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Experimental Study of Baker Coded Ultrasonic Signal for Coarse-Grained Material Testing

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Abstract: Ultrasonic testing of coarse-grained materials is affected by scattering noise. We propose a hardware-friendly Barker modulation (0/1 amplitude) that conserves resources. Experiments on the specimens ($1.0\,\mathrm{mm}$ grain size) show that, despite the probe frequency being $500\,\mathrm{kHz}$, the bottom echo signal-to-noise ratio (SNR) reaches its peak at $350\,\mathrm{kHz}$, yielding a $2.53\,\mathrm{dB}$ SNR gain compared to traditional pulse-echo methods; the impact of surface reflections on the filtered signal is negligible. Future work will focus on Golay codes to detect flaws.

Keywords: coarse-grained materials, Barker code, code excitation, ultrasonic testing, phase coding

Introduction

In the industrial field, coarse-grained materials, characterized by large grain size and low grain boundary density, can effectively suppress grain boundary slip and creep failure, making them core materials for high-temperature service components. They are widely used in aerospace, nuclear power, and other fields, such as aero-turbine blades and nuclear reactor pressure vessels. However, their aggravated stress concentration easily initiates microcracks, leading to local damage. Therefore, accurate flaw detection in these materials is of vital importance.

However, severe structural scattering noise and anisotropy seriously reduce the signal-to-noise ratio (SNR) of conventional ultrasonic testing and limit the effective penetration depth. Phase-coding excitation[1] technology provides a promising solution by encoding broadband frequency information into a deterministic signal sequence[2], which can be decoded using a matched filter to suppress random scattering noise[3]. This study employs Barker code encoding excitation with hardware-friendly 0/1 amplitude modulation to simplify excitation circuitry, combined with matched filter compression technology, to improve the SNR.

Existing research shows that phase coding technology can enhance the SNR of ultrasonic testing through pulse compression[4], but most studies focus on non-coarse-grained materials[5]. There remains a gap in coding schemes for coarse-grained materials under the pitch-catch mode. Therefore, this study investigates a rectangular sample ($130 \times 180 \times 330mm$) made of ZG20CrMoV cast steel (with an average grain size of $1.0\,\mathrm{mm}$), prepared by machining. Probes are used and a long Barker code sequence composed of 13-bit codes and 13×5 pulses, with modulation of 0/1 amplitude, is applied to the transmitting probe. Combined with a modulation-matched filter based on probe response, the study investigates the improvement effect on bottom echo SNR, demonstrating significant SNR gain.

Methodology

Barker code, a binary code group with specific regularity, was proposed by R.H. Barker in the early 1950s. It is an aperiodic sequence: a j-bit Barker code $\{X_1, X_2, X_3, \ldots, X_j\}$ consists of elements each taking values of $+1$ or -1, and its autocorrelation function is defined as follows:

$$R(j) = \sum_{i=1}^{N-j} X_i X_{i+j} \tag{1}$$

For $j \neq 1, |R(j)| \leq 1$, confirming that Barker code is the optimal finite binary sequence. Among known Barker codes, the longest one contains 13 bits. The mainlobe-to-sidelobe ratio of its autocorrelation function equals the compression ratio, i.e., the code length j.

To reduce hardware implementation complexity, this study performs a unipolar modification on the traditional bipolar Barker code sequence, adjusting its amplitude range from $[-1, 1]$ to $[0, 1]$. Specifically, a binary amplitude modulation strategy is adopted: zero level (0) represents the -1 polarity in the original sequence, while unit level (1) denotes the $+1$ polarity, with phase modulation of unipolar coding achieved by time-domain flipping operation of the signal. This improvement strategy avoids the need for positive/negative voltage drive circuits in traditional bipolar excitation, significantly simplifying power amplifier design and enhancing system engineering applicability.

The waveform of the modified 13-bit Barker code sequence is shown in Figure 1, where the coding rule maps "$+1$" in the original sequence to high level (1) and "-1" to low level (0), forming a unipolar pulse sequence.

