Research on ultrasonic guided wave dispersion compensation for steel strand defect detection

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Abstract: Ultrasonic guided waves detection technology is a new nondestructive testing technology, and it can be used to detect the structural health of steel strands. Because of dispersion separation, it has great impact on the detection results, especially in long distance detection. This paper introduces a method of linear mapping technique for dispersion compensation. The effect of dispersion compensation can be achieved by reconstructing the linear dispersion curve instead of the nonlinear dispersion curve. This paper verifies the processing effect of dispersion compensation method from simulation and experiment while using a single-core rod as an example, and applies this method to the detection signal of steel strand. The results show that the method can focus the guided wave signal, and improve positioning accuracy and signal-to-noise ratio of detection.

1. Introduction

The seven-wire steel strand is made by twisting a plurality of external spiral wires around a internal straight steel wire. It is commonly used in bridges, foundation construction, water conservancy projects, etc. However, environmental factors during applications, which lead to fatigue damage, wire breaking and other phenomena, affect the operation safety of the entire project, so it is practically significant for the structural health detection of steel strands[1].

Nondestructive testing technology based on ultrasonic guided waves has the advantages of long detection distance, large single-point excitation coverage, fast detection and high checking. It has been widely used in the detection of defects in rails, pipes, flat plates, rods, etc.[2], and can achieve structural health testing of steel strands. Because of dispersion characteristics, the ultrasonic guided waves of different frequencies will propagate at different speeds, the guided wave signal will be widened and its amplitude will decrease with the increase of the propagation distance in the time domain. It is not beneficial to extract and identify characteristic signals, which seriously affect the positioning accuracy, so it is very important for the dispersion compensation of guided waves.

The common methods for dispersion compensation of guided wave signals include time-distance domain mapping, time reversal method and linear mapping. The time-distance domain mapping method is to map signals from the time domain to the distance domain for processing. Wilcox
reconstructed the dispersion signal by propagating the received signal backward to t=0, and applied it to phased array imaging to process the damage dispersion signal[3]. The time reversal method performs the inverse processing of the received dispersion signal, and uses it as an excitation signal to form the focus in propagation and reduce the dispersion. Mathias Fink used the time-reversal mirror of an array transducer to focus the signal propagating in the waveguide, and improved the SNR[4-5]. The linear mapping method implements dispersion compensation by a F-K domain processing method. Liu and others analyzed the dispersion signal and found that the nonlinear F-K curve is the cause of the signal dispersion. Therefore, we can use Taylor's expansion at the center frequency of the signal to analyze the wavenumber curve, and restore the original Signal by reconstructing the linearized wavenumber curve[6].

In this paper, the theoretical methods of guided wave propagation model and linear mapping method were introduced first. Then taken the straight rod model as an example, we collected the guided wave dispersion signal in the straight rod by numerical simulation and experiment, and processed the dispersion compensation to verify the feasibility and effectiveness. Finally, this method was applied to the detection signal of the steel strand for processing the dispersion signal.

2. Dispersion compensation theory

2.1 Guided wave propagation model

The guided wave signal with a specific mode and frequency is excited by an excitation transducer, and propagates along the waveguide structure. Suppose the excitation signal is \( f(t) \), \( x \) is the propagation distance of the guided wave signal, \( t \) is the corresponding propagation time. Then, the guide wave signal \( u(x,t) \) at any point on the waveguide structure can be expressed as:

\[
 u(x,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \exp[j(\omega t - k(\omega)x)] d\omega \tag{1}
\]

Where \( F(\omega) \) is the Fourier transform of the excitation signal \( f(t) \), and \( k(\omega) \) is the wavenumber corresponding to the angular frequency of a certain mode guide wave.

Assuming that the signal is received by the receiving transducer after reflecting the end face or defect, the acoustic distance propagated by the guide wave is \( x_0 \), and the reflection coefficient of the end face or defect is \( A \), the signal \( g(t) \) received by the transducer can be expressed as:

\[
 g(t) = u(x,t) \bigg|_{x=x_0} = \left. \frac{A}{2\pi} \int_{-\infty}^{\infty} F(\omega) \exp[j(\omega t - k(\omega)x_0)] d\omega \right. \tag{2}
\]

The expression of converting the collected guide wave signal from time domain to distance domain is as follows:

\[
 x = V_{gr} t \tag{3}
\]

Where \( x \) is the propagation distance of guided wave signal, \( V_{gr} \) is the group velocity corresponding to the center frequency of the received signal, and \( t \) is the corresponding propagation time. The propagation velocity of guided wave with different frequencies is different because the frequency of guided wave is not the same. So in the time domain signal, the wave packet of the received signal \( g(t) \) at the characteristic point gets longer, the distance occupied in the corresponding distance domain becomes wider, which affects the positioning accuracy.

