Assessment of lamination defect near the inner surface based on quasi-symmetric circumferential Lamb waves

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Abstract

Lamination is one of the common defect in the manufacturing process of seamless metallic pipes. It is a sub-surface type defect that mostly occurs in parallel to the pipe surface. In this paper, numerical study of the interaction between the quasi-symmetric circumferential Lamb waves (CL₁ mode) and lamination near the inner surface of an aluminum pipe is presented. A quantitative assessment on the circumferential length of lamination based on numerical B-scans is also performed. Demerging-node method is used to establish lamination defect along the circumference by compiling FE code in commercial software. The interaction between CL₁ mode and lamination in a damaged full circular-pipe can be summarized by changing the transmitter excitation positions in a semi-circular pipe at the main pipe, inner sub-pipe and outer sub-pipe. The wave modes propagating in the semi-circular pipe are confirmed with the help of the results of arrival time. By composing the received waveforms of the corresponding receivers in a semi-circular pipe, the detailed wave mode in a damaged full circular pipe can be obtained. The composed waveforms fit well with the original waveforms in a damaged full circular, and each wave mode is labelled obviously. When the CL₁ mode interacts with the lamination, it undergoes multiple reverberations, diffraction, and mode conversion. Based on the propagation characteristics of the waveform, numerical B-scans are performed on damaged and undamaged pipes for quantitative assessment.

Keywords: finite element, metallic pipe, circumferential Lamb waves, lamination

1. Introduction

Seamless metallic pipes are mostly used in pipeline, especially one used for the conveyance of water, gas and petroleum products. Due to harsh working circumstances, the pipes are easy to failure working, and it is necessary to keep seamless pipes working safely. Once the seamless pipe bursts, it will not only cause economic losses, environmental pollution, but will also cause to a devastating effect on human life. Lamination defect is the most common defect in the manufacturing process of seamless pipe, seriously affecting the product quality. It is a type of sheet-like internal defect, which is mainly caused by the internal cracks, bubbles, non-metallic inclusions in the billet, and usually occurs in parallel with the surface of the pipe [1-2]. The existence of lamination defect decreases the effective thickness of pipe, reduces the mechanical properties such as impact toughness, tensile strength and bearing capacity, which shortens the service life of pipe. Therefore, it needs to develop a new method to achieve effective detection of lamination defect in pipes.
The commonly used lamination defect detection method is ultrasonic bulk wave detection method. Although this method has high detection precision, it needs point-to-point detection, and takes a lot of time, which greatly reduces the detection efficiency.

Circumferential Lamb waves method is a newly emerging inspection technology in non-destructive testing. Circumferential Lamb waves can propagate along the circumference of the pipe, and has low attenuation range. It is especially suitable for the detection of the axial and radial defects. Cheong et al. [3] detected and quantified the axial crack in pipe using circumferential Lamb waves. Liu et al. [4] used circumferential Lamb waves for the detection of axial crack on the outer surface of thick-walled pipe, and improved the defect recognition capability by using amplitude envelop imaging method based on continuous wavelet transform. Satyarnarayan et al. [5] used high order circumferential Lamb waves to identify the corrosion defects on the inner and outer surface of pipe, and obtained the linear relationship between the amplitude of the reflected signal and the defect depth. Liu et al. [6] used circumferential Lamb waves for the detection of inner and outer defects in a thick-walled pipe, using a modified time reversal method. Currently, the inspection of lamination defect with circumferential Lamb waves in a pipe was seldom explored.

Due to the dispersion and multi-mode characteristics of circumferential Lamb waves, it is difficult to identify useful information from the received waveforms. In order to utilize the waveforms and extract information related to lamination defects, it is necessary to better understand the interaction between circumferential Lamb waves and lamination. For this reason, this paper studies the interaction between circumferential Lamb waves and lamination defect near the inner surface of a steel pipe, and performs numerical B-scans on a damaged and undamaged pipe for quantitative assessment on the circumferential length of lamination defect.

