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Application of the Correlation Technique to Electromagnetic Ultrasonic Nondestructive Evaluation: Theoretical Study and Computer Simulation

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ABSTRACT

A new frequency-modulated *m*-sequence correlation technique was described. It has been seen that the frequency modulation scheme leads to higher signal-to-noise ratio than direct sequencing and less hardware effort than PSK modulation scheme. The operating frequency of the correlation system was deduced. The optimal frequency for the frequency-modulated *m*-sequence correlation system should be 1.35 times of the center frequency of the transducer. The application of this correlation technique to electromagnetic ultrasonic system was computer-simulated.

Keywords: Correlation Technique, *m*-sequence, Frequency Modulation, Signal-to-Noise Ratio Enhancement, Electromagnetic Ultrasonics, Nondestructive Evaluation

1. INTRODUCTION

The conventional pulse-echo technique is widely used in nondestructive evaluation. These real-time ultrasonic systems are often limited in average transmitted power by peak power constraints even in highly attenuating propagation media. The electromagnetic ultrasonic systems are also encountering the same difficulty. Theoretical studies suggest that the correlation techniques can overcome some of the drawbacks of classical pulse-echo techniques. By transmitting a continuous coded, large time-bandwidth signal and then compressing it into a short, high resolution pulse at the receiver the total signal-to-noise ratio is improved.

A number of reports have been given on the feasibility of the correlation techniques alternate to pulse-echo systems. The coded signals include chirp[1-3], random noise[4-5], Barker code[6], *m*-sequences[7-11], and Golay codes[12], etc.. All the correlation techniques have the advantage of very high signal-to-noise ratio enhancement, which enables them to retrieve echo signals buried in receiver noise.

An ultrasonic correlation system may be represented as shown in Fig. 1. If $x(t)$ is the broadband coded signal applied to the transducer, and $h(t)$ is the global transmit-receive impulse response of the transducers and the propagation medium, then the received signal is of the form

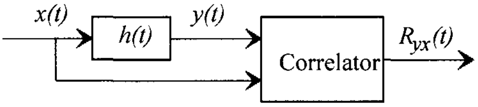

Fig. 1. Schematic block diagram of ultrasonic correlation system.

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$$y(t) = \int_{-\infty}^{+\infty} h(u)x(t-u)du = x(t) * h(t) \tag{1}$$

In correlation based systems the received signal is then cross correlated with a delayed replica of the transmission signal. The output is

$$R_{yx}(t) = \int_{-\infty}^{+\infty} y(\xi)x(\xi - t)d\xi = R_{xx}(t) * h(t) \tag{2}$$

where $R_{xx}(t)$ is autocorrelation function of the transmitted signal $x(t)$.

The signal-to-noise ratio enhancement ($SNRE$) of a correlation system is given by[13]

$$SNRE \approx \alpha BT \tag{3}$$

where α is the duty cycle of the transmitted signal, T is the system integration time, and B is the half-power bandwidth of the received signal. For digital signals it is more convenient to write $SNRE$ as

$$SNRE = nNB\delta \tag{4}$$

where N is the number of bits in the transmit burst, n is the number of transmitted bursts correlated, and δ is the width of 1 bit.

The pseudorandom m-sequences have been studied for use in ultrasonic NDE systems by a lot of authors. These signals were chosen because they are easily generated and have bandwidths which are essentially independent of the transmitted signal duration.

In this work, a frequency-modulated m-sequence correlation technique is proposed and theoretical studied and computer simulated for applying it to the electromagnetic ultrasonic systems.

2. EVALUATION OF M-SEQUENCES CORRELATION TECHNIQUES

The m-sequences are special pseudorandom codes which can be produced by any finite length shift register[14]. The principle of m-sequence generation is shown in Fig. 2. A k-bit shift register with the feedback connection of modulo-2 sum of the output of the last bit and the outputs of one or more other bits fed into the first bit. For each successive clock pulse, the stored elements shift over one bit to the right. A $N(=2^k-1)$-bit m-sequence will be obtained from the output.

