Simulation on guided waves in the pipe with defects

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Abstract. In this paper, the finite element numerical simulation is used. The transmission and reflection of both L(0,1) mode and F(1,1) mode of the ultrasonic guided wave were simulated. The transmission and reflection of the ultrasonic guided wave in the pipe were analyzed when the defect in different axial, circumferential, and depth. When the defect's size changes in the axial direction and circumferential direction, the trend of the two kinds modes' reflection coefficient is the same. In a certain size, the reflection coefficient of F(1,1) is higher than the L(0,1). When the depth of the effect change, the trend of the two modes' reflection coefficient is different.

1. Guided Waves in Pipes

Ultrasonic guided waves are produced by multiple reflections and scattering in the propagation medium[1-3]. They were caused by the boundary of the medium. Phase velocity and group velocity are the main parameters of guided waves. The phase velocity is the velocity of a certain point in the wave along the propagation direction of the wave, so it can represent the propagation velocity of a certain point on the phase. Group velocity is the propagation velocity of multiple frequency waves in a dispersive medium[4]. It is the propagation speed of special characteristic points such as the maximum or minimum amplitude point on the propagating wave packet. Group velocity is the propagation speed of the entire wave group, and it is the energy propagation speed[5-8]. Guided waves propagate at the group velocity. It has dispersion and multi-mode two characteristics[9-11]. There are three modes of ultrasonic waves propagating in the pipe, the longitudinal axisymmetric mode L(0,m), the torsional mode T(0,m) and the bending mode F(n,m). The theoretical dispersion curve of guided wave propagation in a Φ20mm×2000mm steel pipe is shown in Figure1 and Figure2. The mode displacement of steel pipe with center frequency 50kHz, diameter 20mm is shown in Figure3 and Figure4.
As can be seen from Figure 1, at the same frequency point, there are many different modes at the same time, as the frequency increases, the more the number of modes, the more complex the wave propagation characteristics in the medium. For example, when the frequency is 50kHz, the propagation modes are longitudinal mode L (0,1), bending mode F (1,1), and torsion mode T (0,1). When the frequency is 200kHz, the number of propagation modes increases to eight. Because the propagation speed is relatively close, the echoes of each mode will be difficult to distinguish. Except for the L (0,1) and F (1,1) modes, there is no cut-off frequency, other modes have corresponding cut-off frequencies. Throughout the propagation process, the L (0,1), F (1,1) and T (0,1) modes have always existed, and as the frequency increases, the T (0,1) mode propagates speed remains the same. L (0,1) and F (1,1) propagation speed changes irregularly. T (0,1) has no dispersion, and its group velocity and phase velocity are equal. There are dispersion phenomena in the propagation of other modes. As the frequency is higher, the dispersion becomes more serious. In the low-frequency range (<100kHz), it can be seen that the L (0,1) mode dispersion is relatively small. And in theory, there are only L (0,1) and F (1,1) modes exist, L (0,1) and F (1,1) modes have a large speed difference, which is easy to identify and analyze in an actual detection.

When the frequency is less than 50kHz, the L (0,1) mode curve is stable, therefore, the dispersion of the L (0,1) mode in this frequency range is very small. The frequency is 50kHz-100kHz, the bending mode F (1,1) curve is stable, so the dispersion of F (1,1) mode propagating in this frequency range is very small. F (1,1) mode radial displacement and axial displacement do not exist. When the frequency range is 0-100kHz, the bending mode has only T (0,1) mode, this is a good frequency band for testing...
using bending modes, but bending modes are difficult to excite and are not applicable in actual testing projects. It can be seen from Figure 2 that the displacement distribution of different modes is different. The radial displacement of the longitudinal mode \(L(0,1)\) gradually increases from the center of the cross-section to the surface of the pipe. The bending mode \(F(1,1)\) axial displacement is greater than \(L(0,1)\) change. The radial displacement of bending mode \(F(1,1)\) does not change much. Vertically, if the bending mode \(F(1,1)\) is selected, the frequency is 100kHz for detection, which has high detection sensitivity, but the detection distance will be small. Therefore, the numerical modeling used in this paper mainly uses the longitudinal guided wave \(L(0,1)\) mode, and the frequency is selected to be 50kHz. This mode can be generated by vertical excitation with a low-frequency straight probe.

