Study on Propagation Characteristics of Ultrasonic Guided Wave for EMAT Sensor

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Abstract: Guided wave technology using Electromagnetic Acoustic Transducer has the advantages of withstand high sensitivity, low attenuation, quickly and efficiently detection etc. To effectively detect the defects, it is necessary to study the propagation characteristics of guided wave. In this paper, the dispersion and multimode characteristics of guided waves are studied by the disperse simulation software, and the variation rule of propagation is analyzed by the geometric parameters of plate and pipe. The results show that the dispersion characteristics of guided wave are depended on the material, the thickness and inner diameter, and it is better at lower frequencies and smaller thickness. This is helpful to the selection of excitation mode, operating frequency and transducer structure parameter.

Keywords: Dispersion characteristics, Guided wave, Lamb wave, Electromagnetic ultrasonic, Nondestructive testing.

1. Introduction

The thin plate of less than 6 mm thickness is widely used in the aerospace, automotive, shipbuilding. After the long-term use, the plate will be subject to erosion and corrosion, and often leak accident, which not only caused huge economic losses, but also pollute the environment. Therefore, Non-destructive testing (NDT) of plate-type structure is needed.

The conventional detection methods of DNT include piezoelectric ultrasonic, eddy current, magnetic particle, penetrate, ray detection technology [1]. However, the traditional NDT is by-point detection method, and the detection efficiency is low. The electromagnetic ultrasonic nondestructive testing can detect longer distance, and energy attenuation is small. The particle vibration of ultrasonic guided wave can occur in the inner and outer surfaces and central of the material, which sound field runs throughout the wall thickness, so it can detect each defect of the material [2]. Electromagnetic ultrasonic NDT is commonly used to the detect plate and pipeline in industry.

Ultrasonic guided waves are generated due to the presence of the media boundary. At the surface of an elastic half-space or the two elastic half-space, due to the discontinuity of the media nature, the wave will occur wave converter when being subjected to the reflection or transmission.

Subsequently, the various types of reflection wave and transmission waves propagate respectively at the constant speed. The propagation velocity is only related to the density and elastic properties of the material, and does not depend on the characteristics of the volatility itself, thereby forming the guided wave [3]. Guided waves can be generated in the plates and tubes.
As guided wave propagating in the waveguide, the reflection occurs at the upper and lower interface. The characteristic of the reflected wave depends only on the solid elastic parameters of waveguide and is regardless of the nature of the volatility itself. According to the elasticity theory, when the material properties of the media are constant, the phase velocity and the group velocity of ultrasonic guided wave propagating in the waveguide vary with frequency. This phenomenon is dispersion. The dispersion is an important concept of the guided wave. According to the difference of dispersion reason, it can be divided into physical dispersion and geometric dispersion. Physical dispersion is caused by the characteristics of the media, and geometric dispersion is caused by the geometric effect of the media. Due to the influence of the thickness of the layer, the speed of the wave propagation in the layer is changing with wave frequency. This phenomenon is the geometric dispersion [2].

Dispersion curve is used to describe and predict the relationship among the phase velocity, group velocity, mode, frequency and thickness. Guided wave excitation, reception and defect discrimination are based on the solving of the dispersion equation, drawing and analysis of dispersion curves. The curves of Phase velocity dispersion is helpful to find the excitation condition of desired optimal mode, and the curves of group velocity dispersion can be used to predict the ideal mode propagation velocity [4].

For a steel plate of a certain thickness, there are two or more guided wave modes at each frequency point, and the number of modes of guided wave also increases rapidly with the frequency increasing. The phenomenon is called multi-modal phenomenon of guided wave. Multi-mode characteristics of guided wave cause a lot of trouble in the process of solving practical problems. In the practical application of the electromagnetic ultrasonic flaw detection, it is needed to stimulate a single mode or fewer modes of guided waves, so as to detect plate, rail and pipeline defects effectively.

