

Techniques of Spectrum and Correlation Characteristics for Ultrasonic Ranging System

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Abstract

Both the spectrum and correlation characteristics are important in constructing excitation sequences to realize the multichannel ultrasonic sensors working together. For LFM excitation sequence, there should not be too many simultaneously fired ultrasonic sensors, because of the limited available frequency band of the ultrasonic ranging system. The optimized CFM excitation sequences are proposed to trigger multiple-user ultrasonic sensors in this paper. Comparing with the CFM excitation sequences without optimization, the NSGA-II based optimization CFM excitation sequences are more spectrally matched to the ultrasonic ranging system. Moreover, the ultrasonic crosstalk among multichannel sensors of an ultrasonic ranging system can be eliminated. Real experiments using an ultrasonic ranging system consisting of eight-channel SensComp 600 series electrostatic sensors excited with optimized CFM excitation sequences validate the suitability of the proposed method. The idea of optimizing CFM excitation sequences can also be used for the ultrasonic ranging system which has more than eight ultrasonic sensors.

Keywords: *ultraosnic ranging system, crosstalk, chaotic, frequency modulation*

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1. Introduction

Ultrasonic sensors have been widely used for distance measurement and obstacle avoidance because of their small size, low price and simple hardware interface. To obtain 360° panorama distance information, an ultrasonic ranging system consisting of multichannel ultrasonic sensors is required [1]. One problem with such sensors in an ultrasonic ranging system operating in close proximity is the well-known crosstalk phenomenon, where one ultrasonic sensor receives echoes transmitted by another ultrasonic sensor [2]. Usually, the ultrasonic receiver cannot judge whether the received echo is created from its own transmission or not, so false time-of-flight (TOF) measurement often occurs. In order to avoid ultrasonic crosstalk, most ultrasonic ranging system triggered their sensors sequentially [3], which limit the work efficiency of the ultrasonic ranging system. To eliminate the ultrasonic crosstalk, some researchers adopted different code and modulation schemes constructing excitation sequence to assign each ultrasonic sensor a recognizable signature. Jörg and Berg [4] first applied pseudorandom sequences to give each ultrasonic sensor a marker. A matched filter in the receiving circuit then identified the associated source sensor. Ureña and his colleagues [5] used a 13-bit Barker code to construct their excitation sequences for ultrasonic sensors. While the available Barker codes limit their application. Golay codes [6-11] were applied in ultrasonic ranging system to avoid crosstalk and increase the signal to noise ratio (SNR). Chaotic codes [12-13] were also used to eliminate crosstalk in multichannel simultaneously triggered ultrasonic ranging System. Fortuna et al. [12] exploited chaotic pulse position modulation (CPPM) to fire the ultrasonic sensor. Yao et al. [13] proposed chaotic pulse position width modulation (CPPWM) excitation sequences as the transmission sequences of ultrasonic sensors. Nakahira [14] used binary-coded frequency-shift keyed signals to drive ultrasonic sensors to eliminate crosstalk. Meng et al. [15-16] proposed pseudorandom frequency modulation and frequency-hopping pseudorandom pulse-width modulation sequences to excitation ultrasonic sensor, and the result of avoiding crosstalk was not good. The signals with linear frequency modulation (LFM) [17] were used as the transmission signals of ultrasonic sensors, which could avoid

crosstalk. But the spectra of LFM excitation sequences are not totally matched to that of the ultrasonic ranging system. And the number of available LFM excitation sequences is limited because of the narrow bandwidth of the ultrasonic ranging system. In order to make the spectrum of excitation sequence match to that of the ultrasonic ranging system, Pollatowski and Ermert [18] applied transmitter signals with a constant amplitude level and nonlinear frequency modulation. However, they did not research how to obtain the good correlation characteristics of the excitation sequences.

