Ultrasonics 71 (2016) 29–39

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

A Volterra series-based method for extracting target echoes in the seafloor mining environment

Haiming Zhao [a,b], Yaqian Ji [a,*], Yujiu Hong [a], Qi Hao [a], Liyong Ma [c]

[a] School of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China
[b] State Key Laboratory of High Performance Complex Manufacturing, Central South University, Changsha 410083, China
[c] School of Mechanical Engineering, Hebei University of Architecture, Zhangjiakou 075051, China

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 23 May 2016
Accepted 23 May 2016
Available online 24 May 2016

Keywords:
Underwater acoustic detection
Target echo detection
Seafloor mining
Volume reverberation
Volterra series

ABSTRACT

The purpose of this research was to evaluate the applicability of the Volterra adaptive method to predict the target echo of an ultrasonic signal in an underwater seafloor mining environment. There is growing interest in mining of seafloor minerals because they offer an alternative source of rare metals. Mining the minerals cause the seafloor sediments to be stirred up and suspended in sea water. In such an environment, the target signals used for seafloor mapping are unable to be detected because of the unavoidable presence of volume reverberation induced by the suspended sediments. The detection of target signals in reverberation is currently performed using a stochastic model (for example, the autoregressive (AR) model) based on the statistical characterisation of reverberation. However, we examined a new method of signal detection in volume reverberation based on the Volterra series by confirming that the reverberation is a chaotic signal and generated by a deterministic process. The advantage of this method over the stochastic model is that attributions of the specific physical process are considered in the signal detection problem. To test the Volterra series based method and its applicability to target signal detection in the volume reverberation environment derived from the seafloor mining process, we simulated the real-life conditions of seafloor mining in a water filled tank of dimensions of 5 × 3 × 1.8 m. The bottom of the tank was covered with 10 cm of an irregular sand layer under which 5 cm of an irregular cobalt-rich crusts layer was placed. The bottom was interrogated by an acoustic wave generated as 16 μs pulses of 500 kHz frequency. This frequency is demonstrated to ensure a resolution on the order of one centimetre, which is adequate in exploration practice. Echo signals were collected with a data acquisition card (PCI 1714 UL, 12-bit). Detection of the target echo in these signals was performed by both the Volterra series based model and the AR model. The results obtained confirm that the Volterra series based method is more efficient in the detection of the signal in reverberation than the conventional AR model (the accuracy is 80% for the PIM-Volterra prediction model versus 40% for the AR model).

1. Introduction

The interest in underwater ocean or sea mining of minerals, particularly, the cobalt-rich crusts (hereafter, crusts for short), is growing because they contain traces of rare metals that could exceed the content in land deposits. Mining the crusts causes the seafloor sediments to be stirred up and suspended in sea water. The suspended-sediment induced volume reverberation is a dominant and unavoidable cause of interference of the active sonar used for seafloor mapping. The main problem arising here is to extract the target echo signal in reverberation. The purpose of this research was to present a method for the detection of an ultrasonic signal in reverberation generated from the underwater seafloor mining environment.

The detection of the signal in reverberation is currently performed using a stochastic model, in which the reverberation is considered as a stochastic process. The frequently-used stochastic models are the non-stationary Weibull distribution [1] and the autoregressive (AR) model [2,3]. Kay [2] first proposed the AR model for the reverberation that was shown to be a more accurate model than Fast Fourier Transform processors. However, modelling of the reverberation was found to be difficult to implement because of the non-stationarity of the reverberation. Subsequently, Carmillet [3] improved his model by analysing the locally stationary of reverberation and established a suboptimal detector for the signal in reverberation. In practice, however, the use of the

* Corresponding author.
E-mail address: saqlag_yaqian@sina.cn (Y. Ji).

http://dx.doi.org/10.1016/j.ultras.2016.05.019
0041-624X/© 2016 Elsevier B.V. All rights reserved.

stochastic model is frequently invoked not on physical grounds, but rather because of mathematical convenience, or the model is used in an ad hoc manner. This approach leads to the physical attributes of the phenomenon being overlooked. Recently, with the development of nonlinear dynamics and chaos theory, there is growing evidence that certain underwater acoustic signals with disorder behaviour similar to stochastic signals are, in fact, chaotic and generated by a deterministic nonlinear dynamical system. The idea that sea clutter may be modelled as a chaotic process was first reported by Leung and Haykin [4]. Subsequently, Haykin et al. [5–7] proposed a signal detection method in chaos based on the neural network model and illustrated its application to a radar clutter-dominated ocean environment. Assuming that reverberation is generated from a deterministic nonlinear dynamical system, Takens' embedding theorem [8] can be used to develop a model that represents a reconstruction of the system responsible for generating the reverberation. Volterra series expansions [9] represent a frequently used model for the representation and analysis of nonlinear dynamical systems. The idea of the Volterra series expansion is to form a nonlinear adaptive filter to obtain the prediction values of the observed time series. Volterra series have been widely used to build a model of an observed dynamical phenomenon as well as reverberation [10–12].

