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Research on the Signal Transmission System of Medical Endoscopic Ultrasound

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ABSTRACT

Aiming at the problem that most of the traditional medical endoscopic ultrasound signal transmission systems adopt single-pulse excitation signals, resulting in a relatively small ultrasonic transmission power and affecting the imaging quality of the system, a medical endoscopic ultrasound signal transmission system based on coded excitation technology was studied. The advantages of the encoded excitation signal over the traditional pulse excitation signal were analyzed. Four common encoded signals and their characteristics were comprehensively evaluated, and it was determined to use the Barker code as the system encoded signal. The signal transmission system was constructed by using MD1210 and TC6320. The experimental results show that this signal transmission system can effectively output the encoded excitation signal and transmit it to the ultrasonic transducer.

KEYWORDS

Medical Endoscopic Ultrasound; Signal Transmission System; Coding Excitation Technology.

1. INTRODUCTION

Medical endoscopic ultrasound imaging technology is the product of the continuous development and integration of high-tech such as electronic endoscopy technology, ultrasonic sensing technology, micro-electromechanical technology, and modern computer technology. It is one of the important means of clinical detection and has a very broad application prospect. Its imaging process includes: probe preparation and insertion, ultrasonic signal generation and transmission, signal reception and conversion, signal processing and image generation, and image storage and analysis. The main function of the medical endoscopic ultrasound signal transmission system is to generate and transmit ultrasound signals, and it is an important component of the medical endoscopic ultrasound imaging system.

2. THE WORKING PRINCIPLE OF THE MEDICAL ENDOSCOPIC ULTRASOUND SIGNAL TRANSMISSION SYSTEM

The function of the medical ultrasonic signal transmission system is to generate high-frequency electrical pulses and transmit them to the ultrasonic transducer. These high-frequency electrical pulses are converted into ultrasonic waves through the inverse piezoelectric effect of the transducer and then propagate in human tissues. When ultrasonic waves propagate in tissues and encounter interfaces with different acoustic impedances, reflected waves are generated. These reflected waves are received by the transducer and converted into electrical signals through the positive piezoelectric effect. The

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received electrical signals are usually very weak and need to be amplified, filtered and other processed by the echo signal receiving system before subsequent digital imaging processing can be carried out.

In the field of medical endoscopic ultrasound imaging, the ultrasound energy emitted by the ultrasound probe cannot be amplified without limit; otherwise, it will cause significant damage to the patient's internal organs and tissues. For this reason, the State Administration of Technical Supervision has issued relevant safety standards to limit the peak acoustic power and average acoustic power of the ultrasound probe. Most traditional endoscopic ultrasound systems adopt single-pulse excitation signals, and their circuit schematic diagrams are shown in Figure 1. This kind of signal generally has a small duty cycle, a relatively low peak acoustic power, and is limited by the signal transmission area of the ultrasonic transducer, resulting in a small ultrasonic transmission power. Often, the peak acoustic power is close to the safety standard, but the average acoustic power is still far below the safety standard. If the average acoustic power is to be increased, the signal duty cycle can only be raised, which in turn will reduce the image resolution of the system and affect the imaging quality of the system [1,2].

