

Quantitative Evaluation of Ultrasonic Techniques for the Detection and Monitoring of Corrosion in Pipes

by

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Declaration of Originality

All material contained in this thesis has been conducted independently by myself under the supervision of Dr. Frederic Cegla. All work which has been conducted by other parties and used in this thesis has been fully referenced.

A handwritten signature in black ink, appearing to read 'Richard Howard', with a stylized, cursive script.

Richard Howard

29/09/2017

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Abstract

Corrosion of the oil and gas pipeline infrastructure has the potential to lead to catastrophic consequences, including loss of life. By performing continual diagnostic non-destructive evaluation (NDE) assessments of the pipeline infrastructure, corrosion can be tracked, mitigated and controlled. However, the sheer scale of the modern pipeline networks around the world requires new innovative techniques to efficiently and cost-effectively monitor and screen for corrosion.

Currently there are two well-established ultrasonic techniques for monitoring and screening corrosion. Spot measurements extract the pipe wall thickness at a single point location. This method can extract an accurate value of wall thickness, but the measurement is highly localised. In contrast, long range guided waves (LRGWs) screen for damage by exciting a pulse which travels axially down a pipe and will reflect off any large areas of corrosion. This method has a large coverage area, but is much less sensitive to corrosion than the spot measurement techniques.

The first part of this thesis explores the sensitivity of a circumferential guided wave technique, which is suggested to mitigate against some of the disadvantages of existing methodologies. This method propagates a guided wave around the circumference of a pipe, and uses either the reflected pulse from the defect or the through transmitted pulse, to detect the presence of a defect. The viability of this method was assessed by modelling the ultrasonic response to a range of different defects and using probabilistic techniques. The S_0 , SH_1 and SH_0 modes were studied and it was revealed that in reflection the technique is able to detect narrow and deep defects, whereas in transmission wide defects are detectable. Wavelength normalised results are also presented.

The second part of this thesis investigates the interaction between spot measurement (shear bulk waves) and hemispherical pits. This is with a view to further understanding the mechanics behind the interaction between shear waves and pitting corrosion, and to assessing current transducer types to the tracking and monitoring of individual pits. It was found that an anisotropic relationship exists between the pit's location relative to the shearing direction of the bulk wave. This is due to either the inherent anisotropy of the transducer or the mode conversion of the shear wave.

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Contents

1.1	Industrial Motivation	26
1.1.1	Corrosion in Oil and Gas Pipelines	26
1.2	Overview of NDE Techniques for Corrosion Management	27
1.2.1	Non-Destructive Permanently Installed Corrosion Monitoring Techniques	27
1.2.1.1	Ultrasonic Wall Thickness Measurement	28
1.2.1.2	Potential Drop - Field Signature Method	29
1.2.1.3	Intrusive Physical, Electrical and Electrochemical Techniques	29
1.2.1.4	Acoustic Emission	30
1.2.2	Corrosion Screening Techniques using Long Range Guided Waves	30
1.3	Area of Interest and Project Objectives	31
1.3.1	Corrosion Morphology	32
1.3.2	Corrosion Distribution	33
1.3.3	Coverage Against Sensitivity Trade Off	34
1.4	Outline of Thesis	35
2.1	Introduction	37
2.2	Mechanics of Ultrasonic Bulk Waves	37
2.2.1	Scattering and Mode Conversion	39
2.3	Guided Waves	40
2.3.1	Shear Horizontal Waves	40
2.3.2	Lamb Waves	43
2.4	Finite Element Method	45
2.4.1	Automation of FEA	46
2.4.1.1	Creation of a structured mesh	47
2.4.1.2	Modelling of defects via the changing of the material characteristics of a defect	48

2.5	Summary	48
3.1	Introduction	49
3.1.1	Literature Review	50
3.1.1.1	Guided Wave Measurements for Thickness Evaluation.....	50
3.1.1.2	Guided Wave Tomography	52
3.2	Measurement Principle	52
3.3	Temperature Compensated Average Thickness Extraction Method	54
3.3.1	Effective Group Velocity Extraction Method using SH Guided Waves	54
3.3.2	Average Thickness Extraction Algorithm	55
3.3.3	Temperature Compensation.....	57
3.4	Experimental Validation of Temperature Compensated Thickness Extraction Using the SH Wave	58
3.4.1	EMAT Construction, SH Signal and Beam Shape	59
3.4.2	Temperature Compensation Results	61
3.5	Finite Element Modelling.....	62
3.5.1.1	Simulation of B-Scans using the Finite Element Model	65
3.5.2	Finite Element Convergence using Uniformly Thick Plate	65
3.5.3	Notch Defect of Variable Width.....	66
3.5.4	B-Scan of Finite Width Defects	67
3.5.4.1	In-depth Example B-scan Result from a 60x1mm Hann Profile Defect	67
3.5.4.2	Finite Element Results of a Wide Range of Defect Dimensions.....	68
3.5.5	Discussion on Interaction of Finite Width Defects and SH Waves	70
3.5.5.1	Experimental Validation of B-Scans	71
3.6	Conclusion	72
4.1	Introduction	74
4.1.1	Overview of Guided Wave Reflection Literature	76
4.2	Overview of Model Setup.....	77
4.2.1	Finite Element Model.....	77
4.2.2	Defect Profiles and Dimensions Modelled in the Finite Element Model	78

4.3	Guided Wave Measurement Modalities and Selection of Input Toneburst Parameters	79
4.3.1	Estimating the Average Thickness from A-Scan Data	80
4.3.1.1	Expected Thickness of Direct Path between Transducers	81
4.3.2	Defining Normalised Reflection Amplitude	82
4.3.3	Selection of Input Toneburst Parameters	82
4.3.3.1	Transmission Input Toneburst Parameters	83
4.3.3.2	Reflection Input Toneburst Parameters	86
4.4	Overview of a Sample of Thickness and Reflection Profiles	90
4.5	Models of Probability of Detecting a Defect Incorporating Measurement Pitch	94
4.5.1	Overview of Probability of Detection	94
4.5.2	Method for Determining Probability Distribution from Transmission Measurements	96
4.5.2.1	Variability Due to Noise in Transmission	96
4.5.2.2	Variability Due to Defect Position in Transmission	97
4.5.3	Method for Determining Probability Distributions from Reflection Measurements	100
4.5.3.1	Baseline Probability Distribution Due to Noise without a Defect Present...	100
4.5.3.2	Variability Due to Noise with a Defect Present.	100
4.5.3.3	Variability Due to Defect Position in Reflection	101
4.6	Results and Discussion of Probability of Detection Study	102
4.6.1	Effect of Measurement Pitch	102
4.6.2	Probability of Detecting Hann Profile Defects using Guided Waves	105
4.6.2.1	Wavelength Normalised Probability Images	108
4.6.2.2	Design Implications and Discussion on the Limitations of Short Range Guided Waves	109
4.6.3	Increasing Sensitivity through the Data Fusion of Probability Images	110
4.6.3.1	Comparison of Data Fusion Results with Long Range Guided Waves	111
4.7	Conclusion	112
5.1	Introduction	114

5.1.1	Introduction to the use of spot measurements for the detection of corrosion	115
5.2	Quantitative Estimation of Area Coverage of Spot Measurements	116
5.2.1	Spot Measurement Coverage Model Using Area Approximation Method.....	116
5.2.2	Approximate Spot Measurement Coverage	117
5.2.3	Discussion and Implications for Spot Measurement Uses	118
5.3	Summary and Possible Use of Spot Measurements as Pit Monitoring Solution	119
6.1	Introduction	120
6.1.1	Review of Literature on Bulk Wave Reflections from Non-Planar Surfaces....	121
6.2	Configuration and Validation of the 3D Finite Element Models.....	123
6.2.1	Overview of the Bulk Wave Transducer Setups Studied	124
6.2.1.1	High Temperature Wall Thickness Monitoring Sensor	124
6.2.1.2	Shear Electromagnetic Acoustic Transducers	125
6.2.1.3	Semi-Circular Compressional Piezo-electric Transducers	126
6.2.2	Validation of Finite Element Model and Determination of the Effective EMAT Aperture	127
6.2.2.1	EMAT Validation Experimental Setup.....	128
6.2.2.2	Validation against Existing Experimental Data.....	128
6.3	Signal Processing Methods.....	130
6.3.1	Normalised Amplitude Definitions	130
6.3.1.1	Determination of the First Backwall Amplitude	131
6.3.1.2	Determination of the Pit Signal Amplitude	132
6.3.2	Time of Flight Method to Estimate Wall Thickness	132
6.4	Effect of Sloped Backwall with Variable Gradient.....	134
6.5	Effect of Pitting on Bulk Waves	139
6.5.1.1	Finite Element Model Containing Hemispherical Pits	139
6.5.2	Effect of Pitting Directly Under the Transducers.....	140
6.5.3	Effect of Position and Orientation of the Pit Relative to the Transducer	146
6.5.3.1	Shear Wave Transducers	147
6.5.3.2	Semi-Circular Compressional Transducer	151

6.5.4	Discussion of Observed Phenomena in Shear Wave Results: Beam Shape and Mode Conversion	152
6.5.5	Experimental Validation of the Mode Conversion Phenomenon	154
6.6	Future Transducer Design Considerations	157
6.7	Summary.....	157
7.1	Introduction to an Individual Pit Monitoring System	159
7.1.1	Discussion of Potential Issues and Analysis Framework.....	160
7.1.1.1	The Use of A Priori Information	160
7.1.1.2	Placement Error, Number of Operators, and Compatible Techniques or Equipment.....	161
7.1.2	Finite Element Model.....	164
7.2	Analysis of Different Time Traces and Classification Scheme	164
7.2.1	Classification Scheme	166
7.2.1.1	Further Discussion and Inferences from the Time Traces Results.....	167
7.3	Identification Routines	168
7.3.1	Presence of a Backwall Decay: Class 1 Identification	169
7.3.1.1	Clear Pit Signal: Class 2 Classification	170
7.3.1.2	Thickness Algorithms - Generic and Class 2	171
7.3.1.3	Potential Class 3 Identification: Added Noise and No Prominent Peaks.....	172
7.4	Results	172
7.4.1	Waveguide Setup.....	172
7.4.1.1	Class 1 and Generic Thickness Algorithm	172
7.4.1.2	Class 2 and Class 2 Thickness Algorithm	173
7.4.2	12.5mm EMAT Results	175
7.5	Discussion on the Transducer Design Requirements and Capabilities for Pit Identification and Monitoring.....	177
7.6	Summary.....	179
8.1	Thesis Summary	181
8.2	Summary of Main Findings	183

8.2.1	SH1 Guided Wave Monitoring System	183
8.2.2	Multimodal Corrosion Monitoring using an Array of Guided Wave Measurements 184	
8.2.3	Interaction between Shear Bulk Waves and Pitting Corrosion.....	184
8.2.4	Discussion of the Ability of Ultrasonic Techniques to the Detection of Corrosion- Like Defects	185
8.3	Suggested Future Work	187
9.1	Zero Phase Slope Method Derivation	190
9.2	Average Thickness Extraction of a Half Notch using SH Guided Waves.....	191
9.3	Visualisation of SH1 Scattering	194
9.4	Summary of input toneburst operating parameters from a selection of GW reflection studies	196
9.5	A0 probability images and part thickness hole probability images.....	197
9.6	Issue of Deadzones When Using Windowing Techniques	199
9.7	Derivation of First Backwall Reflection Amplitude Fields	202
9.8	Validation of the Longitudinal Finite Element Model	202