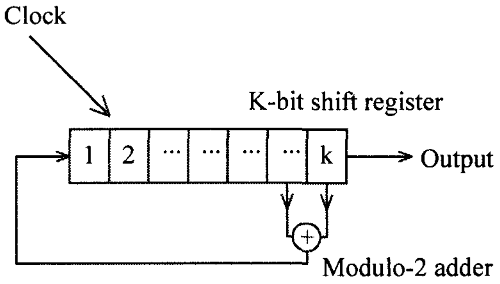


Fig. 2. The principle of m-sequences generation.

Two types of transmission schemes have been proposed for systems which use pseudorandom m-sequences direct transmission and phase shift keying (PSK) modulation. In direct transmission, the code is clocked at a rate which is greater than the upper cut-off frequency of the transducer so that the resolution of the system will be determined only by the transducer. In phase modulation, the code is clocked at less than half of the rate required for the direct transmission method and used to phase-modulate a carrier at the center frequency of the transducer. Elias and Moran[7] compared these two techniques and the results show that the phase modulation is a more efficient means of transmission, simply because much less of the signal spectrum falls outside the transducer passband and therefore is not wasted as in the directly sequenced system. But they agreed that the phase shift keying modulation is more complicated to implement than direct sequencing.

In this work a simpler modulation method - frequency modulation is proposed. Instead of phase modulating sine carrier we modulate a master clock. This is also a more efficient means than direct transmission.

Fig. 3(a) is a 31-bit m-sequence whose binary

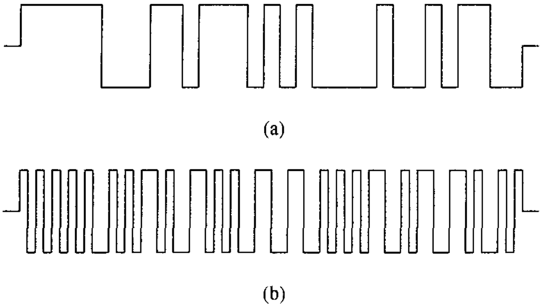


Fig. 3. (a) The m-sequence (b) frequency-modulated m-sequence.

1 and 0 levels are assigned numerical values of +1 and -1 respectively. Fig. 3(b) is a frequency-modulated pseudorandom *m*-sequence signal.

2.1 m-sequence

The ideal autocorrelation function of an *m*-sequence can be expressed as

$$R_{xx}(t)=\begin{cases} N\delta-(N+1)|t|, & |t|\le\delta \\ -\delta, & \delta<|t|\le(N-1)\delta \end{cases} \tag{5}$$

where $=1/f_s$ is bit width, f_s is clock frequency.

The power spectrum of pseudorandom *m*-sequence signal can be obtained by Fourier transforming its autocorrelation function. For large values of N, by Fourier transforming Eq. (5) one may therefore obtain the power spectral density of the *m*-sequence signal

$$\Phi_{xx}(f)=\frac{N}{\pi^2 f^2}\sin^2(\pi f\delta) \tag{6}$$

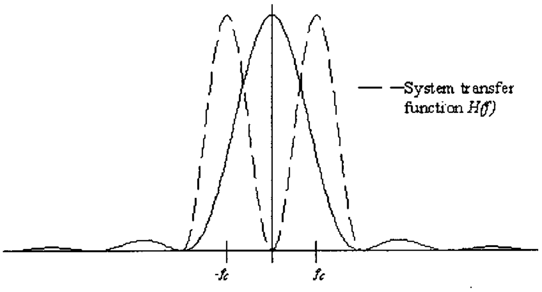


Fig. 4. The power spectrum of a pseudorandom *m*-sequence.

The power spectrum of pseudorandom *m*-sequence is shown in Fig. 4, where the transfer function of a broadband transducer, *H(f)*, is also shown symbolically.

