SOUND PROPAGATION IN SHALLOW WATER

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A multipath problem in an underwater acoustic channel is discussed in this paper. For underwater acoustic communications the main problem encountered is the presence of multipath propagation caused by reflection and scattering of the transmitted signals at the surface and the bottom. Multipath propagation causes significant degradation of the underwater acoustic communication signals. Echos, which are delayed from direct path underwater acoustic signals, can be represented by impulse responses, which have cepstrums concentrated farther from the cepstral origin. A cepstral analysis and homomorphic deconvolution method is discussed as a means of detecting the multipath effect. The results of numerical simulation are presented in this paper.

INTRODUCTION

Shallow water acoustics is distinctly different from the open ocean, deep-water environment. Acoustic signals in shallow water normally interact repeatedly with both the sea surface and bottom. An underwater acoustic channel is often characterized by multipath propagation and temporal variation. In a shallow water channel the principal mechanism of the multipath formation is reflection of the signal at the surface and bottom boundaries and any other waterbone objects [2]. Signal degradation caused by multipath propagation is the major problem. According to [7], sound propagation in shallow water is highly sensitive to changes in the geometrical parameters like water depth, source-receiver range or bottom slope leading to variations in the impulse response of the underwater acoustic sound channel.

Many problems can be modeled as a linear system where the output signal y(t) is the convolution of the input signal x(t) with the signal h(t). The shallow water channel can be modeled by a time-varying impulse response and can be written as:

$$h(t) = \sum_{k=-\infty}^{K} \alpha_k \delta\left(t - \tau_k\right) \tag{1}$$

where α_k and τ_k are respectively the attenuation and the delay associated with the k^{th} path and K is the number of the path.

The signal transmitted by an underwater acoustic channel can be written as the convolution of the transmitted signal with the channel multipath impulse response. Cepstral analysis and homomorphic deconvolution technique can be used to detect the multipath effect. In this paper the received CW signal is analyzed, and the results are interpreted in connection with the multipath propagation.

1. CEPSTRAL ANALYSIS AND HOMOMORPHIC DECONVOLUTION

Cepstral analysis uses a form of a homomorphic system, which converts the convolution operation to an addition operation. Homomorphic systems can be divided into a canonical representation consisting of a cascade of three individual systems. These systems are the Fourier transform, the complex logarithm and the inverse Fourier transform (see Fig.1). The transformation of a signal into its cepstrum is a homomorphic transformation and the idea of the cepstrum is a fundamental part of the theory of the homomorphic systems for processing convolved signals [2, 3, 5]. The cepstrum analysis can be used to detect echoes or periodicity.

For the first time the cepstrum (power cepstrum) was defined as the power spectrum of the logarithmic power spectrum:

$$c(\tau) = \left|F[\log S(f)]\right|^2 \tag{2}$$

Another form of the cepstrum is the complex cepstrum, which is defined as the inverse Fourier transform of the complex logarithm of the complex spectrum. In terms of mathematical formula the complex cepstrum is given by:

$$c(\tau) = F^{-1}[\log X(f)] = F^{-1}\left[\log|X(f)| + j\phi_X(f)\right] \tag{3}$$

The cepstrum can be used for detection of any periodic structure in the spectrum, including harmonics, echoes and multipath.

The power cepstrum is superior to the complex cepstrum because it doesn’t have phase unwrapping problem. But in the power cepstrum the phase information is lost, so the original signal can’t be recovered from the power cepstrum. The power cepstrum is usually used to estimate the echo delay time, and then the complex cepstrum is used to remove the echo and recover the original signal. In case of echo detection in echo hiding system, we don’t need to recover the original signal so the power cepstrum is enough to estimate the echo delay. In the power cepstrum, the impulse corresponding to the echo delay is more visible than the peak in the complex cepstrum. To regenerate the time series and retain the necessary phase and frequency information, the complex cepstrum must be used.

Using the Z-transform, the following three steps must be done to obtain the complex cepstrum:

$$X(z) = \sum_{-\infty}^{+\infty} x(t) z^{-t}, \quad z = e^{\sigma + j\omega} \tag{4}$$

$$\hat{X}(z) = \log X(z) = \log|X(z)| + j\arg[X(z)] \tag{5}$$

$$\hat{x}(T) = \frac{1}{2\pi j}\oint_C \hat{X}(z) z^{T-1} dz, \quad T = 0, \pm1, \pm2, \ldots \tag{6}$$

where x(t) is the original data, X(z) is its Z-transform and T is the pseudo-time (quefrency) in the cepstrum domain.

