Use of Lamb Waves High Modes in Weld Testing

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Abstract
It is well known the use of ultrasonic waves in weld testing. The most popular ultrasonic techniques are the transversal waves with a single transducer and longitudinal waves for the case of TOFD. One alternative is the use of fundamental Lamb waves with the advantage that they can be used far from the weld. However, the low frequencies associated with these fundamental modes are not suitable for high resolution testing. In this paper the use of overtones modes in weld testing, with high phase velocities were studied. A phase velocity method was used to identify the different Lamb mode echoes obtained from edges, weld and a notch in a 5 mm thickness plate.

Keywords: Lamb Waves, Ultrasonic Guided Waves, Weld Inspection.

1. Introduction

Ultrasonic Testing is a well-established technique for the flaw detection in welds. At the beginning, a simple transducer working in pulse-echo mode used to be used. Currently, Phased Array and TOFD techniques are used in weld testing routinely. The change from an A-scan to tri-dimensional imaging presentation has been determinant in the increasing acceptance of the ultrasonic technique.

All these techniques have the common characteristic that should be applied relatively close to the welds. There are several industrial applications where it is advisable to monitor (from a distance) structures or even industrial processes. An example of this is the online monitoring testing during a welding process.

Guided waves in plates (plate waves) using the SH and SV modes are a possible solution for long range monitoring applications. In the case of SH mode propagation, the oscillation of particles is parallel to the plate element while for the case of SV modes the movement is perpendicular. This last case is known as Lamb waves and it could be presented in two ways: symmetrical or anti-symmetrical. The Figure 1 shows a drawing of these modes [1].

Lamb and SH waves have the advantage that its stress field covers all the plate between the two boundary conditions. This is very convenient for testing if we compare to the classic methods using transversal wave transducers. Another advantage is its long-range propagation property with low attenuation. For this reason the plate waves (in SH or Lamb wave modes) are one of the most promising technique for testing the composites plates [2].

Nevertheless, plate waves have the inconvenient of dispersion phenomenon, where the phase velocity and group velocity depend on the frequency and the thickness of the plate. This has a consequence on the form of ultrasonic pulse, which elongates when it propagates through the plate. More problematic are the reflections of these waves with defects and other geometrical features like the own welding. Moreover, mode conversion could be a consequence because of these interactions.
The dispersion for the case of Lamb waves has two fundamental modes: symmetrical $S_0$ and anti-symmetrical $A_0$, which have limit values as the frequency tends to zero. As the frequency increases, other overtones appear at specific values. The classical recommendation for plate wave applications, the frequency ranges should be low enough to avoid overtones, which are often considered a complication for NDT purposes.

Additionally, using a low frequency range to avoid overtones implies a long wavelength and a low resolution for flaw detection in plates. The aim of this paper is to analyze the use of overtones and its interaction with weld defects. A phase velocity method would be used to identify the Lamb modes from reflected echoes [3, 4]. A variable angular transducer of 1 MHz was used in pulse echo testing.

### 1.1 Theoretical Models.

As we describe above, dispersion means a relation between phase and group velocity with frequency and plate thickness. In Figure 2 we show these relations using the Disperse software obtained for our experimental case [5].

The Figure 3 shows the Perspex wedge angle vs. frequency. The red arrow at 1 MHz points to the direction of the increased phase velocity. This result could be also obtained from the Snell law [6]. This means that the $A_0$ has the lowest velocity and the $A_2$ has the highest velocity. As we can observe $A_2$ is the highest possible mode with a 1 MHz transducer in our case. Curiously, the group velocity does not show the same monotonically increasing functions like the phase velocity.

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$^1$ Also for SH modes.
Figure 2. Theoretical curves obtained from Software Disperse. Upper: Phase velocity vs. Freq. Lower: Group velocity vs. Freq. It was obtained for a steel plate with 5 mm thickness. The red line shows the transducer frequency of 1 MHz.

Figure 3. Angle in Perspex vs. Frequency obtained for a steel plate with 5 mm thickness (Disperse). The red arrow shows the transducer frequency and direction of the increment in the phase velocity.
2.0 Experimental Methods.

