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Self-similarity property of acoustic data acquired in shallow water environment

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Abstract

Underwater acoustic modeling in shallow water environment is difficult since sound waves reflect several times between the surface and the water bottom. This article discusses an underwater acoustic characteristics analysis method based on self-similarity. It is found that acoustic signal has good self-similarity in shallow water. The actual towed hydrophone linear array was established and it was used for underwater acoustic signal acquisition experiment in Qilihai Reservoir which is located in the suburb of Tianjin, China. It can be derived that the signals acquired by hydrophones have self-similarity by the analysis of the variance of *m*-aggregated time series. It is proved that the characteristics of self-similarity can be used for the sound pulse propagation in shallow water.

Keywords: Fractal, Self-similarity, Towed hydrophone linear array, Shallow water environment

1. Introduction

The hydrophone array plays an increasingly important role in access to the ocean information. For example, active acoustic detection methods can also be used for real-time monitoring of marine fish density and behavior [1-3]. Compared with the traditional way, the method of ocean acoustic waveguide and hydrophone linear array can implement thousands of square kilometers of real-time imaging, and continuous monitoring in specified sea water. As a type of active acoustic detection, underwater seismic exploration is widely used in the detection of potential seabed oil, natural gas resources reservoir, combustible ice, and other resources. Norwegian Gullfaks oil field went into operation in 1986. In order to improve the efficiency of field collection, the four time-lapse seismic measurements were fulfilled in 1985 (baseline data), 1995, 1996, and 1999, respectively. Through time-lapse seismic data, they carried out analysis and forecasting the movement of water injected. As a result, the recovery factor of oil fields to increase about 2% [4]. In the monitoring oilfield mined, seismic data can also be used. Swanston et al. [5] compared the seismic data of a drilling platform in the Gulf of Mexico in before and after 8 years of mining, the difference of sound respond between water and the hydrocarbon compound can be used for resources monitoring [5]. Acoustic data also can be used for monitoring carbon fixation in the deep ocean. By analyzing the data of 1994, 1999, and 2001 in the same seismic reflection exploration region, it can clearly draw the conclusion that data reflected CO_2 changes [6].

Results of recent studies have proved that many natural and artificial systems have self-similarity [7-16]. It is very useful that self-similarity is a considerable key-property in understanding of widely existing nonlinear physical systems. By dividing complex networks into boxes containing nodes within a given 'size', Song et al. [7] find that complex networks have the scale-free nature, which is one of the evidences in the self-similarity confirming. Self-similarity is a common characteristic of many communication networks [8-10]. For example, the traffic of World Wide Web, as a typical communication network, also has the characteristic of self-similarity [9]. Self-similarity is also in the Ad Hoc wireless network transmission. As a result, the traffic in Ad Hoc networks can be predicted by methods such as fuzzy logic system [10]. Fermann [11] studied the pulse propagation characteristics in nonlinear Schrödinger equation optic–fiber amplifier through the self-similarity method. From the study of Liang [12], it can be concluded that the signals of ultra-wideband radar do not have self-similarity. Considering the case of the multi-scale structure of the sea and the sea surface shape changes over time, Guan et al.

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[13] established the one-dimensional fractal sea surface model and simulated the wave motions with the time variation using close-form solution of sea wave nonlinear differential equations. Qian [14] used Koch curve, instead of sine curve, to model the sea surface scattering properties with sound waves and electromagnetic waves approximately.

The main purpose of this article is to verify whether the acoustic signals in shallow water have self-similarity. We have established a hydrophone line array with 24 sensors in shallow water, and actual data acquisition experiment was conducted in Qilihai Reservoir, Tianjin, China. In Section 2, we introduced the property of hydrophone linear array and data acquisition experiments conducted in Qilihai Reservoir. Then the waveform of the original data sequence was presented. In Section 3, we analyzed the self-similarity of the multi-channel hydrophone data sequence by variance-time plot.

2. Workbench testing and field data acquisition experiment

As shown in Figure 1, we implemented an m-aggregated hydrophone linear array and collected the acoustic signals in 4,000 samples per second. The actual system components and test instruments are listed below.