The three-step inverse definition to return to the time domain is:

$$\hat{X}(z) = \sum_{-\infty}^{+\infty} \hat{x}(t) z^{-T} \tag{7}$$

$$X(z) = \exp[\hat{X}(z)] \tag{8}$$

$$x(t) = \frac{1}{2\pi j} \oint_{C'} X(z) z^{T-1} dz \tag{9}$$

In practice Fourier transform is used instead of the Z-transform.

The homomorphic deconvolution technique can be used to separate convolved signals. Multiplication in the frequency domain is identical to the convolution in the time domain, so by taking the logarithm this multiplication reduces to a sum of the individual logarithms. The next system is a linear time invariant (LTI) system, which takes the complex logarithm of the product of two signals. To come back to the original time domain inverse transformation can be done. The block diagram for the homomorphic deconvolution technique is given in Fig.1.

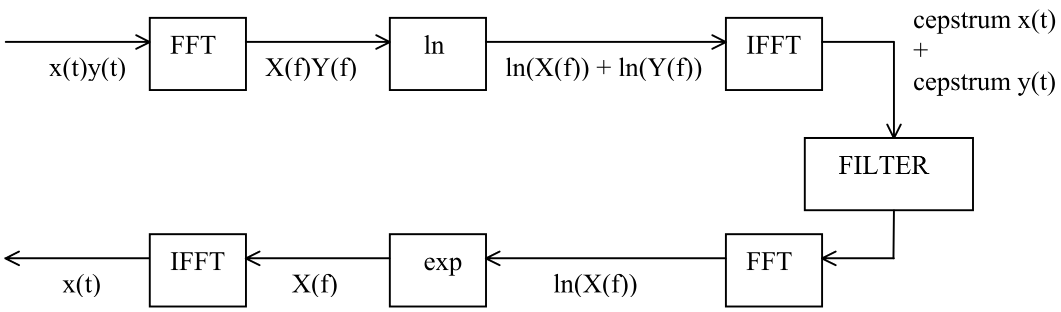

Fig. 1. Homomorphic deconvolution block diagram

2. NUMERICAL SIMULATION

In this section an example was presented to illustrate the multipath effect and the homomorphic deconvolution described above. In order to test the theory of the cepstral analysis and the homomorphic deconvolution technique and the possibilities of taking advantage of these techniques for detecting multipath effect in the underwater acoustic channel, the numerical example was simulated in Matlab.

The underwater acoustic channel was described as a convolution channel. The received composite signal was modeled as the convolution of the transmitted pulse signal with the impulse response corresponding with each path.

In the numerical simulation, the parameters chosen for the transmitter and the receiver depth, the range and the water depth are not a full set of parameters describing the underwater acoustic channel. The depth of shallow water is 50 m. The distance R between the source and the receiver is 300 m. The source depth is 10 m and the receiver depth is 20 m. The transmitted signal is chosen to be a CW (continuous wave) pulse with center frequency of 2 kHz and pulse duration of 5 ms (Fig. 2).

