NDT AND SHM OF WELDS AND HEAT AFFECTED ZONES USING WELD GUIDED LAMB WAVES

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Abstract
An ultrasonic method is described which exploits the preferential guiding of Lamb waves by the weld region of a steel plate. The method uses symmetric $S_0$ modes, which, by judicious choice of frequency, propagate in the weld and heat affected zone. The method is suitable as a means for NDT and SHM of cracks and corrosion in the weld region using either edge mounted or small, inexpensive, low profile permanently mounted surface transducers.

Keywords:
Welds, Lamb waves, corrosion, weld guided waves.

1. Introduction

This paper summarises work on the use of ultrasonic Lamb waves for the detection of corrosion type defects in welded steel structures. Ultimately, it is hoped this will improve the efficiency with which tanks used for the storage of water, ballast or fuel may be inspected for corrosion. Current methods used for inspection require access to the internal surfaces of storage tanks and a visual assessment of corrosion. This is both a time consuming and expensive procedure, requiring emptying of the tanks and inhospitable working conditions. An alternative to local inspection is to use guided waves to inspect large areas from a single sensor.

Complications associated with guided wave inspection arise because, in general, the waves propagate with different velocities at different frequencies (i.e. dispersion), and also because the excitation and reception of unwanted modes result in overlapping and confusing signals. Typical practical problems associated with the use of guided waves also arise from reflections from plate edges, the presence of stiffeners, the presence of imperfections in the welds, joints, and thickness changes.

It is commonly accepted [1] that the weld joint is the most critical area from a performance perspective, because many detrimental features can occur; these include changes in microstructure, welding imperfections and the presence of residual stress. It is also believed [2], that these imperfections can result in selective corrosion, either in the weld itself or in the heat affected zone (HAZ) adjacent to the weld. The work described here shows how corrosion-like defects may be detected in a weld region using $S_0$ Lamb waves. This uses both edge and surface mounted transducers.
2. Theory

Figure 1 shows the phase and group velocities calculated for both $A_0$ and $S_0$ as a function of frequency for a 6 mm thick steel plate. The essential principle exploited here is that preferential guiding occurs within the weld [3]. This arises primarily because of the local increase in thickness of the weld relative to the plate, giving rise to a local decrease in phase velocity relative to the phase velocity in the surrounding plate. It is believed that this results in total internal reflection within the weld, in a manner analogous to that found in optical waveguides. The effectiveness with which the wave is guided will depend partly upon the extent to which the velocity in the plate is less than that in the weld, as determined by the thickness, modulus and density difference, and partly on the mono-chromaticity of the wave-packet. This effectiveness will be indicated by the slope of the phase velocity curve shown for $S_0$ over the range of frequencies comprising the wave-packet. In addition, waveguide efficiency is also likely to be influenced by changes in weld geometry.

A consequence of the slopes of the phase velocity dispersion curves shown in Figure 1 is that only $S_0$ will be guided in this manner in the frequency range used here. This is because of the negative slope in the phase velocity/frequency graph, whereas $A_0$ which has a positive slope with respect to increased thickness will not be guided in this fashion.

3. Specimens

Two test specimens were chosen for evaluation and demonstration of operating principles and performance. These were: Plate 1), a specimen comprising two 1m x 2m x 6mm thick DH grade steel plates butt welded together to give a finished test plate 2m square with a weld having an average thickness of approximately 8mm down the middle. This was a visibly good quality weld with a weld bead formed on both sides of the plate. Plate 2), an intermediate sized specimen comprising two DH steel plates 0.5m x 2m x 4mm butt welded together, with a weld bead on one side of the plate only. In this instance, the weld thickness was approximately 6mm and the weld quality was much poorer in comparison with that for plate 1), with several discontinuous weld regions or flaws visible along the weld bead. This plate probably represented a worst case in terms of weld quality. Both corners of one end of plate 2 were deliberately removed in order to reduce direct reflections originating from the...
plate edges. Transducers were located adjacent to the weld lines at the plate ends at the locations shown in Figure 2. Images of an edge mounted transducer located adjacent to the weld on plate 1, and of surface mounted transducers adjacent to the weld on plate 2 are shown in Figure 3. Part through, and through holes of varying depths and diameter were deliberately introduced either into the heat affected zone adjacent to the weld, or the weld itself in order to simulate the presence of corrosion. Sizes and locations of these holes are also shown in Figure 2.