Since the propagation characteristics of each mode are different, and the different mode is sensitive to different defect, it is important to study the characteristics, excitation and reception of mode. The certain work focus on the propagation characteristics, excitation and receiving of the guided wave and design of electromagnetic acoustic transducer structure. Lowe [4] of Imperial College do a lot of work in guided wave theory, and Lowe calculate the dispersion equation into a general-purpose computer program. The developed Disperse software is used to calculate the dispersion curves of plate and pipeline. Zhengqing Liu [5] of Tongji University studied the characteristics, excitation and vibration displacement changes of Lamb waves in the plate. Shi Yan et al did lamb’s propagation experiment for Electromagnetic Acoustic Transducer (EMAT) in steel plate and pipe, and this work is not enough [6-10]. Songsong Li [11] take advantage of the low-frequency Lorentz force EMAT, by changing the frequency of the transducer signal, effectively excite the desired Lamb wave mode of guided wave. The study proposed the signal-to-noise ratio of A0 mode is greater than the rest of the modes, and the A0 mode is selected to verify the detect capabilities of electromagnetic ultrasonic nondestructive testing. Cun-Fu He, Long-Tao Li et al study the propagation and dispersion characteristic of circumferential guided wave in thin-walled pipes, and identify a single circumferential guided wave mode can be excited in the pipeline [12].

Although the relevant work is already done some, but it is still not perfect. In order to find the ideal guided wave mode to improve the ability of the non-destructive testing of guided wave, it is necessary to discuss the relationship between the dispersion characteristics of the guided wave and the physical and geometric characteristics of the plate and pipe, and analyze the propagation variation of guided wave with the different material, thickness and inner diameter.

2. Basic Theory of Guided Wave in the Plate and Tube

Lamb wave is the most common wave in electromagnetic ultrasonic nondestructive testing. It’s a special the stress wave that is synthesized by the longitudinal and transverse waves in waveguide, in which the thickness and excitation acoustic wavelength are of the same magnitude order [8]. When Lamb wave propagates in the plate, the particles of entire thickness do complex vibration. Its displacement occurs not only in the direction of wave propagation, but also in the direction of the vertical plate. Lamb wave has the two basic types, symmetrical(S) type, and anti-symmetric(A) type, represent with S0 , S1 , S2, ... , Sn and A0 , A1, A2 , ... , An, respectively. The types are determined by the symmetric or anti-symmetric movement of the particles comparing to the intermediate layer of the plate. Symmetrical type refers to which the particle vibrations in the upper and lower surfaces of the sheet are of the opposite phase, while the intermediate form of vibration is coincident with the longitudinal wave. Conversely, in Anti-symmetric type, the particle vibrations in the upper and lower surfaces of the sheet are of the same phase, while the intermediate form of vibration is coincident with the transverse wave.

Reflection occurs in the surface of inner and outer walls when ultrasonic propagating in the tube, forming guided waves as a result of interference. The same phase velocity corresponds to different ultrasonic wave frequencies, which makes guided wave propagating with different modes. As the wave frequency changes, the phase velocity changes, and the guided wave propagation is dispersive. The guided waves in tube have three different propagation modes: longitudinal mode, torsional mode and flexural mode, represented with L(0,m), T(0,m) and...
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F(n,m) respectively, among which the circumferential order n=1,2,3… and the mode number m=1,2,3,….
Circumferential order n indicates the propagation formation when guided waves spiral transmitting around the wall, corresponding to non-axisymmetric mode of guided waves. The mode number m reflects the vibration formation in the thickness direction of the pipe [9]. The longitudinal mode and torsional mode are axisymmetric, while the flexural mode is non-axisymmetric. The formers are all uncounted when n=0 and the latter one is uncounted when n=1,2,3,…It is difficult to describe the above three kinds of mode accurately. When wall thickness is small and radius is large, the L(0,m) mode corresponds to Lamb wave and the T(0,m) mode to SH wave in plate.

The dispersion curves of guided wave only refer to the material own physical and geometric characteristics. Physical properties mainly involve the kind and the main parameters of material. The parameters include the density of material, the longitudinal velocity and shear velocity of guided wave propagating. The geometric feature mainly includes the thickness and inner diameter.

3. Simulation Study on Propagation Characteristics of Guided Wave and Discussion

Guided wave detection technology, with high sensitivity, slow energy decay, many types, quickly, efficiently, etc, has become the main form of nondestructive testing of plates and steel pipes. Guided wave owns multi-modal characteristics and dispersion characteristics, thus, increasing the difficulty of signal excitation, transmission, reception and processing, limiting it’s widely use in industrial production. Therefore, the influencing factors of guided wave propagation are studied to select the ideal mode for effective nondestructive testing of plates and steel pipes.