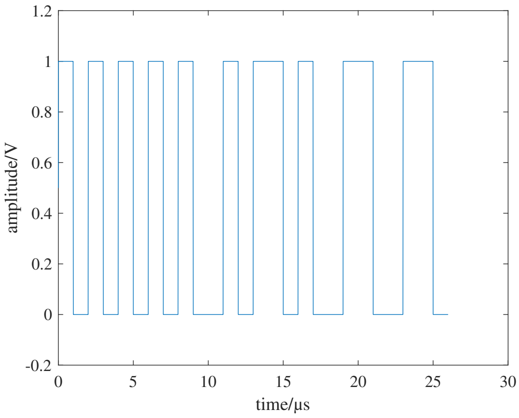

Fig. 1: Modified Barker code sequence waveform

Barker-coded excitation technology achieves pulse compression of detection signals by applying a phase-modulated sequence (e.g., 13-bit binary sequence) at the transmitter and using a matched filter at the receiver. The signal processing flow of the matched filter is shown in Figure 2, whose design principle is derived from the criterion of maximizing the output signal-to-noise ratio (SNR). According to signal detection theory, the output SNR reaches the theoretical maximum when the system satisfies the following conditions:

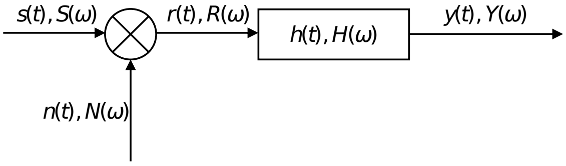

Fig. 2: The model of signal process

SNR optimization model: The system output SNR is given as follows, where E denotes the echo signal energy and n_0 represents the noise power per unit bandwidth.

$$SNR \le \frac{\int_{-\infty}^{+\infty} \left| s\left(\omega\right) \right|^2 e^{j\omega t_0{}^2} d\omega}{2\pi \frac{n_0}{2}} \le \frac{2E}{2} \tag{2}$$

Frequency-domain matching condition: When the frequency response function $H\left(\omega\right)$ of a linear system satisfies the complex conjugate relationship with the input signal $s\left(t\right)$, as shown as follows, the system output SNR attains the maximum value. This linear system is defined as a matched filter.

$$H\left(\omega\right) = kS^{*}\left(\omega\right) e^{j\omega t_0} \tag{3}$$

Time-domain response characteristic: The complex conjugate property of the frequency response function corresponds to the time-reversal operation of the signal in the time domain. Given an input signal $s\left(t\right)$, the impulse response of the matched filter can be expressed as follows:

$$h\left(t\right) = s\left(T - t\right) \tag{4}$$

where T is the duration of the signal.

This characteristic enables the matched filter to achieve pulse compression through correlation operations, effectively suppressing scattering noise. The signal after the matched filter is shown in Figure 3.It demonstrates that although the signal amplitude range is halved, the unipolar Barker code still achieves pulse compression after matched filter processing, verifying the effectiveness of this improvement method in reducing hardware resource requirements while maintaining signal processing performance.

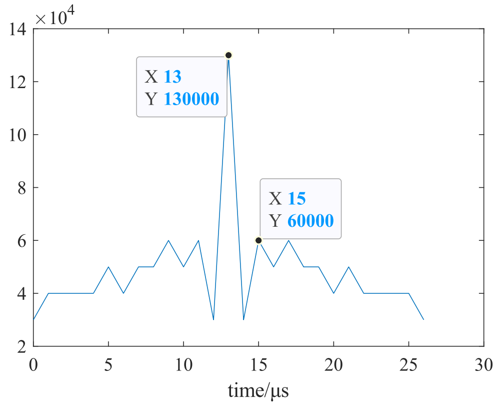

Fig. 3: Modified Barker code matched filtering results

Results

A self-developed 32-channel ultrasound detection system, which integrates signal generation, power amplification and data acquisition, was used for the experiment. The system is connected to two 500 kHz center frequency broadband ultrasound probes ($1inch$ in diameter), which are arranged unilaterally to form a transmitter and a receiver detection mode. The host computer sends control commands to generate a 13-bit unipolar Barker code sequence (0/1 magnitude) to drive the transmitting probes to generate ultrasound signals; the acoustic signals acquired by the receiving probes are amplified by the system for quantization; the acquired data are transmitted to the host computer for offline signal processing, including matched filtering and compression, and signal-to-noise ratio calculation. The experimental conditions are shown in Table 1. The object of this experiment is a coarse crystalline material with the dimensions shown in Figure 4, and the speed of sound in the three directions is about $6000m/s$. This experiment is carried out in the direction of the depth of $130mm$.