Optimization techniques have also been applied to construct excitation sequences in multichannel ultrasonic ranging system. Griep et al. [19] adopted a global optimization technique to select proper coding signal for multiple-user ultrasonic ranging system. Osamu Hikino and his colleagues [20] optimized PN sequences to reduce autocorrelation function's side-lobe. Nakahira et al. [14] used a combination of simulated annealing and hill climbing to minimize the peaks in the cross-correlation function as well as minimize the maximum side-lobe in the autocorrelation function. Meng et al. [21] applied a genetic algorithm (GA) to optimize short CPPM and pseudorandom PPM triggering sequences in order to improve correlation characteristics (i.e. minimize the side-lobe in the autocorrelation function and the peaks in the cross-correlation function). Yao et al. [13] adopted nondominated sorting genetic algorithm II (NSGA-II) to optimize CPPWM excitation sequences in order to sharpen the autocorrelation and flatten the cross-correlation as well as to maximize echo energy. The spectrum matching and correlation characteristic are both important in the multiple-user ultrasonic ranging system. As we know, an ultrasonic ranging system, which has a bell-shaped magnitude spectrum, acts like a band-pass filter. If the spectrum of the excitation signal does not match that of the ultrasonic ranging system, some of energy cannot be transmitted by the ultrasonic system. In other words, it does not make full use of the bandwidth of the ultrasonic ranging system. The good correlation characteristics can eliminate cross-talk among multichannel ultrasonic sensors firing simultaneously. To our knowledge, not many researchers considered how to make the spectrum of the excitation sequence match to that of the ultrasonic ranging system as well as improve the correlation characteristics. In this paper, the chaotic frequency modulation (CFM) excitation sequences are proposed for multiple-user ultrasonic ranging system. To obtain the excitation sequences which are spectrally matched to the ultrasonic ranging system as well as have the best correlation characteristic, the NSGA-II is applied to optimize the CFM excitation sequences.

The remainder of this paper is organized as follows. Section 2 explains the principle of the LFM excitation sequence. The principle of CFM excitation sequence is presented in Sect. 3. Section 4 introduces the CFM excitation sequences optimization. The experiments and results are shown in Sect. 5. Finally, in Sect. 6, the conclusions are described.

2. The Principle of Linear Frequency Modulation (LFM) and Chaotic Frequency Modulation (CFM)

In the linear frequency modulation (LFM) excitation sequences, the frequency of carrier signal increases or decreases linearly in a fixed time interval. The LFM signals are transmitted with constant amplitude. So their amplitude contains no information. The carrier signal of the traditional LFM signal is sinusoidal wave $s(t)$, which is represented as follows,

$$s(t) = \sin(\omega_c t) . \quad (1)$$

Where ω_c is the angular frequency of sinusoidal wave. As the hardware realization of a square signal is much easier than that of a sinusoidal signal, the following square signal $q(t)$ is used as the carrier signal of excitation sequences for ultrasonic ranging system.

$$q(t) = \begin{cases} 1 & nT_c \leq t < (n+1/2)T_c \\ 0 & (n+1/2)T_c \leq t \leq (n+1)T_c \end{cases}, n = 0, \pm 1, \pm 2, \dots \quad (2)$$

Where T_c is the period of the square signal, and $T_c = 2\pi\omega_c$. The square wave $q(t)$ can be described by its Fourier series.

$$q(t) = \frac{1}{2} + \sum_{p=0}^{\infty} \frac{2}{\pi(2p+1)} \sin[(2p+1)\omega_c t]. \tag{3}$$

From the Fourier series in (3), we can find two things. On the one hand, the square wave is a composite of a direct-current component and harmonic components at odd multiples of the basic frequency. On the other hand, the lower the frequency of the spectral component is, the smaller the energy of the corresponding harmonic component is. Because the ultrasonic ranging system works as a pass-band filter, only the harmonic components within the pass-band of the ultrasonic ranging system are received. The other harmonic components can not be transmitted by the ultrasonic sensor. Therefore, to make the fundamental harmonic be transmitted by the ultrasonic sensor, the period of the square signal must be set based on the spectrum of the ultrasonic ranging system. Chaotic series have characteristics such as sensitivity to small changes in initial conditions, sharp autocorrelation functions and flat cross-correlation functions. The chaotic series are applied to modulate carrier frequency in this paper. In chaotic frequency modulation (CFM) excitation sequence, the carrier frequency is changed with the chaotic series. The principle of CFM is illustrated in Figure 1, where the top one is the modulation characteristics of carrier frequency, the bottom one is the CFM excitation sequence. The k th carrier frequency f_k is modulated as follows,

$$\begin{cases} f_k = 1/t_k \\ t_k = \frac{y_k + 1}{2} (T_u^{CFM} - T_l^{CFM}) + T_l^{CFM}, \quad k = 1, 2, \dots, n \end{cases} \tag{4}$$