List of Figures

1.1	<i>Operation of an ultrasonic wall thickness sensor and the resulting time trace from a) a smooth backwall, and b) a rough backwall.....</i>	<i>28</i>
1.2	<i>a) operation of a long range guided wave system and b) an illustrative resulting time trace containing reflections from pipe features (welds) and defects.....</i>	<i>31</i>
1.3	<i>Example pits with different aspect ratios defined by depth and diameter (a): b) narrow and deep c) elliptical or hemispherical d) shallow and wide e) subsurface f) undercutting, and pit governed by g) horizontal or h) vertical microstructure [1].....</i>	<i>33</i>
1.4	<i>Corrosion distributions with a a) high and b) low corroded to non-corroded area ratio.....</i>	<i>35</i>
1.5	<i>Current ultrasonic corrosion monitoring and screening techniques plotted on a sensitivity-coverage area curve.....</i>	<i>35</i>
2.1	<i>Bulk wave reflection and mode conversion at a metal-air boundary of a) longitudinal, b) shear vertical and c) shear horizontal waves.....</i>	<i>40</i>
2.2	<i>Shear horizontal a) phase velocity and b) group velocity curves in a steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$).....</i>	<i>43</i>
2.3	<i>Mode shapes at 50kHz in a 10mm thick steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$), showing exaggerated antisymmetric and symmetric displacements from DISPERSE [2].....</i>	<i>44</i>
2.4	<i>Phase (a) and group (b) velocity curves for both the symmetric and antisymmetric Lamb waves modes in a steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$).....</i>	<i>45</i>
3.1	<i>Guided wave travelling around the circumference of a pipe.....</i>	<i>49</i>
3.2	<i>Shows a schematic of a cross-section of an unrolled pipe (i.e. a plate), with two transducers 500mm apart with a uniform wall thickness thinned from 10mm to 9mm.....</i>	<i>53</i>
3.3	<i>a) The input signal to the transmitting transducer (blue), which is a 250kHz 5 cycle Hann windowed pulse ($c_s = 3235\text{m/s}$), and the resultant analytically calculated time</i>	

	<i>trace received by the receiving transducer (0.5m separation in a 10mm thick plate): SH0 (red) and SH1 (green) b) Expanded input signal, and spectra c).....</i>	<i>54</i>
3.4	<i>Shows the group velocity curves for the non-dispersive SH0 (blue) and dispersive SH1 (red) modes in steel ($c_s = 3235\text{m/s}$) produced in DISPERSE [2]. The effect of a change in the thickness of a plate using a pitch catch SH guided wave setup is shown, as well as the resulting change in the group velocity (at a single frequency-thickness value).....</i>	<i>55</i>
3.5	<i>Windowing of the input and output SH1 signal in Figure 3.3.....</i>	<i>56</i>
3.6	<i>Analytical group velocity curve fitted to an experimentally extracted group velocity curve, for a 200kHz 5 cycle Hann toneburst over 0.5m in a 10mm plate with 40dB AWGN.....</i>	<i>57</i>
3.7	<i>Two SH1 group velocity curves with $c_{s,-20^\circ\text{C}} = 3236\text{m/s}$ and $c_{s,20^\circ\text{C}} = 3260\text{m/s}$.....</i>	<i>58</i>
3.8	<i>Windowing of the FEA SH0 and SH1 modes with a 250kHz 5 cycle Hann windowed over a 500mm propagation distance in a 10mm thick plate ($c_s = 3260\text{m/s}$).....</i>	<i>58</i>
3.9	<i>a) Schematic of the experimental setup, b) configuration of Tx and Rx EMAT transducers on an aluminium plate to reduce edge reflections.....</i>	<i>59</i>
3.10	<i>PPM EMAT schematic from above showing the direction of the Lorentz force created and SH wave propagation direction.....</i>	<i>60</i>
3.11	<i>Amplitude distribution (dB, relative to max) of the wavepacket emitted by a 50mm wide SH source when excited at 200 kHz with a 5 cycle Hann windowed toneburst with a shear velocity of 3260 m/s.....</i>	<i>61</i>
3.12	<i>Experimental time trace produced by a single measurement with the SH transducer, showing the gated SH0 (red) and SH1 (green) modes. This was produced using a 200kHz 5 cycle Hann toneburst over a propagation distance of 500mm in a 10mm thick plate.....</i>	<i>61</i>
3.13	<i>The effect of temperature on a) the extracted thickness (blue) and the extracted thickness without temperature compensation is shown in green ($c_s = 3140\text{m/s}$), b) the measured shear velocity (red) using the group velocity thickness extraction methods with SH waves in an aluminum plate. Error bars are 95% range in the extracted thickness values.....</i>	<i>62</i>
3.14	<i>a) The finite element model containing a notch, b) is a cross-section of the notch, which has a variable width and fixed depth of 1mm.....</i>	<i>63</i>

3.15	a) Illustration of the finite element model, containing a circular shaped defect. b) Cross-section of the Hann profile defect c) is a cross section of a part thickness hole d) plan view of part thickness hole.....	64
3.16	Schematic of a B-scan performed over 300mm which has been simulated by the FE simulation. The guided wave is sent between the Tx and Rx over a propagation distance of 500mm.....	65
3.17	Extracted thickness using the group velocity method of a 10mm thick plate from three finite element models with different element sizes, modelled in POGO.....	66
3.18	The extracted thickness using the group velocity method from a 10mm thick FE plate model containing a notch of variable width using SH waves at 250kHz with 20 elements through the plate thickness, performed in ABAQUS.....	67
3.19	a) The waterfall plot of Hilbert enveloped signals of the B-scan performed in POGO, using a 250kHz 5 cycle Hann windowed input pulse, b) shows the thickness extracted (blue) from the B-scan. The expected thickness (red) is also shown.....	68
3.20	Finite Element B-Scans of 3 defects, a) Hann profile defect with SH waves b) Part-thickness Hole with SH waves using 250kHz 5 cycle Hann windowed toneburst over 500mm propagation in a 10mm thick plate.....	69
3.21	Extracted average thickness B-Scans of 3 defects, a) Hann profile defect with SH waves b) Part-thickness Hole with SH waves using 250kHz 5 cycle Hann windowed toneburst over 500mm propagation in a 10mm thick plate.....	70
3.22	Extracted thickness from experimental data (red) and the FE model (blue) of a 60x5mm Hann profile defect using SH waves using a 250kHz 5 cycle Hann windowed toneburst.....	72
4.1	a) The single transducer setup studied in this chapter, which inputs a directional guided wave pulse at a single location. b) The proposed array setup. c) The proposed short range guided wave rapid scanning or screening setup.....	76
4.2	Reflection and b) transmission finite element model, containing a circular shaped defect. c) Cross-section of the Hann profile defect or d) a part thickness hole. e) Schematic illustration of a B-scan performed over 300mm which has been simulated by the FE simulation.....	78

4.3	<i>Illustrative Hilbert enveloped signals of a) baseline signal at Tx, b) baseline signal at Rx, c) raw signal at Tx with the defect at p, d) baseline subtracted signal at Tx with defect at p, e) signal at Rx with defect at p.....</i>	<i>80</i>
4.4	<i>A plan view of the plate showing, the transmitting transducer Tx, the receiving transducer Rx and the multiple ray paths through an off-centre defect. The direction in which the two transducers are being scanned is indicated.....</i>	<i>82</i>
4.5	<i>The top row illustrates the time traces of the three different input wave pulses used for the simulations with each guided wave mode. The bottom row illustrates the radiated wave field for each transducer and guided wave mode based on a Huygen's model simulation.</i>	<i>85</i>
4.6	<i>a) Group velocity dispersion curves for both the symmetric and anti-symmetric Lamb wave modes in a steel plate ($c_s = 3235\text{m/s}$, $c_l = 5960\text{m/s}$) b) Group velocity curves for the non-dispersive SH0 and dispersive SH1 modes in steel ($c_s = 3235\text{m/s}$) produced with DISPERSE [2]. The centre frequencies of the three modes studied are indicated by the marker on the curves for both the average thickness (T) and reflection (R) methods.....</i>	<i>86</i>
4.7	<i>Illustration of the method used to select the operating frequency range of the input signals for the A0 and S0 modes by applying limits to the a) phase velocity curves b) group velocity curve and c) attenuation due to fluid loading, produced using the DISPERSE software package [2].</i>	<i>88</i>
4.8	<i>Time traces of the input and output waveforms of the a) S0, b) A0, and b) SH0 modes over a 500mm propagation distance in a 10mm thick plate, produced using the DISPERSE software package [2], using the input toneburst parameters from Table 4.2.....</i>	<i>89</i>
4.9	<i>Extracted average thickness change profiles from finite element B-scans of three centrally located (250mm propagation from transducer) 90x2mm Hann profile defects (top row) and three centrally located 90x2mm part thickness holes (bottom row) using the, A0, S0, and SH1 modes, with operating parameters shown in Table 4.1.....</i>	<i>90</i>
4.10	<i>Time traces of the A0, S0 and SH1 modes for a plate with no defect (blue) and with a 90x2mm Hann profile defect. The propagation distance was 500mm and the nominal thickness was 10mm.....</i>	<i>91</i>
4.11	<i>Top row – extracted thickness profiles for three defects (60x2mm, 90x2mm, and 120x2mm) defects using the S0 mode with the defects placed 125mm away from the</i>	

	<i>Tx nodes. Bottom row – same setup as top row but with the defect placed 375mm away from the Tx nodes.....</i>	<i>93</i>
4.12	<i>a) Reflection coefficient profiles of the S0 mode from five 30mm diameter Hann profile defects with varying depth, using a 90kHz 3 cycle Hann windowed toneburst. The corresponding reflection signals with the defect in the central position are also shown in b). As defined by equation 4.2, a normalised amplitude range of -0.1 to 0.1 is displayed.....</i>	<i>93</i>
4.13	<i>Illustration of the TP, FP, TN and FN areas used in the calculation of the POD and PFA in equations 4.9 and 4.10.....</i>	<i>95</i>
4.14	<i>Determination of p(thickness/defect position). a) An example of a highly sampled absolute thickness profile which is being sampled at the first position where $n = -1, 0, 1$ and $k = 0$. b) The same absolute thickness profile which is being sampled at a different array/sample position where $k = 0.5X$, c) The maximum values of the thickness profile, m_k, d) An example histogram of the thickness change values of the m_k.....</i>	<i>98</i>
4.15	<i>p(thickness/defect) distributions, with unit area, for a 60x1mm Hann profile defect with 30dB SNR using different transducer pitches (50mm, 75mm, 100mm, 125mm, 150mm), with the defect centrally located in the plate and a guided wave propagation distance of 500mm in a 10mm thick plate, using a 200kHz 25 cycle Hann windowed S0 guided wave pulse.....</i>	<i>99</i>
4.16	<i>Gaussian summation method, a) the assumed spread due to noise is applied to all data points in the reflection amplitude profile, b) the individual Gaussian distributions with the same spread and different means c) the summation of all the Gaussian distributions gives the probability distribution due to noise, defect and pitch.....</i>	<i>102</i>
4.17	<i>Twelve POD curves as a function of transducer array or scan pitch illustrating the sensitivity of the S0 and SH1 modes to changes in defect diameter, 20mm (blue), 30mm (green), 60mm (red), 90mm (light blue), and 120mm (purple), for defects of depths of 1, 2, and 5mm with an SNR of 30dB. The guided waves were propagated over 500mm in a plate with 10mm baseline thickness.....</i>	<i>104</i>
4.18	<i>POD curves in reflection mode as a function of array or scan pitch for three guided wave modes with a noise level of 30dB SNR (a) A0, b) S0, c) SH0) for a range of Hann profile defects with diameters of 10 to 80mm and a fixed depth of 5mm. d) shows an exploded view of b) in the 0.98 to 1 range of PODs.....</i>	<i>105</i>

