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M-sequence Pulse Compression technique for Improvement of Ultrasonic Thickness Measurement in Non-Destructive Testing

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Abstract: Non-destructive testing (NDT) using an ultrasonic transducer is a wide technique for measuring thickness of materials, including inspecting for material corrosion. The pulse-echo method is an acoustic pulse transmission to determine the time of flight (TOF), which is commonly used for distance measurement. The pulse propagation distance can be determined using the relationship between TOF and the speed of sound in the material. However, a conventional pulse-echo technique can detect background noise, which affects measurement accuracy. The M-sequence pulse compression technique generates by a pseudorandom sequence using a linear feedback shift register (LFSR), which enhances the cross-correlation properties of transmitted signals. Moreover, the M-sequence signal can be applied to improve the signal-to-noise ratio (SNR) and to reduce background noise. The M-sequence pulse compression technique achieves the best signal and ensures a stable measurement of the reflected signal. In this study, the different *n*-th order of the M-sequence signals on TOF deviation and material thickness determination, which is a near-field area of the transducers is proposed. The results of the M-sequence pulse compression technique are shown.

Keywords: Non-destructive Testing, Thickness Measurement, Ultrasonic Measurement, M-sequence

1. INTRODUCTION

Ultrasonic non-destructive testing (NDT) is a widely utilized technique for measuring the thickness of materials and detecting corrosion. This method employs high-frequency sound waves, typically in the range of 1 to 10 MHz, which are transmitted into the material under inspection. The interaction of these waves with material, such as reflection, refraction, and attenuation, provides valuable information about its internal structure. Among various ultrasonic techniques, the pulse-echo method is commonly used, wherein an acoustic pulse is transmitted and the time of flight (TOF) of the reflected signal is measured. The propagation distance of the pulse is then calculated based on the TOF and the known speed of sound in the material [1-6]. TOF refers to the delay between the transmission of an ultrasonic signal and the reception of its echo reflected from the target. However, accurately identifying the acoustic signal is often challenging due to the presence of reverberations and the low signal-to-noise ratio (SNR) in conventional methods. In addition, environmental noise and signal scattering on the target surface can further degrade measurement accuracy. To improve the TOF signal, pulse compression techniques have been introduced to enhance both SNR and distance resolution. Frequency sweep modulated burst signals or coded pulse sequences are used as the transmitted signals. The received signal is then correlated with a reference signal, which is typically one cycle of the transmitted waveform. When the signals match, a distinct and sharp peak appears in the cross-correlation function, enabling precise signal detection. Moreover, this process inherently suppresses background and environmental noise [7-12]. One effective pulse compression technique is based on the M-sequence signals, which are pseudorandom sequences generated by a linear feedback shift register (LFSR). These sequences exhibit excellent cross-correlation properties, significantly improving SNR and reducing noise. Consequently, the M-sequence pulse compression technique enables more reliable signal detection and ensures consistent, high-accuracy measurements [13-22]. Moreover, in this experiment, M-sequence signals were transmitted to measure material thickness ranges from 0.2 to 0.4 inches (5.08 to 10.16 mm). These distances lie within the near-field zone of the ultrasonic transducer [23].

This research proposes the use of M-sequence signals of different *n*-th orders to evaluate their impact on TOF deviation and material thickness determination. The results of the M-sequence pulse compression technique for measuring material thickness, which is a near-field area, are presented.

2. THEORY

2.1 M-sequence modulation

The M-sequence is generated using LFSR with n parts and XOR gate, which produces a periodic pseudorandom binary sequence consisting of 0 and 1. The length of the LFSR, denoted as n, defines the order of the M-sequence. For an n-th order M-sequence, the total number of binary elements in one full cycle is $L=2^n-1$. Each complete cycle of the M-sequence contains exactly L bits. Variations in the M-sequence arise from different initial seed values and feedback tap positions in the LFSR. The example of generating 3rd-order M-sequence and cross-correlation function of 3rd-order M-sequence pulse compression is indicated in Figure 1.

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† Taro Keisoku is the presenter of this paper.

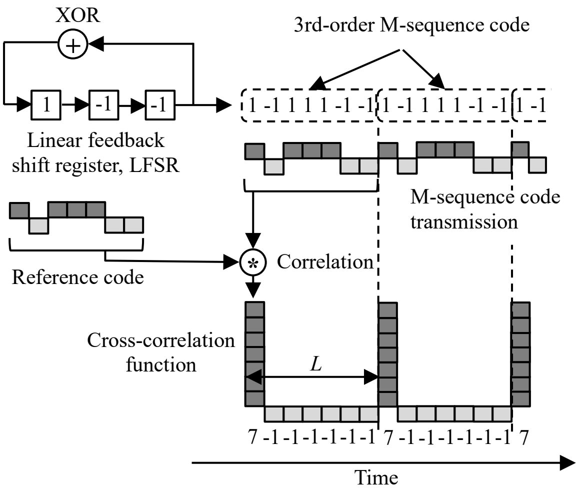

Fig.1 Cross-correlation function obtained by the 3rd-order M-sequence pulse compression