Where pulse number n is related to the length of the CFM excitation sequence; T_l^{CFM} and T_u^{CFM} are the lower limit and upper limit of all the pulse periods, respectively; y_k is a chaotic series, which is generated by the Ulam-von Neumann transform [23] shown as follows:

$$y_k = 1 - 2y_{k-1}^2, y_k \in (-1, 1), k = 1, 2, \dots, n. \tag{5}$$

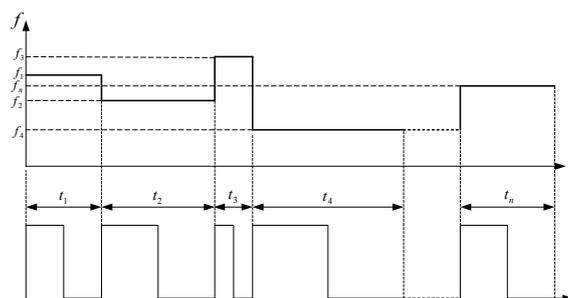


Figure 1. The Principle Diagram of CFM

3. The Cfm Excitation Sequences Optimization

The correlation characteristic is a key evaluation criterion in constructing excitation sequences of the multiple-user ultrasonic ranging system. The smaller the maximal side lobe of autocorrelation function and the peak of cross correlation function, the easier it is to reject crosstalk. So the correlation characteristic R is defined as follows:

$$R := \max(R_{a-\max}, R_{c-\max}), \tag{6-a}$$

$$R_{a\text{-max}} := \max(R_{11}(m), \dots, R_{M_T M_T}(m)), \quad (m = 0, \dots, N - 1 - \delta), \quad (6\text{-b})$$

$$R_{ii}(m) = \begin{cases} \sum_{n_x=0}^{N-m-1} x_{n_x+m}^i x_{n_x}^i & m \geq 0 \\ R_{ii}(-m) & m < 0 \end{cases}, \quad (i = 1, 2, \dots, M_T), \quad (6\text{-c})$$

$$R_{c\text{-max}} := \max(R_{ij}(m)), \quad (m = 0, 1, 2, \dots, 2N - 1), \quad (6\text{-d})$$

$$R_{ij}(m) = \begin{cases} \sum_{n_x=0}^{N-m-1} x_{n_x+m}^i x_{n_x}^j & m \geq 0 \\ R_{ij}(-m) & m < 0 \end{cases}, \quad i, j = 1, \dots, M_T, i \neq j. \quad (6\text{-e})$$

Where $R_{a\text{-max}}$ is the maximal side-lobe among all the autocorrelation functions, $R_{c\text{-max}}$ is the maximal peak among all the cross-correlation functions, $R_{ii}(m)$ is the autocorrelation function of the i th echo sequence, $R_{ij}(m)$ is the cross-correlation function of the i th and j th echo sequences, M_T is the number of channels in multiple-user ultrasonic ranging system (eight in our experiments), δ is the half width of the main-lobe envelope of the autocorrelation function, and N is the total number of samples in the echo sequence. To obtain the best correlation characteristics, the R should take the minimum value. The matched spectrum is also important in constructing excitation sequences for the multiple-user ultrasonic ranging system. As we know, an ultrasonic ranging system, which has its central frequency and bandwidth, works like a band-pass filter. If the frequency bandwidth of the excitation sequence does not match that of the ultrasonic ranging system, some energy out of the bandwidth of the ultrasonic ranging system is lost. So the key is to distribute most of the energy of the excitation sequence in the frequency bandwidth of the ultrasonic ranging system. The corresponding index is defined as follows:

$$S := \max[re1, re2, re3, re4], \quad (7\text{-a})$$

$$re1 := \max(amp_{out_i, in_i}) / \max(amp_{in_i, in_u}), \quad (7\text{-b})$$

$$re2 := \max(amp_{in_u, out_u}) / \max(amp_{in_i, in_u}), \quad (7\text{-c})$$

$$re3 := \text{sum}(amp_{out_i, in_i}) / \text{sum}(amp_{in_i, in_u}), \quad (7\text{-d})$$

$$re4 := \text{sum}(amp_{in_u, out_u}) / \text{sum}(amp_{in_i, in_u}). \quad (7\text{-e})$$