4.19	<i>Example probability image used to display the POD results for a range of defect sizes. b) a recursively interpolation of a) by using a third order cubic interpolation. The example shown here shows the POD using S0 mode, via the average thickness method presented, for a range of defects with a pitch of 50mm.....</i>	<i>106</i>
4.20	<i>Probability of detection in transmission for the S0 mode (top row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of defect diameters (10-60mm) and depths (1-5mm).....</i>	<i>107</i>
4.21	<i>Probability of detection in reflection for the S0 mode (top row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of defect diameters (10-60mm) and depths (1-5mm).....</i>	<i>108</i>
4.22	<i>Contour plots of the POD as a function of defect depth and diameter showing both the S0 mode and the SH hybrid for both measurement methods (a - reflection, b - transmission), with the defect diameter normalised to the wavelength of the centre frequency of the input toneburst. Contours are for 0.5 and 0.95 POD, the pitch is 10mm and SNR is 30dB.....</i>	<i>109</i>
4.23	<i>Data fused probability images for Hann profile defects using the S0 mode or hybrid of SH0 and SH1 modes for 10, 50 and 100mm pitches at 30dB SNR over a propagation distance of 500mm in a 10mm thick plate. Lines of constant cross sectional area (CSA) are overlaid.....</i>	<i>111</i>
5.1	<i>Schematics of spot measurement data collection (i) and display conventions (ii, and iii) for A-scan (top row), B-scan (middle row) and C-scan (bottom row) methods.....</i>	<i>115</i>
5.2	<i>Schematics of a) a monitoring setup using bulk wave transducer array, b) a scan using bulk wave transducers. The unit cell of the central transducer is indicated.....</i>	<i>116</i>
5.3	<i>Schematic of the a) parameters and setup used in the spot measurement coverage model with an example undetectable (A) and detectable defect (B) defect, b) method used to calculate coverage using the area method described in equation 5.1.....</i>	<i>117</i>
5.4	<i>a) Probability image of the POD for a 10mm wide transducer using the area approximation method (equation 5.1) b) contour plot of the probability image in a) with lines of constant 0.1-1 POD.....</i>	<i>118</i>

6.1	<i>Schematic of bulk wave interactions with different flat-bottom hole defects inferred from the existing literature and illustrations of the associated signal envelopes.....</i>	<i>122</i>
6.2	<i>Reproduction of part (c) and (d) in figure 6.1 from [3]: Comparison of simulated backwall reflection signals when the inner surface is flat and has a FBH located directly beneath the wall thickness sensor with a diameter of 3.2mm (2λ) and a depth of (a) 0.4mm ($\lambda/4$) and (b) 3.2mm (2λ). Dashed lines represent the Hilbert envelopes of the associated signals.....</i>	<i>123</i>
6.3	<i>a) The base 36x36x10mm³ FE model to which different defects or geometries can be added and different nodal inputs to model different transducer types. b) 2MHz centre frequency Hann windowed toneburst: 3 cycles (i) and 5 cycles (ii). c) 5MHz centre frequency Hann windowed toneburst: 3cycle (i) and 5 cycle (ii)</i>	<i>124</i>
6.4	<i>a) Geometry of the high temperature waveguide sensor, b) paths taken by the surface wave and the 1st backwall reflection, and c) a typical time trace d) Node configurations of a waveguide with a 12mmx1mm transmitting (Tx) and receiving (Rx) sets, e) magnitude of the enveloped first backwall amplitude field, and the pulse's displacement field at 2×10^{-6}s in the y=0 plane (f) and x=0 plane (g). e-g were obtained with a 3 cycle Hann windowed toneburst at 2MHz centre frequency.....</i>	<i>125</i>
6.5	<i>a) Illustration of an EMAT, b) illustration of a butterfly coil and magnet inside an EMAT, c) a typical EMAT time trace, c) node configurations of an EMAT with a 10mmx10mm aperture, d) magnitude of the enveloped first backwall amplitude field, and the magnitude of the pulse's displacement field at 2×10^{-6}s in the y=0 plane (e) and x=0 plane (f). d-f were obtained with a 3 cycle Hann windowed toneburst at 2MHz centre frequency.....</i>	<i>126</i>
6.6	<i>a) Illustration of a dual element PZT transducer, b) the segmentation and input nodal configuration of a pitch catch PZT, c) magnitude of the enveloped first backwall amplitude field, the pulses's displacement field at 1.2×10^{-6}s in the y=0 plane (d) and x=0 plane (e). c-e were obtained with a 3 cycle Hann windowed toneburst at 5MHz centre frequency.....</i>	<i>127</i>
6.7	<i>Illustration of the FE model used to verify the EMAT aperture using a 7mmx2mm deep flat bottomed hole (FBH).....</i>	<i>128</i>

6.8	a) Experimental signal using an EMAT with a 2MHz 5 cycle Hann windowed toneburst reflecting off a 7x2mm part thickness hole, showing the first (i,ii) and second reflections (iii,iv,v) off the backwall or defect, b) the simulation of a) using a EMAT with a 10mmx10mm aperture.....	128
6.9	a) Comparison of signals from an experimental pulse echo measurement of a 7mmx2mm part thickness hole (blue line) with an FE model (red line) simulation of an EMAT with a 12.5mmx12.5mm aperture with a 2MHz 3 cycle input toneburst (simulated signal is filtered from 3 to 5 cycles in post processing), b) Hilbert enveloped of the signal in a).....	129
6.10	a) magnitude of the backwall amplitude displacement field of the first backwall pulse in the same direction (S1) as the input toneburst for a EMAT with a 12.5mmx12.5mm aperture. The pulses's displacement field (in S1 direction) along the y=0 plane (b) and x=0 plane (c) at 2×10^{-6} s using a 3 cycle 2MHz Hann windowed toneburst.....	130
6.11	a) Schematic of a spot measurement setup b) illustration of the windowing used in the method to determine the backwall and pit amplitudes.....	130
6.12	Illustration of method used to extract wall thickness, using a time trace a) which is divided into two: b) the input signal in the time trace is cross correlated with the input toneburst ² to find a first time value and c) the first backwall signal is cross correlated with the input toneburst to find the second time value.....	134
6.13	Illustrations of the sloped backwall model, a) cut-through of the model, b) projected views of the sloped backwall models with the shear transducers (b) and compression transducer (c) defining the terminology which distinguishes between the two orientations: perpendicular (i) and parallel (ii).....	135
6.14	a) Back wall amplitudes and b) extracted thicknesses for the three transducers types (blue – EMAT 10mm, red - waveguide, and green - semi-circular compressional) in either the perpendicular (dashed) or parallel (solid) orientations for back wall slope angles of 0°-20°.....	136
6.15	Waterfall plots for the two shear transducers (a and b - EMAT 10mm, c and d - waveguide), in the principle shearing component (i), other shear component (ii) and the longitudinal component (iii) in either the perpendicular (a, c) or the parallel orientations (b, d). The ii) and iii) results are -20dB the peak in i)	137

6.16	<i>Waterfall plots for the semi-circular compression transducer in the x shearing component (i), y shear component (ii) and the longitudinal component (iii) in either the perpendicular (a) or the parallel orientations (b). The ii) and iii) results are -6dB the peak in i).....</i>	<i>138</i>
6.17	<i>Schematic of how the hemispherical defects were defined in the FE model a) central cut-through b) underside view of a hemispherical defect.....</i>	<i>140</i>
6.18	<i>Illustration of the hemispherical pit variables which are able to be altered in the FE model: a) cut-through of an off centre hemispherical defect, b) backwall projection, and c) exploded view from inside dashed rectangle in a) of a cut-through of a pit.....</i>	<i>140</i>
6.19	<i>a) Backwall amplitudes, b) pit amplitudes and c) extracted thicknesses for the four transducers types (blue – EMAT 10mm, green - waveguide, red - semi-circular compressional, and cyan – EMAT 12.5mm) for pit radii from 0mm to 8mm.....</i>	<i>142</i>
6.20	<i>Extracted thicknesses for the four transducers types (blue – 10mm EMAT, green - waveguide, red - semi-circular compression transducer, and cyan – 12.5mm EMAT) for a centrally located pit for radii from 0mm to 3mm.....</i>	<i>143</i>
6.21	<i>Normalised waterfall plots for the four transducers types in the same displacement direction as the input excitation direction (a) EMAT 10mm – S1, b) EMAT 12.5mm – S1, c) waveguide – S1, and d) semi-circular compression – L) for a centrally located defect for pit radii of 0.5mm to 8mm.....</i>	<i>144</i>
6.22	<i>Example simulated signals received by a) a Waveguide and b) an EMAT 10mm for centrally located pits with radii of i) 2mm, ii) 4mm, iii) 6mm and iv) 8mm.....</i>	<i>146</i>
6.23	<i>Back wall amplitudes for three pit sizes which are moved relative to the EMAT 10mm transducer as shown in d), for a) a 4mm, b) a 6mm, and c) a 8mm pit size.....</i>	<i>147</i>
6.24	<i>ai) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the 10mm EMAT with a 6mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction).....</i>	<i>148</i>

- 6.25 ai) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the 12.5mm EMAT with a 6mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction).....149
- 6.26 ai) Back wall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the waveguide with a 3mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction).....150
- 6.27 The three orientations (parallel, 45° and perpendicular) relative to the separation between the two halves of the semi-circular compression transducer.....151
- 6.28 ai) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the semi-circular compression transducer with a 6mm pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction).....152
- 6.29 The top row are results from a 12.5mm EMAT with a 6mm pit and the bottom row from a waveguide setup up with a 3mm pit. a) and d) are the backwall amplitudes in an image format for defect positions of $r = -10\text{mm}$ to 10mm in 1.25mm steps and θ in 22.5° steps. b) and e) are the pit amplitudes plotted over the same position space as a) and d). c) and f) are expanded versions of Figure 6.10a and Figure 6.4e.....154
- 6.30 a) schematic of the experimental setup, b) photograph of the test plate sample, and c) a photograph of the experimental setup taken in February 2017.....155
- 6.31 Measured experimental backwall amplitude of a 6mm defect with a radial position between 0 and 15mm (solid lines), and the simulated back wall amplitude of an EMAT12.5mm on a 1" plate with a 6mm defect with a radial position of 0 to 10mm