3.1. Simulation Study on Propagation Characteristics of Guided Wave in the Plate

1) Thickness impact on propagation characteristics of Lamb wave.

Ultrasonic guided waves continuously reflect on the upper and lower surfaces of plate, forming the Lamb waves through interference effect. Therefore, for the determined material of the plate, the plate thickness is the main factor of Lamb wave propagation.

Assuming the object of study is steel plate whose density is 7.932 g/cm³. The longitudinal velocity is 5.96 m/ms, and the shear velocity is 3.26 m/ms. When the thickness of plates are 1 mm, 2 mm, 3 mm, 4 mm, respectively, simulate the phase velocity dispersion curves of Lamb wave within 0-5 MHz.

The results are shown in Fig. 1, which Ai represents the symmetric mode and Si represents the anti-symmetric mode.

Observing the dispersion curve horizontally, we can see that there are only S0 and A0 modes at the low frequency. At the same time, the number of Lamb wave mode is increasing in specific frequency, and the length of Lamb wave modes are closer each other.

Comparing the dispersion curve vertically, when the thickness of plate changes from 1 mm to 4 mm, the frequency band of only existing S0 and A0 modes becomes narrow, and the upper limit frequency becomes low.

It can be concluded as fellows: for the plate of the same material, with the increase of plate thickness, the frequency band of only existing S0 and A0 modes become narrow at the low frequency, and the upper limit frequency become low. In the high frequency band, the number of Lamb wave mode increase in specific frequency, and the length of Lamb waves in different mode are closer each other with the frequency raising.

![Fig. 1. Dispersion curves of Lamb wave propagation in steel plate with different thickness. (a) 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm.](image)

2) Material impact on propagation characteristics of Lamb wave.
For a plate of the same thickness, Lamb wave dispersion curves have essential differences due to the difference in materials selecting, the density of the material, the longitudinal velocity and shear velocity of the guided wave propagation.

The thickness of each plate is assumed to 1 mm, measure the dispersion curves of steel plate, aluminum plate and copper plate within the frequency range of 0-10 MHz. The parameters are shown in Table 1. The simulation results are shown in Fig. 2.

### Table 1. Reference of plate parameters setting with thickness is 1 mm.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$V_l$ (m/ms)</th>
<th>$V_s$ (m/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.932</td>
<td>5.96</td>
<td>3.26</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.7</td>
<td>6.32</td>
<td>3.13</td>
</tr>
<tr>
<td>Copper</td>
<td>8.4</td>
<td>4.4</td>
<td>2.2</td>
</tr>
</tbody>
</table>

$V_l$ is Longitudinal Velocity, $V_s$ is Shear Velocity.

In Fig. 2 the frequency of range is 0-2 MHz when there are only A0 and S0 mode for steel plate. For copper plate, the range is 0-1.2 MHz. A0 mode Lamb wave phase velocity is 0.3 m/ms when the frequency is close to zero for steel plate, and S0 mode Lamb wave phase velocity is 5.5 m/ms. So it is easy to distinguish wave mode for in range of low than 2 MHz for steel. For copper plate, there is only S0 mode Lamb wave, the phase velocity is 3.8 m/ms when the frequency is close to zero. In the high frequency band, it’s obvious that the mode number of copper plate in any frequency point is more than the number of the steel and aluminum plates in the same frequency.

It can be seen that compared to copper plate, the mode number of steel and aluminum plates is smaller in the same frequency. Therefore, steel and aluminum plates are more suitable for nondestructive testing.

### 3.2. Simulation Study on Propagation Characteristics of Guided Wave in the Pipe

1) Steel pipe wall thickness impact on propagation characteristics of guided wave

Assuming the object of study is steel pipe whose density is 7.932 g/cm$^3$ and the inner diameter is 50 mm. When propagating, the longitudinal velocity is 5.96 m/ms, and the shear velocity is 3.26 m/ms. When the wall thickness of pipe are 1 mm – 4 mm, respectively, measure the guided wave dispersion curves within 0-5 MHz. The results are shown in Fig. 3.