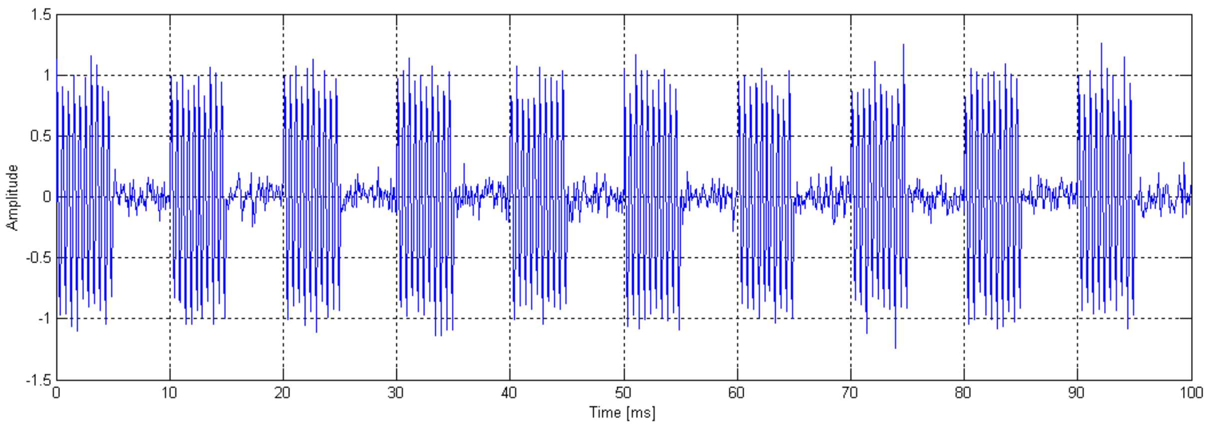

Fig. 2. Transmitted pulse signal for the case of 7dB SNR

A Gaussian noise was added to the transmitted signal to produce a noisy signal with the two signal-to-noise ratio (SNR) cases (respectively 28dB and 7dB). The acoustic environment is characterized by a constant sound speed c=1500m/s everywhere. The underwater channel was described as a convolution channel. Fig. 3 shows the multipath model of the underwater communication channel.

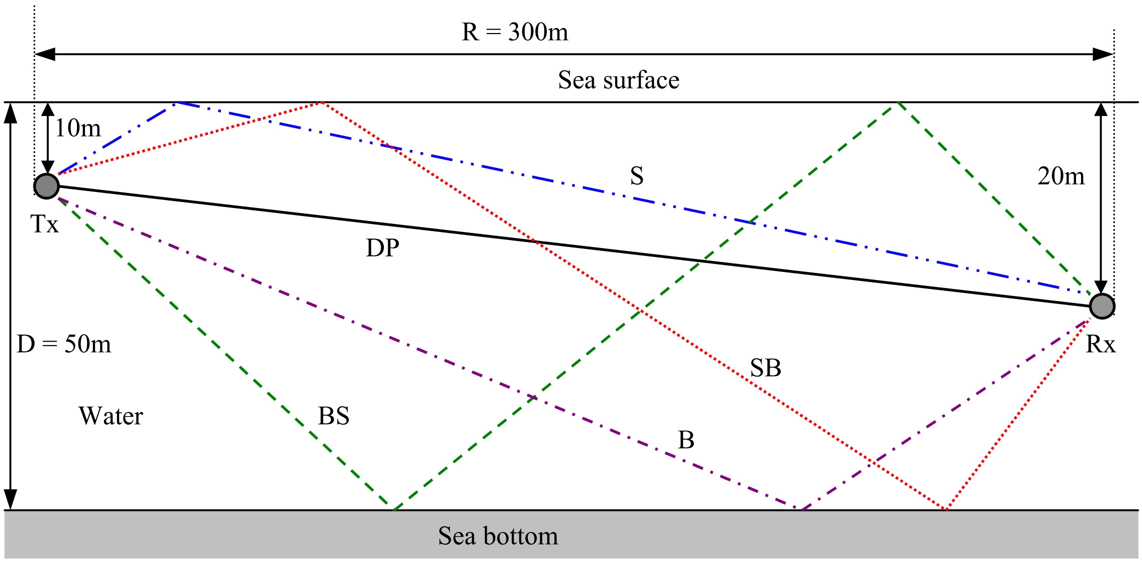

Fig. 3. Multipath model of the underwater communication channel

This model consists of the paths that interact with both boundaries, namely the sea surface and the bottom. In Fig. 3 five paths were shown in the order of their expected arrival time: a direct path – DP (black), a surface bounce path – S (blue), a bottom bounce path – B (purple), a surface interaction followed by a bottom interaction – SB (red) and a bottom interaction followed by a surface interaction – BS (green).

The time domain equation of the underwater channel is given by:

$$h(t) = \sum_{k=0}^{4} \alpha^{k} \delta\left(t - \tau_{k}\right) \qquad (10)$$

where the τ_k denote delay time between two successive multipath arrivals, coefficients α^k take into account possible attenuation on every propagation path. Coefficient α was assumed as 0.9.