![Diagram showing plates with dimensions, hole and transducer location.](image)

**Figure 2.** Schematic diagram showing plates with dimensions, hole and transducer location.

![Images showing transducers and holes.](image)

**Figure 3.** (Left) An edge mounted longitudinal wave transducer adjacent to the weld of plate 1, and (right) two surface mounted transducers (10mm diameter) adjacent to the weld of plate 2.

### 3. Experimental method

Essential elements required for a weld guided wave inspection system include the selection of a suitable operating point on the dispersion curve (as shown in Figure 1 and described above), the choice of wavepacket length and cycle content, and practical choices in terms of suitable transducers, waveform generator and amplifier/receivers.

Hanning or sine wave windowed wavepackets comprising between approximately 5 and 20 cycles were chosen for propagation along the weld regions. Figure 4 shows an example of a 13 cycle 200kHz wavepacket used for measurements with plate 2.
With a choice of frequencies of between 160kHz and 250kHz and the range of thickness of noted above for the two test plates implied operating regions on the dispersion curves shown in Figure 1 of between approximately 1MHz mm and 1.75MHz mm.

A convenient method for generating $S_0$ modes is by simply coupling of a longitudinal transducer via a gel couplant to the plate edge. These transducers comprised commercial wide band, low frequency longitudinal wave types. For those circumstances when it was neither possible nor desirable to use edge coupled transducers, for example, in SHM applications when access is frequently only possible to a surface and when permanent installation is required, then surface mounted 1mm thick, “wrap-around” 10mm diameter PZT disks were glued directly to the plate surface adjacent to the weld using an epoxy resin.

The selective excitation and reception of both $S_0$ and $A_0$ modes using PZT disks have been described by, for example, Niuwenhuis et al [5] and Giurgiutiu [6]. Giurgiutiu [6] describes the use of a simplified point force model for the steady state sinusoidal excitation to give the peak and minimum frequencies ($f$) for amplitude in terms of transducer width ($2a$), wave number ($n$) and phase velocity ($v$):

$$f_{\text{min}} = \frac{v \cdot n}{2a}$$  
$$f_{\text{max}} = \frac{v \cdot (n + \frac{1}{2})}{2a}$$  

Thus for example, using a value of 6.2mm for an effective weld thickness with a phase velocity for $S_0$ of approximately 5300ms$^{-1}$ implies a PZT transducer width of approximately 10.6mm for the first maximum at 250kHz. Using a value of 5.1mm for the plate thickness together with a transducer of width 10.6mm and velocity of 2520ms$^{-1}$ implies a maximum for $A_0$ mode at approximately 126kHz, and for a velocity of 2630 ms$^{-1}$ for the effective weld thickness implies a minimum for $A_0$ at approximately 250kHz. In practice, it was found that sufficient output of the $S_0$ was obtained at frequencies extending to below 200kHz. Thus, with a single PZT transducer with width of ~10mm, it should be possible to obtain sufficiently pure $S_0$ modes at between ~250kHz - 200kHz, whilst suppressing the generation of $A_0$.

Excitation and reception of wave packets was via either a “Wavemaker duet” pulser receiver, or a PCI arbitrary waveform generator, A to D converter, band filtered pre-amplifier and laptop for waveform storage and analysis. Excitation and reception was via either a single transducer in a pulse-echo configuration for the Wavemaker, or a pitch catch arrangement using pairs of transducers for the arbitrary waveform generator and A to D converter system. Averaging was employed to reduce random noise, and digitisation artifacts from the A to D converter were removed by FFT narrow band filtering of the received signals at the excitation frequency.
4. Results

Figure 5 shows waveforms received in pulse-echo mode for plate 1, with an edge transducer located at approximately 20mm intervals either side of the central weld (i.e. between x = 900 and x =1100 as shown in Figure 2) and with a 20mm diameter through hole in the heat affected zone, adjacent to the weld, at a distance of 1.5m from the transducer. In this instance, excitation was via a 20 cycle, 200kHz wavepacket.

A careful inspection of Figure 5 shows discrete reflections originating from the hole and the plate end, with propagation both along the weld and heat affected zone (as seen by transducer locations between x =940 and x =1040) and in the plate itself. The plate end reflections indicated a weld group velocity of approximately 4740ms⁻¹ and a plate group velocity of 5050ms⁻¹.