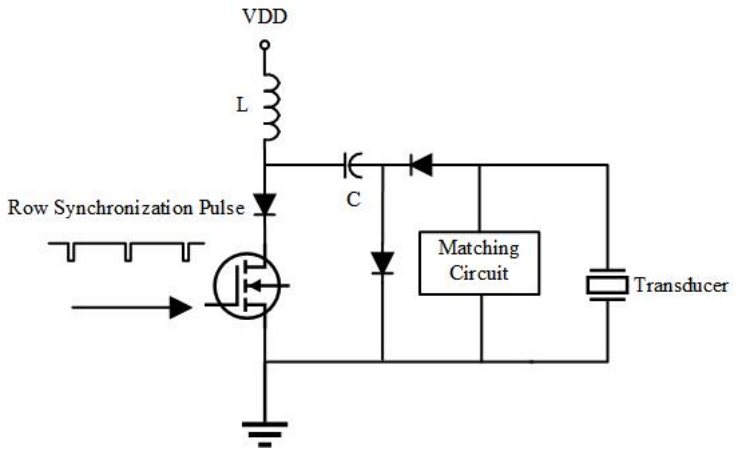
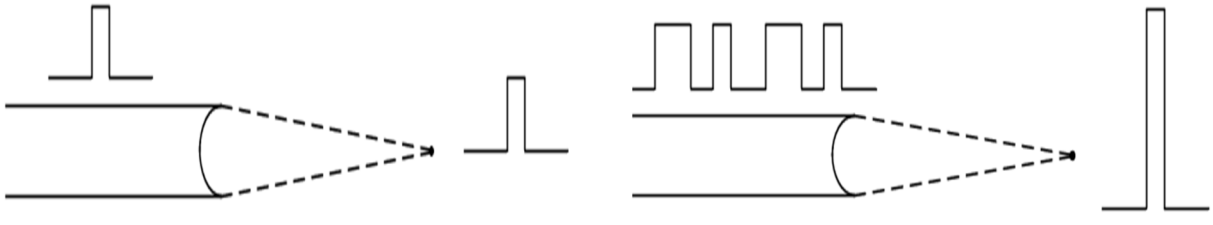


Figure 1. Schematic diagram of Traditional single-pulse Excitation Circuit

The coding excitation technology widely used in the field of radar detection can solve this problem very well [3]. The coding excitation technology is applied to the medical endoscopic ultrasound system, enabling the ultrasonic transducer to receive a set of continuous coded signal pulses generated by the signal transmission system. The duration of this set of signal pulses is much longer than that of the traditional single-pulse signal. While ensuring the peak acoustic power of the ultrasonic transducer, the effect of increasing the average acoustic power is achieved. Moreover, the echo signal received by the ultrasonic transducer, after signal processing, can obtain a pulse signal with the same pulse width as the traditional single pulse but a higher amplitude, as shown in Figure 2, which improves the signal-to-noise ratio of the system.



(a) Single-pulse excitation **(b)** Encoded signal pulse excitation

Figure 2. Comparison chart of traditional single-pulse excitation and encoded signal pulse excitation

3. CODING EXCITATION TECHNOLOGY

The coding excitation technology is actually based on the traditional pulse-echo technology. Its core lies in using coding technology to generate pulse signals at the transmitting end to excite the ultrasonic transducer. This technology generates a long string of encoded sequence signals by modulating the frequency or phase of the signal, replacing the traditional single-pulse excitation. Since the pulse duration of the long string excitation signal is much longer than the pulse response time of the sensor, it can significantly increase the carrying energy of the transmitted signal, thereby improving the average acoustic power of the signal. When these encoded excitation signals enter human tissues, the generated echo signals are also a long sequence of signals.

3.1. The Principle of Coding Excitation Technology

Figure 3 shows the schematic diagram of the ultrasonic coding excitation system. The system includes several links such as ultrasonic encoded excitation signal transmission, echo reception and signal processing.

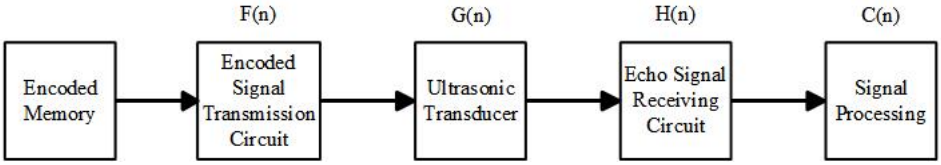


Figure 3. Schematic diagram of the ultrasonic coding excitation system

From the perspective of the digital signal field, the entire ultrasonic coding excitation system can be approximately equivalent to a linear system. Let the encoded excitation signal be F(n), the echo signal response be H(n), the transfer function be G(n), and the signal after signal processing be C(n), then we can obtain:

$$C(n) = F(n) * G(n) * H(n). \quad (1)$$

In the formula, "*" represents the convolution operator.