Where $[in_i, in_u]$ is the frequency band of the ultrasonic ranging system, and $(out_i, in_i) \cup (in_u, out_u)$ is the frequency ranges out of the ultrasonic ranging system. For the SensComp 600 series electrostatic sensors used in our experiments, the frequency band is [40, 70] kHz, i.e., the values of in_i and in_u are 40 kHz and 70 kHz, respectively. The values of out_i and out_u are set to 5kHz and 100kHz, respectively. The symbol amp in (7) represents the amplitude of corresponding frequency band, and the symbols \max and sum mean "taking the biggest" and "calculating the sum", respectively. To obtain the excitation sequences with the best matching spectrum, the S should take the minimum value.

A long excitation sequence increases processing time, so its length is not very long normally. The length of each CFM sequence is limited to be about 2 ms in our experiments. In the CFM excitation sequences optimization, the NSGA-II is used to optimize T_i^{CFM} , T_u^{CFM} and the chaotic initial values of (5), to obtain the minimum values of R and S . The NSGA-II based CFM excitation sequences optimization procedure is presented as follows:

Step 1: Generating initial parent population $A_{P \times Q}$ randomly, where P is individual number and Q is the float-code length. Let $P=100$, $Q=10$ (corresponding to ten values, which include T_l^{CFM} , T_u^{CFM} , and eight chaotic initial values for eight channels ultrasonic ranging system); the maximum generation number is set to 100; the range of chaotic initial value is (0, 1).

Step 2: The individual fitness values are obtained by calculating R in (6) and S in (7).

Step 3: According to the individual fitness values in step 2, the population is sorted and each individual is endowed with a non-dominated rand.

Step 4: Calculating the crowding distance of individuals with the same non-dominated rand.

Step 5: Selecting the individuals that have smaller non-dominated rand and the larger crowding distances as parent population.

Step 6: The offspring population is generated by crossing and mutating from parent population.

Step 7: Combining the offspring population with the current generation population, which ensures the elitist individual reserved.

Step 8: Selecting the individuals from the combining population for the next generation. Repeat Step 2 to Step 8 until either the non-dominated rank is small enough and the crowding distance is large enough, or the maximum generation number is reached.

4. Experiments and Results

Figure 2 shows the hardware schematic diagram for one channel of the ultrasonic ranging system. The excitation sequence, whose length was set to 2 ms, was sent from the FPGA (field-programming gate array). The excitation sequence was amplified by the power amplifier, and the peak-peak amplitude of the amplified sequence is about 300V. Then it triggered the ultrasonic sensor to transmit ultrasound. After band-pass filtering, automatic gain amplification and shaping circuit, the polarity correlation between the reference echo sequence and the binary echo sequence was realized. Here it should be noted that the reference echo sequence was recorded from an obstacle placed 40 cm in front of the ultrasonic sensor. The excitation sequence and its echo sequence are different due to the band-pass filter action of the ultrasonic sensor, so the correlation characteristic between the excitation sequence and its own echo sequence is not good. Therefore, we used echo sequence instead of the excitation sequence as the reference sequence. A zero-crossing algorithm [5, 14] was used to implement the polarity correlation operation. Finally, the distance between ultrasonic sensor and obstacle was calculated if the echo sequence was identified to be from the ultrasonic sensor's own transmission. In our experiments, the SensComp 600 series instrument-grade electrostatic sensor was used as both transmitter and receiver. Its central frequency is approximately 52kHz. The frequency band of the ultrasonic sensor is between 40kHz and 70kHz. Its beam angle is about 15°. The frequency band of the band-pass filtering is approximately [30, 80] kHz.