![Waveform diagram](image)

Figure 5. Detailed time traces recorded adjacent to the weld of plate 1 as a function of location for the single edge mounted transducer, showing 6mm hole and plate edge reflections. S₀, 200kHz, 20 cycle toneburst.
Because detailed results using the single transducer were only obtained after completion of the 6mm through thickness hole, a new 2mm deep flat bottomed hole was drilled adjacent to the weld, halfway along the plate length at the location shown in Figure 2. Figure 6 shows results using two different longitudinal wave transducers and a range of different wave packets containing between 10 and 20 cycles, between frequencies of 161kHz and 200kHz. It may be noted that the 2mm depth hole was easily distinguishable from the background. It was estimated that the 6mm through hole, 2mm flat bottomed hole reflection and coherent background noise level had amplitudes of approximately -15.5dB, -22dB and -39dB relative to the rear wall reflections respectively. By also making measurements of hole reflection amplitude at a distance of 0.5m by locating the transducer on the opposite plate edge, it was possible to estimate that there was approximately 2dB loss for the weld guided wave over a propagation distance of 2 metres.

![Figure 6](image)

**Figure 6.** Comparison between the different longitudinal wave transducers using various frequencies, gains and toneburst cycles for plate 1. $S_{th}$. Transducers located at $x=1000$, $y=0$.

Clearly, good results with easily distinguishable reflections from test defects were obtained by using a transducer mounted on the edges of the plate. Also of significant interest is the case when it is not possible to gain access to a plate edge, where it is then necessary to use permanently mounted surface transducers.

For permanently mounted transducers with omnidirectional properties, it is desirable to suppress the background coherent noise level. The technique adopted here was to use a baseline subtraction method. This approach was similar to that suggested by, for example, Clarke et al [7] who used a combination of optimal base-line subtraction and optimal stretch methods to compensate for the influence of temperature on the changes in wave propagation as a result of changes in elastic properties and density.

In order to apply a baseline subtraction strategy, baseline reference waveforms for plate 2 were obtained without the presence of any holes over a range of temperatures between approximately 18ºC and 23ºC. Temperature of the plate was recorded with an accuracy of
approximately 0.1ºC. A hole of diameter of approximately 25mm with gently curved base having successively larger depths was deliberately introduced into the plate. This was at a distance of 1.25m from the transducers at the location shown in Figure 2. Waveforms were obtained over a period of a few days, with waveforms recorded for each hole depth at the same temperatures (to an accuracy of 0.1ºC) as used for the initial baselines. Figure 8 shows the results of subtracting baseline reference waveforms recorded with maximum hole depths at the centre of the hole of a) 2.5mm, b) 3.25mm, c) 4mm with the central region of the hole having just broken through, and d) a through hole.

![Figure 8: Residual waveforms recorded for plate 2 after base-line subtraction using the surface mounted transducers as a function of hole depth for the 25mm diameter hole present at a distance of 1.25m. Same amplitude scales for each trace. a) hole depth 2.5mm, b) 3.25mm, c) 4mm with the central region of the hole having just broken through, and d) a through hole.](image)

Examination of Figure 8 showed that both the through depth and partially breaking hole were clearly visible. It was estimated that the through hole (d), the partially breaking hole (c), and coherent background noise level had amplitudes of approximately -10dB, -14dB and -20dB relative to the rear wall reflections respectively. It was noteworthy that the presence of the hole also altered the phase of the waveform at locations after 0.5ms, with the net result that incomplete cancellation occurred. This is particularly noticeable for the end plate reflection at approximately 0.8ms, with a larger residual signal as the hole depth increased.

In an attempt to estimate the influence of the poor bond line quality and the presence of weld flaws on the signal to noise ratio and coherent background noise level, a further hole was introduced at a distance of 0.75m from the transducer pair. This was approximately 19mm diameter, again with a gently curved base, having a maximum depth of 2.5mm. Figure 9 shows the residual baseline subtracted signal.
Figure 9. Residual waveform recorded for plate 2 after base-line subtraction using the surface mounted transducers for a 2.5mm deep, 19mm diameter hole present at a distance of 0.75m. $S_0$, 200kHz. Same amplitude scale as used in Figure 8. Waveforms recorded at same temperatures.

Figure 10. Left, 19mm, 2.5mm deep hole introduced at a distance of 0.75m from the transducer pair for plate 2. Right, a typical weld flaw for plate 2 at a distance of 0.47m from the transducer pair.

