Simulation Research on Defect Detection in Station Process Pipelines using Ultrasonic Guided Waves

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Abstract. COMSOL Multiphysics was used to establish an ultrasonic guided wave detection model of bend pipes to resolve the defect detection challenge presented by gas station process piping, analyzing the propagation characteristics of the ultrasonic guided wave in the pipeline and the influence of its detection defect signal according to different factors. The results showed that the T (0, 1) mode guided wave generated by the sinusoidal current signal at a frequency of 50 kHz propagated along the pipeline axis, displaying a high rate of corrosion defect detection in bend pipes. The intense defect echo signals at excitation frequencies of 30 kHz, 50 kHz, and 70 kHz are compared and analyzed, indicating that the optimal excitation frequency was between 50 kHz and 60 kHz for a pipe with an exterior diameter of 219 mm and a wall thickness of 8 mm. In addition, the echo signals in straight pipes and bend sections were compared and analyzed, showing that the bend characteristics affected defect detection and caused a deviation in the axial positioning of these flaws. Therefore, the larger the distance between the defects and the bend, the larger the deviation of the axial positioning of these defects.

1. Introduction

The process pipelines in a gas propagation station mainly include the inlet/outlet pipelines, blow off pipelines, and vent pipelines. Since the diameters of these pipelines differ, it is impossible to use internal detection to examine their interiors. In addition, most pipelines in the station are located underground, making it impossible for all the pipelines in the station to be examined via traditional non-destructive detection methods [1].

The current non-destructive testing technologies used for pipeline defect detection include leakage flux [2], ray, [3] and ultrasonic [4] methods. Of these, leakage flux and ultrasonic testing denote the primary methods for oil and gas pipeline detection, of which ultrasonic guided wave technology has the absolute advantage in terms of detecting distance. Compared with the point-by-point scanning of conventional detection, ultrasonic guided waves can be used for long-distance pipeline detection due to minimal signal attenuation when propagating in solid matter. Furthermore, the guided wave can detect the liquid-filled pipe since it only conducts in the pipe wall. During the station detection process, it can significantly reduce the excavation volume, shorten the construction period, and save costs. Applying ultrasonic guided waves for detecting station process piping allows production to continue safely.
Rose and Zhao were the first to study pipe bend detection [5, 6]. Aristegui, Lowe, and Cawley tested and studied liquid-filled pipelines, attempting to apply the bending mode guided wave for pipeline detection [7, 8]. Shin and Rose excited the detection ability of non-axisymmetric mode guided waves by controlling the surface loading conditions [9]. Analyzing the guided wave mode before and after the bend, Ding et al. [10] verified that the longitudinal mode of ultrasonic guided waves could be used to detect the pressure bend pipeline. He et al. [11] studied the propagation characteristics of circumferential ultrasonic guided waves in thin-walled tubes. They obtained a relatively simple method for examining circumferential guided waves, verifying the relationship between the wedge angle of the inclined probe, the frequency dispersion phenomenon, and the mode conversion of circumferential guided waves. Combining the chaotic oscillator detection system with ultrasonic guided wave detection, Zhang et al. [12] of Jinan University proposed an effective method to evaluate the detection distance of ultrasonic guided waves that considered the influence of the signal-to-noise ratio, defects, and pipeline parameters.

This paper considered the bend section of the natural gas transmission station as the research object, examining the principle of ultrasonic guided wave detection to identify defects and station process pipelines. COMSOL Multiphysics finite element software was used to establish a model for ultrasonic guided wave detection. An array simulation was performed to detect defects in the process bend piping of the station, analyzing the propagation characteristics of ultrasonic guided waves in the pipeline. The ultrasonic guided wave signals with or without defects were compared and studied while analyzing the influence of these flaws.

2. Theoretical basis for ultrasonic guided wave detection of the station bend pipeline

2.1. Ultrasonic guided wave detection principle for the station bend pipeline

The detection principle for ultrasonic guided wave detection [13] is shown in Figure 1. The probe array emits an ultrasonic energy pulse that encompasses the entire circumferential direction and pipe wall thickness, propagating a specific distance. The same probe array then detects the return signal, identifying any change in the pipe wall thickness, whether on the interior or exterior of the wall, and produces a reflection signal received by the probe array. Therefore, the metal defects on the inner and outer pipe walls caused by corrosion or erosion can be detected. The metal faults can be identified according to the shape characteristics of the pipeline (such as the weld contour) due to the additional waveform conversion signal generated by the defects.