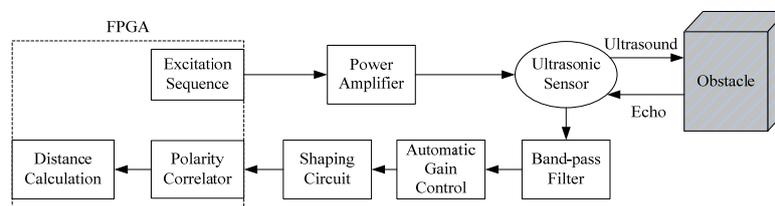


Figure 2. Hardware Schematic Diagram for One Channel of the Ultrasonic Ranging System

The ultrasonic ranging system which consists of eight-channel ultrasonic sensors needs eight LFM excitation sequences. Considering the frequency band of the ultrasonic sensor is [40, 70] kHz. So the swept frequency range of all the LFM excitation sequences must be within [40, 70] kHz. Both the correlation characteristic and the spectrum of LFM excitation sequence are related with the swept frequency range of LFM excitation sequence. For

comparison, LFM 1 and LFM 2 with a duration time of 2 ms were constructed. A 49.25 kHz to 54.75kHz swept frequency digital square signal was used as the LFM 1 excitation sequence. Figure 4 shows the LFM 1 excitation sequence and its spectrum, and the corresponding echo sequence, and the autocorrelation function of binary echo sequence. LFM 2 excitation sequence whose instantaneous frequency increases linearly from 37.98 kHz to 66.02 kHz was constructed. The LFM 2 excitation sequence and its spectrum, and the corresponding echo sequence, and the autocorrelation function of binary echo sequence are illustrated in Figure 5. Here it should be noted that the echo sequences were reflected from an obstacle placed 40cm in front of the ultrasonic sensor. And the sample period was $1\ \mu\text{s}$. In Figure 3(b) and 4(b), the black lines are the spectra of the LFM excitation sequences, and red lines are the spectrum of the ultrasonic ranging system (i.e., URS in Figure 3(b) and 4(b)). Figure 3(b) shows that most energy of LFM 1 signal is distributed in the frequency band of the ultrasonic ranging system. From Figure 4(b), we can find that the spectrum of the LFM 2 signal is of almost rectangular shape, which does not match the spectrum of the ultrasonic ranging system. Comparing Figure 3(c) with Figure 4(c), we can see that the corresponding echo amplitude of LFM 1 is higher than that of LFM 2. Therefore, the LFM excitation sequence with a narrower swept frequency range has a fuller use of the bandwidth of the ultrasonic ranging system. For the correlation characteristics comparison, we only present the autocorrelation functions of binary echoes corresponding to different LFM excitation sequences. From Figure 3(d) and 4(d), we can infer two conclusions. Firstly, LFM excitation sequence with a wider swept frequency range offers more narrow width of autocorrelation function's main-lobe. Secondly, the wider the swept frequency range of LFM excitation sequence is, the lower the side-lobe of autocorrelation function is. In a word, the LFM excitation sequence with a wider swept frequency range has a better correlation characteristic.

