The Application of Chaotic-FM Signal to UWAC System: Theory and Sea Test Results

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Abstract

In order to improve the data rate of long-range underwater acoustic communication (UWAC) system working on low frequency band, a new type of communication mode is presented, that is Chaotic Frequency Modulation (CFM) M-ary mode. Firstly, this paper introduces chaotic sequences into UWAC field. Secondly, the paper studies CFM signal and its good properties. Finally, one sea test is designed to verify its performance. The experimental results are in excellent agreement with theoretical results. The CFM M-ary mode is both feasible and reliable. It can improve the data rate of UWAC system.

1. Introduction

In general, the working distance of long-range underwater acoustic communication (UWAC) system is between 20km and 200km. Signal attenuates seriously after long range propagation. Sometimes the bit error rate (BER) is too high to get correct information. There are two means to tackle this problem [1][2]. First, the working band under 1kHz is selected. Second, the spread-spectrum techniques are used to obtain spread-spectrum gain and improve the SNR of the demodulated signal.

Since long-range UWAC system works on low frequency band, the data rate must be very low. The focus of this paper is on the methods of improving the data rate. A new communication mode, which is Chaotic Frequency Modulation (CFM) M-ary mode, is presented. And the properties of CFM signal are studied in detail.

2. CFM M-ary Mode

2.1. M-ary Mode

In common spread-spectrum system, the sender is given a unique address code. Assume the positive phase of the code represents bit 1 and negative phase represents bit 0. So the communication bit stream becomes code phase stream. If one of the two phases is send out during one code time length T, one bit information is obtained. The data rate is:

\[ R = \frac{1}{T} \]  

If a set which contains M (M=2^n) orthogonal codes is given to the sender, n bits information can be represented by a code C which is one element of the set. The sender transmits code C and the receiver does correlation calculation between C and all of the codes in the set. Only code C can be matched out because of the orthogonal property. So n bits information can be obtained just by sending one code. The data rate is:

\[ R = \log_2 M / T \]

So M-ary mode can improve the data rate of the UWAC system.

2.2. Chaotic sequences

Using M-ary mode to improve the data rate, the main problem is searching numerous orthogonal codes to constitute a larger set.

The ordinary codes used in spread-spectrum communication system are m sequences, GOLD sequences and Kasami sequences etc. They all have good random and orthogonal properties. But the number of them is very small. Finding more orthogonal codes must use other methods.

The chaos phenomenon appears in non-linear dynamic system. The chaos process is similar to random process. It is sensitive to the initial value. If there is a little change of the initial value, the chaos process will be independent as before. So numerous orthogonal codes can be found[3]-[5].

This paper studies improved Kent Map and its application to UWAC system.

Improved Kent sequence is defined as:

\[
y_{i+1} = \begin{cases} 
\frac{(1 + (a - y_i))}{a} & -1 \leq y_i < 2a - 1 \\
\frac{(a - y_i)(1 - a)}{2a - 1} & 2a - 1 \leq y_i \leq 1 
\end{cases}
\]

where \(0 < a < 1\), \(-1 \leq y_i \leq 1\)

Given a initial value between \([-1,1]\) randomly, a Kent sequence can be generated. Assume the length of the sequence is 511. As shown in Fig.1, the maximum of the auto-correlation’s side lobe is 0.120, the maximum of the cross-correlation is 0.136.
However, there is a significant difference between chaotic sequence and GOLD sequence, i.e. the former is not a binary sequence. In order to use the chaotic sequence in the ordinary system, the first work is quantizing it. Fig 2 shows the correlation of the quantized Kent sequence, the maximum of the auto-correlation’s side lobe is 0.123, the maximum of the cross-correlation is 0.141. So both the maximum of the auto-correlation’s side lobe and the maximum of the cross-correlation become larger after Kent sequence is quantized. The reason is that the random property of Kent sequence is damaged by the quantizing process.

2.3. Chaotic Frequency Modulation

To keep the good correlation properties of the chaotic sequence, this paper proposes a new type of modulation mode, that is CFM. This mode does not quantize the chaotic sequence any more. Directly modulating the carrier by chaotic sequence, this mode maintains the random properties of the sequences, and lead to many other good properties.