	<i>(dashed lines). Both the perpendicular (blue) and parallel (red) orientations are shown.....</i>	<i>156</i>
6.32	<i>Measured experimental backwall amplitude of a 4mm defect with a radial position relative to the centre of the EMAT between 0 and 15mm, both the perpendicular (blue) and parallel (red) orientations are shown.....</i>	<i>157</i>
7.1	<i>Three phases of operation of an individual pit monitoring system (IPMS).....</i>	<i>159</i>
7.2	<i>Three possible permutations of pit detection and sensor placement during IPMS implementation.....</i>	<i>162</i>
7.3	<i>Hilbert enveloped time traces from a 10mm EMAT exciting a 2MHz 3 cycle pulse in a 10mm steel plate, sonifying a 6mm radius pit placed a range of locations relative to the transducer.....</i>	<i>165</i>
7.4	<i>Hilbert enveloped time traces from a waveguide transducer exciting a 2MHz 3 cycle pulse in a 10mm steel plate, sonifying a 4mm radius pit placed at a range of locations relative to the transducer.....</i>	<i>166</i>
7.5	<i>Illustrative time traces of the devised classification scheme, showing the class 1 (pit not detected), class 2 (pit detected), and class 3 (ambiguous) time traces – and all sub classes.....</i>	<i>168</i>
7.6	<i>Workflow of the class 1 routine.....</i>	<i>170</i>
7.7	<i>Workflow of the class 2 routine.....</i>	<i>171</i>
7.8	<i>Class 1 images (top) and generic thickness images (bottom) applied to the results from the waveguide transducer over the pit position space (radial positions=0-10mm, angular positions=0-360°). The results for four pit radii are shown, 2mm (left) to 5mm (right).....</i>	<i>173</i>
7.9	<i>In-depth class 2 images (top, showing a breakdown of the black areas in Figure 7.8 top) and Class 2 thickness images (bottom) applied to the results from the waveguide transducer over the pit position space (r=0-10mm, θ=0-360°).....</i>	<i>174</i>
7.10	<i>Hilbert enveloped time trace from a waveguide interrogating a 2mm radius pit at (r=0, θ=0°), with the 3 highest peaks indicated.....</i>	<i>175</i>
7.11	<i>Class 1 images (top) and generic thickness images (bottom) applied to the results from the 12.5mm EMAT transducer over the pit position space (r=0-10mm, θ=0-360°).....</i>	<i>176</i>

7.12	<i>Class 2 images (top) and Class 2 thickness images (bottom) applied to the results from the 12.5mm EMAT transducer over the pit position space ($r=0-10\text{mm}$, $\theta=0-360^\circ$).....</i>	<i>177</i>
7.13	<i>Hilbert enveloped time trace from a 12.5mm EMAT interrogating a 5mm radius pit at ($r=7.5, \theta=0^\circ$), with the 3 highest peaks indicated.....</i>	<i>177</i>
8.1	<i>The three corrosion monitoring setups compared and their equivalent cylindrical axis along which they act.....</i>	<i>186</i>
9.1	<i>Cross sectional profile of a a) 1mm deep Hann profile half notch, b) 1mm deep part thickness hole half notch, c) B-scan schematic of a 60mm diameter half notch.....</i>	<i>192</i>
9.2	<i>Extracted average thickness B-scan, using a 250kHz 5 cycle Hann windowed toneburst over a propagation distance of 500mm in a 10mm thick plate, of a a) 1mm deep 60mm wide half notch with a Hann profile, b) 1mm deep 60mm wide half notch with a rounded end of constant thickness.....</i>	<i>193</i>
9.3	<i>Displacement field of the SH0 and SH1 pulses (250kHz centre frequency 5 cycle toneburst width) on the top surface of the plate at 0.07, 0.1, 0.13ms, as the two modes pass through a 60x5mm Hann profile defect placed in the centre of the plate.....</i>	<i>195</i>
9.4	<i>Probability of detection for the A0 mode in transmission (top row) and in transmission (bottom row) with pitches of 10, 50 and 100mm, over a range of Hann profile defect diameters (10-60mm) and depths (1-5mm).....</i>	<i>197</i>
9.5	<i>Probability of detection in transmission for the S0 mode (top row), A0 mode (middle row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of part thickness hole diameters (10-60mm) and depths (1-5mm).....</i>	<i>198</i>
9.6	<i>Probability of detection in reflection for the S0 mode (top row), A0 mode (middle row) and the SH0 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of part thickness hole diameters (10-60mm) and depths (1-5mm).....</i>	<i>199</i>
9.7	<i>a) Schematic of the ‘deadzone’ which is represented as the thickness change required for peak of the pit signal to occur within the pit signal window b) shows broad areas of thickness deadzones for a range of centre frequencies and toneburst widths. (using a shear transducer $c_s = 3260\text{ms}^{-1}$), c) is the colour plot equivalent of b).....</i>	<i>201</i>
9.8	<i>The Hilbert enveloped time traces of a longitudinal pulse reflecting off either a a) 4mm and b) 5mm radius pit. The experimental (blue) and simulated (red) second,</i>	

third and fourth backwall reflections are shown. (5MHz 3 cycle Hann windowed toneburst, 10mm thick steel plate).....203

List of Tables

4.1	<i>Summary of the characteristics of the wave pulses which were used in the transmission finite element analysis.....</i>	<i>84</i>
4.2	<i>The selected reflection operating parameters of the A0, S0 and SH0 modes.....</i>	<i>88</i>
4.3	<i>The standard deviation in the extracted thickness for the three guided wave modes over a propagation distance of 500mm in a 10mm thick plate for three different signal to noise ratios (20, 30, 40dB), using the input characteristics shown in Table 4.1....</i>	<i>97</i>
7.4	<i>Overview of waveguide and 12.5mm EMAT results, showing the minimum and maximum radial pit positions required in order to either identify a pit (Pit Identification) or measure thickness change (using the generic algorithm). The amplitude of the pit signal at the central position (0,0) is, also, given in dB.....</i>	<i>179</i>
9.5	<i>Summary of S0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature.....</i>	<i>196</i>
9.6	<i>Summary of A0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature.....</i>	<i>196</i>
9.7	<i>Summary of SH0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature.....</i>	<i>197</i>
9.8	<i>The percentage change in amplitude between the simulated and experimental signals from various features in the 4mm and 5mm time traces in Figure 9.8.....</i>	<i>203</i>

Chapter 1

Introduction

1.1 Industrial Motivation

The corrosion of pipes and pipelines is a common problem for the oil and gas industry, and the cost and complexity of managing the network is unrelenting. In the US alone, there are just under 250,000km of pipework carrying petroleum products [4], and in 2014 corrosion cost the US oil and gas industry an estimated \$8bn [5]. Not only is there a constant financial burden to mitigate pipe corrosion, there is also a risk of catastrophic failure of components which could cause loss of life, substantial damage to the environment and ecosystems, and large scale reputational damage to the operator. Non-destructive evaluation (NDE) provides a diagnostic means of analysing corrosion, without the costly shutdown time, and is an essential part of modern corrosion management, improving the ability to quantify the state of corrosion over the pipe infrastructure and allowing industry to operate more safely and cost effectively. The scale of the problem, however, means that many traditional NDE methods are not suitable for large scale NDE applications and there is a need to develop corrosion monitoring, inspection, and screening systems that can accurately and cost effectively measure and monitor corrosion over a large area. This has led to an inherent trade-off between the area over which a single sensor can interrogate and the sensitivity of that sensor to corrosion.

1.1.1 Corrosion in Oil and Gas Pipelines

Corrosion is a natural and inevitable process in which materials tend towards their lowest possible energy state. It is generally caused by an electrochemical process, whereby a material is gradually degraded, resulting in the deterioration of the material and potentially the associated structure, unless the process is monitored or mitigated against [6], [7]. There are many different forms of corrosion which can affect a given material, and the form of corrosion depends on the material and environment in which the material is located. The most well-known corrosion process is rusting, when iron combines with oxygen to form rust (iron(III) oxides). Most corrosion is caused by the formation of an electrochemical cell (analogous to a battery), whereby the anode (usually a metal) is oxidised in the presence of an electrolyte and a cathode (a different part of the same piece of metal or another metal). The oxidation process results in a chemical change of the metal to a ‘corrosion product’,

which has different physical characteristics compared to the original metal; this results in metal loss. The environment and chemical species involved in the corrosion will dictate how the corrosion forms on the inner surface of a pipe and different forms of corrosion will have different morphologies. The two morphologies of interest to this study are uniform and pitting corrosion (see section 1.3.1).

1.2 Overview of NDE Techniques for Corrosion Management

There are many ways in which pipeline corrosion is managed, and these are broadly categorised into passive techniques and active techniques. Passive techniques include cathodic protection and the application of coatings, whilst some examples of active techniques are the use of corrosion inhibitors and non-destructive evaluation (NDE). NDE is used by the oil and gas industry to gain up-to-date diagnostic information regarding the integrity of a pipeline, which is then used as part of the decision process regarding the management of the structure. NDE techniques can be split into three broad categories: screening, inspection and monitoring. Inspection traditionally refers to the process of an operator performing manual measurements over an area of pipe, and can be time consuming and costly, due to the sheer scale of the pipeline infrastructure, access difficulties, and the labour-intensive nature of data acquisition. In contrast, screening involves performing a quick NDE technique over a large area to identify potential locations where corrosion has occurred, before conducting targeted inspections to further aid the diagnostic process. Monitoring consists of a permanently installed sensor which continually and frequently relays back information regarding the structural health of the pipeline; more widely this field is known as structural health monitoring (SHM). Whilst inspection allows a flexible approach to NDE and targeting of a specific area, the time between inspections of the same location can be long and infrequent. Monitoring allows continuous and frequent data collection regarding the structural health of pipelines, and has the potential (like screening) to cover a large area of pipeline infrastructure. This thesis is, therefore, focused on screening for or monitoring corrosion. The next section will outline existing screening and monitoring techniques

1.2.1 Non-Destructive Permanently Installed Corrosion Monitoring Techniques

Corrosion monitoring can be either direct or in-direct and intrusive or non-intrusive. NDE techniques are described as direct (detecting metal loss or corrosion features) and non-intrusive (does not require access to the inside of the pipe). Several NDE corrosion monitoring techniques are now described.

1.2.1.1 Ultrasonic Wall Thickness Measurement

There are many measurement techniques which use the timing of reflected waves from a boundary (i.e. echo-location) to detect and measure the distance of an object. For example, low frequency electromagnetic waves (RADAR), low frequency sound waves (SONAR), and UV, visible or IR light (LIDAR) can all be exploited for this task in air or water. High frequency elastic waves ($>20\text{kHz}$, known as ultrasound) are able to propagate through solids and can be used to echo-locate features within a pipe wall. By measuring the time taken for a pulse to reflect off a feature (known as the time of flight, TOF), as well as knowing the propagation speed, the thickness of a pipe wall can be measured. This is one of the simplest implementations of ultrasonic NDE. A permanently installed version of this technique is commercially available by a range of operators [8]-[15], which are able to relay back wall thickness values to an operator. The individual sensors are generally low powered devices and have been adapted to be installed on a range of oil and gas infrastructure components.

