Study on the Response Law of Pipeline Damage Size based on Ultrasonic Guided Waves

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Abstract

To address the difficulty of quantitatively evaluating early-stage damage in in-service metallic pipelines, this study establishes a three-dimensional transient finite element model of a pipeline based on the low-dispersion L(0,2) ultrasonic guided-wave mode excited at 70 kHz. The effects of circumferential damage size, depth, and axial length on echo characteristics are investigated in detail. The results show that, with the damage position kept constant, both the damage echo amplitude and the reflection coefficient increase significantly with the growth of circumferential coverage, while the increasing trend gradually slows in the large-coverage range. When the damage depth increases from 25% to 100%, the reflected echo energy continues to rise, indicating that the L(0,2) mode is highly sensitive to wall-thinning damage. By contrast, when the axial length varies from 1 mm to 5 mm, the reflection coefficient changes only slightly, suggesting that this mode is not sensitive to the axial length of damage. These findings demonstrate that circumferential size and damage depth are the dominant factors affecting guided-wave echo intensity, and they can provide a basis for quantitative damage evaluation and feature selection in pipelines.

Keywords

Ultrasonic Guided Wave; Finite Element Analysis; Pipeline Inspection; Damage Assessment.

1. Introduction

Metal pipelines operating for long periods under corrosion, cyclic loading, and complex media are highly vulnerable to damage such as wall thinning, cracks, and local corrosion. Once such defects continue to grow, they can easily trigger leakage or even rupture accidents, posing a direct threat to the safe operation of petroleum and transportation systems. Compared with conventional ultrasonic and radiographic methods, ultrasonic guided-wave testing offers advantages such as long propagation distance, large coverage in a single inspection, and suitability for rapid online screening. Therefore, it has attracted extensive attention in the field of non-destructive testing for long-distance pipelines [1-2].

The echo characteristics of guided waves are influenced not only by the propagation path but also by the geometric size of damage. Without clarifying the relationship between damage-size parameters and echo intensity, it is difficult to further achieve damage severity evaluation and parameter inversion. Existing studies have mainly focused on guided-wave mode selection, signal processing, and pattern recognition [3-5], whereas a compact summary of the effects of circumferential size, damage depth, and axial length under the L(0,2) mode still has clear engineering significance. On this basis, a three-dimensional finite element model is established in this paper to analyze the relationship between pipeline damage-size parameters and guided-wave response.

2. Principle of Pulse Eddy Current Testing

Under 70 kHz excitation, the axisymmetric L(0,2) mode in the pipeline exhibits low dispersion and is suitable for long-range inspection. In this study, the pulse-echo method is adopted. A piezoelectric transducer emits a narrowband wave packet into the pipeline, and the guided wave propagates along the axial direction. When it encounters damage, reflection, transmission, and scattering occur. The corresponding echo signals are then collected at the receiving end through a multi-channel piezoelectric array.

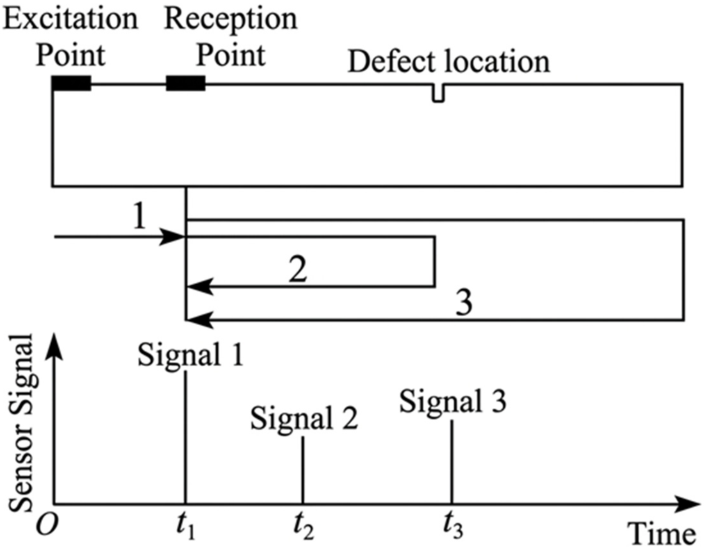

Fig 1. Schematic diagram of ultrasonic guided-wave inspection

3. Finite Element Model and Parameter Settings

Table 1. Key simulation parameters

Parameter	Value	Parameters	Value
Pipe outer diameter	73 mm	Pipe wall thickness	5.5 mm
Pipe length	1050 mm	Excitation frequency	70 kHz
Number of excitation cycles	5	Damage location	550 mm
Number of receiving channels	8	Excitation/receiving mode	Array piezoelectric transducers

Fig 2. Pipeline model

A three-dimensional transient finite element model of a straight pipe was established using COMSOL Multiphysics. An externally attached piezoelectric-array configuration was adopted for both excitation and reception. The excitation signal was a 70 kHz sine wave packet modulated by a 5-cycle Hanning window. To facilitate analysis of size-parameter effects, the axial damage position was fixed at x_d = 550 mm. Eight evenly distributed receiving channels were arranged along the pipe circumference. The direct-wave and damage-echo characteristics were extracted from the average of the eight-channel signals. The pipeline model is illustrated in Figure 2, and the key parameters are listed in Table 1.

4. Analysis of Damage-Size Effects

To characterize the damage-response intensity, the reflection coefficient η is introduced as the evaluation index. Here, A1 denotes the average amplitude within the direct-wave time window, and A2 denotes the amplitude of the average signal from the eight channels within the damage-echo time window. A larger η indicates a more pronounced local impedance mutation caused by damage and stronger scattering and reflection effects.

$$\eta = A_2 / A_1 \tag{1}$$

In this paper, the geometric dimensions of damage are described by circumferential coverage ratio B%, depth ratio C%, and axial length La. Under the same damage position, the echo differences among different size conditions are compared. The specific damage-parameter settings are listed in Table 2.