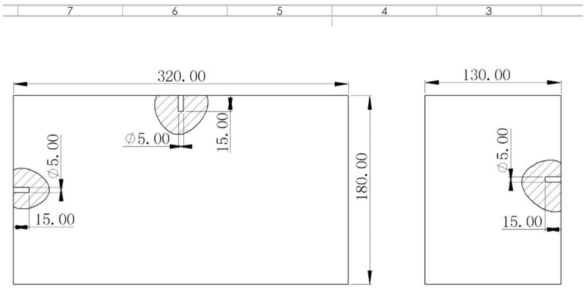

Fig. 4: Dimensional diagram of coarse crystalline material

The host computer sends control commands to generate a 13-bit unipolar Barker code sequence (0/1 magnitude) to drive the transmitting probes to generate ultrasound signals; the acoustic signals acquired by the receiving probes are amplified by the system for quantization; the acquired data are transmitted to the host computer for offline signal processing, including matched filtering and compression, and signal-to-noise ratio calculation. The experimental conditions are shown in Table 1. The object of this experiment is a coarse crystalline material with the dimensions shown in Fig. 6, and the speed of sound in the three directions is about $6000m/s$. This experiment is carried out in the direction of the depth of $130mm$.

Tab. 1: Experimental conditions

condition	Pulse	Barker coded
frequence/kHz	300–500	300–500
Number of pulses	5	13×5=65
excitation voltage/V	200	50
system gain/dB	10	18

Frequency response characteristics: The excitation frequencies are set to $300kHz$, $350kHz$, $400kHz$, $450kHz$ and $500kHz$, and the 65-bit Barker code (13×5 pulse sequence) is used for the excitation.It was found that: When the excitation frequency is $350kHz$, the peak signal-to-noise ratio (SNR) of the bottom echo (13.97dB) is significantly higher than that at $300kHz$ (8.9dB), $400kHz$ (10.57dB), $450kHz$ (6.28 dB), and $500kHz$ (5.90 dB).This phenomenon is attributed to the serious high-frequency attenuation of the ultrasonic signal in the propagation of coarse-crystalline materials, while the frequency of $350kHz$ is the best match for the acoustic scattering of coarse-crystalline materials, which effectively suppresses the incoherent scattering noise at the grain boundaries. The results are shown in Figure.5.

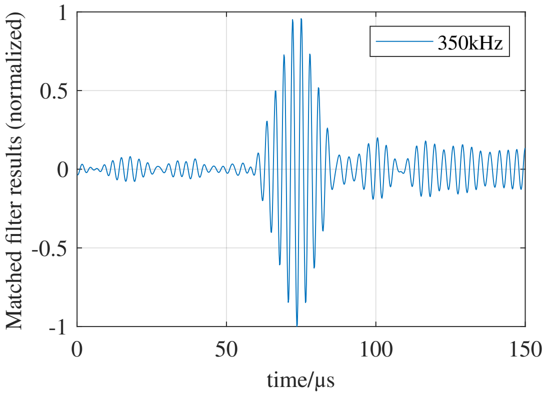

Fig. 5: Bottom surface echo signal at an excitation frequency of 350 kHz

Coding excitation gain comparison: Compared with the traditional single-pulse excitation mode, Barker code at different frequencies achieved SNR improvements, with specific gain values of 1.06dB($300kHz$), 2.53dB($350kHz$), 0.67dB(400kHz), 0.02dB($450kHz$), and -0.99dB($500kHz$), as detailed in Table 2.

