The Simulation for Ultrasonic Testing Based on Frequency-Phase Coded Excitation

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ABSTRACT

Large time-bandwidth product coded signal and pulse compression in radar field has been introduced into ultrasonic testing. Linear frequency modulation (LFM), a frequency coded signal, is usually used to improve the time resolution, but the sidelobe of LFM should be suppressed to detect smaller flaws nearby. Barker coded signal of length 13, a binary phase coded signal, is usually used to suppress the sidelobe, but the wave width of results is larger than LFM. So a frequency-phase coded excitation is proposed to obtain good testing results with higher time resolution and lower sidelobe of. It combines the frequency and phase coded signal. LFM is applied to each sub-pulse of Barker code, and it is called LFM-B13. The simulations are carried out using K-wave toolbox in Matlab. The results of simulations demonstrate that, when using LFM-B13 excitation, the main sidelobe level is suppressed better and the time resolution is improved higher than using LFM excitation. The time resolution of LFM-B13 excitation is approximately 40% higher than that of LFM excitation, and the sidelobe of LFM-B13 excitation is approximately 4dB lower than that of LFM excitation, when 60% bandwidth of 5MHz central frequency transducers are used in the simulations of penetrating experiments.

Keywords: simulation, ultrasonic testing, coded excitation, pulse compression, K-wave

1. INTRODUCTION

It has been demonstrated that linear frequency modulation (LFM) excitation signal with pulse compression can improve the time resolution of the ultrasonic testing results (Mohamed et al, 2015) (Sato, Ueda, & Tada, 1972) (Barros, Machado & Costa-Félix, 2006). But there are sidelobes in the results, representing an inherent part of the pulse compression mechanism. In order to suppress the main sidelobe, frequency weighting of the output spectrum is usually used in radar systems. But the method can also increase the wave width of the testing results (Mahafza & Elsherbeni, 2003). To reduce the sidelobe, phase coded excitation signal is employed, such as Barker coded, Golay sequence (Chen & Deng, 1988) (Rouyer, Mensah, Vasseur & Lasaygues, 2014). Usually sidelobe suppression of phase coded excitation signal is better than that of frequency coded excitation signal.

In order to obtain the lower main sidelobe level (MSL) and the higher time resolution, frequency-phase coded excitation signal is proposed. It combines the frequency and phase coded signal. LFM and Barker coded of length 13, as the typical ones of the frequency and phase coded signal, are employed in ultrasonic testing. In the combination, LFM is applied to each sub-pulse of Barker code, and the combined signal can be called LFM-B13. The MSL of LFM-B13 is almost equal to that of 13 bit Barker coded signal. And the time resolution of LFM-B13 is also improved.

2. THE FREQUENCY-PHASE SIGNAL

2.1 LFM-B13

Barker codes of length 13 is a typical phase coded signal. It is usually used in the pulse compression radar systems because of its low autocorrelation properties (Mahafza, 2002). In time domain, it is defined as,

\[ s_{B_{13}}(t) = \alpha(t) e^{i2\pi f_0 t + \varphi(t)} \]  \hspace{1cm} (1)

Where the \( f_0 \) is the central frequency, and the \( \alpha(t) \) and \( \varphi(t) \) are expressed as,

\[ \alpha(t) = \frac{1}{\sqrt{P_T}} rect \left( \frac{t - P_T/2}{P_T} \right) \]  \hspace{1cm} (2)

\[ \varphi(t) = \begin{cases} 0 & \text{for } t \leq P_T/2 \\ \pi & \text{for } t > P_T/2 \end{cases} \]  \hspace{1cm} (3)

\[ f_0 = \frac{f_{13}}{13} \]  \hspace{1cm} (4)

\[ \varphi(t) = \begin{cases} 0 & \text{for } t \leq P_T/2 \\ \pi & \text{for } t > P_T/2 \end{cases} \]  \hspace{1cm} (5)