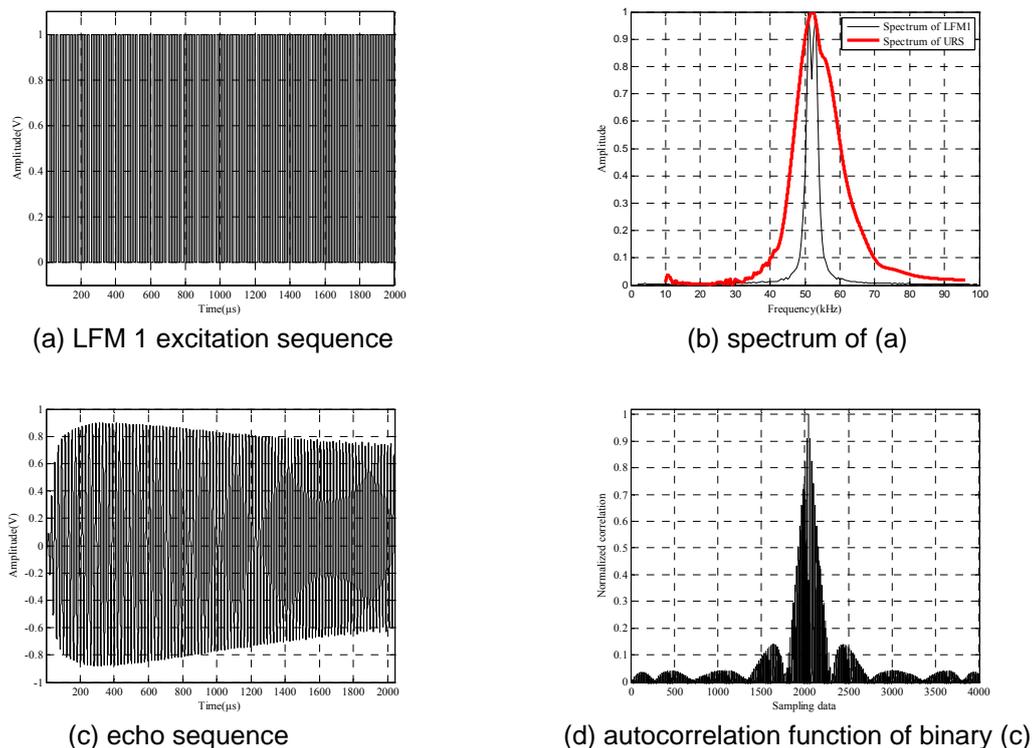


Figure 3. The Results of LFM 1 Excitation Sequence

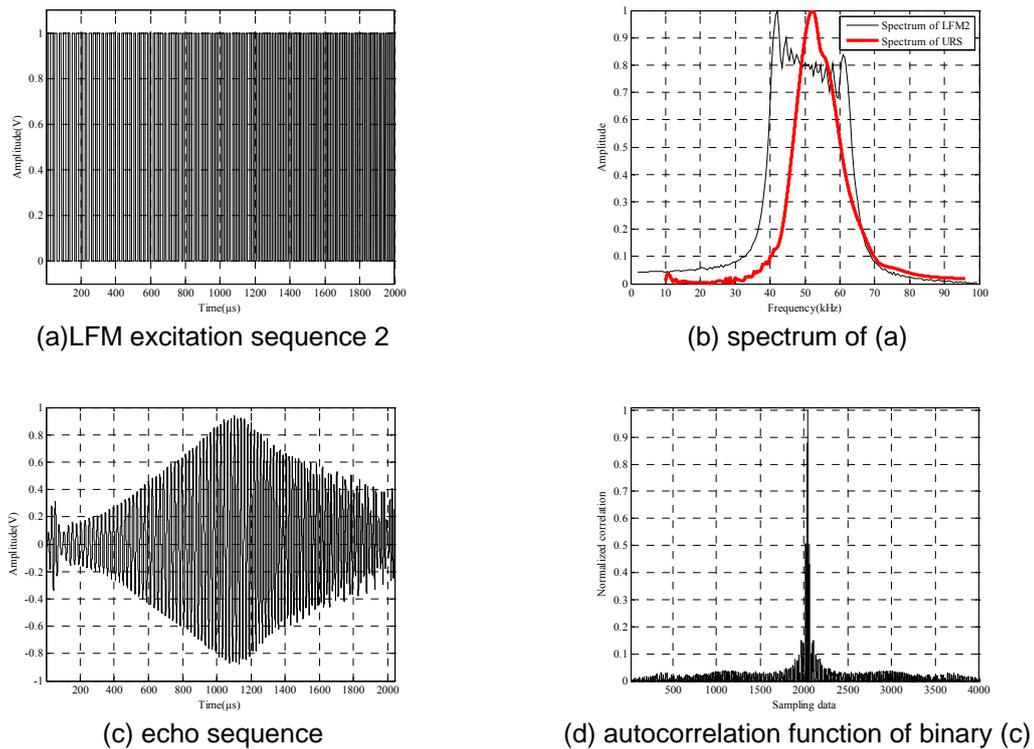


Figure 4. The Results of LFM 2 Excitation Sequence

5. Conclusion

The chaotic frequency modulation (CFM) excitation sequences, which can generate more available excitation signals, are proposed in this paper. The nondominated sorting genetic algorithm-II is adopted to optimize both the spectrum and correlation characteristic of the CFM excitation sequences. After optimization, the CFM excitation sequences are spectrally matched to the ultrasonic ranging system as well as have best correlation characteristic. Real experiments have been implemented using an ultrasonic ranging system consisting of eight-channel SensComp 600 series electrostatic sensors excited with 2 ms CFM sequences. Experimental results show that spectra of the optimized CFM excitation sequences can match to the system and can work together without crosstalk.

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