Crosstalk Elimination Method Based on Chaotic Binary Amplitude Shift Keying

*Yao Zhenjing, Hong Li, Li Yanan

Department of Disaster Prevention Instrument, Institute of Disaster Prevention, Sanhe 065201, China
zjyang4@sina.com

Abstract. The important indicators of multichannel ultrasonic ranging system are correlation characteristics and energy efficiency. The excitation sequences with good correlation characteristics can help avoid crosstalk among multichannel ultrasonic sensors. High energy efficiency can enhance measurement range. This paper proposes a crosstalk elimination method by using the optimal binary excitation sequences modulated with chaotic codes, which include chaotic binary amplitude shift keying (c-BASK), chaotic binary phase shift keying (c-BPSK) and chaotic binary frequency shift keying (c-BFSK). To obtain the both best correlation characteristics and energy efficiency, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) is applied to optimize the chaotic binary excitation sequences. Real experiments have been conducted using an ultrasonic ranging system that consists of eight-channel SensComp 600 series instrument-grade electrostatic sensors excited with chaotic binary modulation sequences. The experimental results show that the c-BFSK outperforms the c-BASK and c-BPSK in terms of the correlation characteristics and energy efficiency. With 2 ms c-BFSK excitation sequences, the longest measurable distance was 720 cm (i.e., increased 11% and 27% with c-BPSK and c-BASK, respectively) with maximal relative error 2.4%.

Keywords Ultrasonic crosstalk, Chaotic series, Energy efficiency, Correlation characteristic

1 Introduction

Ultrasonic sensors have been extensively applied on ranging system, thanks to their hardware construction simple and price is low. In order to obtain all directional distance information, a sensor ring with multiple ultrasonic transducers is required in a ranging system [1]. The ultrasonic crosstalk problem is occurred, when these sensors in a ring are working simultaneously [2]. Generally, ultrasonic receiver cannot distinguish whether the received echo from its own transmission or not, so the incorrect time-of-flight (TOF) measurements often occur.
The effective crosstalk elimination method is to give each ultrasonic sensor a unique excitation signature in the transmission and then identify the signature using a correlation technique in the receiver. Jörg and Berg [3] were the first to give a recognizable signature of each sensor in the transmission using pseudorandom code and frequency modulation. And then in the receiving circuit, the identification of the transmitted source sensor was by a matched filter. Subsequently, some researchers have applied different codes and modulation schemes to construct excitation sequences as a transmission signature to solve the ultrasonic crosstalk problem. Barker codes [4] were used to avoid crosstalk in ultrasonic system, although the available Barker codes limit their application. In ultrasonic distance measurement system, Golay codes [5–7] were applied to restrain crosstalk and increase the signal-to-noise ratio. But the realization complexity of Golay codes restricts their application. The BFSK and BPSK signals [8] were applied to drive multiple piezoelectric ultrasonic sensors with narrow bandwidth. In ref. [9] and [10], BPSK modulation was used to construct the transmission signals of ultrasonic system. But they adopted different codes to modulate, i.e., Alvarez et al. [9] used complementary sequences codes and Iwasawa et al. [10] applied M sequence. The chaotic codes [11-14] with good correlation characteristic were exploited to construct the ultrasonic emission signals. Fortuna et al. [12] adopted chaotic pulse position modulation (CPPM) to excite the ultrasonic transducer to restrain crosstalk and improve the efficiency of ultrasonic distance measurement system. And to minimize the correlation functions of CPPM signals, Meng et al. [13] optimized the chaotic initial value by genetic algorithm. Chaotic pulse position–width modulation (CPPWM) signals triggered the ultrasonic transducer were proposed to suppress crosstalk [14].

The measurement range in ultrasonic ranging system can be enhanced with high energy efficiency excitation sequence. Meng et al. [15] adopted spectrum optimization of a CPPM excitation signal to improve energy efficiency. In order to both obtain the best echo energy and correlation characteristics, Yao et al. [14] used non-dominated sorting genetic algorithm II to optimize the CPPWM sequences in ultrasonic ranging system.

This paper aims to exploit the novel crosstalk elimination method by applying chaotic binary modulation excitation sequences which includes chaotic binary amplitude shift keying (c-BASK), chaotic binary phase shift keying (c-BPSK), and chaotic binary frequency shift keying (c-BFSK). To both improve energy efficiency and correlation characteristics, the NSGA-II is used to optimize the proposed excitation sequences. The ultrasonic distance measurement system consisting of eight-channel SensComp 600 series ultrasonic transducers was designed and recommended the best chaotic binary modulation approach for ultrasonic sensor via experiments.