\[ \alpha(t) = \frac{1}{\sqrt{P_T}} rect \left( \frac{t - P_T/2}{P_T} \right) \]  \hspace{1cm} (6)

\[ \varphi(t) = \begin{cases} 0 & \text{for } t \leq P_T/2 \\ \pi & \text{for } t > P_T/2 \end{cases} \]  \hspace{1cm} (7)

\[ f_0 = \frac{f_{13}}{13} \]  \hspace{1cm} (8)

\[ \varphi(t) = \begin{cases} 0 & \text{for } t \leq P_T/2 \\ \pi & \text{for } t > P_T/2 \end{cases} \]  \hspace{1cm} (9)

\[ \alpha(t) = \frac{1}{\sqrt{P_T}} rect \left( \frac{t - P_T/2}{P_T} \right) \]  \hspace{1cm} (10)

\[ \varphi(t) = \begin{cases} 0 & \text{for } t \leq P_T/2 \\ \pi & \text{for } t > P_T/2 \end{cases} \]  \hspace{1cm} (11)
\[ \varphi(t) = \{ \pi \pi \pi \pi \pi \pi \pi \pi \pi \pi \pi \pi \pi \} \] (3)

Where the \( T_p \) is the time width of each sub-pulse of Barker code, and the \( P \) is the length of Barker code which is equal to 13 in this paper.

LFM is the typical one of the frequency coded signals and it can be expressed as,
\[ s_{LFM}(t) = \frac{1}{\sqrt{T_p}} rect \left( \frac{t}{T_p} \right) e^{j2\pi(f_o t + B t^2/2T_p)} \] (4)

Where the \( T_p \) is the time width of LFM, and the \( f_o \) is the central frequency, and the \( B \) is the bandwidth of LFM. The LFM-B\(_{13}\) combines expression (1) and expression (4), it can be expressed as,
\[ s_{LFM-B_{13}}(t) = \alpha(t) e^{j2\pi(f_o t + B t^2/2T_p + \varphi(t))} \] (5)

### 2.2 Pulse compression

The pulse-compression algorithm is realized including the mismatched filter and the matched filter. The mismatched filter is a linear time-invariant system, and in time domain the output is defined as,
\[ y_{mismatched}(t) = s(t) * h_{mismatched}(t) \] (6)

Where \( s(t) \) is the received signal which is excited by the LFM-B\(_{13}\) signal as expression (5), and the \( h_{mismatched}(t) \) is the time domain response of the mismatched filter. The \( h_{mismatched}(t) \) is obtained through the conjugate and turning transformations of the reference signal as expression (1). And the expression (6) can be deformed in frequency domain as,
\[ \text{FFT}\{ s(t) * h_{mismatched}(t) \} = S(f) \cdot H_{mismatched}(f) \] (7)

Where the \( S(f) \) and the \( H_{mismatched}(f) \) can be expressed as,
\[ S(f) = \text{FFT}\{ s(t) \} \]
\[ H_{mismatched}(f) = \text{FFT}\{ h_{mismatched}(t) \} \] (8) (9)

Therefore in the frequency domain, the output of the mismatched filter can be expressed as,
\[ y_{mismatched}(t) = \text{FFT}^{-1}\{ S(f) \cdot H_{mismatched}(f) \} \] (10)

The matched filter is also a linear time-invariant system, and in time domain the output is defined as,
\[ y_{matched}(t) = y_{mismatched}(t) * h_{matched}(t) \] (11)

Where the \( h_{matched}(t) \) is the time domain response of the matched filter. The \( h_{matched}(t) \) is obtained through the conjugate and turning transformations of the reference signal as expression (4). And the expression (11) can also be deformed in frequency domain same as the mismatched filter,
\[ y_{matched}(t) = \text{FFT}^{-1}\{ Y_{mismatched}(f) \cdot H_{matched}(f) \} \] (12)

So the \( y_{matched}(t) \) in the expression (12) is the output of the pulse compression based on the LFM-B\(_{13}\) excitation signal.

