The System and Method of Ultrasonic Testing Based on Linear-Frequency-Modulation Technique

Jiaying ZHANG¹, Tie GANG¹⁺, Sen CONG¹, Changxi WANG¹, Wei FENG¹

¹State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, China
phone: +86 451 86418173, fax: +86 451 86416186, e-mail: gangt@hit.edu.cn

Abstract
In the traditional ultrasonic testing, there is a conflict between the propagation distance and the time resolution. Aiming to solve the problem, a real-time ultrasonic testing system is developed based on linear-frequency-modulation (LFM) technique. The system is smaller in size, compared with the system which is composed of waveform generator and so on. Since the system is open, it can be easily updated according to requirements. The signal generation part is based on direct-digital-synthesizer technique and the signal processing part is based on pulse-compression technique. There are dual channels for data acquisition, one for the echo and another one for the reference signal. Therefore, the coefficient of the matched filter is variable. Ultrasonic time-of-flight-diffraction (TOFD) testing the system is accomplished, and the distance resolution and the signal-to-noise ratio are better than the conventional pulse-echo system. And the flaws in the test sample can be detected by the system.

Keywords: ultrasonic testing, signal processing, pulse compression, linear frequency modulation, time of flight diffraction, direct digital synthesizer

1. Introduction
Nowadays, ultrasonic testing method has been widely used, especially in the traditional materials with relatively low ultrasonic attenuation. However, there are a lot of highly attenuating materials, so the power of the exciting signal needs to be increased. However, higher average power means longer pulses, which means the spatial resolution is inferior [1]. To solve the problem, the theory of LFM and pulse compression in radar system was introduced into ultrasonic testing. The theory can control the power of the exciting signal and the time resolution respectively [2, 3]. References [4-6] are about the LFM signal used in air-coupled ultrasonic testing and in TOFD testing, showing the enhancement of the system’s signal-to-noise ratio and the distance resolution. In this paper, a real-time ultrasonic testing system was developed. The system is small in size and is of good stability, so it is convenient to be used in the construction site.

2. The design and realization of the developed system

2.1 The design and realization of the hardware

The hardware of the system is composed of three sections: exciting signal generation section, data acquisition section and signal processing section. The signal generation section is based on direct-digital-synthesizer technique, and the waveform parameters are controlled by double microprocessor chips for the reason that the exciting signal is stable and can be controlled in real time. The data acquisition section has dual channels, one for the echo and another one for the reference signal used in pulse compression. The advantage of dual channels is that the reference signal can vary with the exciting signal, so the disturbed exciting signal will not affect the pulse-compression results. The signal processing section can produce compression waves when the echo waves are processed by matched filter.

2.1.1 The signal generation section
The waveform excited in this section should meet the requirements of ultrasonic testing. The time width of the waveform ranges from 1 μs to 1 ms, and the bandwidth of the waveform ranges from 1 MHz to 20 MHz. The modular design method is used in this section, and the general design block diagram is shown in Figure 1.

Users can set the waveform parameters with the host computer. The main function of the USB communication module is to transmit the data of the host computer to the controller of the waveform parameters, and the controller determines the signal produced by the generation module. The signal is then applied to the ultrasonic transducer after being filtered and amplified.

The communication module is based on USB 2.0 technique, and the core chip of the module is CY7C68013A made in Cypress. Two microprocessor chips in the controller of parameters are 51 series microcontroller and CPLD (Complex Programmable Logic Device). Thereinto, the former is responsible for the pulse width and the duty cycle while the latter is responsible for the centre frequency, bandwidth and amplitude. The waveform generation module is important in this section with its core chip AD9910 made in Analog Devices. The realization of the filter is enabled by analog circuit. The power amplifier is linear. The workflow of the section is shown in Figure 2.
2.1.2 The signal acquisition and processing section

There are four modules in the section, and the general design block diagram is shown in Figure 3.

The signal acquisition and processing section

The ultrasonic transducer
The pre-amplifier
The No.1 module of data acquisition
The No.2 module of data acquisition
The module of pulse compression
Host computer

Figure 3. The general design block diagram of the signal acquisition and processing section

The modules of data acquisition in the section adopt A/D converters, and their sampling rate is 50MSPS and sampling resolution is 8bit. Moreover, there is a synchronizing signal between the two modules, so the data is collected simultaneously. Lower sampling rate and lower sampling resolution during the development process will lead to the lower costs of the development, therefore the transformation of production schedule will be promoted. The last but not the least, the collected data will be applied to the process of pulse compression, and the results will be displayed to users.

2.2 The design and realization of the software

2.2.1 The basic theory of LFM signal

The complex expression of LFM signal is:

\[ x(t) = e^{\frac{j \omega_0 t^2}{2}} = e^{j\theta(t)}  \quad 0 \leq t \leq \tau \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1) \]

In the expression, \( \beta \) is bandwidth and \( \tau \) is pulse width. The instantaneous frequency of LFM signal is the differential of the phase function, and its expression is:

\[ F_i(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} = \frac{\beta}{\tau} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2) \]

So there are two kinds of frequency modulation for LFM signal. If \( \beta > 0 \), it is the up-chirp, and if \( \beta < 0 \), it is the down-chirp. They are equivalent, and the up-chirp mode is adopted in this paper. The time-bandwidth of LFM signal is large, so a matched filter is required to compress the signal into a narrower pulse. It is similar to sinc function, and its time resolution is \( 1/\beta \) [7-9].