Table 2. Damage-parameter settings

Parameter type	Value range
Circumferential coverage ratio B%	5%,10%,15%,20%,30%,45%,55%,60%,75%,85%,90%,100%
Depth ratio C%	25%,50%,75%,100%
Axial length La	1 mm,2 mm,3 mm,4 mm,5 mm

With the damage depth fixed at 75% and the axial length fixed at 4 mm, the circumferential coverage ratio was gradually increased from 5% to 100%. The simulation results show that the direct-wave segment changes little under different cases, whereas the damage-echo amplitude continuously increases as the circumferential size grows. When the damage occupies only a small circumferential proportion, the echo is weak and can easily be affected by structural ringing and background noise. As the circumferential coverage expands, the damage-echo wave packet becomes progressively clearer, and the reflection coefficient increases markedly.

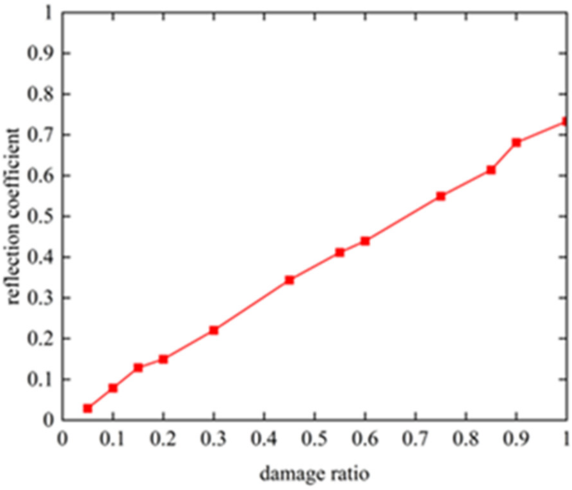

Fig 3. Relationship between circumferential damage ratio and reflection coefficient

From the physical point of view, an increase in circumferential coverage is equivalent to enlarging the effective scattering cross-section encountered by the guided wave over the pipe cross-section, making the local acoustic-impedance discontinuity more pronounced. As a result, more incident energy is reflected and scattered at the damage location. In most of the investigated range, the reflection coefficient shows a good positive correlation with circumferential coverage. However, when the damage gradually approaches full circumferential coverage, the growth trend slows down, indicating that the scattering cross-section is approaching saturation. Therefore, circumferential size can be regarded as one of the key sensitive parameters governing the echo intensity of the L(0,2) mode.

With the circumferential coverage ratio fixed at 30% and the axial length fixed at 4 mm, the damage depth was increased from 25% to 100%. The results show that, as the depth increases, both the extent and gradient of the high-stress region near the damage become more pronounced, and the damage-echo amplitude received at the receiver increases continuously. This indicates that the L(0,2) mode is highly sensitive to wall-thinning damage. The essential reason is that, as the damage deepens, the local effective cross-sectional area is further reduced, the abrupt change in pipe-wall stiffness and the degree of acoustic-impedance mismatch are intensified, and consequently more guided-wave energy is reflected at the defect.

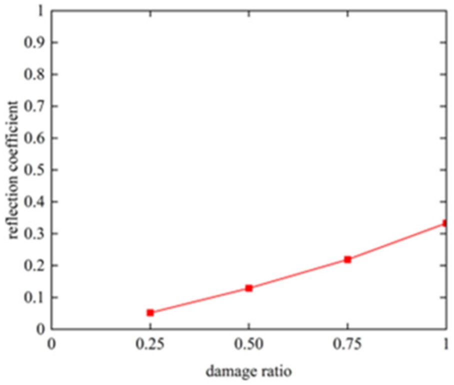

Fig 4. Relationship between damage depth ratio and reflection coefficient

Furthermore, with the circumferential coverage ratio fixed at 30% and the damage depth fixed at 75%, the axial length was increased from 1 mm to 5 mm. The simulation results indicate that the echo waveforms under different conditions are generally similar and that the variation in reflection coefficient is small. This suggests that, within the current size range, the axial length is much smaller than the guided-wave wavelength and is therefore insufficient to significantly alter the instantaneous scattering intensity of the L(0,2) mode. Compared with circumferential size and depth, the effect of axial length on echo intensity is relatively weak, and it should be treated as an auxiliary parameter in practical damage evaluation.

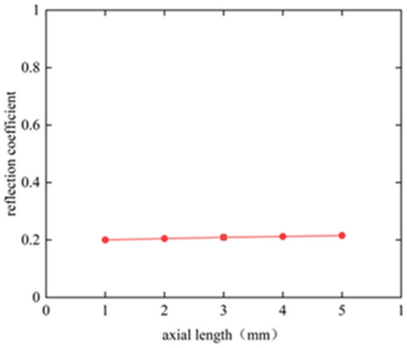

Fig 5. Relationship between axial damage length and reflection coefficient

5. Summary

Based on a three-dimensional finite element model, this paper investigates the relationship between pipeline damage-size parameters and guided-wave response under the L(0,2) mode. The results show that increasing the circumferential coverage ratio significantly enhances the damage-echo amplitude and reflection coefficient, while a gradual saturation trend appears in the large-size range. Increasing damage depth continuously strengthens scattering and reflection effects and is another key sensitive parameter. By contrast, within the range of 1-5 mm, the axial length has only a minor influence on echo intensity. In summary, circumferential size and damage depth should be considered priority features for quantitative evaluation of pipeline damage, whereas axial length can be incorporated as an auxiliary parameter. These findings can provide references for feature selection, damage characterization, and the subsequent development of intelligent identification models in ultrasonic guided-wave inspection.

References

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