![Image](image-url)

**Figure 1.** The working principle of the long-distance, ultrasonic remote detection method for pipelines

2.2. Group velocity and phase velocity

The phase velocity denotes the propagation velocity of the guided wave at any point in a fixed frequency wave group. In practical engineering, the transducer is typically used for pulse excitation to fix the frequency of the guided wave within a specific range. Group velocity refers to the wave group velocity of the composite wave, consisting of guided waves at different phase velocities, which change continuously [14]. The calculation of the phase and group velocities is shown in formula (1) and formula (2).
2. Where \( C_p \) and \( C_g \) are the phase velocity and group velocity of the guided wave, respectively. \( k \) is the wave number, \( \omega \) is the angular frequency, and \( f \) is the central frequency of the guided wave.

When \( \Delta \omega \) and \( \Delta k \) are close to 0, the group velocity is calculated as shown in formula (3).

\[
C_g = \frac{d\omega}{dk} \tag{3}
\]

According to formula (1) and formula (3), it can be concluded that:

\[
(C_p + \frac{d(C_p)}{dk}) \cdot \frac{d(C_p)}{dk} = 0 \tag{4}
\]

Because \( k = \frac{2\pi f}{C_p} \), it can be deduced that:

\[
C_g = C_p + \frac{d(C_p)}{df} \tag{5}
\]

In practical applications, the group velocity of the guided wave can also be calculated as shown in formula (6).

\[
C_g = \frac{C^2_p}{C_p + \frac{d(C_p)}{df}} \cdot \frac{d(C_p)}{d(d \cdot f)} \tag{6}
\]

Where \( d \) denotes the thickness of a flat plate consisting of a uniform material or the wall thickness of a uniform, circular tube.

When \( C_p = C_g \), it shows that no frequency dispersion phenomenon is evident in the waveform of the mode.

2.3. Frequency dispersion and multimode characteristics of guided waves in a circular tube

Guided wave frequency dispersion characteristics [15] and multimodal properties [16] significantly impact the propagation of ultrasonic guided waves in a pipeline. The frequency dispersion and multimodal characteristics should be examined extensively when selecting ultrasonic guided wave modes for pipeline detection to reduce the attenuation degree of ultrasonic guided waves and improve their sensitivity for identifying defects. The frequency dispersion curve of the guided wave refers to the curve of the propagation velocity of each guided wave mode that changes over time, clearly reflecting the frequency dispersion and multimodal characteristics. The frequency dispersion equation of a guided wave is as follows:

\[
|c_{ij}| = 0 \text{ for } i, j = 1, 2, 3, 4, 5, 6 \tag{7}
\]

Where \( c_{ij} \) is related to the pipe size (inner and outer diameters), the density of the material, the lame constants and, the frequency \( \omega \), and the wave number. The frequency dispersion curves of the group and phase velocities can be drawn by solving the equation.

According to the guided wave frequency dispersion equation, a MATLAB simulation was used to obtain the axisymmetric longitudinal mode frequency dispersion curve of a steel pipe with an exterior diameter of 219 mm and an interior diameter of 104 mm. The group velocity - frequency dispersion curve in a range of 0 kHz ~ 40 kHz is shown in Figure 2 (a), while the phase velocity - frequency dispersion curve is shown in Figure 2 (b).
According to the frequency dispersion curve in Figure 2, the T (0, 1) torsional mode is usually excited in a frequency range of 0 kHz to 400 kHz when applied for detection. Therefore, the guided wave in this range is non-frequency dispersive, while the group velocity does not change in the low-frequency range, displaying a fixed value. Consequently, it is challenging to generate frequency dispersion during transmission, while the wave packet stability is not easily disrupted, which is suitable for long-distance pipeline detection. The most pronounced characteristic of the T (0, 1) mode is that the axial and radial displacement of its particles is all zero and only occurs in the tangential direction throughout the transmission process. This mode displays a unique defect detection ability not evident in any other mode, allowing for any fault to be identified regardless of its type. Therefore, the T (0) mode guided wave is typically used for station pipeline detection. Furthermore, the T (0, 1) mode guided wave displays an extended propagation distance due to a lack of radial displacement and energy leakage. Therefore, this paper mainly analyzes the propagation characteristics of the T (0, 1) torsional mode in the pipeline and its influencing factors.