The rest of this paper is structured as follows. Section 2 presents the principle of chaotic binary modulation excitation sequence. The correlation characteristics and energy efficiency are explained in section 3. Section 4 introduces the optimization algorithm of the proposed excitation sequences. The experiments and discussion are shown in section 5, followed by the conclusions in section 6.
2 The Principle of Chaotic Binary Modulation Excitation Sequence

2.1 Chaotic Codes

Chaotic codes had been used to construct excitation sequence because of their good correlation characteristics. In this paper, the Ulam–von Neumann transformation \[16\] was used to produce chaotic codes as follows,

\[
y_i = 1 - 2y_{i-1}^2, \quad y_i \in [-1,1] \quad i = 1, 2, \ldots
\]

Binary chaotic codes were generated by the following formula,

\[
\text{sgn}(y_i) = \begin{cases} 0 & y_i < 0 \\ 1 & y_i \geq 0 \end{cases} \quad i = 1, 2, \ldots
\]

2.2 Chaotic Binary Modulation Scheme

The binary modulation techniques include BASK, BFSK and BPSK, which have two states of amplitude, frequency and phase, respectively. In the proposed chaotic binary modulation approach, the variation of amplitude, frequency and phase are on the basis of chaotic codes. Since the hardware implementation of a square wave is much easier than a sinusoidal wave, the square wave is adopted as the carrier signal of chaotic binary modulation sequences.

2.2.1 c-BASK

In c-BASK, the amplitude of a fixed-frequency carrier wave is changed with each symbol of base-band signal using binary chaotic codes. Mathematically, the form for c-BASK sequence can be written as,

\[
x_{\text{BASK}}(t) = c(t) \left( \frac{1}{2} + \sum_{k=0}^{\infty} \frac{2}{\pi(2k+1)} \sin \left( \frac{2\pi(2k+1)t}{T_c} \right) \right),
\]

where \( c(t) \) generated by formula (2) is binary chaotic codes used to change the amplitude of carrier signal.

2.2.2 c-BPSK

With c-BPSK, the chaotic information is contained in the phase of the modulated carrier signal. The c-BPSK is given by the following formula,
where \( T_s \) is the symbol width of base-band signal. In c-BPSK, the base-band signal is the binary chaotic codes.

### 2.2.3 c-BFSK

C-BFSK transmits the chaotic information using two carrier frequencies \( f_1 \) and \( f_2 \) to represent symbol states. Mathematically this is written by the following,

\[
X^c_{c-BFSK}(t) = \begin{cases} 
\frac{1}{2} + \sum_{k=1}^{\infty} \frac{2}{\pi(2k+1)} \sin\left[2\pi(2k+1)f_1 t + \frac{1 - c(t)}{T_s}\right] & \text{if } c(t) = 1 \\
\frac{1}{2} + \sum_{k=1}^{\infty} \frac{2}{\pi(2k+1)} \sin\left[2\pi(2k+1)f_2 t + \frac{1 - c(t)}{T_s}\right] & \text{if } c(t) = 0 
\end{cases}
\]

### 3 The Correlation Characteristics and Energy Efficiency

#### 3.1 Correlation Characteristics

Correlation characteristics [15] include the autocorrelation function and cross-correlation function. In the ultrasonic distance measurement system, the autocorrelation function signal is defined as follows,

\[
R_s(m) = \begin{cases} 
\sum_{n=0}^{N-1} x_n x_{n+m} & m \geq 0, i = 1, 2, \ldots, M \\
R_s(-m) & m < 0 
\end{cases}
\]

where \( M \) is the channel number of ultrasonic distance measurement system, \( x_n \) and \( x_{n+m} \) are the \((n+m)\)th and \( n \)th sampling site of the \( i \)th echo signal, respectively, \( N \) is the sample number in the echo sequence.

The definition of the cross-correlation function is given as follows,

\[
R_{ij}(m) = \begin{cases} 
\sum_{n=0}^{N-1} x_{n+i} x_{n+j} & m \geq 0, i = 1, \ldots, M, j = 1, \ldots, M, i \neq j \\
R_{ij}(-m) & m < 0 
\end{cases}
\]

where \( x_{n+i} \) is the \( n \)th sampling site of the \( j \)th echo signal.
6  Conclusions

In this paper, a crosstalk elimination method based on the optimal binary excitation sequences modulated with chaotic codes is presented in this paper. The optimized chaotic binary modulation sequence based NSGA-II both has the best echo correlation characteristics and energy efficiency. Real experiments using an ultrasonic ranging system, which consists of eight-channel SensComp 600 series instrument-grade electrostatic sensors excited with binary sequences, showed that the c-BFSK outperforms the c-BASK and c-BPSK in terms of the energy efficiency and correlation characteristics among the chaotic binary modulation sequences. The maximum measurable distance was 720 cm with 2 ms c-BFSK sequences. The maximal absolute error is 6.2 cm and the maximal relative error is 2.4%.

The results of this paper can be also used in robots which install multiple ultrasonic sensors simultaneous working.

Acknowledgment. The research work of this paper is sponsored by the Seismic Technology Spark Plan Foundation of China (No. XH14072), Scientific Technology Research Projects for Higher Schools in Hebei Province (No. ZD20140204), Special Fund of Fundamental Scientific Research Business Expense for Higher School of Central Government (Projects for creation teams) (No. ZY20110104), the Seismic Technology Spark Plan Foundation of China (No. XH12076), and National Natural Science Foundation of China (No. 60475028).

References


