Experimental study on the damage monitoring of a Pi-type pipeline based on ultrasonic guided waves

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Abstract. Aiming at the damage of the prefabricated counter bore at the elbow of the scribble pressure pipeline, a test system is established based on the ultrasonic guided wave technology, and the end echo interference is eliminated by arranging a multi-channel sensor array to achieve accurate positioning of the pipeline damage and return the measured damage. Comparing the wave amplitude value with the 3% DAC curve to calculate the pipe damage cross-sectional loss rate, the test results show that the average relative error between the monitored damage cross-sectional loss rate and the actual cross-sectional loss rate is 3.46%, and the average relative error of damage location is 2.05%.

1. Introduction

Ultrasonic guided wave technology adopts the pulse-echo principle. The acoustic signal excited by the sensor is reflected back and forth on the inner and outer walls of the pipe multiple times to produce a multi-mode guided wave propagating along the axial direction of the pipe. The guided wave encounters the pipe structure during the propagation process. Changes in the pipeline, such as damage, welds and flanges, will generate echo signals, and the structural information of the pipeline can be identified by feature extraction and analysis of the echo signals [1]. Because it has the following advantages (1) arranging a sensor array in one part of the pipeline can realize the global detection of long-distance pipelines, with high efficiency; (2) The sensor array is small in size and light in weight, suitable for pipeline detection in the final assembly state (3) The sensor array is bonded to the outer wall of the pipeline to realize real-time online detection of the pipeline without moving the sensor. Ultrasonic guided wave technology has been more and more widely used in pipeline damage monitoring [2-3].

The damage of a zigzag steam pipe generally occurs at the elbow. Due to the complicated pipe shape, the measurement of guided waves propagating in a single direction will be interfered by the end flange echo, which makes it difficult to accurately locate the damaged part. In this regard, a damage detection test based on guided wave technology was carried out for the actual pipeline form.

2. Propagation characteristics of guided waves in round tubes

2.1. Guided wave propagation mode

The elastodynamic theory can obtain the dispersion equation of guided wave propagation in a hollow tube:

\[ C_{ij} = 0 \quad (i, j = 1, 2, 3, 4, 5, 6) \]  \hspace{1cm} (1)
where, \( c_{ij} \) is a function related to pipe diameter, Lame's constant, density, angular frequency and wave number of the material. By solving the dispersion equation, the dispersion curve of guided wave propagation in the hollow tube can be obtained.

There are three modes of guided waves propagating in the tube along its axial direction, namely longitudinal mode \( L(0,m) \), torsion mode \( T(0,m) \) and bending mode \( F(n,m) \), longitudinal mode. The state-guided wave \( L(0,2) \) has the fastest group velocity and small rate of change. It reaches the receiving sensor first among all the echo signals and the waveform will not be distorted. It is easy to identify and distinguish in the time domain. In addition, the axial displacement distribution of \( L(0,2) \) guided wave in the tube wall is uniform and relatively large, the radial displacement along the tube wall is small, and energy leakage is small during the propagation process, usually \( L(0,2) \) Guided waves for pipeline damage detection [4-6].

2.2. Single-direction guided wave excitation control in the pipeline

The single-turn sensor array is symmetrically arranged by PZT piezoelectric sensor units. The number of sensors is greater than the maximum order of the bending mode in the excitation frequency band (and the highest order of the bending mode \( F(n,1) \) greater than the cutoff frequency in the excitation frequency band) Order \( n \). If a circle of sensor array is used, the wave propagating in both directions will be excited from the sensor, and echoes will be generated at both tube ends, resulting in the complexity of the received signal and the difficulty in judging useful signals. Arranging two circles of the sensor array can realize the excitation of one-way ultrasonic guided waves. The installation of the two-channel excitation sensor is shown in Figure 1. The first circle sensor corresponds to channel 1 and serves as the standard output; the second circle sensor corresponds to channel 2, and the initial phase can be changed relative to the standard output. The distance between the two sensors is \( d \).

![Figure 1. Schematic diagram of sensor layout](image)

Taking sine excitation as the research object, according to the ideal situation, that is, the change law of the two-channel excitation signal, it is completely coupled to the pipe guided wave motion equation. The guided wave vibration equations generated by the two-channel excitation are as follows:

\[
\begin{align*}
    y_1 &= A_1 \sin(\omega t + \varphi) \\
    y_2 &= A_2 \sin(\omega t + \varphi + \Delta \varphi)
\end{align*}
\]

(2)

When the two-channel output signal propagates in the pipeline, the propagation in a certain direction disappears. The relationship reflected in the quantity equation is that the displacement of the two fluctuations is 0 after the superposition. According to the nature of the periodic function, the amplitude of the two fluctuations should satisfy \( A_1 = A_2 = A \).