- 32channel hydrophones;
- 24-bits analog–digital converter;
- hydrophone space is 2 m;
- 40-m flexible segment;
- PCI-interface data reception card;
- data real-time storage based on double ping-pang structure;
- Tektronix model 4104B oscilloscope.

The 32 sensors were evenly distributed within the exploration cable. Each node is responsible for a signal acquisition of 16 hydrophones. In order to ensure the synchronization of the collected data of each channel in the array, we designed a high-precision unified acquisition clock synchronous system of linear array. After sensing the changes of underwater sound intensity by hydrophones of each channel, signals were amplified and filtered through a fully differential conditioning circuit, then digitized by 8-channel Sigma-Delta ADC. At last these data were uploaded and stored in host computer through the cascade-type channel individually.

We use the temperature-compensated crystal oscillator in the head of hydrophone linear array to generate the high stability of the clock as the master clock. Then it was transmitted over unshielded twisted pair to every data acquisition unit (DAU). The slave clock source in every DAU is voltage-controlled temperature-compensated crystal oscillator (VCTCXO). DAU is not using VCTCXO in an open loop environment, but letting the acquisition circuits of the data output pulses and the master clock locked to zero retardation by using phase-locked loop. With high-precision sampling clock generation and transmission system, the array can acquire signals simultaneously at sub-microsecond level, which is important in offshore environment.

Actual data acquisition experiment was applied in the Qilihai Reservoir, as illustrated in Figure 2, in the eastern suburb of Tianjin. Average depth of the reservoir is about 4 m. The total area of it is approximately 16.26 km^2. The bottom of the lake is slime layer, and has some ups and downs. Hydrophone line array is placed on the surface of water. Meanwhile, in the not far distance from the array, we placed a point-like sound source as the sound excitation source in the experiment.

Figure 1 Actual hydrophone line array debugged in processing workshop. Hydrophones were distributed uniformly on the tow rope laid on the ground. The PC in the upper right corner of the figure is mainly used to store real-time data and reflected echo.

Figure 2 Panorama of Qilihai Reservoir. The reservoir is located in the northeastern part of Tianjin, China, with an average depth of 4 m, freshwater quality, soft muddy bottom, part of the regional water plant distribution.

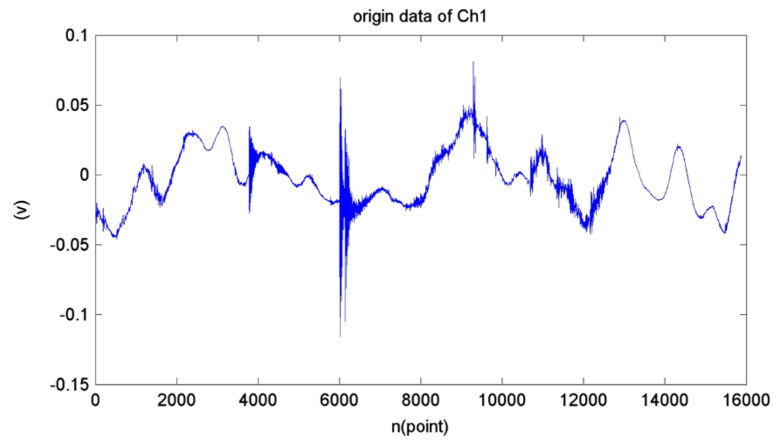

Figure 3 Original waveform signal of CH1 of the hydrophone in Qilihai Reservoir. Left for a point-like sound source excitation of direct wave and the reflected echo pulses.

Characteristics of acoustic wave propagation in shallow water are more complex than that of in the deep water, because the ups and downs of the bottom of reservoir are analogous with the water depth. Sound reflection in underwater between surface and bottom is even more than deep water. Therefore, the shallow water acoustic modeling is more difficult. This article discusses the acoustic signal analysis method based on fractal, which can be used for forecasting or targeting an underwater artificial signal. Thereby, it will reduce the difficulty of establishing acoustic propagation model of shallow water environment.

In order to observe the wave form of the original data sequence of the experimental data acquisition, we read hydrophone CH1 data firstly. Figure 3 shows the original waveform of the time-domain sequence. Meanwhile, the data of the power spectrum of the CH1 hydrophone was shown in Figure 4.