By Fourier transforming Eq. (2) we get

$$\Phi_{yx}(f)=\Phi_{xx}(f)\cdot H(f) \tag{7}$$

where $_{yx}(f)$ is the Fourier transform of the correlator output. Eq. (7) implies that if $_{xx}(f)$ contains frequencies much higher than those present in *H(f)*, the signal energy would simply be wasted. For a broadband transducer with center frequency at f_c, the highest significant frequency may roughly be considered to be close to $2f_c$. Then, from Fig. 4 we have the following criterion for the clock frequency

$$f_s=\frac{1}{\delta}=2f_c \tag{8}$$

It was verified[15] that the signal-to-noise ratio of *m*-sequence correlation output reaches a maximum at approximately $f_s=2f_c$.

The maximum of the power spectrum of *m*-sequence shown in Fig. 4 is at zero frequency where the transfer function of the transducer is zero. That implies the spectrum of the *m*-sequence is not matched to the transducer transfer function and thereby a substantial amount of signal energy is wasted. The better matching can be achieved by using modulated *m*-sequence.

2.2 Frequency-modulated m-sequence

The ideal autocorrelation function of the frequency-modulated pseudorandom *m*-sequence can be expressed as

$$R_{xxm}(t)=\begin{cases} N\delta_m-(3N-1)|t|, & |t|\le\frac{\delta_m}{2} \\ (N-3)|t|-(N-2)\delta_m, & \frac{\delta_m}{2}<|t|\le\delta_m \\ 4t-(4n+1)\delta_m, & n\delta_m<|t|\le(n+\frac{1}{2})\delta_m \\ -4t+(4n+3)\delta_m, & (n+\frac{1}{2})\delta_m<|t|\le(n+1)\delta_m \end{cases} \tag{9}$$

where $_m=1/f_{sm}$ is bit width, f_{sm} is clock frequency,

$n=1,\dots,(N-2)$.

The power spectrum of frequency-modulated pseudorandom signal can be obtained by Fourier transforming its autocorrelation function. We get the power spectral density of the frequency-modulated m-sequence signal

$$\Phi_{xxm}(f) \approx \frac{4N}{\pi^2 f^2}\sin^4\frac{\pi f\delta_m}{2} \tag{10}$$

It is shown in Fig. 5. By proper selection of clock frequency, the maximum of the spectrum can be shifted to the center frequency of the transducer. We get when the clock frequency

$$f_{sm} = \frac{1}{\delta_m} \approx 1.35 f_c \tag{11}$$

the maximum of the spectrum is at the center frequency of the transducer.

It is clear that the signal spectrum can now be much better matched to the transducer transfer function.

2.3 Comparison of output signal-to-noise ratio for two types of m-sequences correlation techniques

The m-sequence and frequency-modulated m-sequence correlation systems will be compared on the basis of their output signal-to-noise ratios. In order to make the comparison meaningful, we will assume that both types of systems are being used under maximal performance condition, i.e. the clock frequency $f_s=2f_c$ for direct transmission case, and $f_{sm}=1.35f_c$ for frequency modulation case. The signal-to-noise power ratio is defined here as the ratio of the peak signal power and the average noise power.

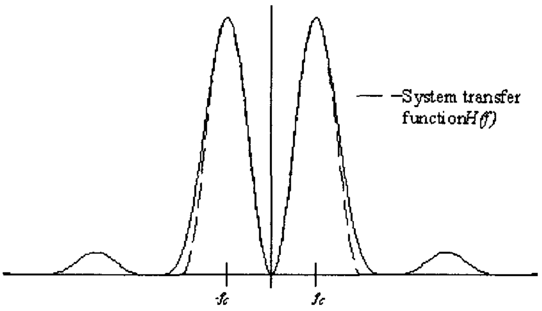


Fig. 5. The power spectrum of a frequency-modulated pseudorandom signal obtained by Fourier transforming the autocorrelation function.