It can be obtained from the convolution commutation law that:

$$C(n) = F(n) * H(n) * G(n). \quad (2)$$

Ideally, Eq. 2 should satisfy:

$$C(n) = N\delta(n) * G(n). \quad (3)$$

$$N\delta(n) = F(n) * H(n). \quad (4)$$

In the formula, $\delta(n)$ represents the unit impact function.

From the above formula, it can be obtained that the echo signal of the ultrasonic coding excitation system, after signal analysis and processing, should be N times the input coded signal, where $N>1$. It is indicated that the use of encoded excitation technology can increase the amplitude of the echo signal while ensuring the peak acoustic power of the ultrasonic transducer, increase the average acoustic power of the ultrasonic transducer, and effectively solve the contradiction between the axial

resolution of the system and the transmission power of the ultrasonic transducer under the traditional single-pulse excitation.

3.2. Common Encoded Signals and Their Characteristics

According to the different encoding methods, encoded signals can be divided into frequency-domain encoded signals and phase-encoded signals. Among them, frequency-domain encoded signals include Chirp signals and pseudo-Chirp signals, and phase-encoded signals include Barker codes, Golay sequence pairs and M sequences [4].

3.2.1. Chirp Signal

The Chirp signal was proposed by R. H. Dicke and can be expressed as:

$$s(t) = \cos(2\pi(f_0 t + 0.5Kt^2)). \quad (5)$$

In the formula, f0 represents the resonant frequency of the ultrasonic transducer, and K is the frequency modulation index.

The frequency modulation width B of the Chirp signal can be calculated by Eq. 6:

$$B = KT. \quad (6)$$

In the formula, T represents the duration of the Chirp signal.

Due to its excellent autocorrelation property, the Chirp signal can increase the amplitude of the ultrasonic signal and suppress noise, thereby improving the depth and quality of the imaging. In high-frequency ultrasonic imaging, Chirp signals are often combined with matched filters to increase the penetration depth of ultrasonic signals and improve the axial resolution and signal-to-noise ratio of the system. Furthermore, the Chirp signal can reduce the sampling data required for reconstructing high-quality ultrasound images, lowering the data acquisition time and hardware requirements. However, due to the spectral overlap among harmonic components, the Chirp signal excitation is always affected by the distance side lobes, and an additional set of suitable analog signal transmission circuits needs to be designed, which increases the difficulty of system design. If the side lobes are suppressed, mismatch filtering can be performed on the ultrasonic signal. However, this will also widen the main lobe, reduce the system resolution and lose the signal-to-noise ratio.

3.2.2. Pseudo-chirp Signal

The pseudo-chirp signal can be expressed as:

$$s(t) = \text{sign}(\cos(2\pi(f_0 t + 0.5Kt^2))). \quad (7)$$

In the formula, sign is a symbolic function.

The application of pseudo-chirp signals in ultrasonic systems can optimize the axial resolution and the signal-to-noise ratio of the system. However, it is still disturbed by distance side lobes, which affects the ultrasonic imaging results to a certain extent.

3.2.3. Barker Code

Barker code is a non-periodic binary coding sequence discovered by R. Baker in 1953, and the value of each code element of it is only +1 or -1. Barker's aperiodic autocorrelation function is shown as Eq. 8:

$$\chi(m,\ 0)\ =\ \sum_k C_k C_{k\ +\ m}. \tag{8}$$

The value range of k is from 0 to P -1 - |m|. When m = 0, χ = P; when m≠0, χ = -1, 0 or 1.

It can be seen from Eq. 8 that the main and side lobe ratio of the Barker autocorrelation coefficient is equal to the code length P, and the values of the side lobes are only +1, 0 and -1. This low side lobe characteristic enables the application of Barker codes in ultrasonic systems to effectively reduce the influence of distance side lobes on the system, and it is one of the more ideal coding methods.