The underwater channel impulse response is connected with the arrival time of the individual path. By simple geometrical parameters of the underwater channel and knowing the speed of the sound in water it is possible to calculate the arrival time of the echoes. The arrival times of the appropriate paths were shown in Fig. 4. Thus, propagating along different paths in the underwater acoustic channel, the transmitted signal comes to receiver in the form:

$$y(t) = \sum_{i=0}^{4} \alpha_i y_i \left(t - \frac{d_i}{c} \right) \tag{11}$$

where c is the sound speed in water, $y_0(t)$ is the direct path signal with d_0 separation between the transmitter and the receiver, α_i is the attenuation associated to the i^{th} path and $y_i(t)$ is an individual path from the sea boundaries traveling a total distance d_i.

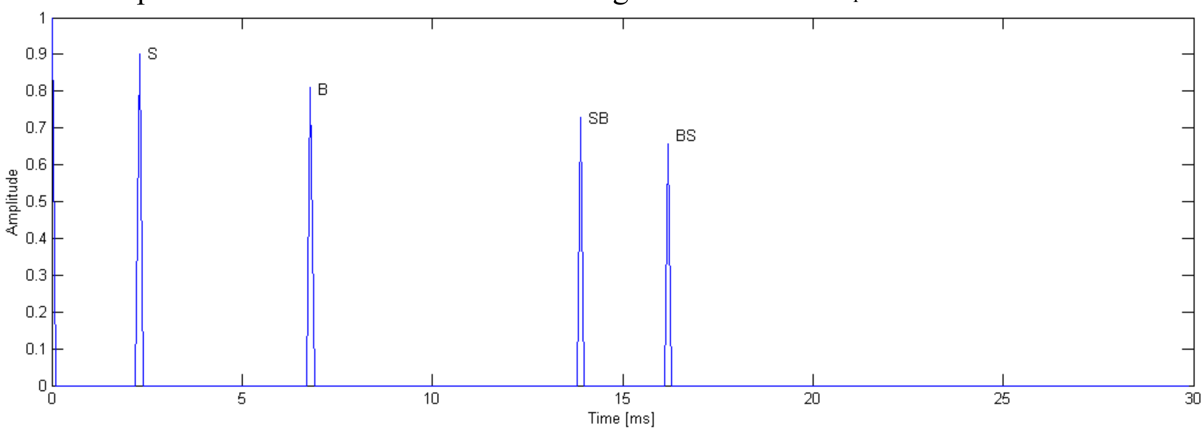

Fig. 4. Underwater channel impulse response

One pulse signal transmitted by the underwater channel showing in Fig. 5 was convoluted with the underwater channel impulse response.

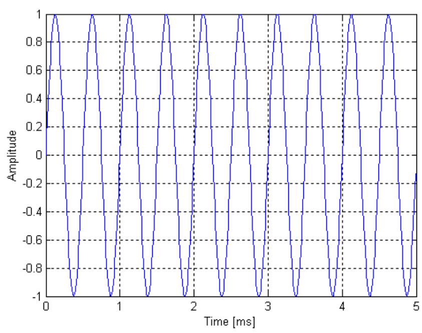

Fig. 5. One pulse transmitted signal

Since a Gaussian noise was added to the simulated transmitted signal and the difference in the arrival times of the individual bottom-reflected and the surface-reflected (phase-reversed) signals are too short, the received signals are heavily overlapped and it is not possible to distinguish the received signals from each other. The overlapped received signal was shown in Fig. 6.