Among them, the most prominent signal-to-noise gain is found in the 350kHz band, which is 2.53dB higher than that of the traditional pulse excitation mode, indicating that the Barker code excitation at this frequency matches well with the acoustic properties of the materials to be measured, which effectively suppresses the background noise interference and strengthens the echo signal strength. On the contrary, in the high-frequency bands of $450kHz$ and $500kHz$, the SNR of the signals are relatively low regardless of the impulse method or the Buck Code excitation, which is mainly attributed to the significant enhancement of the influence of the high-frequency acoustic wave by the scattering at the grain boundary, resulting in the decrease in the amplitude of the echo signal and the increase in the relative proportion of noise.In addition, the SNR of the Barker code is lower than that of the pulse method at $500kHz$ frequency, and the reason considered is that it is affected by the intrinsic characteristics of the Barker code, and the sidelobe structure results in the exacerbation of the aliasing effect of the sidelobe energy with the active signal.

Tab. 2: Comparison of signal-to-noise ratio (SNR) gain between Barker code excitation and traditional single-pulse excitation

Frequency	Pulse	Barker coded
300kHz	7.84	8.9
350kHz	11.44	13.97
400kHz	9.73	10.40
450kHz	6.26	5.90
500kHz	6.89	6.28

Multiple reflection robustness: As shown in Figure 5 ($350\,\mathrm{kHz}$ excitation, Barker code length $185\,\mu\mathrm{s}$), the surface-bottom multiple reflection signals excited by the long code (one echo time of about $45\,\mu\mathrm{s}$) have a significantly reduced impact on the main target echo after matched filtering. The matched filtered output is characterized by a sharp main peak and low side flaps. The analysis shows that: The SNR on the left side of the main peak is about 21dB, which is mainly limited by the intrinsic sidelobe and noise (the theoretical value is 22.3dB). The SNR on the right side of the main peak decreases to about 13.9dB, which is affected by the superposition of the intrinsic flap, noise, attenuation, and residual energy from multiple reflections. Crucially, the multiple reflection energy does not form an interference peak at the main peak location, but is effectively dispersed and suppressed in the sidelobe region by the excellent autocorrelation properties of the Barker code. This proves that the algorithm effectively suppresses the overlapping periodic reflection interference and ensures the reliability of the main target echo detection.

Conclusion

This study systematically investigated the optimization strategy and robustness of the hardware-friendly 0/1 amplitude Barker code modulation excitation technique for noise suppression and signal enhancement in ultrasonic testing of coarse-grained materials. The main conclusions are as follows:

(1) A specific mid-frequency band is identified as the optimal detection band for coarse-grained materials. Experiments show that the bottom echo SNR is significantly enhanced and outperforms other bands under excitation in this band. This band effectively balances high-frequency attenuation and grain boundary scattering noise.

(2) The Barker code excitation with 0/1 amplitude modulation yields significant gains in the dominant band. Compared with traditional pulse excitation, a significant SNR gain (up to 2.53dB) can be achieved, demonstrating the effectiveness of this coded excitation in enhancing target echoes through signal energy accumulation. However, when the frequency increases, the SNR of both excitation modes is low, and the performance of the Barker code may even be lower to the pulse method because of sidelobe aliasing effects.

(3) The algorithm exhibits strong robustness against multiple reflection interference. The matched-filtered output of the long code shows a sharp main peak (left) with a peak sidelobe ratio of 21 dB. Although the SNR on the right side of the main peak is reduced to 13.9 dB due to the superposition of attenuation and residual multiple reflections, the energy from multiple reflections is successfully dispersed and suppressed within the sidelobe regions without interfering with the main peak position. This confirms the algorithm's effectiveness in suppressing overlapping periodic interference.

In summary, the matched filtering scheme based on the hardware-friendly 0/1 amplitude Barker code excitation, achieves dual enhancement of SNR improvement and interference suppression in the detection of coarse-grained materials, releasing hardware resources. It provides an effective technological pathway for reliable extraction of weak echo signals under strong noise backgrounds. Future work will focus on employing complementary sequence (Golay code) techniques to suppress matched filter sidelobes, thereby further enhancing the detection sensitivity for small defects.

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