3. Self-similarity properties of acoustic signals

For a detailed explanation of self-similarity in time series, see [8-14]. We can discuss its definition briefly here. Our discussion in this section and the next closely follows those sources.

We begin with a zero-mean, stationary time series $X = (X_t, t = 1, 2, 3,\ldots)$, in which the t is a semi-infinite discrete argument. Then, we define the m-aggregated series $X^{(m)} \triangleq \left(X_k^{(m)}; k = 1, 2, 3, \ldots\right)$. The symbol $\triangleq$ means the equality by definition. The way of construction of m-aggregated series is summing non-overlapping elements in the original series X of size m. In fact, the self-similarity of a time series means the series have the *long-term dependence*. At this point, the sequence has the same autocorrelation function.

$$\gamma(k) \sim k^{-\beta}; k \to \infty, 0 < \beta < 1 \qquad (1)$$

Accordance with established practice, the parameter H is the *Hurst* parameter, which is calculated as $H = 1 - \frac{\beta}{2}$.

If for all positive integer m, $X^{(m)}$ has the same distribution as X rescaled by m^H, we can say that X is *H-self-similar*. That is,

$$X_t \triangleq m^{-H} \sum_{i=(t-1)m+1}^{tm} X_i; \forall m \in N \qquad (2)$$

In order to be able to verify whether a sequence is *H-self-similar*, we can use the *variance-time plot* method [9]. It mainly reflects the slowly decline variance of a self-similar sequences when parameter m increases continuously.

The concrete steps are listed below

- Preprocesses sequence X to meet the requirement of zero mean and unit variance;
- For different values of m (starting from two until a relatively large positive integer), generates a plurality of sequences;
- Calculates the variance of the sequences $X^{(m)}$, respectively, and takes the log values;
- Draws variance–time plot, the variance of $X^{(m)}$ is plotted against m in a log–log two-dimensional coordinate system.
- If the variance is all above in the slope of $-\beta$, then the series X has self-correlation; otherwise, the series has no self-correlation characteristics.

If time series X still has self-similarity when m is a large integer, the sequence X can be said to have "long-range dependence." Namely, in the seemingly haphazard

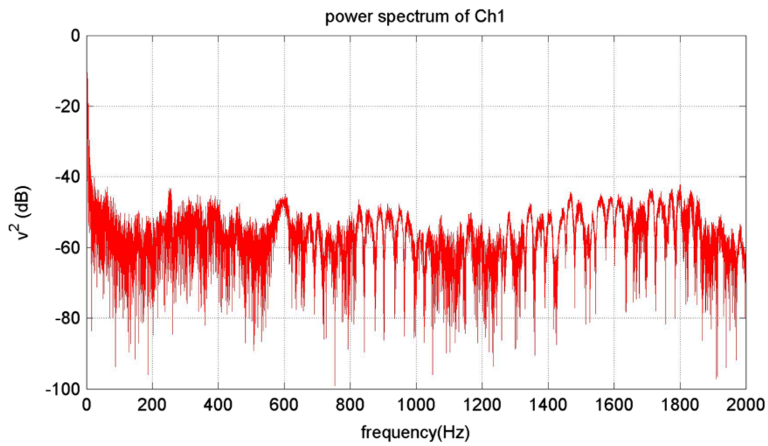

Figure 4 **Power spectrum of CH1 of the hydrophone line array in Qilihai Reservoir.**

sequence, the sequence values after a long time are closely associated with the current value of the sequence. In other words, the time series X elements value x_0 on the impact of the subsequent element values x_t "to be extended to the infinite." This feature is also one of the potential applications of self-similarity in the field of underwater acoustic detection and target identification.

The variance–time plot of the CH1 hydrophone data sequence shown in Figure 5 showed a strong self-correlation in the dataset of the channel.

To further analyze the underwater acoustic signal from the universality of self-similarity, we selected and analysis the data sequence of CH2–CH5 hydrophones in the same time period, mainly to study the original sequence and variance–time law results.