2.2 Linear mapping

Liu et al. pointed out that if the wave number curve \( k(\omega) \) of the guide wave is non-linear, it will cause phase distortion and lead to dispersion separation of the guide wave signal. If the wavenumber curve \( k(\omega) \) is linear, it will not cause dispersion separation. According to this conclusion, the dispersion compensation can be realized by mapping the waveguide signal into the linearly varying wavenumber domain. The frequency domain of the received signal is obtained by Fourier transform, and the wavenumber \( k(\omega) \) is Taylor expanded at the central frequency of \( \omega_0 \) and retained to the first order linear term, the expression is as follows:
\[ k(\omega) \approx k_{lm}(\omega) = k(\omega_b) + k'(\omega_b)(\omega - \omega_b) \]  

(4)

where \[ k(\omega_b) = \frac{\omega_b}{c_{ph}}, k'(\omega_b) = \frac{1}{c_{gr}(\omega_b)} \]. The linearized wavenumber curve is shown in figure 1.

![Figure 1. wave number curve after linearization.](image1)

![Figure 2. The excitation signal.](image2)

3. Numerical simulation

To realize and verify the effect of the above mentioned dispersion compensation method, the ABAQUS software was used to build the straight bar model in this section, the excitation signal is loaded on one end face of the rod, and the receiving node is set every 0.5 m to observe the signal changes in the propagation process of the guide wave signal.

In this paper, L(0,1) mode is selected as the guide wave mode of the excitation signal according to the dispersion curve, the velocity of L(0,1) mode changes slowly at 150 kHz, and the group velocity decreases gradually from 150 kHz. The excitation signal is 200 kHz sinusoidal signal modulated by 5-period Hanning window, the time width is 25 us, as shown in figure 2. It can be seen from the dispersion curve diagram that the L(0,1) mode of 200 kHz is in the region where the group velocity changes rapidly, and the dispersion separation phenomenon can be seen.

Take the monitoring point 1 m above the straight bar, record the direct wave signal and the signal reflected by the end face respectively. The experimental results are shown in figure 3(a). As can be seen from the figure, with the increase of propagation distance, the wave packet of guide wave signal becomes wider and its amplitude decreases significantly. The time width of signal at one-meter acoustic distance is about 80 us, 3.2 times that of the excitation signal. The time width of signal at three-meter acoustic distance is about 170 us, 6.8 times that of the excitation signal.

![Figure 3. Received guided wave signals.](image3)
Figure 3(b) shows the result after using dispersion compensation. After linear mapping method to compensate the time width of 1 m path signal for 42 us, 3 m path signal time width is 87 us, after linear mapping method to compensate the characteristics of signals than dispersion time width is cut by half, signal amplitude has a certain improvement, this method is effective to reduce the dispersion of the signal and realize the focusing of the signal.

4. experimental verification

In order to verify the accuracy of the dispersion compensation method, the following experimental tests were carried out to compare the experimental results on the single-core straight rod with the simulation results, and the dispersion compensation method was applied to the stranded wire for signal processing.

4.1 Single core straight rod experiment

The length of the single-core straight rod selected in the experiment is 1.5 m, and the remaining physical parameters are the same as those used in the simulation. The experimental equipment is shown in figure 4(a), the functional block diagram is shown in figure 4(b), and the excitation signal is selected by 5-cycle Hanning window modulation. The sinusoidal signal, with a frequency of 200 kHz, fixes the piezoelectric transducer to the end face of the straight rod, excites the guided wave of the longitudinal L(0,1) mode, and uses the excitation mode of the pulse echo to receive the end face signal reciprocating in the rod.

The experimental results are shown in figure 5. It can be seen from the figure that there are two modes of guided waves in the signal, and the wave velocities of the two modes are calculated, and the corresponding L(0,1) and F(1,1) modes are respectively. As the propagation distance of the L(0,1) mode increases, the wave packet becomes significantly wider, the amplitude decreases significantly, and the dispersion is severe, which is consistent with the simulation result. The F(1,1) modal dispersion variation is not obvious, which meets the variation law of the dispersion curve. The two modal signals are superimposed and cannot be effectively distinguished at 9.3 m, as shown in figure 6(c).
Figure 5. Straight rod guided wave dispersion signal.