### 2.3 Matlab simulation

Numerical models of ultrasonic wave propagation in carbon steel are built in time domain using Matlab k-wave toolbox. An acoustic wave passing through a medium can cause some changes in density, pressure, etc. And these changes can be described as a series of coupled first-order partial differential equations (Cox, Kara, Arridge & Beard, 2007) (Firouzi, Cox, Treby & Saffari, 2012). These equations are expressed as
\[ \frac{\partial \mu}{\partial t} = -\frac{1}{\rho_0} \nabla p \] (13)
\[ \frac{\partial \rho}{\partial t} = -p_0 \nabla \cdot \mu - \mu \cdot \nabla p_0 \] (14)
\[ p = c^2 (\rho + d \cdot \nabla p_0 - L \rho) \] (15)

Where the \( \mu \) is the acoustic particle velocity, and the \( p \) is the acoustic pressure, and the \( \rho \) is the acoustic density, and the \( \rho_0 \) is ambient density, and the \( c \) is the isentropic sound speed, and the \( d \) is the acoustic particle displacement, and the \( L \) is a linear integro-differential operator.

The model of penetrating simulation is shown in Figure 1. Simulations are carried out using ultrasonic coupling agent as the coupling medium and using carbon steel plane as the test sample. And the penetrating method is used in the simulations. The two transducers used in penetrating method are same, and the geometric centers of both are in line. Around the edges of the model, the perfectly matched layers (PML) are used. PMLs, as absorbing regions, are added to the computational region to eliminate unwanted reflections.

![Figure 1: The model of penetrating simulation](image)
3. THE SIMULATIONS AND RESULTS

The carbon steel plane of 30mm thickness is employed in the simulations. Its velocity of longitudinal wave is 5900m/s, and the velocity of shear wave is 3230m/s. Its density is 7900kg/m³. And the steel is supposed to be isotropic and homogeneous, and the attenuation coefficient of the acoustic wave propagation is a fixed value.

3.1 Different bandwidths

In this part of simulation, the central frequencies of transducers are same as 5MHz, but the bandwidths vary from each one. The -6dB bandwidths are 60%, 100%, 140%, 180% of the central frequency. Although the bandwidths of 100%, 140%, 180% may be difficult to achieve in reality, it is just demonstrated the contrasts of different bandwidths between LFM and LFM-B₁₃ excitation. The coded excitation signals include the LFM and LFM-B₁₃. And the carrier frequencies and the bandwidths of both are same as the central frequencies and the bandwidths of transducers. The time width of both excitation signals is 3µs, and the initial pressure is 10Pa.

The results of simulations are shown in Figure 2, in which -6dB bandwidth of transducers is 60% of 5MHz central frequency. And the envelopes of pulse compression output of LFM and LFM-B₁₃ are shown in Figure 3. Figure 2 shows the received signal (black dash line) and the output of pulse compression (red solid line) in both LFM-B₁₃ and LFM excitation. When the received signal is through pulse compression, the amplitude increases highly and the time width decreases greatly. And it can be found that the amplitude of LFM-B₁₃ excitation received signal changes a little smaller than that of LFM excitation. Moreover, the time width of pulse compression output in LFM-B₁₃ excitation is a little smaller than that in LFM excitation.

Figure 2 The simulations results of 60% -6dB bandwidth of 5MHz central frequency (The black dash line represents the received signal; the red solid line represents pulse compression results)

Figure 3 The simulations envelopes results of 60% -6dB bandwidth of 5MHz central frequency (The black dash line represents the envelope of LFM excitation; the red solid line represents the envelope of LFM-B₁₃ excitation)

Figure 3 shows that when the bandwidth of transducers is 60% of 5MHz central frequency, the time width of pulse compression main lobe of -6dB in LFM-B₁₃ excitation is 0.284µs. It is 59.2% of the main lobe of -6dB in LFM excitation. And the MSL of LFM-B₁₃ excitation is -19.07dB. It is 4.12dB lower than MSL of LFM excitation. So the LFM-B₁₃ excitation can bring the better results than LFM excitation when the bandwidth of transducers is 60% of 5MHz central frequency.