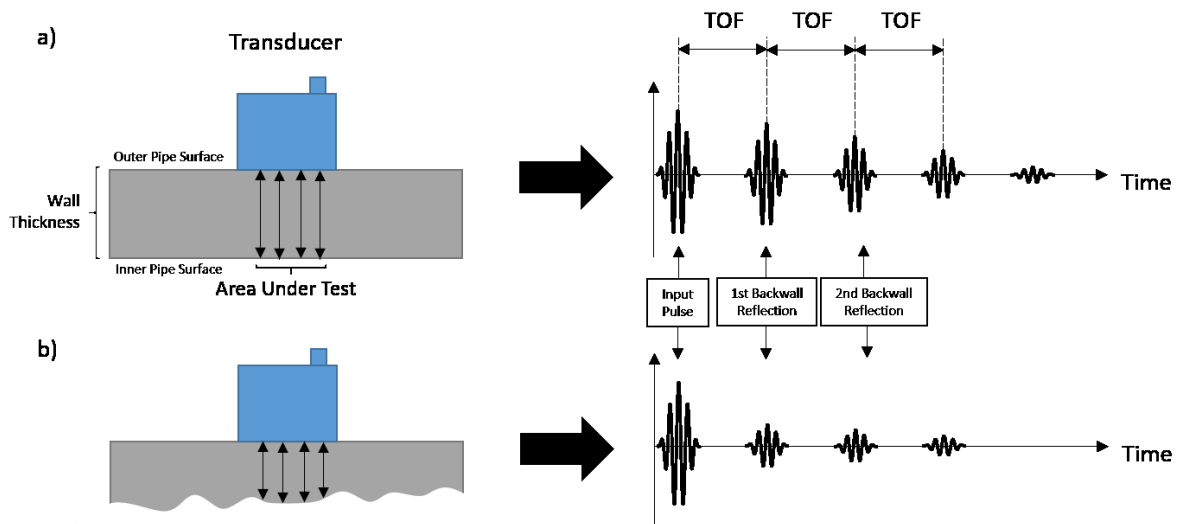


Figure 1.1 Operation of an ultrasonic wall thickness sensor and the resulting time trace from a) a smooth backwall, and b) a rough backwall

The sensor itself can either work in pulse echo (the same transducer emits and receives the echoes) or pitch catch (different transducers emit and receive the echoes). Figure 1.1a shows a pulse echo transducer and the subsequent time trace received. The ultrasonic pulse emitted by the transducer propagates towards and reflects off the inner wall of the pipe, before being detected by the transducer. However, not all the pulse's energy is transferred to the transducer. Some of the pulse's energy is reflected off the top surface back towards the bottom surface, and so the process repeats. The multiple backwall reflections (Figure 1.1) between the top and bottom surfaces are shown as multiple echoes in the time trace each with less amplitude than the previous echo. In order to calculate the thickness of the pipe, b , we need to know the propagation speed, c , and the time of flight:

$$b = \frac{c \times TOF}{2} \quad (1.1)$$

The uniform corrosion of a pipe's inner wall is much more likely to be a rough surface (Figure 1.1b) than a clean flat surface. In this case the rough surface will scatter the ultrasonic pulses as they reflect off the inner wall, resulting in less of the pulse's energy reaching the transducer. Multiple reflections are still possible, albeit with a reduced amplitude. This effect is well understood [16]-[19].

1.2.1.2 Potential Drop – Field Signature Method

The resistance of a material, R , is given by $R = \rho l/A$, where ρ is the resistivity, l is the length of the specimen, and A is the cross-sectional area. Therefore, if metal loss due to corrosion were to occur then A would reduce and the resistance measured between two points (separated by l) will increase. Separate probes are used to inject current and measure resistance. This is the central idea behind potential drop techniques. An alternating current technique is commonly used to detect cracks on the top surface of a metal, as AC currents are limited to the top surface of the metal (low skin depth). However, DC currents are required in order to detect wall thickness reductions, allowing the current to penetrate further into the metal [20], [21].

This technique is currently used in several permanently installed commercial systems available for use in the petroleum and power generation industries. The Roxar CorrOcean FSMTM system uses an array of electrodes to produce a corrosion map of the area under the array [22], [23]. [22] gives the sensitivity of the systems as 0.1% of the wall thickness. Another company, Rowan Technologies, use a similar technique and are also able to produce a 2D map of the wall thickness. A Rowan Technologies brochure [23] states the sensitivity of the system as being 1mm/year for measuring the thinning of a 10mm pipe wall thickness, although increased sensitivity has been observed for thinner components (0.1mm/year for 5mm tank membrane).

1.2.1.3 Intrusive Physical, Electrical and Electrochemical Techniques

A large body of techniques exist which attempt to directly measure the electrochemical process of corrosion [24], [25]. A metal sample is placed in the fluid flow within the pipe and the resistance of the sample, potential with respect to a reference electrode, or the mass loss can be measured depending on the type of measurement required. Although these techniques can be built into new pipelines, they cannot be non-destructively retrofitted to existing pipes.

1.2.1.4 Acoustic Emission

Acoustic emission techniques use an array of high frequency transducers to listen for high frequency elastic energy, released by the formation of cracks occurring as the result of corrosion. This technique is considered to be passive as the input energy is provided by the corrosion mechanism, thus making the equipment simple to install and retrofit; however, it is not quantitative and only gives an indication of corrosion damage. Furthermore, it is difficult to distinguish cracking events from the surrounding noise, especially as they are frequently installed in noisy environments [26].

1.2.2 Corrosion Screening Techniques using Long Range Guided Waves

Low frequency ultrasonic guided waves are used to inspect long lengths of pipe from a single location and are known as long range guided waves (LRGW). A guided wave is any wave that propagates within a 1D structure with a constant cross section. The wave is able to propagate further, because the energy is confined within the structure and therefore cannot dissipate via beam spread (see section 2.3). If the ultrasonic guided wave encounters a defect then a proportion of the signal is reflected and, provided the reflection is large enough, is detected by the transducer [27]. Figure 1.2 demonstrates the operation of LRGWs. The signal in Figure 1.2b shows an example time trace received by the collar transducer, where the reflections from the defect, as well as from weld seams between pipes, are visible.

This technique was originally commercialised for manual corrosion screening, whereby a collar array of transducers is wrapped around the circumference of a pipe (highlighted in green in Figure 1.2a) and an ultrasonic guided wave (in the form of a pulse) can be propagated in either direction axially along the pipe. The lower the frequency of the wave, the further the wave will travel; however, this lower frequency leads to a lower sensitivity of the system to defects. This is because the sensitivity is dependent on the wavelength of the wave relative to the defect's size, as well as the SNR of the setup [28]. The collar generates a guided wave that propagates within the entire pipe cross section and provides 100% coverage over the propagation distance.

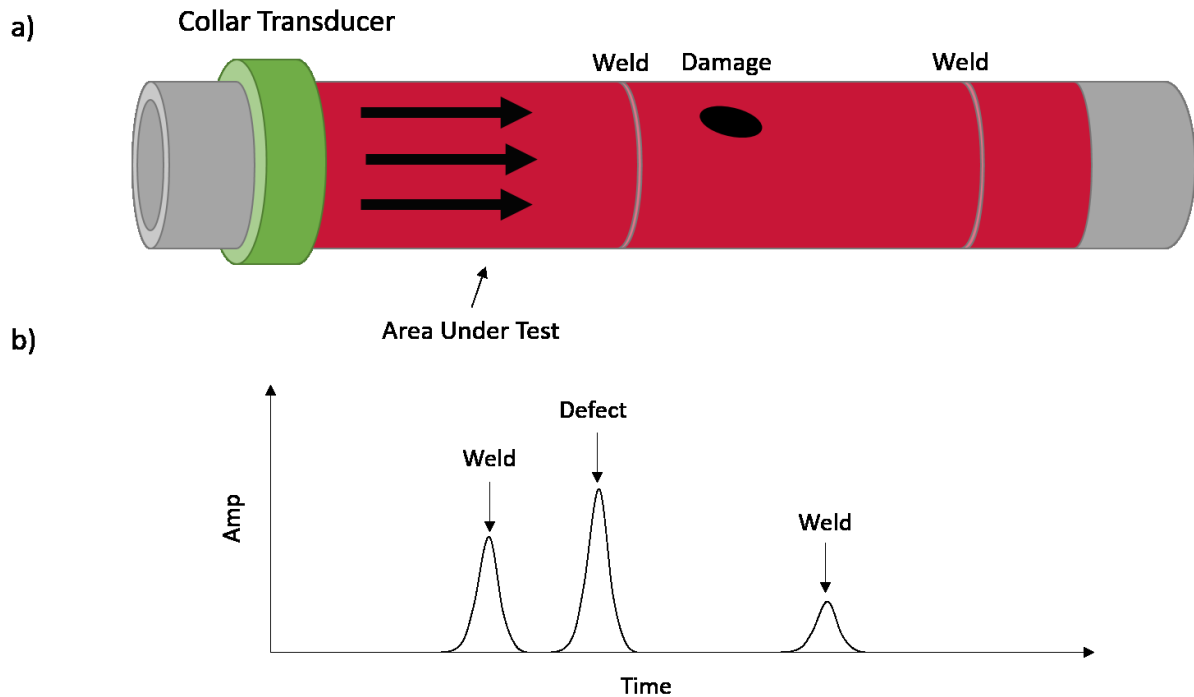


Figure 1.2. a) operation of a long range guided wave system and b) an illustrative resulting time trace containing reflections from pipe features (welds) and defects.

This system has also been adapted for monitoring purposes, for example, Guided Ultrasonics Limited (GUL) with their gPIMS (a permanently installed monitoring system), which has been designed for use on buried or submerged pipes [29]. There is a growing body of research on LRGW monitoring [30]-[33]. Another LRGW system (Subsea Integrity Group) claim to be able to detect defects with less than 1% of the pipe cross section, inspecting 20m-70m either side of the transducer ring [34]. Currently monitoring using LRGWs is not as common as using permanently installed ultrasonic spot measurements.

1.3 Area of Interest and Project Objectives

This study is interested in evaluating several ultrasonic techniques for detecting and measuring corrosion in pipelines. Due to the scale of pipeline infrastructure, particular attention will be given to the spatial coverage of each technique, as well as the sensitivity of individual sensors to the presence of corrosion. This requires two characteristics of corrosion to be simultaneously considered: corrosion morphology and corrosion distribution. The primary interest of this thesis is corrosion monitoring, which is defined as frequent readings/measurements made at exactly the same location(s) (usually via a permanently installed sensor) [35]. This is in contrast with inspections, which are carried out at intervals by an operator and can be performed over an area of pipe, rather than a single location. A screening technique is considered alongside a monitoring technique in chapter 4.

1.3.1 Corrosion Morphology

The morphology of the corrosion will affect how sensitive a single sensor is to detecting and measuring a single incident of corrosion. For example, [36] illustrates how guided wave reflection sensitivity varies with defect shape as well as size, however, given that LRGWs provide 100% coverage, the placement of the defect relative to the sensor is not considered. Two corrosion morphologies are studied in this thesis: uniform and pitting corrosion.

As the name suggests, uniform corrosion occurs either over the entire surface, or at least over a large proportion of a surface, of a component. Multiple electrochemical cells (anodes and cathodes) form on the surface at any given time [1]. Examples of metals susceptible to uniform corrosion are copper and pre-weathered/COR-TEN steel [37]. As discussed above, uniform corrosion is likely to have a rough surface profile.

When corrosion is highly localised it is known as pitting corrosion. Pitting can occur in isolation or in clusters, and, although there is much less mass/metal loss compared to uniform corrosion, is potentially much more dangerous, as it can cause difficult-to-detect isolated points of weakness. A lone pit can easily be the root cause of failure of an entire component. All metals are at risk of pitting because a slight variation in the homogeneity of the metal's surface can cause it to become anodic with respect to the rest of the surface [1]. For example, a small amount of surface damage may lead to a higher corrosion rate [38]. In addition, many materials are coated in a passive oxide layer (e.g. Aluminium [39]) which, if it breaks down in a single location, can lead to increased corrosion rates of the unprotected bulk metal underneath [40]. Pitting corrosion covers a wide range of dimensions and aspect ratios, from narrow and deep defects to wide and shallow defects which border on areas of uniform corrosion. Figure 1.3 shows several different pitting cross-sections. The three pit profiles/cross-sections studied in this thesis are b) narrow and deep, c) elliptical and hemispherical, and d) shallow and wide. Each of these can be defined by two parameters: depth and diameter.