The cross-correlation function of M-sequence is given by Eq. (1).

$$R_m[s] = \frac{1}{L}\sum_{L}^{k=1} m_k m_*^{k+s}, \tag{1}$$

Where m_k is the M-sequence code, b_k and b_{k+s} is ±1, which depends on the M-sequence characters. In the cross-correlation between a continuous M-sequence and a single-cycle reference, the amplitude of the main peak reaches L, while the off-peak values remain constant at -1. When white Gaussian noise is present in the received signal, the peak amplitude of the correlated output increases by a factor of square root L, thereby improving the SNR by the same factor. This SNR enhancement is attributed to the coherent addition of the signal components during the cross-correlation process. The pulse repetition interval of the transmitted signal is governed by the cycle length of the M-sequence, specifically the product of L and the time duration assigned to each binary character. For modulation, the M-sequence binary codes are mapped to the values '1' and '–1', which are then used to modulate a carrier sine wave. The binary '1' and '–1' are typically represented as sine waves with initial phases of 0 and π radians, respectively, corresponding to e^{j0} and $e^{j\pi}$. This modulation scheme forms the basis of typical M-sequence pulse compression used in ultrasonic testing.

2.2 Near-field zone

The near-field, or Fresnel zone, of an ultrasonic transducer refers to the region directly in front of the transducer where acoustic pressure exhibits both constructive and destructive interference. The resulting waveform in this zone is non-uniform and complex, making it unsuitable for accurate TOF measurements due to its adverse impact on signal stability and resolution. According to ASTM E1065-99, *Standard Guide for Evaluating Characteristics of Ultrasonic Search Units*, Part A.6 the standard outlines the measurement of sound field parameters and defines the near-field and far-field regions, as illustrated in Figure 2. The near-field zone is generally not suitable for thickness measurement because it contains higher noise levels caused by various elements of the transducer. The far-field zone is identified as the appropriate region for evaluating the TOF in ultrasonic measurements due to its stable acoustic characteristics.

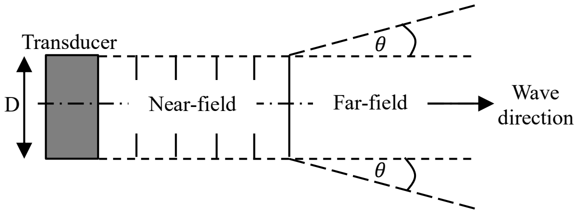

Fig.2 Sound Beam Spread Patterns for establishing search unit performance parameter

The near-field distance N of an ultrasonic transducer can be estimated by Eq. (2).

$$N = \frac{D^2 v}{4f} \tag{2}$$

Where D is the diameter of the ultrasonic transducer, v is a sound velocity in the material, and f is the center frequency of the transducer.

3. EXPERIMENT

In the experiment, an M-sequence signal was applied to a step calibration block with thicknesses ranging from 0.2 inches (5.08 mm) to 0.4 inches (10.16 mm) to compare the measured thickness with the dimension. The measurement result is compared to the result of the calibration certificate obtained from an ISO 17025 accredited laboratory. However, the thickness range measured in this study falls within the near-field zone of the transducer. The experimental setup is illustrated in Figure 3.

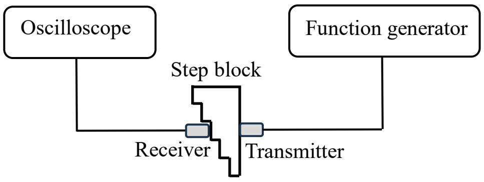

Fig.3 Experimental setup

A function generator, model HMF2550 was directly connected to the ultrasonic transmitter and generated and transmitted the M-sequence signal to the step calibration block. The ultrasonic transmitter, which is 0.25-inch diameter, generates the transmitted signal of 10MHz to the step calibration block. Then, the receiver received a signal and displayed a received signal on the oscilloscope, model RTM3004. Additionally, the received signal displayed on the oscilloscope was recorded to a USB stick about five times. Each collected data was then processed in MATLAB, where the received signal was correlated with a reference signal to determine the measured thickness. Moreover, error and standard deviation (SD) is evaluated. In this experiment, coupling gel was applied to the surface of the material to minimize the impedance mismatch between the step calibration block and both ultrasonic transducers

4. RESULT

As a result, 4th-, 6th-, and 9th-order M-sequences are generated by the function generator as transmitted signals are used to measure the thickness of the step calibration block. The result, which is a far-field area of the transducers, is shown. The far-field distance is approximately 17.09 mm. The near-field distance is less than 17.09 mm. In the experimental result, the cross-correlation function of the received signals, which can identify the high peak, is indicated in Figure 4.