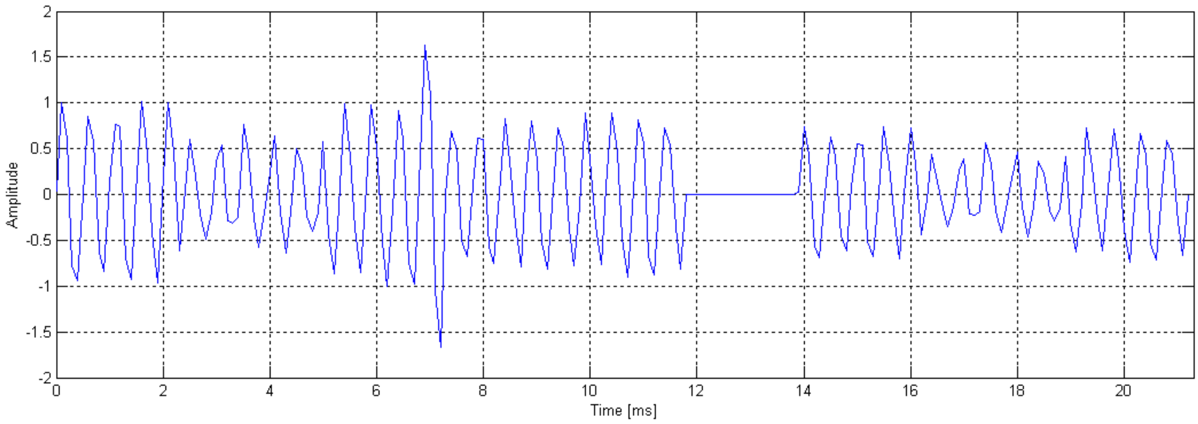

Fig. 6. The received signal for the case of 7dB SNR

The arrival times of the boundaries reflected signals was detected by means of the cepstral analysis. Since the time delays of the transmitted signal are not periodical so the peaks of the complex cepstrum are hardly visible. The complex cepstrum of the received signal without noise and for the two SNR cases is shown in Fig. 7, 9, 11, whereas Fig. 8, 10, 12 show the power cepstrum of the same signals. In both cepstrums there are peaks corresponding to the time delay of the individual paths, but the peaks in the power cepstrum are more prominent than the peaks in the complex cepstrum. Simulation experiments demonstrate the superiority of the power cepstrum in detecting the multipath propagation, but in the power cepstrum the phase information is lost, so the original signal can't be recovered from the power cepstrum.

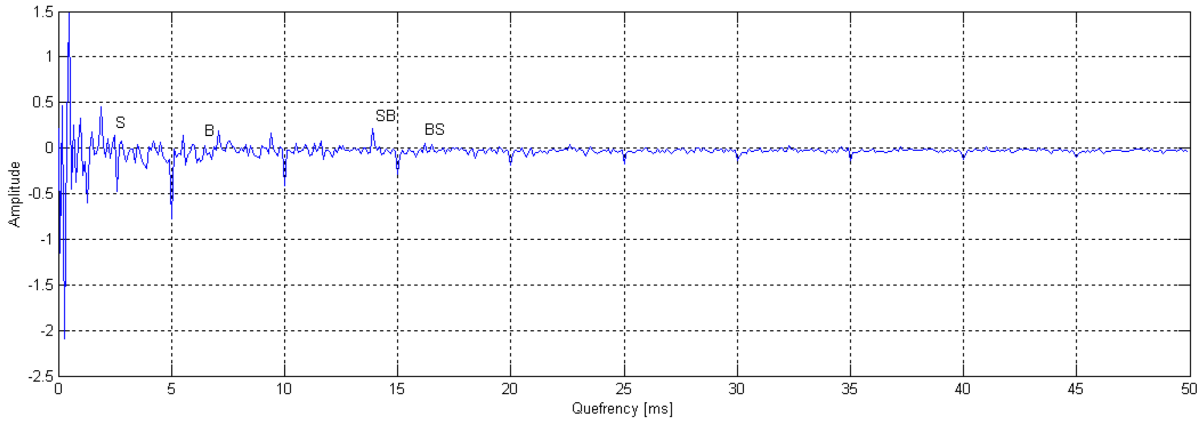

Fig. 7. Complex cepstrum (without noise)