The CFM signal is defined as

\[ s(t) = A\cos(\omega_0 t + B \int c(t) dt) \quad 0 \leq t \leq T \]  

(4)

where T is time length of signal s(t), \( \omega_0 \) is carrier angular frequency, B is band width, c(t) is modulation signal.

Assume k(n) is a Kent map chaotic sequence with length N, the FM time of one chip is \( T_0 = T/N \), so the modulation signal c(t) is defined as:

\[ c(t) = \sum_{n=0}^{N-1} k(n)[u(t-nT_0) - u(t-(n+1)T_0)]/2 \]

(5)

where, u(t) is jump function, r(t) is ramp function.

So,

\[ s(t) = A\cos(\omega_0 t + B \sum_{n=0}^{N-1} k(n)[r(t-nT_0) - r(t-(n+1)T_0)]/2 \]  

(6)

where, u(t) is jump function, r(t) is ramp function.
Assume CFM signal’s time length is 2.5s, carrier frequency is 600Hz, band width is 200Hz, modulation signal is Kent sequence. Fig 3 shows the correlation of the CFM signal, the maximum of the auto-correlation’s side lobe is 0.114, the maximum of the cross-correlation is 0.112.

As shown in Fig 3, the CFM signal has good correlation properties and can be used in M-ary communication system.

CFM signal not only has good correlation property, but also has many other good characteristics as follows.

First, the utilization ratio of spectrum is high. Compare the spectrum of CFM and GOLD BPSK signal. As shown in Fig 4, the spectrum of CFM signal is concentrated in effective band. On the contrary, the spectrum of GOLD BPSK signal has many side lobe outside the effective band. So the CFM signal is more effective in spectrum than GOLD BPSK signal.

Second, B and T of CFM signal can be adjusted independently, so data rate and BER can be adjusted easily. GOLD BPSK signal does not have this good property. Assume the exponent of GOLD code is n, then the period is $N=2^n-1$, and $N=BT$; Apparently N is not change continuously. When n increases 1, N becomes twice as before. If B is constant, T becomes twice as before, data rate becomes half as before. If T is constant, B becomes twice as before. It is difficult to make wide band acoustoelectric energy converter.

Third, Chaotic sequence is not a binary sequence. It has infinite status. In theory, one cannot deduce the initial values and parameters of the chaotic sequence. So CFM signal cannot be decrypted without its copy signal and CFM M-ary communication has high security.

3. Sea test

To study the performance of long range UWAC system based on CFM M-ary mode, one sea test is designed and carried out in the South China Sea in April, 2003. The parameters of CFM signal are listed as follows. The length of chaotic sequence is 127, time length is 5.10s,
band width is 50Hz. The distance is 31km. The matched filter output is depicted in Fig5 and the quantitative analysis results of the sea test data are listed in Table I.

Here, SL is source level, TL is propagation loss, NL is noise level, GT is time gain and SNR is the ratio of signal and noise power. (SNR1: theoretical SNR, SNR2: experimental SNR)

Experimental results show that the received signal’s SNR is in excellent agreement with theoretical value and the correlation between the received signal and its copy signal is greater than 0.4. So the Chaotic-FM M-ary mode is both feasible and reliable.

![Figure 5: Matched filter output of the sea test data](image)

<table>
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<tr>
<th>Range</th>
<th>SL</th>
<th>TL</th>
<th>NL</th>
<th>GT</th>
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<td>dB</td>
<td>dB</td>
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<td>23.7</td>
<td>21.2</td>
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5. References


4. Conclusions

In this paper, the chaotic frequency modulation signal was introduced into UWAC field. CFM signal has many good properties, such as good correlation properties, numerous orthogonal codes, high utilization ratio of spectrum. And the parameters B and T of CFM signal can be adjusted independently.

The quantitative analysis results of the sea test data indicate that the CFM M-ary mode is both feasible and reliable. It can improve the data rate of UWAC system and obtain communication security easily.

Future work would cover detailed implementation issues, such as the use of fast matching algorithms and the development of a real-time CFM UWAC model machine based on DSPs network.