W R_i(\tau) W^T) \quad (4)$$

where, $\bar{R} = \{R_{z1}, R_{z2}, \cdots, R_{zK}\}$ represents the covariance matrix of different time delays, for a matrix M:

$$\text{off}(M) = \sum_{i \neq j} m_{ij}^2 \quad (5)$$

the diagonalizition becomes higher as its value becomes smaller. Givens rotation method is applied to get the unitary matrix V in this study. Then the separating matrix W = V×B can be got, where '#' means pseudo inverse and the estimate of the source vector is y (t) = Wx (t)

SOBI algorithm separates source signals by using the differences of the frequency spectrum of signals. Its separation performance will be reduced when the frequency spectrum structures of the source signals are similar. The key idea of SONS algorithm is to use the non-stationery and time structure of signal. After the received data is whitened, it is divided into non-overlapping blocks and the data in each block is considered as stationery. After computing the time-delay covariance matrix of each data block and the separation is realized by using joint diagonalizing the covariance matrix.

The separation condition of underwater target echo and reverberation signal is discussed in this study by comparing with correlation coefficients in fractional fourier domain from signals of different sensors, from which the number of the 'source' signals is determined when blind source separation method is used.

In order to study the separation condition, experimental personnel execute data acquisition on the lake. First, Fractional Fourier transform is used to analyze the reverberation signal and the target echo signal. And then correlation coefficients of target echo signals of different sensor distances and correlation coefficients of the target echo and reverberation signal of different sensor distances are computed which is shown in Fig. 7.

As is shown in Fig. 7, the red line represents correlation coefficient of target echo signals, from which it can be seen that the correlation coefficient of the data from adjacent sensors is higher than 0.5, as the distance of the two sensors changes, the correlation coefficient is always between 0.3-0.4. The blue line represents correlation coefficient of target echo signal and reverberation signal, from which it can be seen that no matter how far the spatial distance is, the correlation coefficient is always very low (smaller than 0.1) . So when the data from adjacent sensors is analyzed with blind source separation method, the target echo signals of the two sensors can be considered as correlated signals

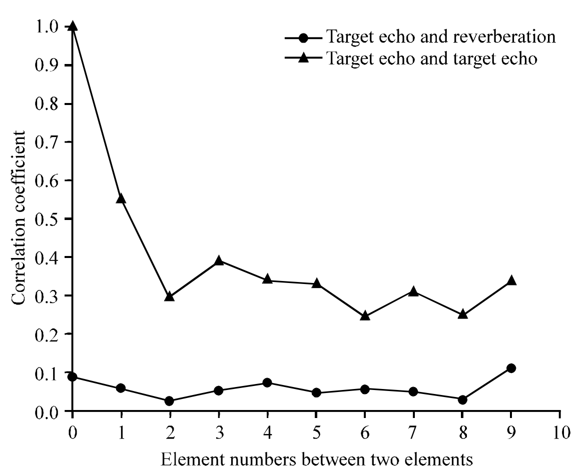

Fig. 7: Correlation coefficient in FRFT domain of different sensor's data

which is a 'source' signal and the target echo signal and reverberation signal are considered as uncorrelated signals, the reverberation is the other 'source' signal.

EXPERIMENTAL DATA PROCESSING AND ANALYZING

In order to verify the validity of the above method, experimental personnel execute data acquisition in the sea. Active sonar transmits chirp pulse and two sensors are used to received echo signals. The received echo signals are shown in Fig. 8 (fs = 1 Hz). Figure 9 is the time-frequency distribution of echo signals. The echo signals are analyzed with blind source separation method in Fractional Fourier domain to get a target signal and a reverberation signal which is shown in Fig. 10 and 11 is the time-frequency distribution of the target signal.