3. Simulation of the ultrasonic guided wave defect detection system

3.1. Finite element theory of ultrasonic guided wave detection

Finite element analysis is a method for solving the infinite unknown quantity using the finite number interaction element. It is a highly efficient and widely-used numerical analysis method. The control equation of dynamics is solved using the finite element method, as shown in formula (8).

$$M \{\ddot{u}\} + C \{\dot{u}\} + K \{u\} = \{F(t)\}$$

(8)

Where M is the mass matrix, C is the resistance matrix, K is the stiffness matrix, F(t) is the load, u is the degree of node freedom, $\dot{u}$ is the first derivative of u, and $\ddot{u}$ is the second derivative of u.

When the central difference method is used to determine ultrasonic guided wave propagation, the velocity and acceleration at a specific time are expressed as shown in formula (9).

$$a_i = \frac{1}{\Delta t^2} (a_{i-\Delta t} - 2a_i + a_{i+\Delta t})$$

$$a_i = \frac{1}{2\Delta t} (-a_{i-\Delta t} + a_{i+\Delta t})$$

(9)

According to formula (8), the equation of motion at time t can be obtained, as shown by formula (10).

$$Ma_i + Ca_i + Ka_i = Q_i$$

(10)

By introducing the difference scheme of velocity and acceleration into formula (9), the recurrence formula of the upper displacement solution at a discrete time can be obtained, as shown in formula (11).
\[ \left( \frac{1}{\Delta t^2} M + \frac{1}{2\Delta t} C \right) a_{t=\Delta t} = Q_t - \left( K - \frac{2}{\Delta t^2} M \right) a_t - \left( \frac{1}{\Delta t^2} M - \frac{1}{2\Delta t} C \right) a_{t-\Delta t} \] (11)

3.2. Establishing the finite element model of ultrasonic guided wave propagation in the station bend pipeline

In this paper, the COMSOL Multiphysics finite element software is used to model the pipeline [19]. An 8-inch pipeline (an outer diameter of 219 mm and a wall thickness of 8 mm) was used to establish a three-dimensional pipeline model. It was constructed from structural steel, the relevant parameters of which are shown in Table 1.1. The 3D pipeline model is shown in Figure 3.

![Figure 3. Three-dimensional pipeline model](image)

In this paper, the T (0, 1) torsional mode guided wave was simulated by loading the instantaneous tangential displacement function to the end. The loading mode is shown in Figure 4.

![Figure 4. A schematic diagram of the guided wave loading mode of the T (0, 1) torsional mode](image)

The loading signal was sinusoidal and modulated via a Hanning window, concentrating the energy near the center frequency to restrain the frequency dispersion and increase the propagation distance. The loading signal is expressed in formula (12).

\[ f(t) = \begin{cases} A(1 - \cos(2\pi ft / n))\sin(2\pi ft) & 0 < t < \tau \\ 0 & t > \tau \end{cases} \] (12)

Where A is the constant, n is the excitation pulse period, f is the center frequency, t is the time, and \( \tau \) is the pulse time of the excitation signal.

In this simulation, the left end face of the pipe model was used as the excitation end, allowing the guided wave to propagate to the right, while the right end was set as the constraint face to fix its six degrees of freedom, as shown in Figure 5.

![Figure 5. A schematic diagram of the full constraint on the right end face](image)
To simulate the propagation of the guided wave more realistically, the length of the grid cell should be less than 1/8 of the wavelength of the guided wave when dividing the cells. The dividing basis is shown in formula (13).

\[ \Delta L < \frac{1}{8} \frac{\min(C_p)}{f} \]  

(13)

Where \( \Delta L \) is the length of the grid cell, \( C_p \) is the phase velocity of the guided wave, and \( f \) is the center frequency.

The phase velocity of each mode at different frequencies and the grid unit length were obtained according to the frequency dispersion curve. The COMSOL Multiphysics software provides predefined, customized methods for generating the grid. During the process of customizing the grid size, the maximum unit size of the grid was equal to 1/8 of the guided wave wavelength. Figure 6 shows the grid division of the pipeline at an excitation frequency of 50 kHz.

During the finite element analysis, nodes were placed at different positions to receive the guided wave signals of each point, allowing the guided wave to propagate through the entire pipeline model. The time setting is shown in formula (14).

\[ T > \frac{L}{\min(C_g)} \]  

(14)

Where \( T \) is the time, \( L \) is the length of the pipeline model, and \( C_g \) is the guided wave group velocity. To ensure the accuracy of the simulation results, propagation distance of the ultrasonic guided wave in unit time was controlled within the unit grid length. The step size was set as shown in formula (15).

\[ \Delta T < \frac{\Delta L}{\min(C_g)} \]  

(15)

Where \( \Delta T \) is the step length.