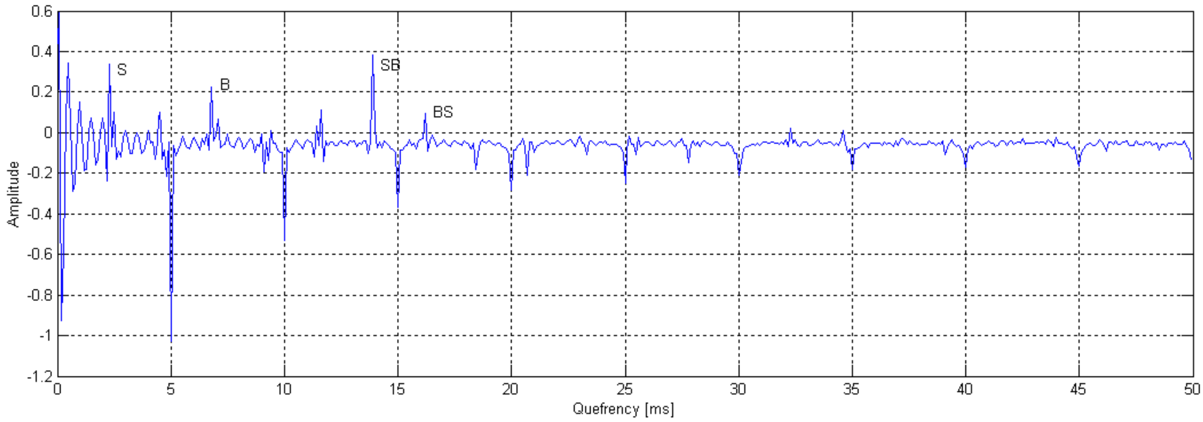

Fig. 8. Power cepstrum (without noise)