Comparing Fig. 9 with 11, it can be concluded that blind source separation of the fractional fourier domain

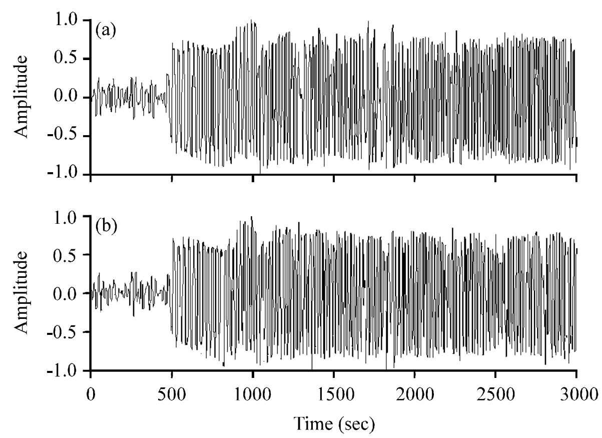

Fig. 8(a-b): Received data of every sensors (a) Data from sensor 1 and (b) Data from sensor 2

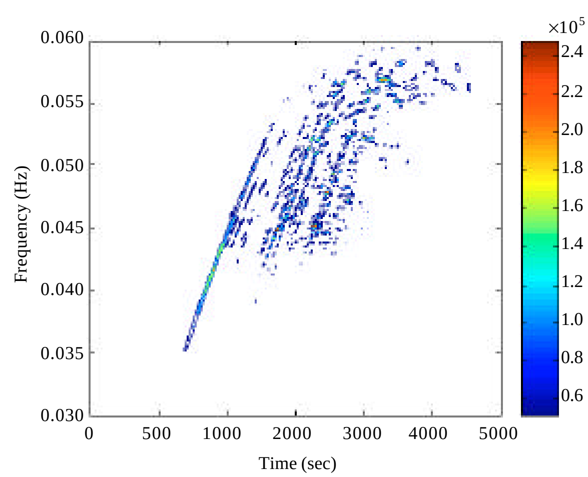

Fig. 9: Time-frequency distribution of received signal

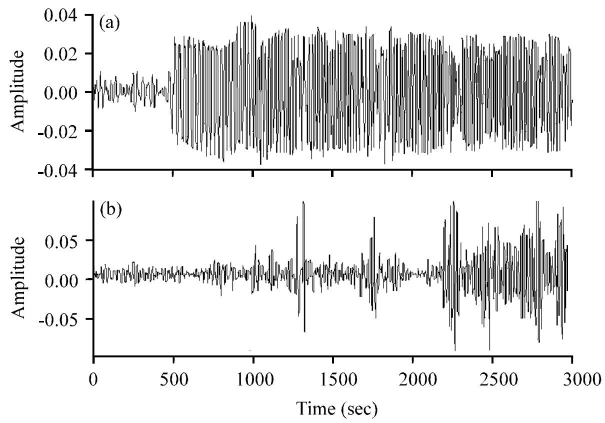

Fig. 10: Results of FRFT-domain blind source separation

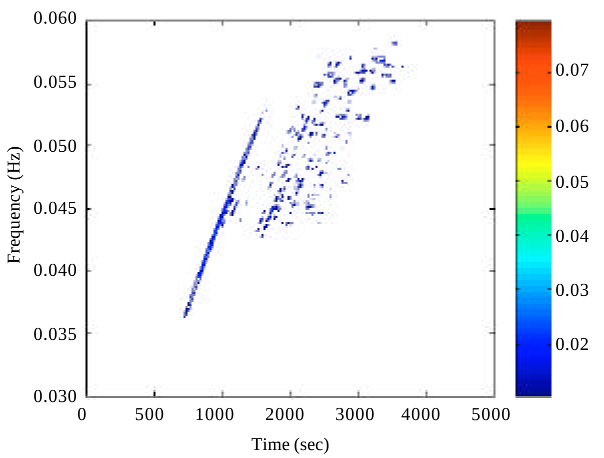

Fig. 11: Time-frequency distribution of target signal

method can separate the target signals under reverberation background and it can extract the highlight characteristics of echo signals.

CONCLUSION

This study adopts Blind Source Separation of the Fractional Fourier Domain method to analyze the echo signals of underwater targets. It can be concluded that this method is of great capacity to analyze the nonlinear and non-stationary data and it is especially suitable to analyze chirp signals. The reverberation in echo signals is restrained and the highlight characteristic is extracted. Experiment results have affirmed the effectivity of the method.

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