2. Principles of Circumferential Lamb Waves and Numerical Modeling

Material properties and sizes of a steel pipe are shown in Table 1. Figure 2 shows the circumferential Lamb wave dispersion curves of phase velocity and group velocity in the steel pipe. According to the order of appearance of each wave mode, the dispersion curves are labelled as CL\_n (where n=0,1,2,…). From the dispersion curves in Figure 2, it can be seen that there are at least two wave modes at an arbitrary frequency. In this paper, only CL\_1 mode interaction with the lamination defect is studied.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$(kg/m³)</th>
<th>Elastic Modulus E(GPa)</th>
<th>Poisson’s ratio $\nu$</th>
<th>Inner radius a(mm)</th>
<th>Outer radius b(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td>7850</td>
<td>206</td>
<td>0.3</td>
<td>100</td>
<td>103</td>
</tr>
</tbody>
</table>
It is already known that the excited CL$_1$ mode not only propagates along the pipe in the clockwise direction, but also propagates in the counterclockwise direction. In order to avoid the superposition of the excited CL$_1$ mode with simultaneous propagation in both directions, a pipe with the circumference of three quarters is chosen to study the interaction between CL$_1$ mode and lamination defect.

As shown in Figure 3, the lamination defect MN is near the inner surface and parallels to the pipe, which divides the pipe into two sub-pipes, the outer sub-pipe and the inner sub-pipe. Lamination defect is modeled by a zero-volume crack, created using demerging-node method. The endpoints of the lamination defect are represented by M (101, $\pi$) and N (101, $\pi/2$) in polar coordinates. According to the displacement wave structures of CL$_1$ mode, a 5-cycle 400-kHz sinusoidal tone burst signal modulated by a Hanning window is selected for approximately symmetrical loading in tangential directions at the end of the pipe (the blue solid line). The generated CL$_1$ mode interacts with the lamination defect and produces different wave propagation phenomena in the main pipe, the outer sub-pipe and the inner sub-
pipe. Then the receiving point \( R_1 (103, \frac{5\pi}{4}) \) and \( R_4 (103, \frac{\pi}{4}) \) on the outer surface of main pipe, \( R_3 (100, \frac{3\pi}{4}) \) on the inner surface of inner sub-pipe and \( R_2 (103, \frac{3\pi}{4}) \) on the outer surface of outer sub-pipe are chosen to receive the propagating waves.

### 3. Analysis and Discussion

In the simulation modeling, the lamination defect divides the main pipe into an inner sub-pipe having dimension \( a=100\text{mm}, \ r=101\text{mm} \) and an outer sub-pipe having dimension \( r=101\text{mm}, \ b=103\text{mm} \). According to the dispersion curves of these pipes, there are only two wave modes (CL\(_0\) mode and CL\(_1\) mode) at 400 kHz. Table 2 shows the group velocities of these two modes in the main pipe, inner sub-pipe and outer sub-pipe, respectively. According to these group velocities, theoretical arrival time is calculated to compare with the numerical arrival time in order to investigate and confirm the circumferential Lamb wave modes propagating in the pipe.

<table>
<thead>
<tr>
<th>Pipe size (mm)</th>
<th>Group velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CL(_0) mode</td>
</tr>
<tr>
<td>Main pipe (( a=100, \ b=103 ))</td>
<td>3195.21</td>
</tr>
<tr>
<td>Inner sub-pipe (( a=100, \ r=101 ))</td>
<td>2812.37</td>
</tr>
<tr>
<td>Outer sub-pipe (( r=101, \ b=103 ))</td>
<td>3123.29</td>
</tr>
</tbody>
</table>

Figure 4 shows the radial and tangential displacements at point \( R_1 \). As shown in this figure, there is a wave packet between the dashed lines, and the corresponding numerical arrival time is 23.0\( \mu \)s. Due to the propagation characteristics of wave reflection, transmission and mode conversion, the new mode CL\(_m\).
generated by CL₁ mode is represented by CL₁CLₘ (where m=0,1). According to the time-of-flight method, the wave mode can be confirmed as the incident CL₁ mode (its theoretical arrival time is 22.322μs). However, after the incident CL₁ mode, there are still two wave packets, which have such small amplitude that the reflected wave modes are not marked in Figure 4. They are the reflected CL₁CL₄ mode (its theoretical arrival time is 54.465μs), and the reflected CL₁CL₀ mode (its theoretical arrival time is 63.698μs), respectively.