A steel plate of 60x20x5 mm welded in the middle was used along with a variable angular transducer UWB1-N of 1 MHz from General Electric. Different Lamb wave modes can be tuned using an angular variation range from zero to 66 grades with this transducer.

The transducer was located in three positions:

- At 140 mm from the edge of the plate.
- At 100 mm from the center of the weld.
- At 100 mm from a notch on the center of the weld.

The Figure 4 shows a photo of the experimental setup. The signal reflected from the edge of the plate was used as a reference echo.

![Figure 4. Experimental set up. The red line shows the position of a notch of 0.5 mm width and 1 mm depth.](image)

An Olympus flaw detector Epoch 600 was used as an ultrasonic pulser-receiver. At each tuned angle, the transducer was moved away from the initial point to 140 and 100 mm respectively. The corresponding time to the maximum amplitude echo was measured each 5 mm every time. Depending if the group is less or greater than the phase velocity this maximum value should be chosen at the head or at the tail of the pulse. The phase velocity method can be shortly described calculating the inverse of the slope in the linear dependence (measured time vs. distance) using the Least Square Method [3, 4].
3.0 Experimental Results and Discussion.

It is shown in Figure 4 the A-scans obtained for the three experimental conditions (explained above), with several tuned angles.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Edge</th>
<th>Weld</th>
<th>Notch on the weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 $A_0$</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>60 $S_0$</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>40 $A_1$</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>30 $S_1$</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>20 $S_2$</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 5. A-scans obtained at different tuned angles using three experimental conditions: reflection from the edge, reflection from welding and reflection from the notch on the welding. The modes were identified using the experimental phase velocity method [3, 4].

In Figure 5, the white arrows show the reflected echoes from the edge. The phase velocity method was applied to identify the modes and any possible converted modes. The red arrows show the weld reflected echoes and the blue arrows the notch reflected echoes.

In Figure 6, it is shown a graph of the distance vs. time relation. This relationship has been modified to zero time origin for comparison. Two experimental cases are shown: the reflected edge echoes case and the reflected weld echoes case. It is clear the increment of the slope (velocity) according to the mode tuned at a given angle.
Finally, the Table 1 shows a comparison between the theoretical phase velocity results and the experimental values. The experimental values were obtained from the results shown in Figure 5. According to Table 1, it is possible to conclude that modes can be truly identified using the phase velocity method. Converted modes from weld were not presented in these experimental conditions for the first echoes. At the other side, from Figure 6 it is possible to compare the echoes from weld relative to the notch. The flat condition of the dispersion curve of $A_1$ mode at 1 MHz has a little consequence over the increased weld thickness in comparison with the notch case.
Table 1. Phase and Group Velocity using the Disperse Software [5].
Phase velocity from experiments. Frequency 1 MHz.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Angle</th>
<th>From Disperse (m/s)</th>
<th>Experimental (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Phase Velocity</td>
<td>Group Velocity</td>
</tr>
<tr>
<td>A0</td>
<td>66</td>
<td>2987</td>
<td>3097</td>
</tr>
<tr>
<td>S0</td>
<td>63</td>
<td>3061</td>
<td>2862</td>
</tr>
<tr>
<td>A1</td>
<td>40</td>
<td>4249</td>
<td>2258</td>
</tr>
<tr>
<td>S1</td>
<td>29</td>
<td>5685</td>
<td>4614</td>
</tr>
<tr>
<td>S2</td>
<td>20</td>
<td>7917</td>
<td>3433</td>
</tr>
</tbody>
</table>

4.0 Conclusions.

Higher Lamb modes are useful to identify defects in welds and these modes can be identified using the phase velocity method. The best condition will be those were the phase velocity has a high value and a flat condition in the dispersion curve. For this case, the influence of the possible increment in the plate thickness will not affect too much the propagation and a low reflection is expected. It could be possible to obtain echoes only from flaws. For every plate and welding condition, it is convenient to adjust the transducer frequency and to combine with higher modes.

5.0 References.

5. Disperse. NDT Lab Department of Mechanical Engineering Imperial College. Version 2.016d, Jun 2005