2.2.2 The realization of pulse compressor

In this paper, the pulse-compression algorithm is realized in frequency domain. The matched filter is a linear time-invariant system, and the output expression is:

\[ y(t) = s(t) * h(t) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3) \]

In the expression, \( s(t) \) is the received signal, and \( h(t) \) is the frequency-domain response of the matched filter. The response is the reference signal through the conjugate and turning transformations. Therefore, the origins of \( s(t) \) and \( h(t) \) are both from the two modules of data acquisition. According to the theory of the FFT (Fast Fourier Transform), the expression (3) can be transformed into expression (4):
When the two modules of data acquisition work well, the output of the matched filter can be expressed as:

\[
y = \text{FFT}^{-1}\{S \cdot H\}
\]

In the above expressions, \(\text{FFT}^{-1}\) is inverse fast Fourier transform. The pulse-compression algorithm described above is based on dual-channel data acquisition. The benefits of it are that modules can use their clocks alone and can ignore the influence of the sampling rate. Meanwhile, the exciting signal can change its frequency and phase at any time. The workflow of the pulse-compression algorithm is shown in Figure 4.

3. The evaluation of system performance

3.1 The evaluation of the exciting signal and the data acquisition section

In order to evaluate the exciting signal, the signal in the boundary of time width and bandwidth should be first tested because of its greater probability of error. The results are shown in Figure 5. In the test, a standard oscilloscope was used to receive the waveform which was excited by signal generation section.

a) Time width is 1μs, bandwidth is 1MHz

b) Time width is 1μs, bandwidth is 20MHz
3.2 The parameters of the exciting signal

A 20mm-thickness carbon steel specimen was detected with the method of TOFD. With the results of the bandwidth experiments, it could be seen that the -6dB width of the compressed signal decreased with the increase of bandwidth when the bandwidth was less than 9MHz. But if the bandwidth was over 9MHz, the -6dB width remained stable. Therefore, the bandwidth of the exciting signal should be more than 9MHz when using the developed system. Through the results of the pulse-width experiments, it can be seen that the -6dB width of the compressed signal varied less than 0.02μs when the pulse width ranged from 1μs to 10μs.

Taking the limit power of the ultrasonic transducer and the energy of pulse into consideration, the pulse width was finally chosen as 5μs.

Before the frequency range is decided, the frequency spectrum of the two ultrasonic TOFD transducers is shown in Figure 6.
The transducers’ nominal centre frequency is 10MHz. It can be seen that the transducers responded well when the frequency was less than 10MHz. From a number of actual testing results, it can be concluded that the exciting signal of LFM waveform with the frequency ranging from 1MHz to 10MHz was better.

3.3 The evaluation of the software—pulse compression

The exciting signal and the TOFD echo are simulated in this paper and they are shown in Figure 7 and Figure 8. The simulation is based on the Matlab software. Applying them into the pulse-compression algorithm designed in the 2.2.2 section, the compressed results were obtained as shown in Figure 9.

From the results of the Matlab simulation, it can be seen that the developed pulse-compression algorithm can meet the requirements.

4. Experiments

A 30mm-thickness carbon steel sample was tested in the experiment with a flaw whose depth is 28.1mm. The sampling rate is 50MSPS. The A/D converter is not filtered. The excitation voltage is 110V. The pre-amplification is 30dB. The experiment result is shown in Figure 10.

From the result, it can be concluded that the flaw echo is clearly recognised and the depth of the flaw calculated is 27.8mm. There is 0.3mm error between the expected data and the measurement made by the developed system. When the traditional ultrasonic TOFD tests the same flaw with the above parameters, the echo is so small that the lateral wave and flaw wave is hardly recognizable. Therefore, promoting the parameters is needed. The better parameters are as the following. The sampling rate is 100MSPS. The A/D converter is with band-pass filter. The pre-amplification is 60dB. The excitation voltage is 400V. The experiment result is shown in Figure 11.
From the result, it can be seen that the flaw echo cannot be easy recognised from the backwall reflection. This can lead a greater error in the calculation. The experiment result indicates that the time resolution of the developed system has been improved greatly compared with the traditional ultrasonic test.

In the following experiments, there are a 20mm-thickness stainless steel sample and a 20mm-thickness stainless steel weld. The results are shown in the Table 1 and Table 2.

Table 1. The result of 20mm-thickness stainless steel sample

<table>
<thead>
<tr>
<th>Drawing size (mm)</th>
<th>Absolute error (mm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>0.2</td>
<td>1.3</td>
</tr>
<tr>
<td>12.0</td>
<td>0.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 2. The result of 20mm-thickness stainless steel weld

<table>
<thead>
<tr>
<th>Drawing size (mm)</th>
<th>Absolute error (mm)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.0</td>
<td>0.4</td>
<td>2.7</td>
</tr>
<tr>
<td>7.0</td>
<td>0.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>

From the results above, it can be seen that when the 20mm-thickness stainless steel sample was tested with the developed system, the absolute error is no more than 0.2mm and the relative error is less than 2%. Moreover, when it comes to the 20mm-thickness stainless steel weld, the absolute error is not more than 0.4mm and the relative error is less than 5%.

5. Conclusions

In conclusion, in this paper, a real-time ultrasonic testing system was developed based on LFM technique. It is portable and stable, which means it is convenient to be used in the construction site. The time width of the exciting signal produced by the system ranges from 1μs to 1ms, and the bandwidth ranges from 1MHz to 20MHz. The pulse-compression algorithm in the system can transform the large time-bandwidth signal into a narrower one. The time resolution would be enhanced by adopting the developed system. The absolute error is no more than 0.4mm and the relative error is less than 5% when testing stainless steel and its weld.

References


