Study on Guided Wave Characteristics of Waveguide Rod

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Abstract. Waveguide rod is currently used as an auxiliary tool in ultrasonic testing. Because the waveguide rod can isolate high-temperature workpiece from ultrasonic sensor, it is often used in monitoring of high-temperature equipment. However, there are dispersion and attenuation when ultrasonic guided wave propagates in waveguide rod, which is not conducive to the monitoring of equipment. In order to improve the monitoring accuracy, the effects of diameters and lengths on the guided wave characteristics of the waveguide rod were analyzed through numerical calculation and experimental research. The results show that the larger the diameter of the waveguide rod, the smaller the attenuation of the ultrasonic guided wave and the weaker the dispersion; the increase in the length of the waveguide rod has no effect on the dispersion of the guided wave, but it will increase the attenuation.

1. Introduction

When the production equipment is running in high temperature environment, serious corrosion will occur due to various factors. For example, high temperature pipelines in petrochemical industry will be corroded and worn due to high temperature and other factors [1]. As a result, the wall thickness of the pipeline is reduced, and even leaks may occur in severe cases. According to the characteristics of the corrosion mechanism of the oil refining device, its corrosion rate is greatly affected by temperature and pressure, especially in high temperature parts, which affects the safe operation of the device [2]. Therefore, it is of great significance to monitor the thickness of these devices and understand their running status in real time to ensure the safety of production.

Ultrasonic thickness measurement is a kind of widely used thickness measurement method. It is used in material thickness measurement and equipment thickness monitoring due to its strong penetrability, high energy and good directivity. In ultrasonic thickness measurement, the piezoelectric sensor should be attached to the surface of the workpiece to be measured. However, the working temperature of the general piezoelectric sensor is in the range of 0°C~60°C. When the temperature approaches or exceeds the Curie’s temperature of the piezoelectric wafer, the piezoelectric effect of the piezoelectric wafer will disappear. Ultrasonic guided wave (GW) testing is a new detection technology, which uses waveguide rod (WGR) to detect high temperature workpiece. As a medium of ultrasonic transmission, WGR can isolate the influence of high temperature on ultrasonic sensor. Shi [3] used partially welded waveguide rods to measure the thickness of high-temperature pipelines. Because of the attenuation and dispersion characteristics of ultrasonic GW, the received echo signal is unclear or noisy when ultrasonic waves propagate in WGR. Bartoli [4] studied the propagation characteristics of low frequency GWs in steel strands. Pavlovic [5] studied the attenuation
characteristics of ultrasonic guided waves of rods embedded in cement. In this paper, the effects of the length and diameter of WGR on the GW characteristics are studied by numerical calculation and experiment.

2. Ultrasonic GW Theory of Longitudinal Mode

When ultrasonic longitudinal wave propagates in WGR, it will reflect at the boundary of the rod, thus forming a series of transverse wave and longitudinal wave. The superposition of these waves forms the GW in WGR. In an isotropic elastic medium, the motion of each particle satisfies the Navier-Stokes equation of motion [6]:

\[(\lambda + \mu) \nabla (\nabla s) + \mu \nabla^2 s = \rho \frac{\partial^2 s}{\partial t^2}\]

(1)

where, \(\lambda\) and \(\mu\) is the Lamé constants; \(s\) is the particle displacement vector; \(\rho\) is the medium density, kg/m\(^3\); and \(t\) is the time, s.

As the longitudinal mode guided waves propagate in the rod only have axial and radial components, which are axisymmetric waves. The Pochhammer frequency equation can be obtained by substituting the boundary conditions into the wave equation of longitudinal GW [7]:

\[
\frac{2\alpha}{R} \left(\beta^2 + k^2\right) J_1(\alpha R) J_0(\beta R) - \left(\beta^2 - k^2\right) J_0(\alpha R) J_1(\beta R) - 4k^2 \alpha \beta J_1(\alpha R) J_0(\beta R) = 0
\]

(2)

\[
\alpha = \frac{\omega^2}{c_p} - k^2, \quad \beta = \frac{\omega^2}{c_s} - k^2, \quad k = \frac{\omega}{c_p}
\]

(3)

where, \(J_0\) and \(J_1\) is the Bessel functions; \(k\) is the wavenumber; \(\omega\) is the angular frequency, rad/s; \(c_p\) is the P-wave velocity, m/s; \(c_s\) is the S-wave velocity, m/s; \(c_p\) is the phase velocity, m/s; and \(R\) is the radius of rod, m.

It can be seen from Eq.(2) that the equation can be regarded as the equation of ultrasonic center frequency \(f\), WGR radius \(R\) and phase velocity \(c_p\) after determining the P-wave and S-wave velocities of WGR. By solving the equation numerically, the relationship between \(c_p\) and \(R\) can be obtained, and the dispersion curve can be drawn, which provides a basis for studying the propagation characteristics of ultrasonic wave in WGR. In reference [8], the dispersion relation curve of steel cylindrical bar is calculated. It can be seen from the results that when the radius of the cylindrical rod is determined, one ultrasonic center frequency may correspond to multiple phase velocities, that is, there are multiple longitudinal GWs in the rod. When ultrasonic wave propagates in the rod, multiple delayed echoes will be generated, which will cause the energy of ultrasonic wave to disperse in each wave and affect the accuracy and sensitivity of ultrasonic sensor detection.