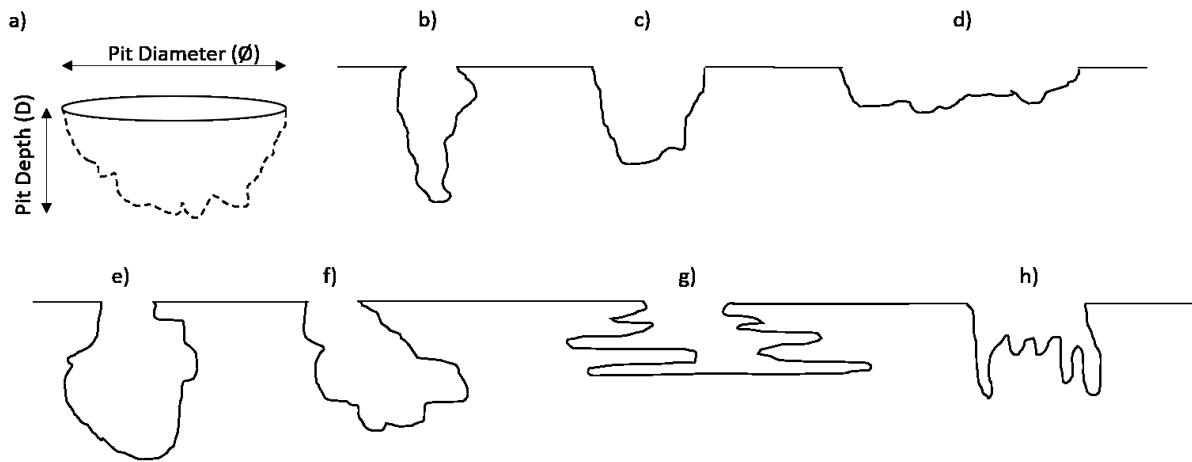


Figure 1.3 Example pits with different aspect ratios defined by depth and diameter (a): b) narrow and deep c) elliptical or hemispherical d) shallow and wide e) subsurface f) undercutting, and pit governed by g) horizontal or h) vertical microstructure [1]

1.3.2 Corrosion Distribution

When selecting a suitable monitoring technique to detect and track corrosion it is necessary to consider the spatial distribution as well as the morphology of the individual corrosion patches. The ratio of the corroded area to non-corroded area is an important factor that needs to be considered [35]. If the area ratio is high (i.e. a large proportion of the inner pipe surface is corroded - Figure 1.4a) then this can be detected using a sparse array of UT spot/point wall thickness measurements, for example. If, however, the isolated corrosion occurs on the inner pipe wall with a low corroded to non-corroded area ratio, then a distributed array of spot sensors is unlikely to detect the corrosion. A greater danger is that the spot sensor may only measure a portion of the corroded area (Figure 1.4b), leading to positive identification of corrosion but the perception of a slow corrosion rate. In this scenario, a monitoring or screening technique with 100% area coverage is required, such as LRGWs. It is also important to consider sensor density. It is possible to cover an entire pipe with spot sensors, however, the cost and complexity of powering, installing and multiplexing between the sensors will make it commercially unviable.

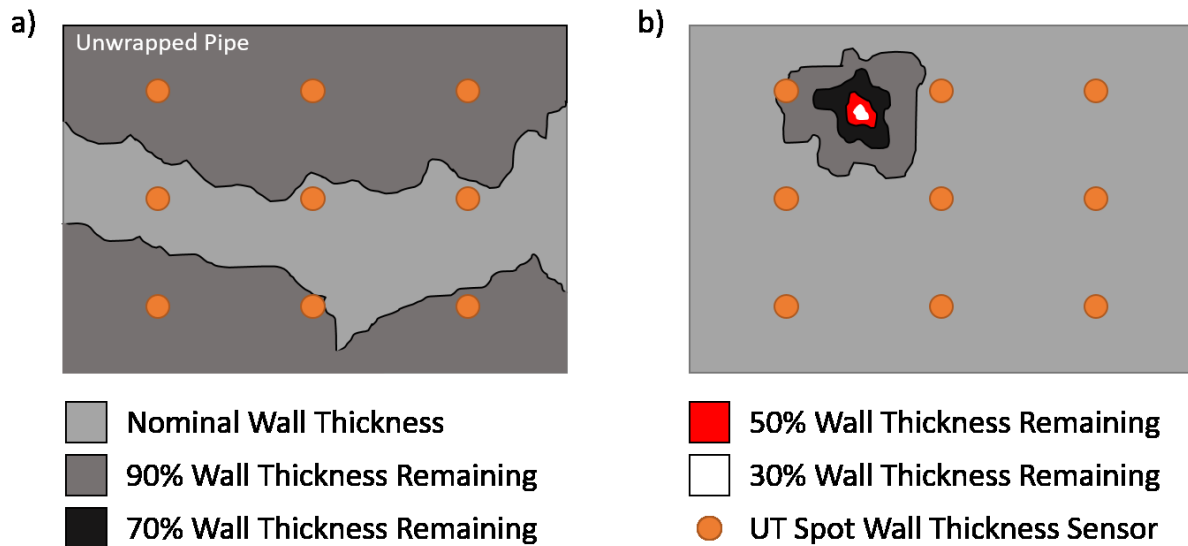


Figure 1.4 Corrosion distributions with a) high and b) low corroded to non-corroded area ratio

1.3.3 Coverage Against Sensitivity Trade Off

Currently it is possible for inspections to create a 2D thickness map of a pipe by performing a series of spot measurements systematically scanned over the area under test (known as a c-scan). This technique requires a skilled operator to perform the measurements and is time consuming, leading to a search for more efficient methods. Conventional LRGW systems excite a wave packet in the pipe or plate at one location and rely on the reflection of the wave from a defect. This enables large areas of oil and gas infrastructure to be screened at any one time (e.g. up to 50m either side of an array of transducers [27]) from a single location/access point on a pipe. However, the defects in the pipe must be sufficiently deep and sharp for a detectable reflection to occur (5% cross sectional area loss is commonly quoted [27] as minimum size that can be detected if the defect shape causes a reflection). Therefore, this system is likely to miss smaller areas of wall thinning that might be of concern. Spot wall thickness monitoring systems accurately measure the thickness of a pipe or plate at a precise location (with a WT sensitivity of around $20\mu\text{m}$ [41]), using the pulse echo or pitch catch method. These spot measurements constantly monitor the average thickness of a pipe (approximately 1cm^2 directly under the sensor) and relay the information back to the plant operator. However, even though multiple sensors can be installed on the same pipe, this system is only able to relay a discretised thickness map of the pipe or plate, thereby potentially missing defects which are not directly under a sensor. The sensitivity/coverage area trade-off is demonstrated in Figure 1.5, illustrating that the current in-service technology occupies either end of the sensitivity/area spectrum. It is therefore the objective of this study to evaluate several techniques which lie between these extremes, with the aim of evaluating both their coverage and sensitivity.

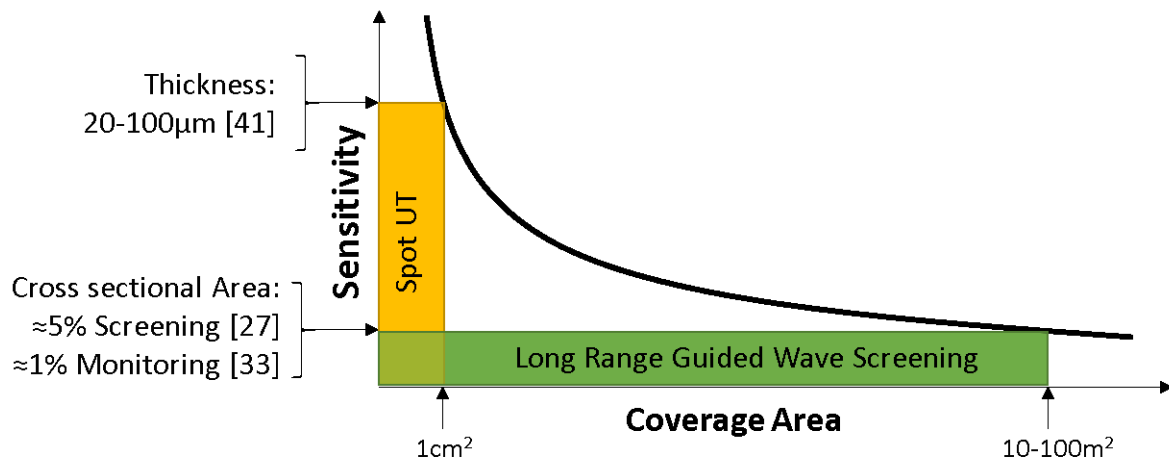


Figure 1.5 Current ultrasonic corrosion monitoring and screening techniques plotted on a sensitivity-coverage area curve.

1.4 Outline of Thesis

The governing wave equations behind ultrasonic bulk wave and guided wave propagation are introduced in chapter 2, along with a brief description of the reflection and mode conversion of bulk waves from boundaries between media. Many of the results in this thesis were generated from finite element (FE) models, therefore an overview of the explicit FE modelling technique is also given. To streamline the generation of the FE models a custom automated routine was devised to simulate the signal response from a range of defect characteristics.

Chapter 3 describes in detail a corrosion monitoring technique which uses a single transducer to propagate a guided wave pulse around the circumference of a pipe. The guided wave pulse propagates through the corroded area and the through transmitted pulse is received by the transducer and analysed. The signal processing method by which the corrosion is measured has been devised to compensate for temperature fluctuations in the pipe, and is tested experimentally. Finite element simulations are then performed on a range of different defects (uniform, notch and Hann profile) to assess the viability of the setup and signal processing.

An array equivalent of the chapter 3 setup is analysed in chapter 4. This arrays setup uses the through transmitted and reflected pulses to provide a complete analysis of the viability of circumferential guided waves for the purposes of monitoring or screening for corrosion. Many FE simulations were performed on Hann profile defects and part thickness holes, with different dimensions and positions relative to the transducers. A probabilistic analysis method is then described which characterises the probability of detection (POD) for each

simulation, thereby allowing for the entire probability space to be mapped. Wavelength normalised and data fused results are also presented. The measurement pitch between elements/transducers in the array are also factored into the analysis. Conclusions regarding circumferential guided waves are then drawn.

Chapter 5 introduces the use of ultrasonic spot measurements for the detection of corrosion in more detail and as well as providing a brief evaluation of the area coverage of spot ultrasonic transducers. Using a simplified model the maximum area coverage of a bulk wave transducer to the detection of pitting corrosion is quantified.

Chapter 6 tests many of the assumptions made in chapter 5 by performing FE simulations of a wide range simulations. Signal processing methods are described which determine the amplitudes of various signal features as well as extract the wall thickness. Models containing sloped backwalls and hemispherical pits with different radii and positions are interrogated by shear and longitudinal bulk waves. The signal response of the different transducers is presented, namely EMATs (electromagnetic acoustic transducers, high temperature waveguides and pitch catch compression).

Chapter 7 briefly evaluates the possibility of using spot ultrasonic measurements to monitor and track individual pits (individual pit monitoring system, IPMS). Practical issues surrounding the technique are first discussed and form the framework of the analysis. A subset of FE results from the previous chapter are qualitatively analysed and form the basis of a classification system, classifying whether or not a pit is detectable in a given time trace. Automated classification routines are then described, and applied to the entire FE data set. The results then allow for the evaluation of an IPMS.