In this study, we examined a detection method of the signal in reverberation derived from the seafloor mining environment. The algorithm is based on the chaotic characterisation of the observed acoustic signal (i.e., reverberation), and on the Volterra series, which is applied to model the dynamical system responsible for generating the reverberation. When the observed signal contains a target component, it does not match the model anymore; hence, the existence of the target component is signified by the presence of a corresponding perturbation at the output of the model. The advantage of this method over the stochastic model is that attributions of the specific physical process are taken into account in the signal detection problem. To test the Volterra series based method, we simulated the real-life conditions of seafloor mining in a water filled tank of dimensions of $5 \times 3 \times 1.8$ m. The bottom was interrogated by an acoustic wave generated as 16 μs pulses of 500 kHz frequency. In addition, echo signals were sampled by a data acquisition card (PCI 1714 UL). The validity of the method was confirmed by the detection of target signal in fifteen observed acoustic signals. The detection of the target in these signals was also performed by the conventional autoregressive model.

2. Experiment description

Before presenting the results of the computations of the Volterra series model, we first describe the experiments and experimental data used in the study. Because the real mining experiment in deep-sea is difficult to conduct, we simulated the seafloor mining environment in the laboratory to validate the method for the detection of the target echo. In our previous study [13], a topography detection system based on a single-beam was developed. The system was composed of an acoustic detection system (including a plane circular transducer at 500 kHz frequency, a data acquisition and processing system, and a single-chip microcomputer control system) and equipment mimicking that used in seafloor mining practice. To simulate the real-life condition of seafloor mining, the helical blades were used to stir up the water and the sediments on the bottom of the tank. The experimental apparatus is schematically shown in Fig. 1(a). Compared with Ref. [13], this paper improved the layout of the helical blades according to the spiral mining head developed by Zhang [14]. The layouts of helical blades before and after adjustment are shown in Fig. 1(b). Fluent® simulation shows that both the velocity field and the concentration field around the improved helical blades are equivalent to that induced by the spiral mining head.

As shown in Fig. 1, the experiment was performed in a cubic water-filled tank ($5 \times 3 \times 1.8$ m dimensions). The 500 kHz ultrasonic transducer was positioned 1–2 m away from the bottom and 1.5 m in front of the helical blades. Using two stepping motors, the Ultrasonic transducer can be moved along x-direction and y-direction to detect different points at the bottom. The bottom under the helical blades was covered with 10 cm of irregular sand layer under which 5 cm of irregular crusts layer was placed. The sand layer was a mixture of loess and experimental sand at a ratio of 3:7. The dimension of the experimental sand was less than 1.18 mm. The dimensions of the crusts were 2–20 mm in width, 1–6 mm in thickness and less than 35 mm in length. The bottom was interrogated by an acoustic wave generated as 16 μs pulses of 500 kHz frequency. According to the statistics of Ref. [15], 65% of the thickness of the crusts on seafloor ranges from 1 to 8 cm. Such crusts require a high accuracy (centimetre-level) detector of the topography. However, the high frequency may increase the acoustic attention generated by the seawater. Hence, a trade-off of 500 kHz is chosen, which ensured a resolution on the order of one centimetre [16]. The (-3 dB) beamwidth of the transducer used, which determines lateral resolution must be 6° to ensure a resolution of 200 mm.

Subsequently, we focus on the three reverberations (surface reverberation, bottom reverberation, and volume reverberation) generated in experiment. Because the mining system is operated on the seamount at depths from 800 to 2500 m, no surface reverberation induced by rough sea surface exists. However, there exists a bottom reverberation induced by scattering of mineral deposits on the incident signals. In addition, the presence of suspended sediment in seawater may generate volume reverberation. In this work, the three reverberations were performed as follows: (1) to suppress the water surface reverberation existing in experiment, the Time Gain Compensation (TGC) hardware circuit was applied. The variable gain amplifier applied in the system was VCA810 with the control voltage varying from -1 V to -2 V, and the corresponding gain was 0–40 dB. In the measurement arrangement shown in Fig. 1, the relatively close distance between the 500 kHz probing transducer and the water surface causes concurrent surface reverberation. This reverberation was suppressed at the receiver using TGC with 0 dB gain. TGC also compensated for the possible attenuation and spreading of the received signals; (2) as the irregular sand and crust layers on the bottom were stirred up by the helical blades, they have introduced volume reverberation; also, (3) bottom reverberation was generated from the scattering of the uneven bottom. The detection of the crusts in the simulated seafloor mining environment was conducted as follows: the stepping motor was activated and the helical blades formed a turbid water environment. The bottom was then interrogated by the acoustic wave. All echo signals were collected by a data acquisition card (PCI 1714 UL) at a rate of 8 MHz using single sampling mode. Each echo signal had a length of 20,000 samples. The transducer was moved to the next sampling location until 15 echo signals were recorded. This procedure was repeated for about 5 min to cover the interrogated area.

3. Chaotic characterisation of reverberation

To apply the method to target signal detection in reverberation, we first must demonstrate that reverberation derived from the simulated seafloor mining environment is chaotic. Chaos is a complicated motion state that is specific to a deterministic nonlinear dynamical system. In the context of a chaotic process, the correlation dimension and Lyapunov exponents are two principal