Figure 5 shows the radial displacement and tangential displacement of R₂, R₃ and R₄, respectively. As shown in Figure 5(a), there exists wave packets between dashed lines, their corresponding numerical arrival time are 54.7μs and 65.9μs, respectively. It can be deduced that when the incident CL₁ mode meets the endpoint M of the lamination defect, transmission occurs and accompanies with mode conversion in the outer sub-pipe. According to the time-of-flight method, these modes can be confirmed as the transmitted CL₁CL₁ mode (its theoretical arrival time is 53.792μs) and the transmitted CL₁CL₀ mode (its theoretical arrival time is 64.281μs). Figure 5(b) is resembled as Figure 5(a), where the first mode is also confirmed as the transmitted CL₁CL₁ mode (its theoretical arrival time is 53.092μs and numerical arrival time is 54.3μs) and the second mode is confirmed as transmitted CL₁CL₀ mode (its theoretical arrival time is 66.305μs and numerical arrival time is 67.2μs) in the inner sub-pipe. These two transmitted modes continue to propagate along each sub-pipe, interact with the other endpoint N of lamination defect.

As shown in Figure 5(a)-(c), the labelled modes between 80μs and 130μs are also confirmed by time-of-flight method. The received original waveforms of R₂, R₃ and R₄, which in the pipe with the circumference of three quarters, can be equivalent to the superposition of the received waveforms of the corresponding receiving point, when CL₀ and CL₁ mode is excited at the end BC of inner sub-pipe and the end AB of outer sub-pipe. It also can be seen that the composed waveforms (red lines) fit well with the original waveforms (black lines). According to these waveforms, when the circumferential Lamb waves is excited either in the inner sub-pipe or in the outer sub-pipe, the waves propagate forward along the sub-pipe and interact with the endpoint N of the lamination defect, then part of them reflect back in each sub-pipe, part of them turn to the other sub-pipe, the remaining waves transmit in the main pipe, and all of the propagation waves accompany with mode conversion. The reflected wave and turning wave into the inner sub-pipe and outer sub-pipe will continue to propagate along each sub-pipe and meet the end M of lamination defect again. Thus, the interaction of CL₁ mode with lamination defect between the two endpoints, creates a continuously multiple reverberation and diffraction.
Figure 5: Radial and tangential displacements at point (a) R₂, (b) R₃, (c) R₄
The interaction between CL\textsubscript{1} mode and lamination defect is so interesting and intuitive that we can use it to assess the circumferential length of the lamination defect. Figure 6 shows numerical B-scans of the undamaged pipe and damaged pipe, respectively. By the comparison, we can see that there is some difference between the black dashed lines. There is no wave reflection in undamaged pipe, but multiple reflections exist in the damaged pipe. According to the interaction of CL\textsubscript{1} mode with the lamination defect, it can be inferred that the region of lamination defect is stretching from 90° to 180°.

![Figure 6: Numerical B-scans of pipe, (a) radial displacement in undamaged pipe, (b) tangential displacement in undamaged pipe, (c) radial displacement in damaged pipe, (d) tangential displacement in damaged pipe](image)

4. Conclusions

This paper explains the interaction between CL\textsubscript{1} mode and lamination near the inner surface of a pipe using finite element method. In order to avoid the complexity of extracting the useful information from the superimposing waveform, a pipe with circumference of three quarters is chosen. This work shows that when CL\textsubscript{1} mode interacts with the lamination defect, reflected wave, turning wave and transmitted wave will be generated. Multiple reverberations, diffraction, and mode conversion occurs in the lamination region. Based on these propagation characteristics, numerical B-scans are performed on the damaged and undamaged pipes for the quantitative assessment of lamination defect.
Acknowledgements

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References