3.3. Propagation characteristics of the ultrasonic guided waves in the pipelines

Six nodes were placed at different positions of the pipeline, from A to F, to receive signals from various locations. Points A (E) and B (D) were both one time the pipe diameter at the upstream (downstream) position of the bend, point C denoted the center of the bend pipe, and point F was twice the pipe diameter at the downstream position. The location of the nodes is shown in Figure 7.
3.3.1. The conversion of the $T(0, 1)$ mode guided wave during propagation. The transient tangential displacement excitation signal was applied to the left end of the pipeline at a period of 5 and an excitation frequency of 50 kHz. The time-domain diagram of each point was extracted, as shown in Figure 8.

![Pipeline node setting diagram](image)

**Figure 7.** Pipeline node setting diagram

**Figure 8.** The time-domain diagram of each $T(0, 1)$ mode guided wave point
Figure 8 (a) and Figure 8 (b) show that the T (0, 1) mode guided wave did not exhibit frequency dispersion during propagation at an excitation frequency of 50 kHz. Figure 8 (c) and Figure 8 (d) indicate that the T (0, 1) mode guided wave always remained independent and clear when passing through the bend. According to Figure 8 (e) and Figure 8 (f), the propagation of the T (0, 1) mode guided wave remained independent and clear after passing through the bend. Therefore, the T (0, 1) mode conversion phenomenon after passing through the bend has little influence on pipeline defect detection.

3.3.2. Energy changes in the T (0, 1) mode guided wave in the bend. Figure 9 is a snapshot of the wave field of the propagating guided wave in the pipeline. Figure 9 (a) and Figure 9 (b) show that the energy of the T (0, 1) mode guided wave was evenly distributed in the straight section of the pipe, while no frequency dispersion was evident when propagating in front of the bend. After the guided waves entered the bend, the energy was gradually distributed uniformly from the circumference to the left and right axis, while the energy decreased on the interior and exterior sides, as shown in Figure 9 (c) and Figure 9 (d). Furthermore, the energy was gradually transferred to the outer axis when the guided waves reached the midpoint of the bend, reaching a maximum at the end of the bend. As illustrated in Figure 9 (e) and Figure 9 (f), the energy was first concentrated on the inner axis when the guided wave exited the bend, after which it was evenly distributed along the circumference.

![Figure 9](Image)
The energy curve of each point during the propagation process of the T (0, 1) guided wave is shown in Figure 10. The energy change in the guided wave passing through each point was drawn according to the energy curve of the six nodes, as shown in Figure 11. The energy of the T (0, 1) mode on the outside axis of the bend center reached the minimum value, while the energy at the end of the bend was 4.59 times that at the center. The guided wave of the T (0, 1) mode also focused energy in the bend, making the defects near the left and right axes of the elbow easier to detect. At the end of the bend, the energy was concentrated near point D on the outer axis, but the focused energy was only 1.12 times that at the beginning of the bend. The T (0, 1) mode displayed energy attenuation during the process of passing through the bend.

Figure 10. The energy curves of each node of the T (0, 1) mode guided wave
4. Simulation results of the defective manifold according to different factors

When ultrasonic guided waves are used to identify an in-service pipeline, the frequency, gas flow rate, pipeline characteristics, and buried depth of the pipe affect the detection signal. Therefore, in this paper, the influence of the frequency and pipeline characteristics on the detection signal was simulated and analyzed in T (0, 1) mode, guided wave detection conditions.

4.1. Analysis of the influence of frequency on the ultrasonic guided wave detection signal

The analytical results showed that mode conversion occurred at the bend when the T (0, 1) mode was used for detection. To reduce the impact of the mode conversion phenomenon on the detection signal, a straight section of pipe section without bends was selected for the experiment. The COMSOL Multiphysics software was used to establish the straight pipe model with defects, with an outer diameter of 219 mm, a wall thickness of 8 mm, and a length of 2 m. The defect position was 0.8 m from the left excitation source, and the depth was 4 mm, as shown in Figure 12. The T (0, 1) mode ultrasonic guided wave was excited at the left end of the pipe, and the receiving and exciting are at the same end.