We introduce the approximation demonstrated by Nahamoo and Kak[16] here to simplify the calculation. For broadband transducer, when the duration of the triangular part of m-sequence autocorrelation function is less than one cycle of the transducer impulse response, i.e. $21/f_c$, the following approximation may be used:

$$\left[R_{yx}(t)\right]_{\text{peak}} = \Phi_{xx}(f_c)\cdot\left[h(t)\right]_{\text{peak}} = \frac{N}{\pi^2 f_c^2}\sin^2(\pi f_c\delta)\cdot\left[h(t)\right]_{\text{peak}} \tag{12}$$

We assume a white noise with zero mean, and $_0$ denotes its power spectral density, the average noise power of the cross-correlated signal is given by[17]

$$e = N\nu_0\delta/2 \tag{13}$$

The signal-to-noise power ratio is obtained by dividing the square of the right hand side in Eq. (12) by the right hand side of Eq. (13). Denoting this ratio by SNR we get

$$SNR = \frac{2N\sin^4(\pi f_c\delta)\cdot\left[h(t)\right]_{\text{peak}}^2}{\pi^4 f_c^4\,\nu_0\delta} \tag{14}$$

When we frequency-modulate the m-sequence by a master clock to increase the efficiency of the correlation system, by using the similar approximation the signal-to-noise power ratio of correlation output may be written as

$$SNR_m = \frac{32N_m\sin^8(\frac{\pi f_c\delta_m}{2})\cdot\left[h(t)\right]_{\text{peak}}^2}{\pi^4 f_c^4\,\nu_0\delta_m} \tag{15}$$

Dividing Eq. (15) by Eq. (14) and using the fact of $\delta_m = 1.48\delta$ we get

$$\frac{SNR_m}{SNR} = 5.5\frac{N_m}{N} \tag{16}$$

When N_m=0.675N, the frequency-modulated m-sequence is as long as the directly transmitted one, we have

$$\frac{SNR_m}{SNR} = 3.7 \tag{17}$$

It shows that for equal input energy the frequency-modulated m-sequence correlation output will give a signal-to-noise ratio almost 3.7 times of that of direct transmission case.

However, there is a problem associated with the correlation techniques, so-called self-noise or range sidelobes. The range sidelobes of random and pseudorandom codes correlator outputs have nonconstant levels and show certain properties of randomness, but the variance of range sidelobes is bound. Siebert[18] calculates that the autocorrelation of any m-sequence code under band-limited conditions will have range sidelobes of maximum height H_m relative to the peak bounded by

$$H_m \le \frac{1}{\sqrt{\alpha BT}} = \frac{1}{\sqrt{nNB\delta}} \tag{18}$$

Due to the range sidelobes, the observed signal-to-noise enhancement is not so obvious as the theoretical prediction, especially under short code case.

3. COMPUTER SIMULATION OF *M*-SEQUENCES ULTRASONIC CORRELATION SYSTEM

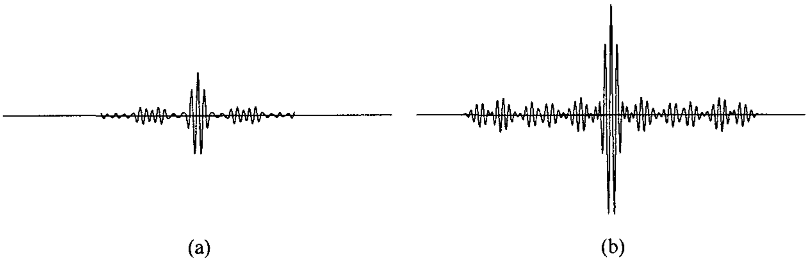
In order to simulate the m-sequences ultrasonic correlation systems, the software is developed. It allows us to simulate the following fundamental steps: m-sequences generation, signal modulation and signal processing. Our software can generate up to 1048575-bit m-sequences, which is enough for most NDE applications. The signal can be transmitted directly, phase modulated and frequency-modulated. As mentioned above, the modulation ensures maximum energy transfer.

In our simulation to the correlator outputs we regarded the transducer as a linear phase bandpass filter with the 6 dB bandwidth B, with a cosine-squared transfer function $H(f)$, centered at the transducer center-frequency f_c

$$H(f) = \cos^2\left(\frac{\pi(f-f_c)}{2B}\right), \qquad f_c - B \le f \le f_c + B \tag{19}$$

and assumed that both types of systems are being used under their optimal condition. Eq. (2) shows that the correlation output is equivalent to the convolution of the autocorrelation function of transmitting signal and the system impulse response. On the basis of this procedure, the m-sequences correlation outputs for a B=40% bandwidth transducer are simulated and the results are shown in Fig. 6.