Up to now, scholars at home and abroad have only discovered a limited number of Barker code sequences [5-9]. For Barker codes of odd lengths, it has been proved that the code length P does not exceed 13. For Barker codes of even lengths, the code length P is a perfect square number. However, further research has confirmed that within the range of 4 to 6084, there are no even-length Barker codes that meet the conditions. For Barker codes with a code length exceeding 6084, they are usually not adopted due to limitations in practical applications. Table 1 details the Barker code sequences with a length of no more than 13 bits.

Table 1. Barker Code Sequence

The sequence length of Barker codes	Barker code sequence
2	+1 +1 or -1 +1
3	+1 +1 -1
4	+1 +1 -1 +1 or +1 +1 +1 -1
5	+1 +1 +1 -1 +1
7	+1 +1 +1 -1 -1 +1 -1
11	+1 +1 +1 -1 -1 +1 -1 -1 -1 +1 -1
13	+1 +1 +1 +1 +1 -1 -1 +1 +1 -1 +1 -1 +1

3.2.4. Golay Complementary Sequence

The definition of a Golay complementary sequence is a pair of finite complementary sequences of equal length and composed of two elements. Complementary sequences are an effective means to reduce the interference of side lobes of aperiodic sequences. Under the conditions of zero Doppler frequency or known Doppler frequency information, the complete elimination of distance side lobes can be achieved by using Golay complementary sequences. The characteristic of the Golay complementary sequence is that for any sequence in the sequence pair, under any partition, the logarithm of the same element in this sequence is equal to the logarithm of the different elements in the other sequence. The aperiodic autocorrelation function of the Golay complementary sequence is :

$$\chi_a(m,\ 0)\ =\ \sum_k a_k a_{k\ +\ m}. \tag{9}$$

$$\chi_b(m,\ 0)\ =\ \sum_k b_k b_{k\ +\ m}. \tag{10}$$

It can be seen from Eq. 9 and Eq. 10 that the value of the side lobes of the Golay complementary sequence is only 0, and it has the most ideal aperiodic autocorrelation characteristic. However, since the Golay complementary sequence requires two mutually independent signal channels to transmit encoded signals, it increases the complexity of the signal transmission system and also limits the speed of the signal transmission system. Furthermore, when using Golay complementary sequences, it is also necessary to ensure that the sequence length P is the sum of the squares of two non-negative

integers and must be an even number. This greatly limits the application of Golay complementary sequences in ultrasound systems. Common Golay complementary sequences are shown in Table 2.

Table 2. Common Golay Complementary Sequences

The sequence length of the Golay code	Golay code sequence
2	+1 +1 +1 -1
4	+1 +1 +1 -1 +1 +1 -1 +1
8	+1 +1 +1 +1 +1 -1 -1 +1 +1 +1 -1 -1 +1 -1 +1 -1
10	+1 +1 -1 +1 +1 +1 +1 +1 -1 -1

In conclusion, Chirp codes and pseudo-Chirp codes can optimize the axial resolution of the system, but larger distance side flaps will affect the quality of ultrasonic imaging. Golay complementary sequences have relatively ideal aperioperiodic autocorrelation, but the dual-signal channel transmission will reduce the system speed. Therefore, in this paper, Barker codes are selected as the encoded signal. The sequence length is 4, and the length of the unit code element is equal to the reciprocal of the center frequency of the ultrasonic transducer. Figure 4 shows the code type of the encoded excitation signal selected in this paper, and f0 is the center frequency of the ultrasonic transducer.