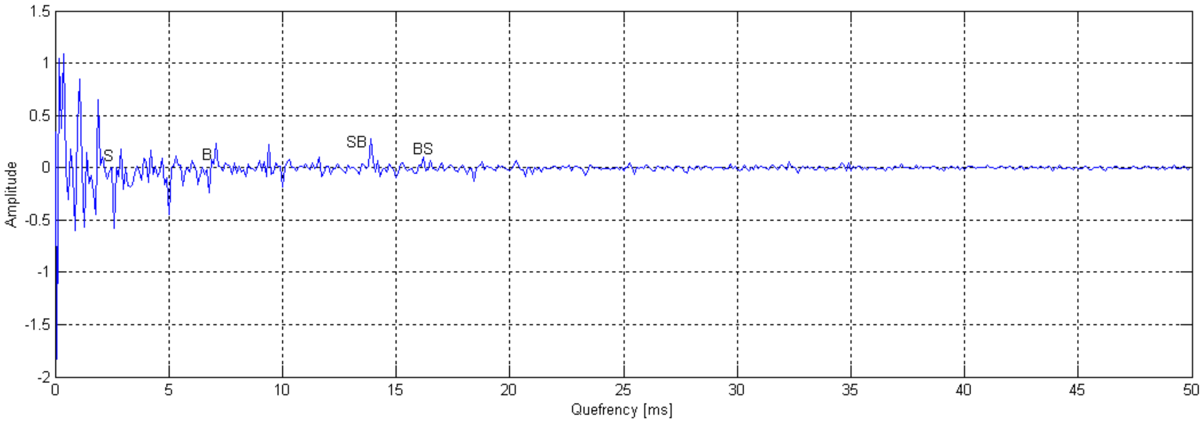

Fig. 9. Complex cepstrum for the case of 23dB SNR

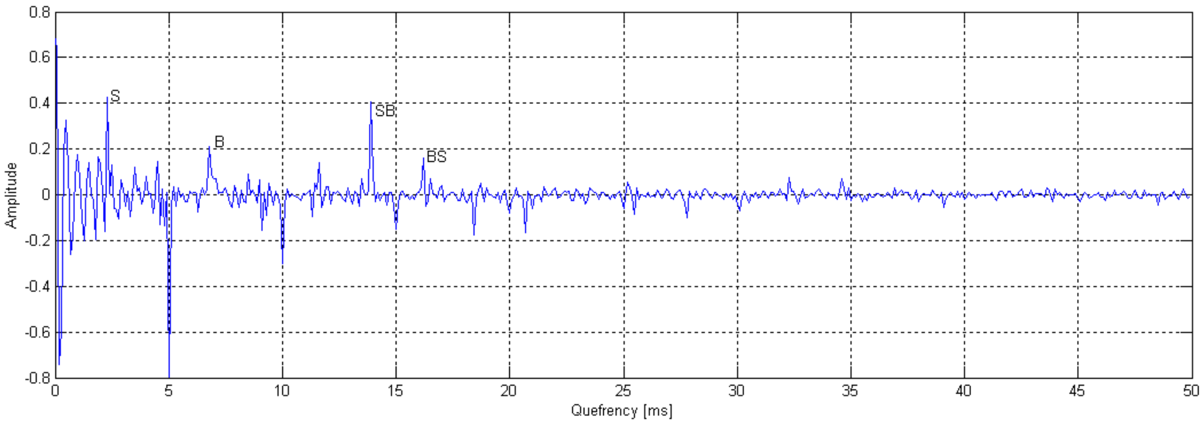

Fig. 10. Power cepstrum for the case of 23dB SNR

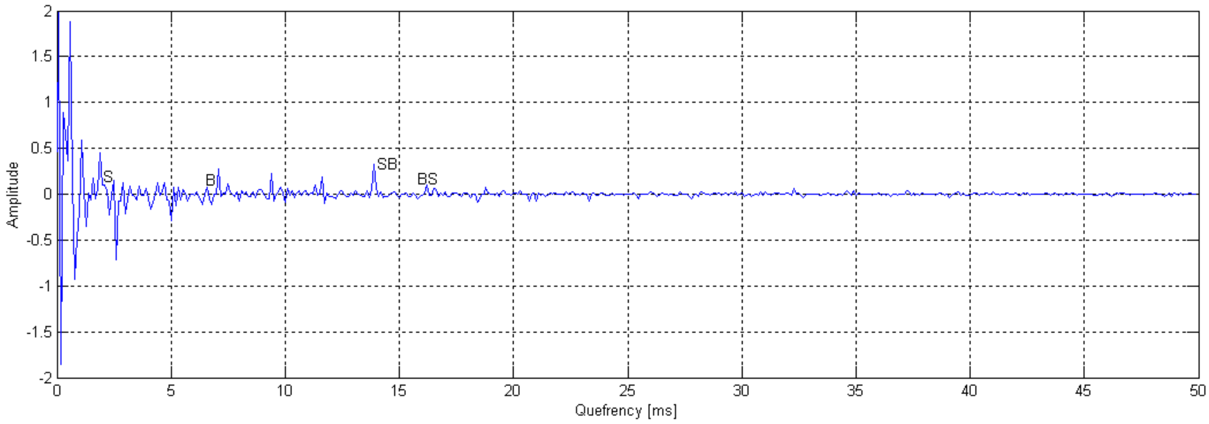

Fig. 11. Complex cepstrum for the case of 7dB SNR

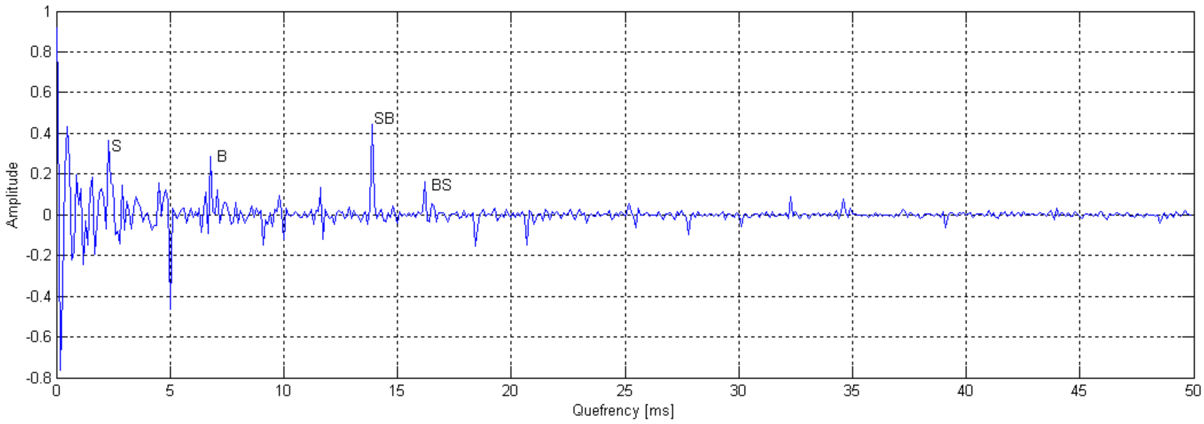

Fig. 12. Power cepstrum for the case of 7dB SNR

There is a phase unwrapping problem in computation of the complex cepstrum. The phase function must be made continuous, so it is important to remove the linear phase component from the unwrapped phase prior to the computation of the complex cepstrum. Fig. 13 shows the principal value of the phase of the received signal. Fig. 14 shows the continuous "unwrapped" phase after removing a linear phase component.