Comparing the correlation outputs of two types of m-sequence transmitting signal, we may see the peak amplitude of frequency-modulated m-sequence correlation output is 2.40 times high as that of directly transmitted m-sequence correlation output (However, the frequency-modulated m-sequence is 1.48 times long as directly transmitted one). This indicates that the modulation is more



(a) (b)

Fig. 6. Simulated m-sequences ultrasonic correlation outputs.; (a) direct transmission, (b) frequency modulation.

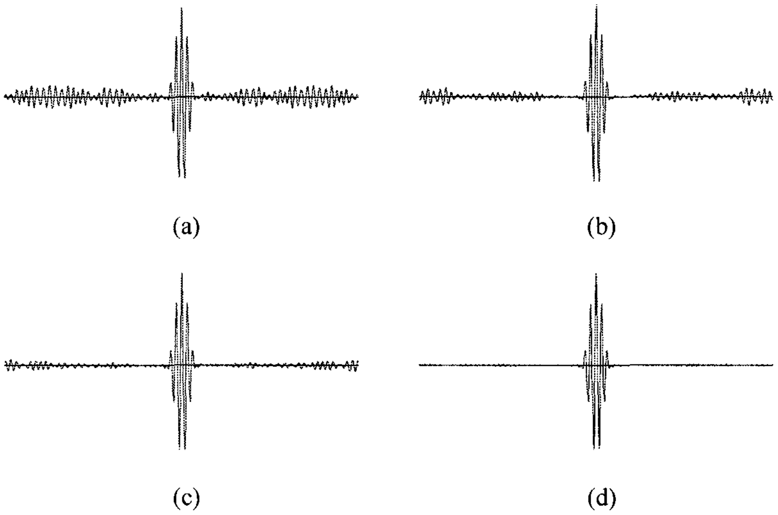

(a) (b) (c) (d)

Fig. 7. Computer simulated correlation outputs using (a) 63-bit, (b) 127-bit, (c) 255-bit and (d) 1023-bit frequency-modulated m-sequences.

efficient means of transmission.

As mentioned before, the presence of range sidelobes in the correlation system will decrease the system performance. In order to produce higher signal-to-noise ratio enhancement and lower range sidelobes level, the longer code should be used. Fig. 7 shows the simulated correlation out puts for 63-bit, 127-bit, 255-bit and 1023-bit frequency-modulated *m*-sequences. The comparisons of signal-to-noise ratio enhancements and range sidelobe levels are shown in Table 1. These results indicate that when the longer code is used, the correlation output will have higher signal-to-noise ratio enhancement and lower range sidelobes level, which will enable the correlation systems to be more powerful to detect the echo signals buried in receiver noise.

Table 1. Comparison of signal-to-noise ratio enhancements and range sidelobe levels for frequency-modulated m-sequences correlation outputs.

Bit number of *m*-sequences	*SNRE* (dB)	H_m
0031	09.6	33.0 %
0063	12.7	23.1 %
0127	15.8	16.3 %
0255	18.8	11.5 %
0511	21.8	08.1 %
1023	24.8	05.7 %

4. FUTURE PERSPECTIVES

The theoretical study and computer simulation in this work have suggested that the frequency modulation scheme leads to higher signal-to-noise ratio than direct sequencing and less hardware effort than PSK modulation scheme. An experimental electromagnetic ultrasonic correlation system on the basis of frequency-modulated *m*-sequence correlation technique is being assembled. By applying the experimental system, the samples with both high and low signal-to-noise ratios will be tested to evaluate the advantage of signal-to-noise ratio enhancement offered by the frequency-modulated *m*-sequence correlation technique.

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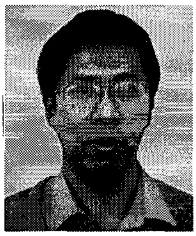

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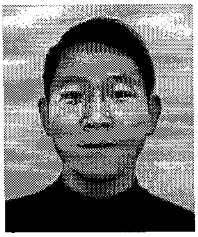

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