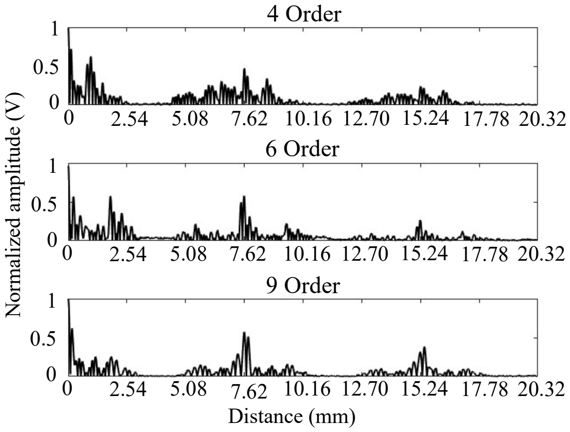

Fig.4 Cross correlation function of received signal at 7.6 mm.

The absolute values of the cross-correlation signals for the 4th-, 6th-, and 9th-order M-sequences were evaluated to identify sharp peaks corresponding to the material thickness of the calibration block. The initial peak of the received signal appeared at approximately 0 mm, while prominent sharp peaks were observed at around 7.62 mm and 15.24 mm. The difference between the initial peak and the first sharp peak corresponds to a measured thickness of approximately 7.6 mm, which confirms the consistency of the measurement. When comparing the cross-correlation signals among the 4th-, 6th-, and 9th-order M-sequences, the 9th-order M-sequence exhibits the lowest SNR. Additionally, the use of the M-sequence technique enables a reduction in the effective near-field distance of the ultrasonic transducer. Moreover, the SNR values were evaluated by calculating twenty times the logarithm of the ratio between the sharp peak amplitude and the maximum noise amplitude, based on the first sharp peak. The SNR results from 4-th to 9-th order of M-sequence are 6.496, 19.247 and 25.471, respectively. The 9th-order M-sequence achieved the highest SNR. A higher SNR indicates better signal quality; therefore, the 9th-order M-sequence is identified as the most suitable signal for material thickness measurement in this research. Moreover, the SD values are presented in Table 1. The SD values of the 9th-order M-sequence are lower compared to those of the lower-order sequences. Figure 5 shows the measurement errors of the 4th-, 6th-, and 9th-order M-sequences at 0.2, 0.3, and 0.4 inches, compared with the results from the calibration laboratory.

Table 1 SD values of the 4th-, 6th- and 9th-order M-sequences from (0.2 – 0.4) inches.

n-th order M-sequence	0.2 inch	0.3 inch	0.4 inch
	(mm)	(mm)	(mm)
4	0.00424	0.00344	0.00195
6	0.00212	0.00260	0.00212
9	0.00260	0.00211	0.00212

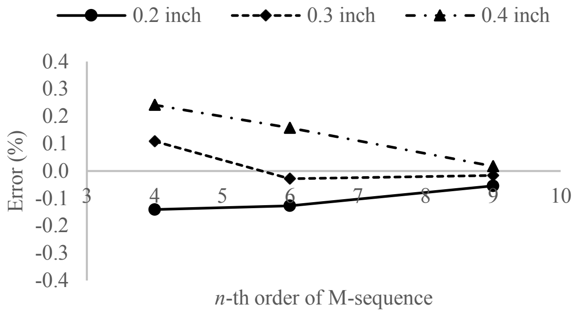

Fig.5 Error of measurement

As a result, the 9th-order M-sequence yielded the lowest SD and error values, due to its enhanced ability to suppress Gaussian noise and improve the SNR through the cross-correlation process. This effectively reduces signal noise, resulting in a smoother and clearer waveform. Therefore, the signal obtained from the 9th-order M-sequence is more suitable for accurately determining the TOF prior to calculating the material thickness.

5. CONCLUSION

The application of M-sequence pulse compression for improving ultrasonic TOF measurement and material thickness determination in the near-field zone has been presented. M-sequence signals of the 4th-, 6th-, and 9th-order were employed as transmitted waveforms, and the cross-correlation method was used to extract TOF from the received signals. Experimental results show that the M-sequence signals effectively improved SNR and suppressed background and environmental noises. The 9th-order M-sequence performed the best, yielding the highest SNR and demonstrating the highest measurement accuracy compared to the results from the calibration laboratory. Moreover, using M-sequence pulse compression enables a significant reduction of the effective near-field distance of the ultrasonic transducer, allowing for accurate measurements even in close-range areas. These findings validate the effectiveness of the M-sequence pulse compression technique in enhancing signal detection and achieving consistent and accurate measurements, especially in near-field conditions where conventional techniques are less reliable.

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