Threshold Methods of Sonar Pseudonoise Phase-shift Signal Detection.

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Abstract--This work deals with digital signal processing. Different methods of processing of signals in an underwater environment are considered.

The threshold methods of sonar pseudo-noise phase-shift signal detection, which are used in asynchronous systems, when the processing period is undetermined and unknown are analyzed by means of computer modeling for different noise models. The authors propose a new method of symbol processing, which is effective in case of impulse noise. This work was supported in part by the federal target program «Scientific and teaching staff of innovation in Russia 2009-2013» under Grant No. P497 (May 13, 2010).

Index Terms--digital signal processing, computer modeling, correlation, noise models, sonar signals, threshold detection, pseudonoise signals, pseudorandom sequences, underwater systems.

I. INTRODUCTION

Detection of sonar signals is an important problem solved by many underwater systems such as communication systems, navigation systems, remote sensing systems. The reliability of the received information depends upon the accuracy of detecting the signal. For example, in communication systems the precise determination of the signal provides the precise synchronization of the receiver and transmitter, which allows data transfer with a minimum of errors. Such factors of the aquatic environment, as attenuation, noises and multipath signal, make the signal processing difficult [1, 2, 3]. Received data may contain noise or echoes. Mobile underwater systems need to operate in a wide dynamic range of signal to noise ratio (SNR), they have to receive data at different distances. To provide such an environment it is important to take into account the form of transmitted signals and the method of detection. Pseudo-noise phase-shift signals are considered in this article since they along with other pseudo-noise signals can operate at SNR below 0 dB. [4]. Moreover these signals differ favorably from other types of pseudonoise signals by the fact that they are resistant to narrow-band interference, and this provides a gain in the distance of transmission in a wireless environment. [5]. Phase-shift signal is sinusoidal pulses with different phases, where the phase changes according to the law of a pseudo-random sequence. Since the method of detection is also of critical importance for providing the accurate reception, in the implementation of the reception equipment it is necessary to choose the method of detection. In this paper, a comparative analysis of the various threshold methods of sonar noise-like phase-shift signal detection is made.

II. DESCRIPTION OF SIGNAL DETECTION METHODS

In this paper 5 different methods of threshold detection of sonar pseudonoise phase-shift signals are considered. The basis for these methods is the correlation analysis, in which the signal search is carried out by the correlation function:

\[ R_k = \sum_{i=0}^{N-1} u_{k+i} \cdot m_i, \]  

(1)

where \( u_{k+i} \) is a sequence of input samples (processed signal); \( m_i \) is a formed indication array of digital copies of the signal; \( N \) is the length of the processed signal.

And when the system is detecting signal with unknown intervals of emission, the signal cannot be detected simply by finding the maximum \( R_k \). Here threshold methods are needed.

**Fixed threshold** [6]. This is the easiest method of threshold detection. It is simple to implement, but is not suitable for environments with varying characteristics, because it’s not adaptive. In this method, the solution of signal detection is made on the basis of expression

\[ R_k > \mu_{fix} \]  

(2)

where \( \mu_{fix} \) is the fixed threshold value.

**Mean correlation value** (MCV), [7]. This method is an adaptive one, i.e. here the characteristics of the channel are measured. Here we use the expression

\[ R_k > \mu_{mcv} \cdot A_k, \]  

(3)

where

\[ A_k = \frac{1}{N} \sum_{i=0}^{N-1} R_{k-i} \]  

(4)

is MCV; \( \mu_{mcv} \) is setup variable.

**Received data power** (RDP), [8]. The following adaptive method we use the expression

\[ R_k > \mu_{rdp} \cdot A_k \]  

(5)

where

\[ A_k = \sum_{i=0}^{N-1} (u_{k+i})^2 \]  

(6)

is Received data power; \( \mu_{rdp} \) is setup variable.
The second correlation function, [9]. It is also an adaptive method. Here, in terms of detection using the second correlation function

$$R_k > \mu_{\text{sec}} \cdot A_k,$$

where

$$A_k = \sum_{i=0}^{N-1} u_{k+i} \cdot m_{2i},$$

is the value of the second correlation function, \(m_{2i}\) is a formed array of second signal digital copy indications, second signal being of the same duration as the required signal and with similar characteristics, \(\mu_{\text{sec}}\) is setup variable.

Symbol processing. This method is proposed by the authors. Here, as in the method with a fixed threshold, we use the expression

$$R_k > \mu_{\text{fix}},$$

where \(\mu_{\text{fix}}\) is fixed threshold value. But in this method of signal detection \(R_k\) is computed symbol by symbol. Phase-shift signal is represented by a binary sequence in the form of the elements that take two values: 1 and -1. And then make the correlation for this sequence:

$$R_k = \sum_{j=0}^{N-1} M_j \cdot s_j,$$

where \(M_j\) is an array containing a sequence of binary values of a mask (1 and -1); \(s_j\) is intermediate value, which holds the result of determining the value of each symbol to the signal being explored; \(C_s\) is the number of symbols in the premise.