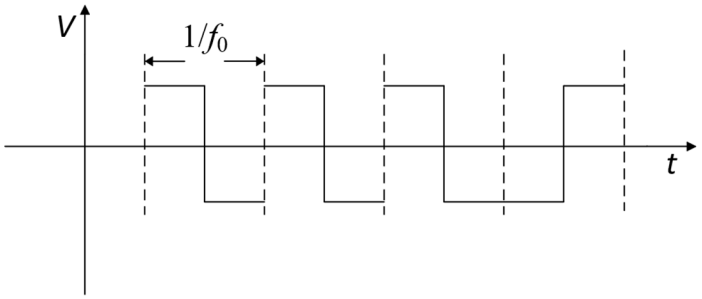


Figure 4. Encode the code pattern of the excitation signal

3.3. Research and Design of Encoded Excitation Signal Transmission Circuit

In the electrical system of medical endoscopic ultrasound, after the encoded excitation signal is determined, a dedicated encoded excitation signal transmission circuit needs to be designed for the encoded signal. This circuit not only needs to be able to generate the encoded excitation signal of the excitation transducer, but also needs to complete the electrical matching of the ultrasound transducer to improve the transmission efficiency of the transducer.

It can be known from Figure 2-3 that the encoded excitation signal transmission circuit needs to achieve the following functions:

(1) It can output positive and negative pulse signals;

(2) The output signal frequency is the center frequency of the ultrasonic transducer or an integer multiple of the center frequency.

According to the above requirements, this paper designs a coded excitation signal transmission system, and its schematic diagram is shown in Figure 5.

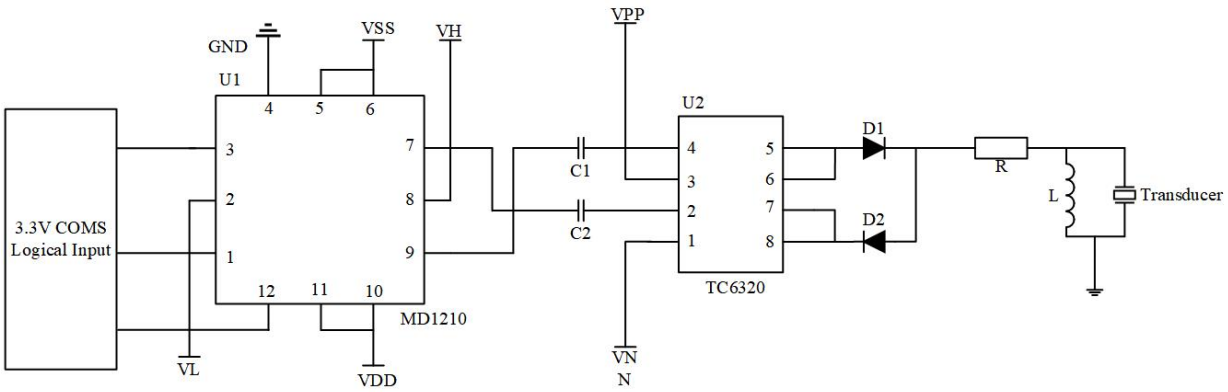


Figure 5. Circuit schematic diagram of the encoded excitation signal transmission system

This system is mainly composed of the encoded signal transmission circuit, the excitation pulse generation circuit and the matching circuit. The MD1210 and ultrasonic signal transmission chip TC6320 produced by Supertech Corporation of the United States are selected as the main part of the encoding excitation signal transmission circuit. Utilize the programmability of STM32 to generate the encoded signal to be transmitted and drive MD1210; MD1210 converts the amplitude of the encoded signal output by STM32 from 3.3V to 5V through the internal conversion circuit to drive TC6320. The N-channel and P-channel MOSFETs inside the TC6320 conduct successively according to the encoded signal to generate high-voltage encoded excitation pulses. The non-contact electromagnetic coupler receives and transmits high-voltage coded excitation pulses to excite the transducer.