2. Model Establishment

According to the pipe size, create the model shown in Figure 5. Defect axial length is indicated by 'a', and the axial corrosion coefficient is defined as the percentage of 'a' vs. wavelength. Defect circumferential length is indicated by 'b', and circumferential corrosion coefficient is defined as the percentage of 'b' vs. the circumference. Defect depth is represented by 'h', and deep corrosion coefficient is defined as the percentage of 'h' vs. the radius. The reflection coefficient \(R\) of the ultrasonic guided wave is defined as \(B(\omega)/A(\omega)\), where, \(B(\omega)\) is the amplitude spectrum of the guided wave echo or defect echo at the end surface, and \(A(\omega)\) is the amplitude spectrum of the excitation signal wave. The larger \(R\) is, the stronger the energy of the reflected echo signal during signal propagation. A modulation signal with an excitation frequency of 50 Hz and a cycle number of 5 is applied to the end face of the pipe with a length of 2 m and a diameter of 20 mm. he propagation process of the ultrasonic guided waves in the rod when there are defects in the rod is shown in Figure 6.

3. Results

Defect depth \(h = 1\) mm, circumferential corrosion is 100\%, axial length corrosion coefficient is simulated according to 10\%, 20\%, 30\%, ..., 90\%. The time-domain waveform of the guided wave propagation when the axial length corrosion coefficient is 90\% is shown in Figure 7, and the relationship between the reflection coefficient and the axial corrosion coefficient is shown in Figure 8.
Figure 7. Waveform with an axial corrosion coefficient of 90%.

Figure 8. Relationship between the reflection coefficient and axial corrosion coefficient.

The change of the axial corrosion coefficient is related to the defect reflection coefficient. When the axial length is greater than 50%, the duration of defect reflection and mode conversion wave becomes longer, the number of converted wave pattern also increases with the increase of the axial corrosion coefficient. This is because as the axial corrosion increases, the front and rear ends of the defect are reflected. From the relationship between the reflection coefficient and the axial corrosion coefficient, it can be seen that the overall trend of defect reflection and waveform conversion wave is consistent, the reflection coefficient of the converted wave is larger than that of the defect, and the reflection coefficient of both does not exceed 25%.

Defect depth $h = 1$mm, axial length is 0.5mm, circumferential length coefficients is simulated according to 12.5%, 15%, 37.5%, ..., 87.5%. The time-domain waveform of the guided wave propagation when the circumferential corrosion coefficient is 87.5% is shown in Figure 9. The relationship between the reflection coefficient and the circumferential corrosion coefficient is shown in Figure 10.

Figure 9. Waveform with circumferential corrosion coefficient of 87.5%.

Figure 10. Relationship between the reflection coefficient and the circumferential corrosion coefficient.

It can be seen from the time domain waveform and the relationship between the reflection coefficient and the circumferential corrosion coefficient that the reflection wave of the defect becomes larger with the circumferential length, and the reflection coefficient thereof becomes larger, and the reflection coefficient of the mode transition mode also becomes larger. But the reflection coefficient changes in a very small range, its value does not exceed 10%.

Defect circumferential length $a = 0.5$mm, circumferential corrosion 100%, deep corrosion coefficient simulated according to 10%, 20%, 20%, ..., 80%, 90%. The time-domain waveform diagram of the guided wave propagation when the deep corrosion coefficient is 90% is shown in Fig. 11. The relationship between the reflection coefficient and the deep corrosion coefficient is shown in Figure 12.
Different depths have different reflection coefficients. As the coefficient of depth increases, its reflection coefficient also tends to increase. According to the size of the reflection coefficient, the depth of corrosion can be quantitatively analyzed. When the depth coefficient is 60%-80%, in the time-domain waveform, the amplitude of the first end echo is small, and the converted mode wave also shows a decreasing trend. The propagation characteristics of F (1,1) reflected waves can be used as a reference, and the corrosion situation cannot be quantitatively analyzed.

4. Conclusion

Numerical simulations verify the ability of low-frequency guided waves to detect small defects in pipes. The echo reflection coefficient changes regularly with the change of axial defects and has good correspondence.

- L (0,1) and F (1,1) modes reflect the same trend when the size of the defect in the pipe is reflected when the circumferential and axial defects change. Regardless of circumferential defects or axial defects, the reflection coefficient of F (1,1) mode is higher than that of L (0,1) mode.

The reflection coefficient of the L (0,1) mode guided wave when the depth defect changes are consistent with the depth transformation, which can better reflect the depth direction of the defect.

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