To determine the value of the symbol \(s_j\) we used the rule:

$$s_j = \begin{cases} 
-1, & \text{if } \sum_{i=0}^{N_s-1} m_{i} \cdot u_{k+i+jN_s} < 0, \\
1, & \text{in other cases} 
\end{cases}$$

where \(u_k\) - a sequence of input signal samples; \(m_i\) - digital copy of a symbol; \(N_s\) - the length of one symbol in the discrete samples.

In fact, this method is a hybrid of the adaptive and fixed methods. It does not measure the characteristics of the channel, but the processing of the signal in parts it is possible to estimate the percentage of signal loss while transmitting in the channel. This method is simple to implement, as there is no need for arithmetic units with high capacity, and the final correlation function is calculated for the binary values. One disadvantage of the method is the fact that it is suitable only for the phase-shift signal.

III. COMPUTER SIMULATION

Methods were modeled in Matlab environment. Sonar pseudonoise phase-shift signal was constructed, channel with noise was modeled. Initial phase of the received signal was assigned as a random variable under the uniform law. In such experiments it was a successful detection if the moment of signal reception was determined accurate up to a symbol. The simulation was conducted for a range of values of signal to noise ratio with the decrement of 1 dB. During the experiment, the average noise power was taken as a constant value that meets the situation in real sonar channel.

For each method of detection the probability of successful detection \(P_{\text{det}}\) was estimated under different SNRs as the number of successful detections to the full number of tests. Under each SNR 273 tests were carried out, that according to Moivre-Laplace theorem, [10], with a confidence level of 0.9 can accurately enough determine the probability of successful detection with a confidence interval of 0.05. Also the probability of false detection \(P_{\text{false}}\) was considered as the number of signal detections in the absence of a signal in the channel to the number of tests. In the analysis of the methods setup variables \(\mu\) were chosen so that \(P_{\text{det}} \rightarrow 1, P_{\text{false}} \rightarrow 0\), and \(\mu \rightarrow 0\). This choice ensures the successful reception of a broad range of SNRs with minimal false detections.

IV. THE RESULTS OF THE TESTS

For a comparative analysis we modeled a signal with a relative sampling frequency \(f^* = 4\), which is defined as the ratio of the discrete sampling frequency \(f_{\text{dis}}\) to the signal-carrier frequency \(f_s\): \(f^* = f_{\text{dis}} / f_s\). For one signal symbol there is \(T_{\text{sym}} = 8\) signal frequency periods or \(N_s = 32\) discretization frequency samples, the signals were coded by pseudo-random sequences of different lengths. Below are the results of modeling for the five methods of threshold signal detection, and modeling of the method of determining the signal arrival of the maximum value. The modeling was carried out for signals coded by binary sequences of lengths 31 and 127. In the experiments 6 different variants of noise generation were used:

1) Additive white Gaussian noise (AWGN).
2) Additive white Gaussian noise with the addition of impulse noise. Impulse noise is outside the signal.
3) Additive white Gaussian noise with the addition of impulse noise. Impulse noise is inside the signal.
4) The noise is uniformly distributed in the frequency band (3 kHz) of the receiver with the addition of impulse noise. Impulse noise is outside the signal.
5) The noise is uniformly distributed in the frequency band (3 kHz) of the receiver with the addition of impulse noise. Impulse noise is inside the signal.
6) The noise is recorded by sonar antenna in shallow sea.

In the modeling of various signal processing systems additive white Gaussian noise is often used. To make the working conditions more real the impulse noise was added, also a noise bandwidth was limited (the received signal in the transmission channel is limited by bandwidth, which is caused by the characteristics of the underwater channel, and receiver-transmitter equipment). For these purposes we conducted computational experiments, in which the noise recorded in the full-scale tests in shallow water was used.
Figure 1. The detection probability for various signal detection methods. Noise generation in variant 1.

Figure 2. The detection probability for various signal detection methods. Noise generation in variant 2.

Figure 3. The detection probability for various signal detection methods. Noise generation in variant 3.

Figure 4. The detection probability for various signal detection methods. Noise generation in variant 4.
V. CONCLUSIONS

This work includes the comparative analysis of 5 threshold methods of sonar pseudonoise phase-shift signal detection. As it was expected, the method of fixed threshold appeared to be the worst by the results of computer modeling. This method doesn’t work when SNR is below 0 dB. The method of mean correlation value and the second correlation function had better results in comparison with the method of fixed threshold. But these methods are not very good at low values of SNR. They have the following limitation: high frequency of false operations and bad adaptation for changing characteristics of channel. The method of received data power shows good results in case of additive white Gaussian noise. But this method doesn’t work in case of bandlimited noise. The symbol processing method proposed by the authors has simple hardware implementation, but it is effective. The symbol processing loses out to the maximum value method in some cases. But in case of impulse noise the symbol processing was the best. Also, the symbol processing method as opposed to the maximum value method may be used in asynchronous system.

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