Chapter 8 reviews the thesis and highlights its main conclusions, furthermore it proposes areas for future work.

Chapter 2

Bulk and Guided Wave Background

2.1 Introduction

The studies presented in this thesis all use ultrasonic techniques to evaluate the integrity of a specimen. This chapter covers the background of the various techniques. It also introduces the finite element method which is used to simulate them. Both shear and longitudinal bulk waves propagate in (semi) infinite elastic media, and in the absence of any boundaries (e.g. the surface of a metal) the shear and longitudinal waves can be treated as independent of one another. However, bulk waves are only of use in NDE when they interact with a feature or discontinuity, such as a boundary between media or a defect, within a sample. At this point the shear and longitudinal waves are no longer independent and are coupled to one another. If the feature has simple geometries then it is, under certain circumstances, possible to analytically derive the ultrasonic response, however, corrosion is unlikely to be uniform and regular. Finite element analysis (FEA) can therefore be used to create a 2D or 3D model of complex defects and simulate the expected ultrasonic response.

Guided wave techniques are also used in this study. Guided waves are formed by confining ultrasonic bulk waves within a structure/waveguide such as a pipe, plate, or cylinder, which then leads to the formation of discrete modes due to the continual reflection of bulk waves off the surfaces of the structure. The derivation of the SH and Lamb wave modes in flat plates is shown in section 2.3 and the dispersion curves of each mode can be calculated using analytical and numerical techniques. However, their interaction with complex defects is not straight forward and was simulated using FEA. Section 2.4 outlines the operation of finite element method/analysis (FEM/FEA) as well as the specific methods employed in this study to ensure the smooth and error free automation of the modelling procedure.

2.2 Mechanics of Ultrasonic Bulk Waves

The principles governing the behaviour of bulk and guided waves are well known and have been covered in-depth in several textbooks [42]-[44]. Without the presence of body forces the equation of motion of an isotropic elastic medium is:

$$(\lambda + \mu)\nabla\nabla \cdot \mathbf{u} + \mu\nabla^2\mathbf{u} = \rho \frac{\partial^2\mathbf{u}}{\partial t^2} \quad (2.1)$$

where, $\mathbf{u}$ is the three-dimensional displacement vector, ρ is the material density, λ and μ are the Lamé constants and ∇^2 is the three-dimensional Laplacian operator. This is also known as Navier's Equation. The Helmholtz decomposition allows $\mathbf{u}$ to be expressed as the sum of the gradient of a scalar ϕ , and the curl of a vector potential Φ .

$$\mathbf{u} = \nabla\phi + \nabla \times \Phi \quad (2.2)$$

where Φ has zero divergence.

$$\nabla \cdot \Phi = 0 \quad (2.3)$$

By substituting the Helmholtz decomposition into Navier's equation two independent wave equations are derived which govern the motion of the longitudinal and shear waves.

$$\frac{\partial^2\phi}{\partial t^2} = c_l^2\nabla^2\phi \quad (2.4)$$

$$\frac{\partial^2\Phi}{\partial t^2} = c_s^2\nabla^2\Phi \quad (2.5)$$

From these two equations, the longitudinal and shear velocities are defined from the material properties.

$$c_l = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (2.6)$$

$$c_s = \sqrt{\frac{\mu}{\rho}} \quad (2.7)$$

Since equations 2.4 and 2.5 are independent of each other the longitudinal and shear waves do not interact with each other in a linear isotropic bulk material. The general solution to both equations is:

$$\phi, \Phi = Ae^{i(k_{l,s}z - \omega t)} \quad (2.8)$$

where z is the spatial coordinate, t is the time variable, A is the wave amplitude, ω is the angular frequency, and $k_{l,s}$ are the longitudinal and shear wave wavenumbers which are defined as:

$$k_{l,s}^2 = \frac{\omega^2}{c_{l,s}^2} \quad (2.9)$$

2.2.1 Scattering and Mode Conversion

The Helmholtz decomposition (equation 2.2) shows that in the bulk of a homogenous material the scalar and vector components can be linearly combined. That is, the full displacement field can be described as a summation of the shear and longitudinal components. When a reflection off a boundary occurs at normal incidence, the reflection coefficient, R , describes the change in amplitude as a wave moves from one semi-infinite medium to another:

$$R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \quad (2.10)$$

where $\rho_{1,2}$ and $c_{1,2}$ are the density and wave velocities of the media 1 and 2. However, when oblique reflections occur the shear and longitudinal components are coupled together, which leads to mode conversion between the two. It must be stated that shear waves can be polarised in any direction orthogonal to the direction of propagation, and the shear vector can be described by its shear vertical wave (SV - polarised in the plane of wave propagation) and the shear horizontal wave (SH - parallel to the boundary between media) component. The SH wave has constant cross-sectional shape perpendicular to the boundary plane and therefore does not undergo mode conversion upon oblique reflection [42], [45]. Figure 2.1a and b illustrates the mode conversion between the L and SV modes, whereby the reflection angle of the mode converted reflection depends mode conversion mechanism (either SV-L or L-SV).



Figure 2.1. Bulk wave reflection and mode conversion at a metal-air boundary of a) longitudinal, b) shear vertical and c) shear horizontal waves.

The relative amplitudes, A , of the incident, i , and reflected, r , L and SV waves are governed by the following equations [42]:

$$\frac{A_{L,r}}{A_{L,i}} = \frac{\sin 2\theta_i \sin 2\theta_r - k^2 \cos^2 2\theta_r}{\sin 2\theta_i \sin 2\theta_r + k^2 \cos^2 2\theta_r} \quad (2.11)$$

$$\frac{A_{SV,r}}{A_{L,i}} = \frac{2\sin 2\theta_i \cos 2\theta_r}{\sin 2\theta_i \sin 2\theta_r + k^2 \cos^2 2\theta_r} \quad (2.12)$$

$$\frac{A_{SV,r}}{A_{SV,i}} = \frac{\sin 2\theta_i \sin 2\theta_r - k^2 \cos^2 2\theta_r}{\sin 2\theta_i \sin 2\theta_r + k^2 \cos^2 2\theta_r} \quad (2.13)$$

$$\frac{A_{L,r}}{A_{SV,i}} = \frac{-2k^2 \sin 2\theta_r \cos 2\theta_r}{\sin 2\theta_i \sin 2\theta_r - k^2 \cos^2 2\theta_r} \quad (2.14)$$

where θ_i and θ_r are the incident and reflected angles.

2.3 Guided Waves

Ultrasonic guided waves are elastic waves which propagate in infinite plates of constant thickness [46], and are created from the superposition of bulk waves continually being reflected between two planes (i.e. the plate boundaries), which gives rise to discrete modes.

2.3.1 Shear Horizontal Waves

A free isotropic plate of thickness, b , with traction free surfaces has boundary condition $y = b/2$ and $y = -b/2$. The shear wave solution to the free plate problem using the two potentials

ϕ and Φ occurs when $\phi = 0$. This results in the following equation of wave propagation in the z direction.

$$\Phi = \Phi_0(y)Ae^{i(k_z z - \omega t)} \quad (2.15)$$

This is similar to equation 2.8, however, the solution is also a function of another spatial term, y (the direction normal to the plate). Substitution of equation 2.15 into 2.5 yields a potential based on the y -dependent sinusoids.

$$\Phi_0(y) = A \sin(k_y y) + B \cos(k_y y) \quad (2.16)$$

where,

$$k_y^2 = k_s^2 - k_z^2 \quad (2.17)$$

where k_s is the shear wavenumber and k_y is the projection onto the y -axis. Since the boundary conditions are traction free this leads to the following condition at $y = b/2$ and $y = -b/2$.

$$(\lambda + \mu) \frac{\partial u_x}{\partial y} = (\lambda + \mu) \frac{\partial}{\partial y} \left(\frac{\partial}{\partial y} \Phi_z + i k_z \Phi_y \right) = 0 \quad (2.18)$$

Equation 2.16 satisfies the above condition when,

$$k_y = \frac{p\pi}{b} \quad (2.19)$$

where $p = 0, 1, 2, \dots$. This leads to the following expression for k_z from equations 2.9 and 2.19,

$$k_z^2 = \left(\frac{\omega}{c_s} \right)^2 - \left(\frac{p\pi}{b} \right)^2 \quad (2.20)$$

Using the relationship $k_z = \omega/c_p$ and equation 2.17 the relationship between the phase velocity, ω , and the frequency-thickness product can be defined as,

$$c_p(fb) = \pm 2c_s \left(\frac{fb}{\sqrt{4(fb)^2 - p^2 c_s^2}} \right) \quad (2.21)$$

where the p term refers to the mode order. The zeroth mode (SH0) is non-dispersive since its velocity is constant, $c_p = c_s$. For all other modes the phase velocity of the wave is dependent on the thickness of the plate. These modes are dispersive since different frequencies travel with different velocities. The phase velocity dispersion curves for modes SH0 to SH8, as described by equation 2.22, are shown in Figure 2.2a up to a frequency-thickness of 10MHz.mm.

Chapters 3 and 4 look to exploit the thickness dependence of the SH1 mode's group velocity. The group velocity of a dispersive wave pulse is the velocity of the pulse envelope and not the phase within. For a SH wave this is given by,

$$c_g(fb) = c_s \sqrt{1 - \frac{(p/2)^2}{(fb/c_s)^2}} \quad (2.22)$$

Figure 2.2b shows the group velocity up to 10MHz.mm.

Another useful property of the SH1 mode (and higher order mode, SH2 etc.) is their cut-off frequency given by,

$$fb_p = \frac{pc_s}{2} \quad (2.23)$$

Any frequency components below a certain frequency-thickness are not able to propagate in that plate. This property could be used to determine the minimum thickness along a path by finding the minimum frequency which can propagate, using Fourier analysis. There is already existing work on this subject [47], [48].

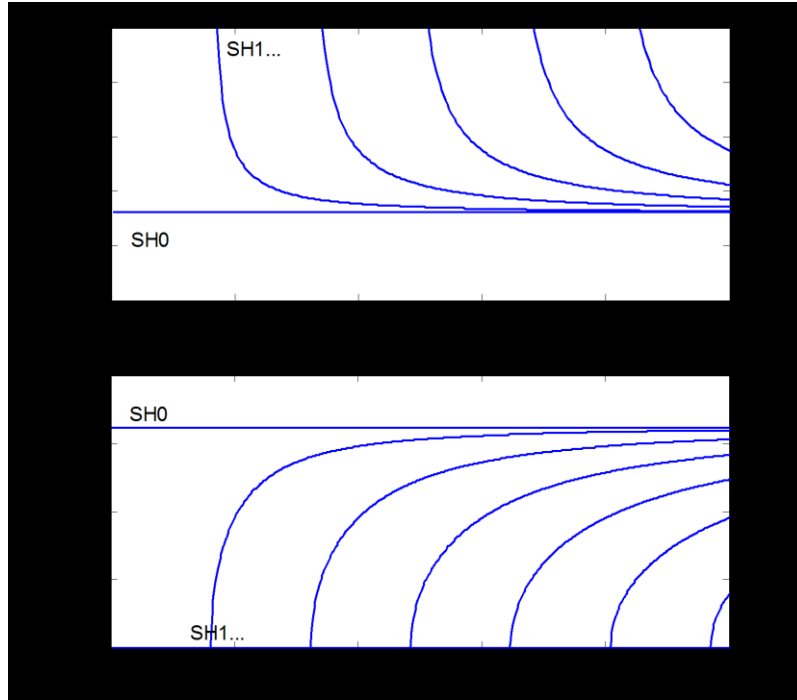


Figure 2.2 Shear horizontal a) phase velocity and b) group velocity curves in a steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$)

2.3.2 Lamb Waves

Lamb waves arise due to the coupling of the shear vertical (SV) and longitudinal (P) waves as mode conversion occurs at the plate boundaries, making their solution much more complex than the shear horizontal waves (SH). The traction free boundary at $y = b/2$ and $y = -b/2$ requires that the SV and P waves have the same wavevector component in the direction of propagation, z , $k_{zs} = k_{zl}$. This leads to the following frequency equations [42]:

$$\frac{\tan \frac{k_{ys}b}{2}}{\tan \frac{k_{yl}b}{2}} = -\frac{4k_z^2 k_{ys} k_{yl}}{(k_{ys}^2 - k_z^2)^2} \quad (2.24)$$

for the symmetric modes, and

$$\frac{\tan \frac{k_{ys}b}{2}}{\tan \frac{k_{yl}b}{2}} = -\frac{(k_{ys}^2 - k_z^2)^2}{4k_z^2 k_{ys} k_{yl}} \quad (2.25)$$

for the antisymmetric modes. The frequency equations can then be solved to find the frequency-thickness dependent wavenumber for a given mode. The wavenumber can then be used to find the mode shape of a mode at a certain frequency-thickness [42]. An example

of the two fundamental symmetric and antisymmetric mode shapes are illustrated in Figure 2.3.