Much better visibility of the 2.5mm deep hole at 0.75m was obtained in comparison with the same depth hole at 1.25m. In this instance, it was estimated that the 2.5mm deep hole had an amplitude of approximately -16.5dB relative to the rear wall reflection. Figure 10 shows both a photograph of the weld hole introduced at 0.75m and also a photograph of a typical weld flaw located at a distance of 0.47m from the transducer.

Possible reasons for the imperfect baseline subtraction seen in Figure 9 include differences of the nominal baseline and hole waveforms measurement temperatures, and the consequence in terms of the presence of weld flaws contributing to the background coherent noise levels. Confirmation that weld defects were probably responsible for the coherent noise levels seen in Figure 9 was obtained by using two edge mounted transducers adjacent to the weld line as shown in Figure 2. The waveform, recorded at 200kHz for this arrangement is shown in Figure 11. Weld flaw reflections are clearly visible.

Figure 11. Waveform recorded for plate 2 containing both holes using the edge mounted transducers $S_0$, 200kHz. Dashed lines show hole locations.
An estimate of the likely influence of temperature on the surface mounted transducers was obtained by deliberately performing a baseline subtraction between the initial plate without a hole and that with both holes by using a temperature difference of 2.0°C. This is shown in Figure 12. Reflections from both the weld flaws and the 2.5mm hole have increased relative to that seen in Figure 9.

Figure 12. Residual waveform recorded for plate 2 after base-line subtraction using the surface mounted transducers for a 2.5mm deep, 19mm diameter hole present at a distance of 0.75m. S0, 200kHz. Same amplitude scale as used in Figure 8. Waveforms recorded with a 2.0°C difference. Dashed lines show hole locations.

A detailed view showing the original phase and amplitude for waveforms recorded with a 2.0°C temperature difference both with and without the holes in the weld flaw region for plate 2 is shown in Figure 13. It is apparent from this Figure that the waveforms for the two cases showed different non-linear time dependent changes in phase and amplitude.

5. Discussion

This study has shown that for good quality welds then it is possible to easily detect a 2mm deep flat bottomed hole at a distance of 1m when using edge mounted transducers. This exploits the waveguide mode of operation in which an S0 Lamb wave preferentially propagates along the weld, and also the directional properties of the transducer which prevent large reflected waves from the plate sides obscuring the waveforms. Based on these results, this suggests that much shallower holes should be detectable at the same distance, or that similar sized defects may be detected at much larger distances, possibly many metres. Although edge mounted transducers are probably preferable since they do not generate confusing side plate reflections, the use of permanently surface mounted transducers can also be used, although the limits on defect detectability will be significantly more influenced by the presence of additional coherent noise because of their omidirectional nature. In these circumstances, temperature related waveform subtraction methods can be employed to reduce
coherent noise. For those situations where inherent flaws are already present in the bond line, then unless the temperatures of reference and test waveform are identical, this will result in imperfect subtraction. This will give some degree of coherent noise because of the non-linear phase and amplitude changes that occur, probably as a result of interference originating from the flaw. This would obscure the presence of defects. In addition, it is possible that other sources of phase and amplitude related errors might also arise. For example, such errors could also originate in electronic time base errors, or temperature and time dependent property changes in the transducer and bond line between the transducer and plate itself. Further work is currently in progress to determine the extent to which these might occur.

It should however be commented, that plate 2 which was used here, presented a particularly poor example of a weld. This probably represented a worst case which would not normally be encountered, and it is likely that a better quality weld would permit reduced coherent noise levels with improved limits on defect detectability.

6. Conclusions

Weld guided modes such as $S_0$ which are guided and propagate preferentially within a weld have been used here to study their potential for corrosion and defect detection in the weld and heat affected zone. It has been shown that with a good quality weld then the wave propagates with little attenuation over considerable distances. In practice, generation and reception via edge mounted transducers, rather than surface mounted transducers is preferable because they are more directional and less susceptible to large interfering reflections, e.g. plate edge reflections. It is also shown that with poorer quality welds and the presence of inherent flaws then this will introduce coherent noise which reduces signal to noise ratios. It is also shown that with permanently mounted transducers then waveform subtraction techniques may be applied. This gives a level of coherent noise proportional to the temperature difference between reference and subtracted waveforms, with contributions from the electronic stability and phase stability of the transducer and adhesive bond. Aspects of the work reported here are the subject of an International Patent Application, Publication Number WO2007/068979.

7. References