When the -6dB bandwidths are 3MHz, 5MHz, 7MHz and 9MHz with 5MHz central frequency, the results are shown in table 1. Table 1 illustrates that the MSL of LFM-B₁₃ excitation is 5.26dB, 7.51dB and 9.36dB lower than that of LFM excitation when the excitation signal bandwidth is 5MHz, 7MHz and 9MHz, although the time width of the main lobe in LFM-B₁₃
excitation is a little larger than that in LFM excitation. Moreover, in actual ultrasonic testing, -6dB bandwidth of transducers can be difficult to achieve more than 100% of the central frequency.

**Table 1** Results of different bandwidth in the same central frequency (5MHz)

<table>
<thead>
<tr>
<th>-6dB Bandwidth (MHz)</th>
<th>Main lobe of -6dB (μs)</th>
<th>MSL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFM-B_{13}</td>
<td>LFM</td>
<td>LFM-B_{13}</td>
</tr>
<tr>
<td>3</td>
<td>0.284</td>
<td>0.480</td>
</tr>
<tr>
<td>5</td>
<td>0.282</td>
<td>0.279</td>
</tr>
<tr>
<td>7</td>
<td>0.269</td>
<td>0.199</td>
</tr>
<tr>
<td>9</td>
<td>0.244</td>
<td>0.157</td>
</tr>
</tbody>
</table>

### 3.2 Different central frequencies

In this part of simulation, the central frequencies of transducers are different, and they are 1.25MHz, 2.5MHz, 5MHz and 10MHz. The -6dB bandwidths of transducers are 60% of its central frequency. The coded excitation signals include the LFM-B_{13} and LFM. And the carrier frequencies and the bandwidths of both are the same as the central frequencies and the bandwidths of transducers. The time width of both excitation signals is 3μs, and the initial pressure is 10Pa. The results of the simulations are shown in Figure 4.

Figure 4 reveals that the MSL of LFM-B_{13} excitation is lower than that of LFM excitation in all four central frequencies. And when the transducers central frequencies less than 10MHz, the main lobe time width of LFM-B_{13} excitation is smaller than that of LFM excitation. When the transducers central frequency is 10MHz, the main lobe time width of LFM-B_{13} excitation is a litter larger than that of LFM excitation.

**Figure 4** The envelopes of the output of pulse compression when -6dB bandwidth of transducers is 60% of different central frequencies (The black dash line represents the LFM excitation results; the red solid line represents LFM-B_{13} excitation results)
4. DISCUSSIONS AND CONCLUSION

The bandwidth of the coded excitation signal affects the results. When the central frequency is 5MHz in simulation 1, the effects of different exciting bandwidth on pulse compression output are shown in Figure 5.

Figure 5 The exciting signal bandwidth effects on main lobe time width and MSL (The black dash line represents the LFM excitation results; the red solid line represents LFM-B\textsubscript{13} excitation results)

Figure 5 shows that excitation bandwidth can have more influence on the time width of LFM pulse compression main lobe. When the -6dB bandwidth is larger, the time width of LFM main lobe is larger. But it has few effects on LFM-B\textsubscript{13} results time width. Figure 5 also shows that LFM-B\textsubscript{13} excitation can better suppressed the main sidelobe than LFM excitation. Moreover, excitation bandwidth affects LFM-B\textsubscript{13} excitation MSL less than LFM.

In conclusion, LFM-B\textsubscript{13} coded excitation signal in ultrasonic testing can suppress the sidelobe better than LFM coded excitation signal. And the time resolution of the pulse compression output is improved when the -6dB bandwidth of transducers is smaller. Moreover, the -6dB bandwidth of transducers have less influence on LFM-B\textsubscript{13} excitation than LFM excitation.

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