When propagating to the right, the distance between the two sensors is \( d \) and the guided wave field is \( \lambda \), then the two waves have a phase difference at a certain point. Superimpose the displacements of the two channel excitation guided waves, then there is

\[
\omega = 2\pi f = \frac{2\pi}{T}
\]

(3)

Where, \( f \) is the frequency of the guided wave, and \( T \) is the period.

\[
(2\pi / T) \cdot (d / \lambda) \cdot T = 2\pi (d / \lambda)
\]

(4)

Similarly, when propagating to the left, the displacement after the superposition of the two waves is

\[
y = y_1 + y_2 = A \sin(\omega t + \varphi) + A \sin(\omega t + 2\pi (d / \lambda) + \varphi + \Delta \varphi)
\]

(5)
If guided wave would be controlled to only propagate to the left and achieve the best superposition effect, that is, to make the two waves completely overlap, the above two equations should meet the following two conditions at the same time

\[ y = y_1 + y_2 = 0 \]
\[ y' = 2y_1' \]

which is

\[ y_1 = -y_2, y_1' = y_2' \]

Solve the above equations together to get

\[
\begin{align*}
\Delta d &= [-2(k_1 + k_2) + 1](\lambda / 4) \\
\Delta \phi &= [2(k_1 + k_2) + 1](\pi / 2)
\end{align*}
\]

Where

\[ k_1 = 0, \pm 1, \pm 2, \pm 3, \ldots; \]

\[ k_2 = 0, \pm 1, \pm 2, \pm 3, \ldots. \]

It can be seen that, in order to control the guided wave to propagate only to the left end of the pipe, the distance between the two sensors should be an odd multiple of \( \lambda / 4 \), and the phase difference between the two channels should be an odd multiple of \( \pi / 4 \). When \( d=\lambda/4 \), the phase difference \( \Delta \phi=\pi/2 \); when \( d=3\lambda/4 \), the phase difference \( \Delta \phi=3\pi/2 \).

In the same way, the following relationship is obtained when the guided wave propagates only to the right end direction and the right end direction

\[
\begin{align*}
\Delta d &= [-2(k_1 - k_2) + 1](\lambda / 4) \\
\Delta \phi &= [2(k_1 - k_2) - 1](\pi / 2)
\end{align*}
\]

When \( d=\lambda/4 \), the phase difference \( \Delta \phi=-\pi/2 \); when \( d=3\lambda/4 \), the phase difference \( \Delta \phi=\pi/2 \).

According to the nature of the periodic function, it is easy to know that for other types of dual-channel excitation with a period of \( 2\pi \), in order to realize the propagation of the guided wave in the same direction, the distance of the sensor and the phase difference between the two channels should also meet the above conditions.

3. Pi type pipeline damage monitoring experiment

3.1. Test object and the damage form

The size of the test pipe in this study is shown in Figure 2.

![Figure 2 Pi type pipeline](image)

The propagation characteristics of guided waves in the pipeline are shown in Figure 3. The damage setting method is counter bore, and the design positions are all at the elbow. The counter bore damage with depth \( h=2\text{mm} \) is made by drilling method. The counter bore diameter is 3mm and 5mm, and the corresponding cross-sectional loss rates are respectively 1.1% and 1.8%.
3.2. Sensor layout and excitation parameter setting
In the experiment, the sensor uses a length-retractable piezoelectric chip, the size of the piezoelectric chip is length L=12mm, width w=3.2mm, and thickness t=0.5mm, as shown in figure 4. Piezoelectric wafers are pasted in the middle of the waist section with epoxy resin at equal distances, arranged in three circles, with an interval of 27mm between each circle, and each circle is uniformly pasted with 12 piezoelectric wafers along the circumference of the tube. The positive and negative electrodes of each piezoelectric wafer are connected in parallel. For connection, the entire 12 piezoelectric wafers are uniformly bonded in the axial direction at the same circumferential angle as the excitation piezoelectric wafers as a guided wave sensor array. The circle near the short leg serves as the excitation array end S1, the circle near the long leg serves as the receiving array end A1, and the middle circle serves as the excitation array end A2.

Figure 4 Schematic diagram of the damage site of the pipe

The parameters of the damage monitoring equipment are set as follows: center frequency, f=150kHz; number of cycles, N=12; amplitude, A=350V; sampling frequency, Fs=12M/s; number of sampling points, Ns=8000.