The original data acquired by the hydrophone array from the shallow environment are analyzed and processed by the following steps. As shown in Figure 6, the mean values of the four channels data are: $\mu_1 = -1.0823$, $\mu_2 = 0.0138$, $\mu_3 = -0.9440$, $\mu_4 = -1.1881$, respectively. Underwater acoustic data collected by hydrophone is not zero mean. The absolute amplitude of the sequence values show greater impact on variance. All these factors do not comply with the self-similarity judgments method for sequence. So, the process of zero mean and unit variance are the premise. Then square differences of different m values are calculated in accordance with the method used by the literature [9,10,14], in order to validate the self-similarity of the data.

It can be seen from the Figure 7 below that the water acoustic data in the shallow water environment not only has strong self-similarity, but also has a characteristic of long-timedependence. Therefore, waveform changes long after can be predicted through the existing data. Thus, we can reduce the requirements of sound field of a shallow water environment modeling before the data analysis.

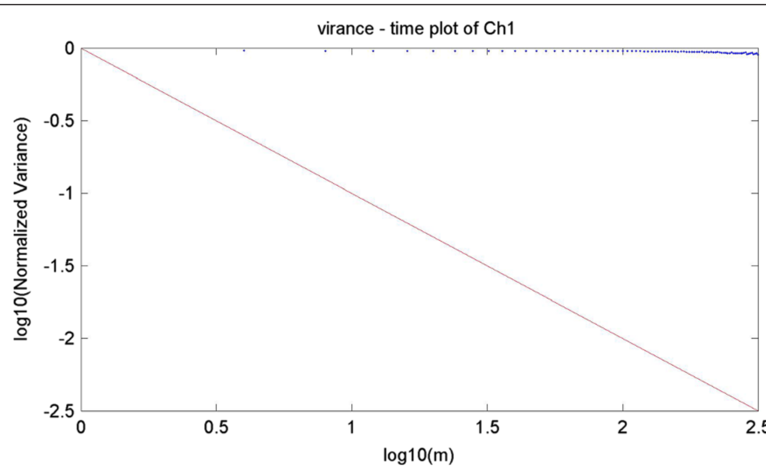

Figure 5 **Variance–time plot of CH1 of the hydrophone line array.**

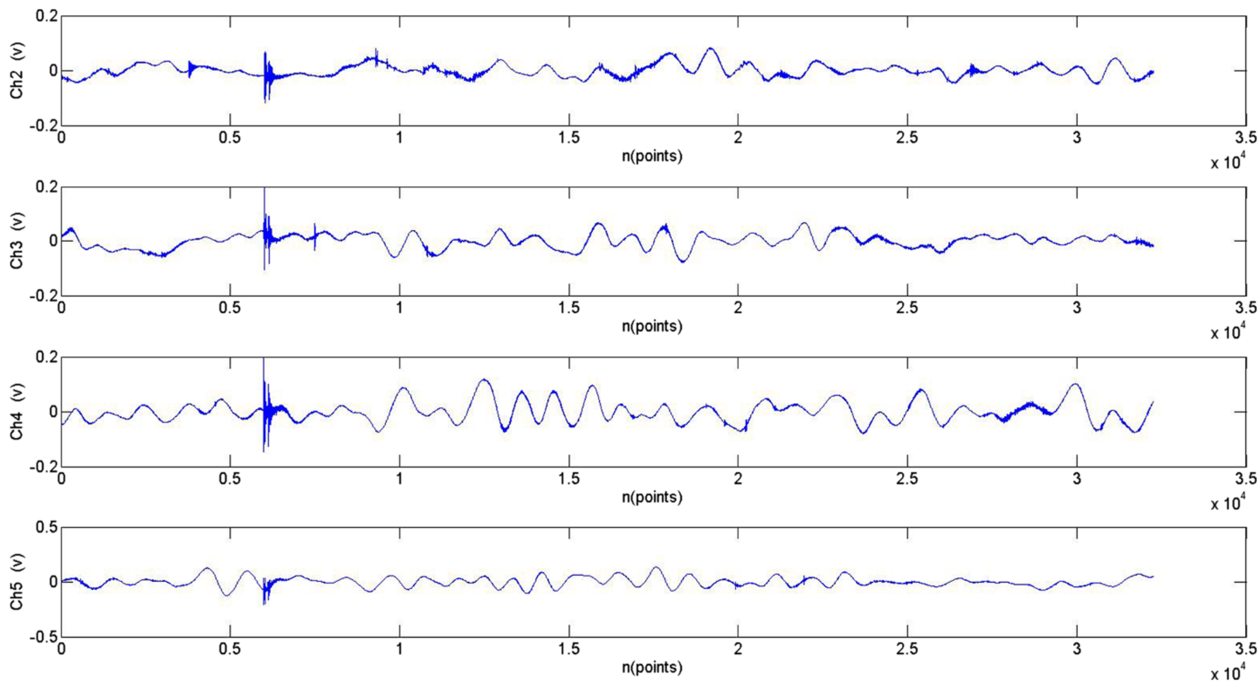

Figure 6 Experimental acquisition of the original waveform signal in Qilihai Reservoir. Left for a point-like sound source excitation of direct wave and the reflected echo pulses, the synchronization performance is good. In the same time, after the strong signal disappears, it is possible to see that there is a large difference due to the environmental impact of the shallow water acoustic signal waveform. It is difficult to analyze signal characteristics by the classic methods.

4. Conclusion