3.3.1. Design of Excitation Pulse Generation Module

Supertech Corporation of the United States is a semiconductor manufacturer specializing in high-voltage analog and mixed-signal products. Its products and technologies are mainly applied in the medical, LED lighting, display, industrial and telecommunications industries. In the field of ultrasound medicine, the American company Superscience also has a series of innovative researches, such as the MD1715 and TC8020 chipsets specifically designed for high-definition medical ultrasound image applications, the integrated high-voltage and high-speed ultrasound pulse generator HV732, and the high-speed source driver MD2133, etc. The excitation pulse generation circuit designed in this paper is mainly composed of MD1210 and TC6320.

(1) MD1210

The MD1210 is a high-speed dual-channel MOSFET driver produced by Supertech Inc. of the United States. It is specifically designed to drive high-voltage P and N-channel MOSFET transistors and is widely used in medical ultrasound imaging, piezoelectric sensor driving, non-destructive testing, and high-speed level conversion, among other fields. The MD1210 features high-speed input and output phases. Its input logic interface voltage range is 1.2V to 5.0V, and the optimal operating input signal range is 1.8V to 3.3V. This driver adopts an adaptive threshold circuit to set the level converter switching threshold and can provide a peak output current of up to 2.0A, depending on the power supply voltage and load capacitance used. The MD1210 also features a low-jitter design, dual matching channels, output that can be lower than ground potential, low inductance packaging, and thermally enhanced packaging, making it an ideal choice for applications that require high performance and high reliability. In the excitation pulse generation circuit designed in this paper, as the driver chip of TC6320, the A and B dual matching channels inside it correspond to the N and P channel MOSFETs inside TC6320. The output current with a peak value of up to 2A provided by the MD1210 can effectively drive the TC6320 and achieve rapid level conversion.

(2) TC6320

TC6320 is an ultrasonic signal transmission chip. It integrates N and P-channel enhanced MOSFET pairs internally, both of which are integrated in 8-pin SOIC and DFN packages. The N and P-channel MOSFET are electrically isolated and relatively independent. The two MOSFETs of TC6320 also integrate gate-source Zener diodes and gate-source resistors, effectively reducing the impact of input terminal anomalies on the chip. By leveraging an advanced vertical DMOS structure and a proven silicon gate manufacturing process, it combines the power handling capability of bipolar transistors with the inherent high input impedance and positive temperature coefficient of MOS devices. A breakdown voltage of 200V and an output peak current of 2A can effectively excite the transducer and reduce the rise and fall time of the high-voltage output. Low on-resistance and low input capacitance help reduce power loss and increase switching speed. In addition, features such as high breakdown voltage, high input impedance, low input capacitance and fast switching speed make the TC6320 widely used in the field of medical ultrasound imaging.

When different power supply schemes are adopted for TC6320, the working conditions of its internal field-effect transistors will also change, and the output signals will also be different. When the TC6320 is powered by a positive power supply, only the P-channel enhanced field-effect transistor operates, and the output signal is a positive pulse. When the TC6320 is powered by a negative power supply, only the N-channel enhanced field-effect transistor operates, and the output signal is a negative pulse. When the TC6320 is powered by positive and negative power supplies, both the N and P channel enhancement field-effect transistors inside it operate, and the output signals are positive and negative pulses. According to the requirements of the excitation pulse generation circuit designed in this paper, the TC6320 adopts a positive and negative power supply scheme, and its working principle is shown in Figure 6