3.3. Test results and discussion
In this experiment, the end-face echo and damage echo signals identified by the monitoring system are shown in Figure 5. By comparing the echo amplitude with the DAC3% curve, the pipe section loss rate of the damaged part can be obtained, and the damage size of the counter bore can be evaluated by simple conversion, and the damage location can be measured by extracting the echo position information.
Figure 5 Visualization results of damage monitoring platform

The damage location and quantitative identification are achieved by comparing the characteristic structure or the attenuation curve of the damage reflection echo of a specific size with the propagation distance. The Distance-Amplitude Correction Curve (DAC) is achieved. The DAC curve is used to set and record the damage threshold. It is generally considered that 100% of the guided wave reflection at the flange corresponds to the 0dB curve; 20% of the guided wave energy reflected at the weld seam corresponds to the -14dB curve; when the damage is 9% of the section loss rate Corresponding to the -26dB attenuation curve, when the damage is 3%, the corresponding -32dB attenuation curve, and when it is lower than -32dB, it can be considered as a noise signal.

According to the geometric size, structural characteristics, service environment, etc. of the pipeline, select the appropriate guided wave detection parameters and excite a single axisymmetric modal guided wave with high signal-to-noise ratio, unidirectional and non-dispersion as much as possible. The wave signal is mapped into the DAC curve to realize the rapid global detection of the pipeline and obtain the damage information.

The results of monitoring damage diagnosis under test conditions are shown in Table 1 and Table 2.

Table 1 Damage location diagnosis results

| No. | Operating condition | Damage location | Positioning | Relative error |
|-----|---------------------|-----------------|-------------|----------------|
| 1   | D1                  | 42.5cm          | 41.7cm      | 1.88%          |
| 2   | D2                  | 42.5cm          | 43.3cm      | 1.88%          |
| 3   | D3                  | 67.5cm          | 67.7cm      | 0.30%          |
| 4   | D3                  | 67.5cm          | 67.7cm      | 0.30%          |
| 5   | D4                  | 87.5cm          | 88.5cm      | 1.14%          |
| 6   | D1+D2               | 42.5cm          | 38.6cm      | 9.18%          |
| 7   | D1+D2               | 42.5cm          | 41.7cm      | 1.88%          |
| 8   | D3+D4               | 67.5cm          | 67.4cm      | 0.15%          |
| 9   | D3+D4               | 87.5cm          | 89.0cm      | 1.71%          |

It can be seen from Table 1 that the average positioning error is 1.0cm, and the maximum positioning error is 3.9cm. The maximum error occurs at the D1 damage position closest to the sensor array. The error value is 9.18%, and the other position errors are all less than 2%.
Table 2: Results of quantitative damage diagnosis

| No. | Operating condition | Actual cross-sectional loss rate | Diagnosed cross-sectional loss rate | Relative error |
|-----|---------------------|----------------------------------|-------------------------------------|----------------|
| 1   | D1                  | 1.06%                            | 1.1%                                | 3.77%          |
| 2   | D2                  | 1.69%                            | 1.78%                                | 5.33%          |
| 3   | D3                  | 1.06%                            | 1.00%                                | 5.66%          |
| 4   | D3                  | 1.69%                            | 1.65%                                | 2.37%          |
| 5   | D4                  | 1.06%                            | 1.09%                                | 2.83%          |
| 6   | D1+D2               | D1-1.06%                         | 1.03%                                | 2.83%          |
| 7   | D2                  | D2-1.69%                         | 1.66%                                | 1.78%          |
| 8   | D3+D4               | D3-1.69%                         | 1.61%                                | 4.73%          |
| 9   | D4                  | D4-1.06%                         | 1.08%                                | 1.89%          |

It can be seen from Table 2 that the average quantitative relative error is 3.46%, the maximum error occurs at the damage of D3, and the error value is 5.66%.

4. Conclusion

Through the arrangement of multi-channel array sensors, the interference caused by the echo from the end flange of the zigzag pipe is eliminated. The damage monitoring device for the zigzag pipe bend is designed and the verification test is carried out. The results show that the ultrasonic guided wave technology has a variety of preset damages in the zigzag pipe. Under the conditions, the accuracy of damage diagnosis is relatively strong. The damage can be accurately located with an average relative error of 2.05%; the average relative error between the damage cross-sectional loss rate estimated by comparing the DAC3% curve and the actual cross-sectional loss rate is 3.46%, and the quantification and positioning accuracy are good.

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