[Fig. 2. Dispersion curves of Lamb wave propagation in 1 mm thickness plate. (a) Steel, (b) Aluminum, (c) Copper.]

[Fig. 3. Guided wave dispersion curves in steel pipe with inner diameter is 50 mm. (a) Wall thickness is 1 mm, (b) 2 mm, (c) 3 mm, (d) 4 mm.]

Observing the dispersion curve horizontally, it is shown that there are only L(0,1) and L(0,2) mode at low frequencies. The number of guided wave mode is increasing with frequency.
Comparing the dispersion curve vertically, when the wall thickness of steel pipe changes from 1 mm to 4 mm, the frequency band of only existing L(0,1) and L(0,2) modes becomes narrow, and the upper limit frequency becomes low. A relationship between the narrowing of frequency band and the increasing of wall thickness is nonlinear. At the same time, the number of guided wave mode is increasing in specific frequency, and the dispersion curves become more intensive and complex. The data of dispersion curve with different wall thickness is shown in Table 2.

Table 2. Dispersion curve data in steel pipes with different wall thickness.

<table>
<thead>
<tr>
<th>Wall thickness</th>
<th>The frequency band only have L(0,1) and L(0,2)</th>
<th>The number of guided wave mode under 5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>0-1.7 MHz</td>
<td>7</td>
</tr>
<tr>
<td>2 mm</td>
<td>0-1 MHz</td>
<td>14</td>
</tr>
<tr>
<td>3 mm</td>
<td>0-0.6 MHz</td>
<td>21</td>
</tr>
<tr>
<td>4 mm</td>
<td>0-0.5 MHz</td>
<td>23</td>
</tr>
</tbody>
</table>

2) Steel pipe inner diameter impact on propagation characteristics of guided wave

Assuming the object of study is steel pipe whose density is 7.932 g/cm³ and the wall thickness is 1 mm. The longitudinal velocity is 5.96 m/ms and the shear velocity is 3.26 m/ms. When the inner diameters of pipe are 50 mm, 100 mm, 150 mm and 200 mm respectively, simulate the guided wave dispersion curves within 0-5 MHz. The results are shown in Fig. 4.

From the above simulation, it can be seen that the inner diameter has a great effect on dispersion curves even the wall thickness is stable.

Although the distribution and trend of dispersion curves are approximately invariable, some mode curves appear cut-off with the increasing of frequency. The numbers of cut-off curves are shown in Table 3.

Table 3. Dispersion curve data in steel pipes with different wall thickness.

<table>
<thead>
<tr>
<th>Inner diameter (mm)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cut-off curves (MHz)</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cut-off frequency of L(0,1) mode (MHz)</td>
<td>4</td>
<td>2.3</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Cut-off frequency of L(0,2) mode (MHz)</td>
<td>4</td>
<td>3</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Cut-off frequency of other modes (MHz)</td>
<td>3.5</td>
<td>2.9</td>
<td>4.8</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Analyzing the dispersion curve vertically, when the wall thickness of steel pipe is same and the inner diameter changes from 50 mm to 200 mm, some modes which can be stimulated at low frequencies can’t exist at high frequencies any more. With the increasing of inner diameter, the cut-off frequency points of these curves become low.

Fig. 4. Guided wave dispersion curves in steel pipe with wall thickness is 1 mm, inner diameter is (a) 50 mm, (b) 100 mm, (c) 150 mm, (d) 200 mm.

4. Conclusions

In this paper, we simulate the guided wave dispersion curves and study the effect factor of the dispersion of guided wave propagation. The simulation result shows that the dispersion and multimodal characteristics are better in the steel and aluminum plates of smaller thickness, and the phase velocity of S0 mode is bigger at the low frequency. Thin steel pipe owns good dispersion property and multimode characteristics, especially the L(0,2) mode, reducing the difficulty of signal processing. At the same time, from the phase velocity dispersion curves, it is shown that the cut-off frequency and phase velocity in a specific frequency of each mode provide the fundamental basis for selecting transducer parameters, working point of guided wave and excitation frequency. This study has guiding significance for the nondestructive testing of ultrasonic guided waves using EMAT.
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