The excitation frequencies were 30 kHz, 50 kHz, and 70 kHz, respectively. The obtained defect echo signals are shown in Figure 13, Figure 14, and Figure 15, respectively.
A comparison between Figure 13 and Figure 14 showed that the defect echo signal amplitude was lower at an excitation frequency of 30 kHz than at 50 kHz. Comparing Figure 14 and Figure 15 indicated clutter interference after the defect echo at a frequency of 70 kHz. This could be attributed to the fact that the ultrasonic guided waves in the defect displayed mode conversion, resulting in an asymmetrical mode echo, which was enhanced by a rise in frequency, leading to signal interference. Therefore, when ultrasonic guided waves were used at a low frequency for pipeline detection, their ability to detect distant defects was weak. However, higher detection frequencies did not automatically enhance the detection resolution and effect. When the frequency is increased, the distinct echo of the defects and welds may display clutter interference, increasing the attenuation degree of the guided wave, elevating the defect detection difficulty, and reducing the effective detection distance. For the pipe with an outer diameter of 219 mm and a wall thickness of 8 mm, the optimal excitation frequency ranged between 50 kHz and 6 kHz.

4.2. **Influence analysis of the bend characteristics on the ultrasonic guided wave detection signal**

A pipeline exhibits many characteristics, such as branch pipes, welds, and bends. The energy attenuation and mode conversion phenomena displayed by ultrasonic guided waves in a bend significantly affect the detection signal. Therefore, this paper analyzed the influence of pipe bends on ultrasonic guided wave detection.
First, a bend model with defects was established, as shown in Figure 16. The outer diameter of the pipe model was 219 mm, the wall thickness was 8 mm, the lengths of the two straight pipeline sections were 1 m each, the bend radius was 1.5 D, the defect distance from the left end was 0.5 m, the defect depth was 1.5 mm, and the axial length was 10 mm.

![Bend model with defects](image)

Figure 16. Bend model with defects

During the detection process, the surface conditions of the pipe on both sides of the bend were not completely consistent, while the influence on the guided wave attenuation was also different. To control the variables and observe the effect of the guided waves on defect detection before and after passing through the bend, the cross-detection was selected at both ends for simulation. The T (0, 1) mode guided wave was excited at both ends of the pipeline using the same end excitation and receiving mode, at an excitation frequency of 50 kHz. The echo signal obtained via two simulations is shown in Figure 17 and Figure 18.

![Echo signal diagram](image)

Figure 17. The echo signal diagram of the first excitation
Figure 18. The echo signal diagram of the second excitation

As shown in Figure 17 and Figure 18, when the guided wave encountered a defect before passing through the bend, the defect echo was clear, the signal strength was high, and it was easy to identify. When the defect occurred near the end of the bend, the echo signal of the defect was disordered, and the intensity was significantly reduced, making it difficult to distinguish the defect from the echo signal of the bend. Therefore, the mode conversion and energy attenuation of the guided wave passing through the bend affect the amplitude of the reflected echo, making the defect challenging to detect. Furthermore, the axial location of the detected defect was affected, that is, the more extensive the distance between the defect and the bend, the more significant the deviation of the axial location of the defect.

5. Conclusion

(1) The propagation process is simulated using the finite element method, and the propagation characteristics of ultrasonic guided waves in the pipeline are analyzed. The COMSOL Multiphysics finite element software is used to simulate the propagation process of ultrasonic guided waves in a pipe with a bend to obtain the mode conversion and energy change in T (0, 1) mode guided wave in the pipeline. The mode transition of the T (0, 1) mode guided wave at the bend is not obvious, continuously maintaining a clear and independent state. When the T (0, 1) mode guided wave enters the bend, the energy is first concentrated to the left and right axis and then to the outside axis, after which it is gradually distributed uniformly along the circumference after passing through the bend. Therefore, it exhibits a high detection ability for corrosion defects on both sides of the bend and inside the pipeline behind the bend.

(2) The influence of the frequency on the ultrasonic guided wave detection signal is examined. At a low frequency, its ability to remotely detect the defect is weak. However, higher detection frequencies do not necessarily enhance the detection resolution and effect. When the frequency is increased, there may be clutter interference in the characteristic echo, such as defects and welds. Moreover, the attenuation degree of the guided wave increases, elevating the defect detection difficulty and reducing the effective detection distance. For a pipe with an outer diameter of 219 mm and a wall thickness of 8 mm, the optimal excitation frequency ranges between 50 kHz and 60 kHz.

(3) The influence of a bend on the ultrasonic guided wave detection signal is analyzed. When the ultrasonic guided wave passes through the bend, it displays energy attenuation and mode conversion phenomena, leading to a distinct reduction in the defect echo intensity. The bend characteristics affect defect detection and cause deviations in the axial location of the detected defects. Therefore, the more extensive the distance between the defects and the bend, the more significant the deviation in the axial location of the defects.
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