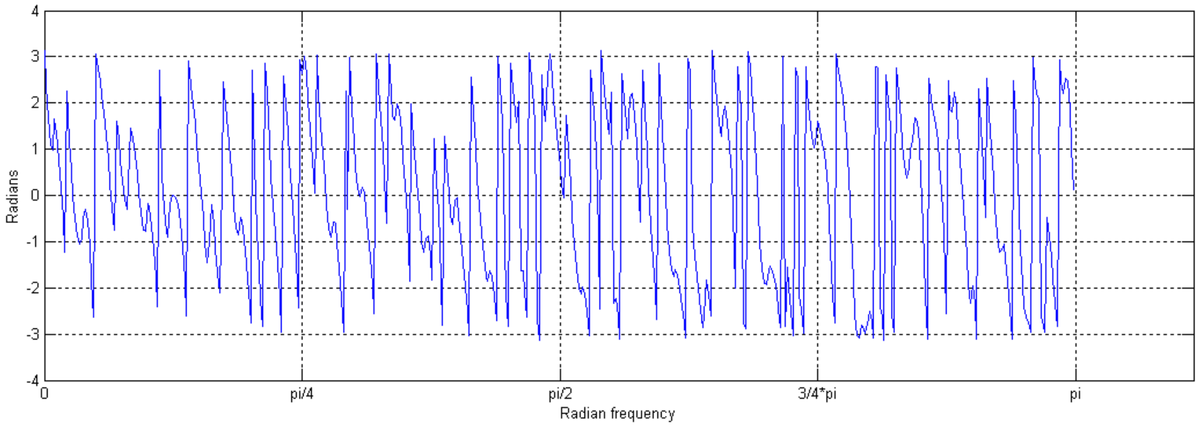

Fig. 13. Principal value of the phase of the received signal for the case of 7dB SNR

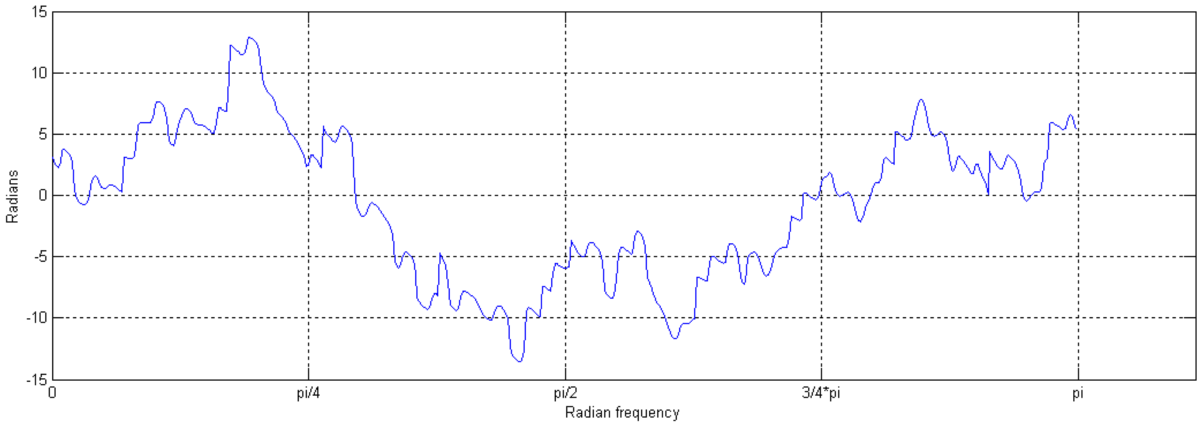

Fig. 14. Continuous “unwrapped” phase of the received signal after removing a linear phase component for the case of 7dB SNR

3. CONCLUSIONS

The multipath effect in the underwater acoustic channel was examined using the numerical simulation and the cepstral analysis. The noise added to the transmitted signal has not a significant influence on the detection of the multipath effect. The sizes of the power cepstrum peaks were comparable.

The above shown method allows the convolved signals in the time domain not only to be separated in the complex cepstrum, but also to remove an unwanted effect completely, and return to the original time signal without this effect.

Future work will concentrate on designing digital “lifters” (a filter in the cepstrum domain), for example comb “lifters” to remove an undesired additive component from the complex cepstrum.

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