Many research results show that the self-similarity is a common phenomenon in the optical fiber, World Wide Web,Ad Hoc Networks, and other communication network traffic data, and other complex systems. In this article, we discuss the self-similarity of underwater acoustic signals collected by towed hydrophone array in shallow water environment. We have collected the same period for four different channel underwater acoustic signal variance–time plot graphics, verified its stable self-similar characteristics.

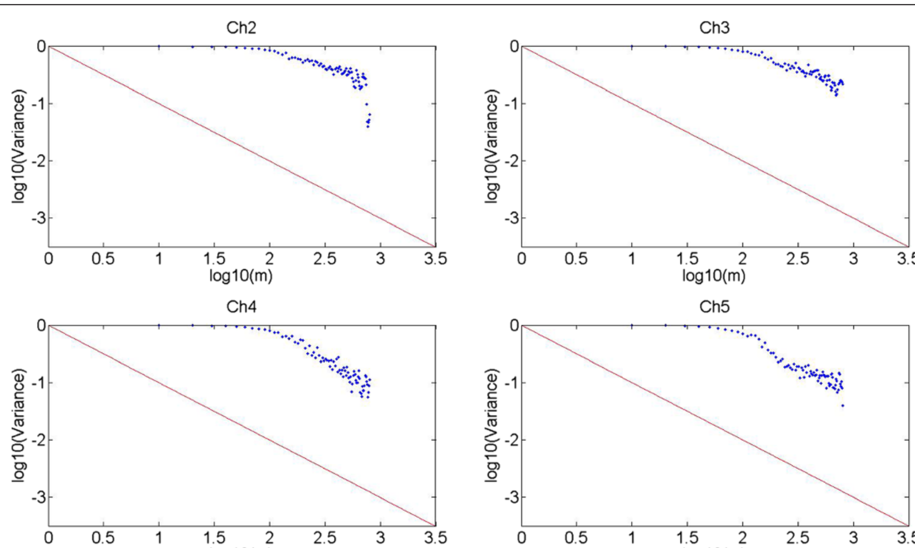

Figure 7 Variance-time plots from CH1–CH4 of the hydrophone line array. The figure shows that in the shallow water environment, acoustic signal of each channel has good self-similarity. The straight line from the upper left zero point to the lower right corner indicates that the slope of a boundary of 0.5. If the variance is located below of the slash, said they did not have the self-similarity, otherwise have self-similarity.

One of the possible reasons for the self-similarity of underwater acoustic signal from shallow waters is the fractal characteristics in the scattering properties of surface and bottom of waters. The nature of water itself has fractal characteristics. After the reflection of the water surface and underwater, the sound signal received by hydrophone line array will contain self-similarity, as the reflective medium has self-similar fractal characteristics. In this article, the underwater acoustic signals' self-similarity is studied in the reservoir environment through the analysis of the actual experimental data. It is proved in this article that the underwater acoustic signals have long-range dependence, which laid the foundation for the future research of underwater target detection and signal processing method from the self-similarity aspect.

Competing interests

The authors declare that they have no competing interests.

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