Using the dispersion compensation method of linear mapping, the L(0,1) mode is used as the compensation mode, and the dispersion signal is processed. The guided wave signal and the envelope diagram are shown in figure 6(a) and (b). For L(0,1) modal signals with propagation distances of 3.2, 6.3, 9.3, 12.5, and 15.5 m, this method improves the signal peak and reduces the width of the wave packet, effectively achieving L(0,1). Focusing of the modal signal, for the F(1,1) mode, the characteristic signals at 4.8, 9.3, and 14.1 m are suppressed, the wave packet is widened, the amplitude of the signal is reduced, and the dispersion is aggravated. For the characteristic signal of two modes overlapping at 9.3 m, the dispersion compensation can distinguish the modes of L(0,1) and F(1,1), and compress L(0,1) modal signal wave packet to improve the amplitude and achieves modal separation, as shown in figure 7(d). The experiment verifies the feasibility and effectiveness of the linear mapping method for compensating for dispersion separation.

(a) Straight rod guided wave dispersion signal
(b) Envelope of the dispersion signal
4.2 Multi-core spiral rod experiment

The experiment selected 1×7-15.20-1860-GB/T 5224-2003 steel stranded wire with a nominal diameter of 15.20 mm and a length of 1 m. It is made of a central steel wire straight rod and six peripheral spiral steel wires. The dispersion curve of the guided wave in the seven-wire steel strand is obtained by the semi-analytical finite element method, as shown in figure 8. The experimental device is shown in figure 4(a). The excitation signal is a sinusoidal signal modulated by a 5-period Hanning window with a frequency of 150 kHz, which excites the guided signal of the longitudinal L(0,1) mode.

The experimental sampling signal is shown in figure 9(a). The L(0,1) modal signal is obvious and is the main excitation mode. Because the seven-wire steel strand structure is more complicated and accompanied by more interference signals, the noise is large. As the L(0,1) modal signal increases with the propagation distance, the signal attenuation is obvious. The signal wave packet is gradually widened after eight-meter acoustic distance. As shown in figure 9(a), the four characteristic signals are separated. The phenomenon is obvious. Figure 9(b) is a comparison diagram before and after the dispersion of the four characteristic signals, and figure 9(c) is an envelope signal diagram corresponding to the four characteristic signals. After the dispersion compensation processing, the L(0,1) mode is obtained. The signal packet width is reduced to achieve L(0,1) modal energy focusing. The feasibility and effectiveness of the method for compensating the dispersion signal of steel strands are verified by experiments.
It can be seen from the above experimental results that the linearly mapped dispersion compensation method has the following effects:

- **Modal selection.** The ultrasonic guided wave is affected by the transducer and the waveguide structure during excitation, and cannot excite a pure single mode. For the required guided wave mode, the compensation can be achieved by using this method to reduce the effect of dispersion separation; for the excited interference mode, the method will suppress its signal and aggravate the dispersion effect, for example L(0,1) and F(1,1) modal signals in figure 6.

- **Improve the resolution of the signal.** When there are multiple modalities in the signal, and when the signals of different modalities cannot be effectively distinguished by aliasing, such as the aliasing signal in figure 6, the modal separation can be achieved by using the method to distinguish different modal signals.

- **Improve positioning accuracy and SNR.** Dispersion separation causes the signal packet to be widened and the amplitude is reduced, which reduces the positioning accuracy and the SNR. This method is used to achieve signal focusing, reduce the width of the wave packet, increase the amplitude of the signal, improve the positioning precision and SNR.

(a) Received signal of seven-wire steel strand  
(b) Signals before and after dispersion compensation  
(c) Local envelope signal before and after dispersion compensation  

Figure 9. Schematic diagram of the experimental results of the seven-wire steel strand.

5. **Conclusion**

Due to dispersion separation, there are some problems in the detection technology based on ultrasonic guided waves, such as poor positioning accuracy, low SNR in long-distance measurement. In this
paper, combined with the frequency dispersion of guided wave in the rod structure, we introduce a
dispersion compensation method of linear mapping, and compensate the dispersion signal in
simulation and experiment. From the experimental results, this method improves the resolution and
positioning accuracy of the guided wave signal, and verifies the effectiveness of the dispersion
compensation.

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