3. Numerical Results

In order to better study GW characteristics, and provide guidance for the design of WGR, the finite element calculation software is used to calculate the process. In this paper the influence of the diameter and length of WGR on the GW characteristics is studied.

3.1. Finite Element Model of Numerical Calculation

Fig.1 is the finite element model of WGR. In order to simulate the excitation of ultrasonic wave, a boundary load along the positive direction of x-axis is applied to the left end surface of a cylindrical rod with equal diameter. The boundary load is a sine function modulated by Hanning window

\[P(t) = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi ft}{n}\right)\right] \sin(2\pi ft) \quad 0 < t < \frac{n}{f}\]

(4)

where, \(n\) is the number of cycles; and \(f\) is the frequency, Hz.
Fig. 2 is the 0.2 MHz, 5 cycles of Hanning window modulation function waveform, the maximum amplitude is 1 Pa. The material of WGR is stainless steel 304. Its density $\rho$ is 7930 kg/m$^3$, Poisson's ratio $\mu$ is 0.2865, and Young's modulus $E$ is 216.9 GPa.

Figure 1. Finite element model of WGR. Figure 2. 0.2MHz, 5-cycle Hanning window function.

3.2. Influence of Diameter on GW Characteristics of WGR

The WGRs with length of 500 mm and diameters of 10 mm, 12 mm, 14 mm, 16 mm, 18 mm and 20 mm are calculated. The axial displacement curve of the particle 50 mm away from the right end face on the center line of WGR is obtained, and the point coordinates are (50, 0, 0). The numerical calculation results are shown in Fig. 3.

Figure 3. Simulation result of displacements in X direction with different diameters.

As can be seen from Fig. 3, three wave packets can be clearly seen when the diameter is 10 mm. With the increase of the diameter, the waveforms become disordered and the width of the three wave packets increases. When the diameter reaches 16 mm, the echo signal is completely submerged in the clutter. After that, the clutter decreases and the echo become clear. From the simulation results, with the increase of WGR diameter, the echo gradually weakened, and the clutter first increased and then gradually weakened. The increase of clutter indicates that the number of modes of ultrasonic GWs increases, that is, the number of modes of ultrasonic GWs increases with the increase of diameter.
With the increase of the number of ultrasonic GW modes, the energy of ultrasonic wave is dispersed into each GW, which leads to the decrease of echo energy and the increase of clutter energy. This is the reason why the waveforms of 10-12 mm and 14-16 mm, 18-20 mm WGRs are obviously different. At the same time, with the increase of the diameter, the phase velocity of each GW gradually approaches a certain value, and the difference between them is small. Therefore, the clutter decreases when the diameter increases to 18-20 mm.

3.3. Influence of Length on GW Characteristics of WGR
The WGRs with diameters of 12 mm and length of 500 mm, 600 mm, 700 mm, 800 mm, 900 mm and 1000 mm are calculated. The axial displacement curve with point coordinates of (50, 0, 0) is made. The results are shown in Fig.4 that with the increase of length, the waveform of the ultrasonic signal does not change, and the amplitude of the echo decreases, indicating that the attenuation of the ultrasonic GW increases. At the same time, with the increase of the length of WGR, the number of GWs does not change, and the clutter does not change, indicating that the length does not affect the dispersion of the GW. So from the simulation results, the increase of the length has no effect on the dispersion of ultrasonic GWs, but it will increase the attenuation.

4. Experiment
A cylindrical rod made by stainless steel 304 is selected as the WGR to study the influence of the diameter and length of WGR on the GW characteristics. An ultrasonic detector TUD300 is used as experimental instrument, and 2.5 MHz single crystal straight probe is selected as ultrasonic sensor.

4.1. Influence of Diameter on GW Characteristics of WGR
The WGRs with length of 500 mm and diameters of 10 mm, 12 mm, 14 mm, 16 mm, 18 mm and 20 mm are selected for the experiment. The results are shown in Fig.5. It is obvious that with the increase of the diameter, the clutter between the primary echo and the secondary echo gradually weakens, and the echo signal becomes clear gradually. Therefore, the increase of the diameter can reduce the
dispersion in the WGR, which is conducive to the thickness detection of ultrasonic. With the increase of the diameter, the gain of the flaw detector decreases from 60 dB to 36 dB, which indicates that the attenuation of ultrasonic GW decreases. Therefore, the increase of diameter is beneficial to the detection of ultrasonic GWs.

4.2. Influence of Length on GW Characteristics of WGR

The WGRs with diameters of 12 mm and length of 500 mm, 600 mm, 700 mm, 800 mm, 900 mm and 1000 mm are selected for the experiment. The results are shown in Fig.6. The results show that the waveforms of different length WGRs are basically the same, but the gain of the instrument increases gradually. Therefore, the length only affects the attenuation of ultrasonic GWs, but has no effect on the dispersion of ultrasonic GWs.
5. Conclusions
(1) The numerical calculation results show that the dispersion of GW increases first and then decreases with the increase of WGR diameter. With the same diameter, the increase of the length of WGR does not change the GW dispersion, but results in the increase of GW attenuation.
(2) The experimental results show that with the increase of the diameter of WGR, the GW attenuation is smaller and the dispersion is less. For the same diameter WGR, the longer the WGR is, the greater the GW attenuation.

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