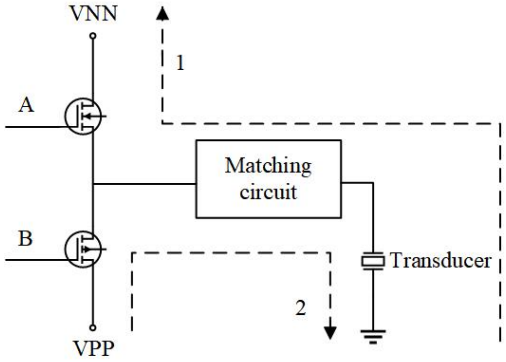


Figure 6. Working principle diagram of TC6320

As shown in Figure 2-5, the TC6320 receives the encoded excitation signal sent by the MD1210 through the A and B channels. The N and P channel MOSFETs inside it conduct in sequence and generate pulse excitation signals to drive the transducer. When the N-channel MOS transistor is on, the internal path of TC6320 includes VNN, matching circuit, ultrasonic transducer and ground. TC6320 emits a negative excitation pulse to the ultrasonic transducer. The amplitude of the negative pulse is equal to the voltage amplitude of VNN, and the duration of the negative pulse is the conduction duration of the N-channel MOS transistor. The path is shown as Path No. 1 in Figure 2-5. When the P-channel MOS transistor is on, the internal path of TC6320 includes VPP, matching circuit, ultrasonic transducer and ground. TC6320 emits a positive excitation pulse to the ultrasonic transducer. The amplitude of the positive pulse is equal to the amplitude of the VPP voltage, and the duration of the positive pulse is the conduction duration of the P-channel MOS transistor. The path is shown as Path 2 in Figure 2-5.

3.3.2. Design of Ultrasonic Transducer Matching Module

Due to the mechanical structure characteristics of the ultrasonic transducer, when it operates near the resonant frequency, its equivalent circuit is capacitive as a whole. In the actual electrical system of medical endoscopic ultrasound, the ultrasonic transducer is connected in parallel to the system as a

whole. If the circuit is not matched, reactive power will be generated when the system is working, affecting the transmission efficiency of the system. The common matching circuit is RL matching, and its circuit schematic diagram is shown in Figure 7.

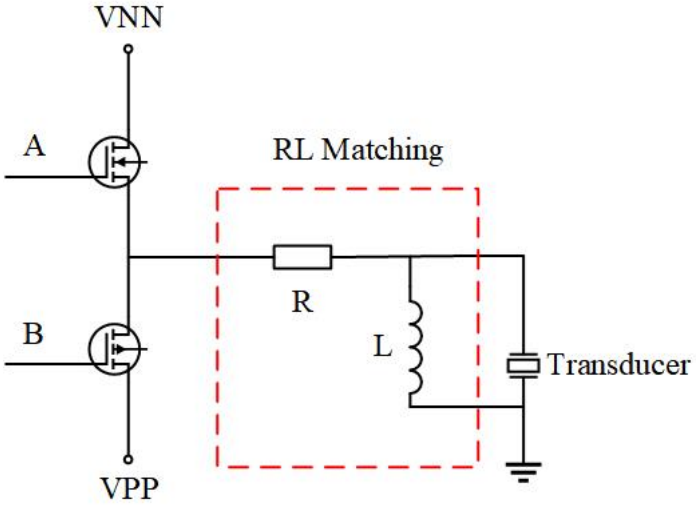


Figure 7. Schematic diagram of RL Matching Circuit

According to Figure 6, it is known from the theory of alternating current that in order for the transducer to achieve the maximum output efficiency, the circuit needs to meet the following conditions:

(1) The impedance of the circuit signal source is equal to that of the load.

(2) The frequency of the circuit signal is equal to the resonant frequency of the transducer.

(3) The overall impedance of the circuit is purely resistive.

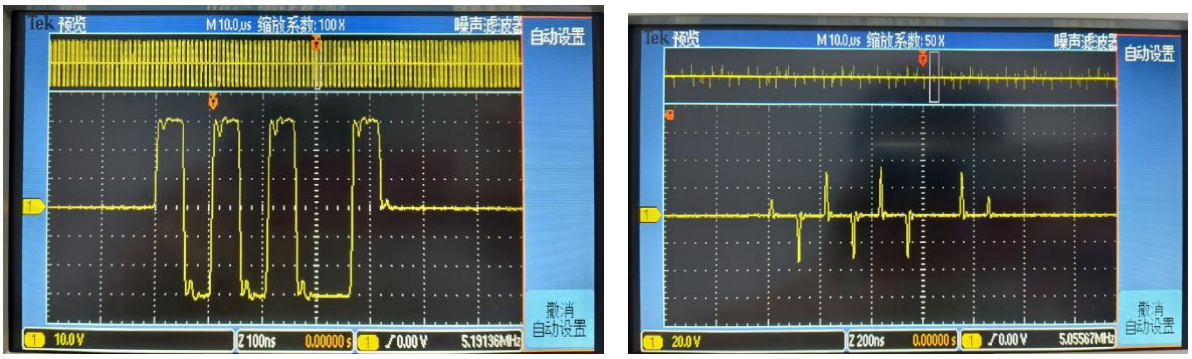
In the general electrical system of medical endoscopic ultrasound, due to the size limitations of the ultrasound probe, the electrical impedance of the ultrasound transducer is very small, usually ranging from 10 to 20Ω. The on-resistance of the N and P channel high-speed field-effect transistor pairs inside the TC6320 is 8-10Ω. The internal resistance of the TC6320 signal source VPP and VNN is relatively large, approximately 50Ω. Obviously, the circuit does not meet the first condition. Therefore, a resistor R needs to be connected in series between the excitation pulse generation circuit and the ultrasonic transducer to achieve impedance matching between the excitation pulse generation circuit and the ultrasonic transducer. The signal source impedance RS, the load impedance resistance RL and the resistance R satisfy the following relationship:

$$R_s = R_L + R. \tag{11}$$

4. EXPERIMENT OF ULTRASONIC ENCODED EXCITATION SIGNAL

In summary, the encoded excitation signal transmission circuit is composed of STM32, MD1210 and TC6320. The encoded excitation signal selects a 4-bit Barker code, which is generated by STM32 to drive MD1210 and TC6320 to generate excitation pulse signals. Figure 8 shows the experimental result of the ultrasonic encoded excitation signal, and Figure 7(a) shows the output signal waveform of TC6320. Combined with Figure4, it can be known that the first three pairs of positive and negative pulse signals constitute the "+1" symbol of the encoded excitation signal, and the fourth pair of negative and positive pulse signals constitute the "-1" symbol of the encoded excitation signal. The output results are consistent with those in Figure 3. The generated excitation pulse signals are transmitted to the ultrasonic transducer through a non-contact electromagnetic coupler. Eight

excitation pulses are generated successively at the signal transition edge, as shown in Figure 8(b). The first six excitation pulses correspond to the first three "+1" code elements of the encoded excitation signal, and the last two excitation pulses correspond to the "-1" code element of the encoded excitation signal. The maximum amplitude of the pulse signal output by TC6320 is 30V and the minimum is -30V. The maximum amplitude of the excitation pulse signal generated after the pulse signal passes through the non-contact electromagnetic coupler is +30V and the minimum is -30V. The ultrasonic transducer accepts these excitation pulses, realizes the electro-acoustic signal conversion, and emits the ultrasonic signal outward.



(a) The output signal waveform of TC6320 **(b)** The output signal waveform of the encoded signal transmission circuit

Figure 8. Experimental result diagram of ultrasonic coding excitation signal

5. SUMMARY

This chapter elaborates in detail the hardware design of the ultrasonic signal transmission system. Firstly, aiming at the problem of low signal transmission power in the traditional ultrasonic signal transmission system, the advantages of the coding excitation technology are expounded, and it is proposed to apply the coding excitation technology to the ultrasonic signal transmission system. By comparing and analyzing several common encoded signals, the 4-bit Barker code was selected as the encoded signal of the ultrasonic encoded signal transmission circuit. According to the selected 4-bit Barker code, the hardware of the ultrasonic coding signal transmission circuit was analyzed and selected, and the ultrasonic coding signal transmission circuit composed of STM32, MD1210 and TC6320 was designed. Finally, through the experiment of ultrasonic encoded excitation signals and by observing the output signal waveforms of the encoded signal transmission circuit through an oscilloscope, the feasibility of the design of the ultrasonic signal transmission system was verified.

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