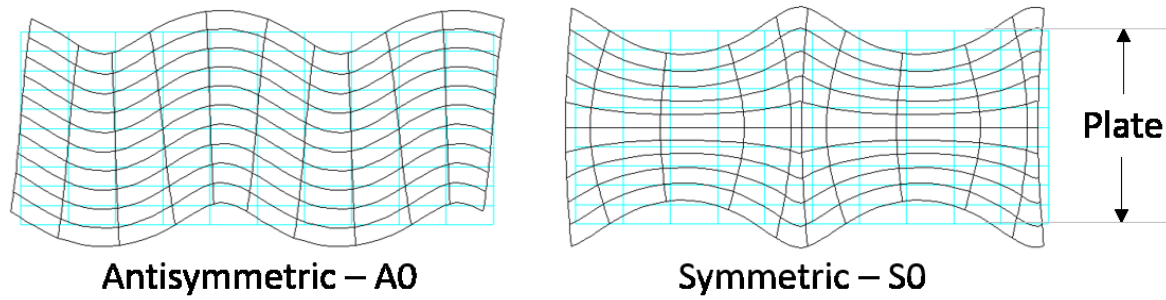


Figure 2.3 Mode shapes at 50kHz in a 10mm thick steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$), showing exaggerated antisymmetric and symmetric displacements from DISPERSE [2]

The through thickness (normal to the plate) wavenumbers are given in terms of ω , c_p and c_s by,

$$k_{ys}^2 = k_s^2 - k_z^2 = \left(\frac{\omega}{c_s}\right)^2 - k_z^2 \quad (2.25)$$

$$k_{yl}^2 = k_l^2 - k_z^2 = \left(\frac{\omega}{c_l}\right)^2 - k_z^2 \quad (2.26)$$

where c_s and c_l are the shear and longitudinal wave velocities. The dispersion relations for the Lamb waves are transcendental and must be solved numerically by combining all four equations, which is usually performed by numerical routines using specialist software (such as DISPERSE [2]). Figure 2.4 shows the phase velocity and group velocity against frequency-thickness respectively for steel plate. As with the SH1 mode all Lamb waves are dispersive and their phase and group velocities are thickness dependent.

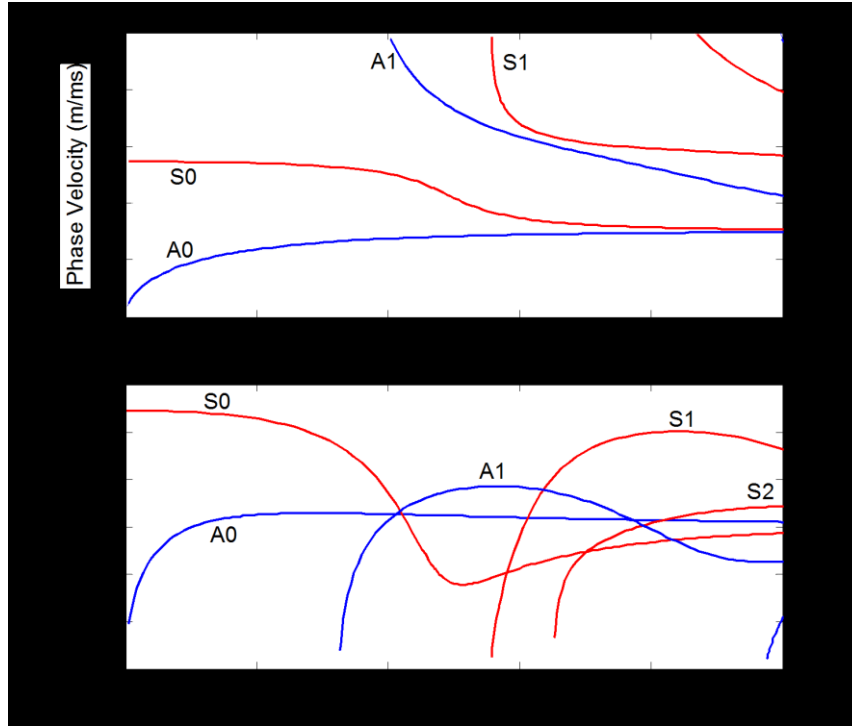


Figure 2.4 Phase (a) and group (b) velocity curves for both the symmetric and antisymmetric Lamb waves modes in a steel plate ($c_s = 3260\text{ms}^{-1}$, $c_l = 5960\text{ms}^{-1}$)

2.4 Finite Element Method

Finite element method/modelling/analysis (FEM/FEA) is a numerical method by which differential equations are solved over a finite domain. To model non-steady state ultrasound the model must also be time dependent. A steady state solution can be found by solving the model in the frequency or time domain. A mesh is created which consists of nodes (points in space) and elements (the space between nodes), which defines the material characteristics of the model. The FEA performed in this thesis is solved explicitly, whereby the state (i.e. displacement of the nodes) at time, t , is used to calculate the state at the next time step, $t+\Delta t$. First the continuous equations 2.4 and 2.5 are expressed in discrete form which is solved for each node in the model [49].

$$[M]\ddot{\mathbf{u}} + [C]\dot{\mathbf{u}} + [K]\mathbf{u} = \mathbf{F}_{ext} \quad (2.27)$$

Where $\mathbf{u}$, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are the displacement, velocity and acceleration vectors respectively, M is the diagonal mass matrix (i.e. material density), C is the viscous damping matrix (i.e. Rayleigh damping, $[C]=0$ in an elastic material) and K is the static stiffness matrix (i.e. Young's modulus and Poisson's ratio), $\mathbf{F}_{ext}$ are the external forces. Equation 2.24 can be expressed entirely in the displacement vector in terms of Δt based on a central difference operator linking $\mathbf{u}$, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$:

$$\dot{u}^t = \frac{1}{2\Delta t}(u^{t+\Delta t} - u^{t-\Delta t}) \quad (2.28)$$

$$\ddot{u}^t = \frac{1}{4\Delta t^2}(u^{t+2\Delta t} + u^{t-2\Delta t} - 2u^t) \quad (2.29)$$

To ensure efficient FEA the time step, Δt , and the element size, Δx , must be small enough to accurately model the scenario. However, they must not be so small that the large computational time inhibits the collecting of enough data. It is generally accepted [50] that the smallest element size, Δx , should be no greater than a tenth of the smallest wavelength in the simulated wave pulse. Significant progress has been made since the Alleyne et al. publication in 1992, and currently the main limitation of finite element modelling is not purely the model size but the trade-off between size and runtime. In 3D, halving the element size will increase the number of elements by 8, requiring the time step to be halved, therefore increasing the runtime by a factor of 16 - unless the timestep is sufficiently small already. More recently lower limits of element size have been suggested, such as 20 nodes per wavelength [51], however, this depends on the complexity of the defect being modelled [49]. The time step must be shorter than the time it takes the wave to travel between nodes ($\Delta t = \Delta x / c$, where c is the wave velocity), if this condition is not met then the solution will become unstable as $c > c_s$ or c_l . Δt scales linearly with computation time.

The smaller the mesh the more data points and the more refined the model, however, this is no guarantee that the model accurately reproduces reality. There are many ways in which a model can be verified, for example, the model can be compared with experimental or analytical results, however, if either setup is costly or complex then it may be difficult to acquire suitable results. Another method is to converge the model by running several models with ever decreasing mesh sizes and time steps) and extracting a numerical value of interest (e.g. amplitude or TOF). The model can be said to be valid if the value converges towards an expected, constant and/or stable value. See section 3.5.2 for an example of convergence. It is worth noting that experimental validation is the gold standard of validation and should be used whenever possible.

2.4.1 Automation of FEA

In this study many models are repeatedly run with only a small variation between concurrent models. To ensure that this procedure runs smoothly and returns no errors a programme was designed which created a structured mesh (a mesh with regularly sized elements), to which

defects were added, either by manipulating the nodes positions or changing the material characteristics of the elements.

2.4.1.1 Creation of a structured mesh

A structured mesh consists of a regular pattern of elements (in this case eight-node brick elements with reduced integration). The 3D structured meshes used in this work are all rectangular cuboids with dimensions in X , Y and Z . The models consist of nodes, which are defined by a number, n_{node} , and 3 coordinates (x , y , z), and elements, which are defined by a number, e_i , and the nodes at the edges of each element (n_1 , n_2 , n_3 , n_4 , n_5 , n_6 , n_7 , n_8). Since a regular 3D shape is being used a geometric relationship holds between the node numbers, n_{1-8} , coordinates (x,y,z) and a given element:

$$e_i = n_y + (N_y - 1)(n_z - 1) + (N_z - 1)(N_y - 1)(n_x - 1) \quad (2.30)$$

$$n_1 = n_y + N_y(n_z - 1) + n_x(N_y N_z) \quad (2.31)$$

$$n_2 = n_y + N_y(n_z - 1) + 1 + n_x(N_y N_z) \quad (2.32)$$

$$n_3 = n_y + N_y n_z + 1 + n_x(N_y N_z) \quad (2.33)$$

$$n_4 = n_y + N_y n_z + n_x(N_y N_z) \quad (2.34)$$

$$n_5 = n_y + N_y(n_z - 1) + (n_x + 1)(N_y N_z) \quad (2.35)$$

$$n_6 = n_y + N_y(n_z - 1) + 1 + (n_x + 1)(N_y N_z) \quad (2.36)$$

$$n_7 = n_y + N_y n_z + 1 + (n_x + 1)(N_y N_z) \quad (2.37)$$

$$n_8 = n_y + N_y n_z + (n_x + 1)(N_y N_z) \quad (2.38)$$

where n_a is the x , y or z coordinate given in factors of the step size ($a/\Delta a$, $a=x,y,z$), N_A is the total number of nodes in the x , y or z direction ($A/\Delta a$ ($A=X,Y,Z$)) and Δa is the step size in each direction ($\Delta x = \Delta y = \Delta z$).

2.4.1.2 Modelling of defects via the changing of the material characteristics of a defect

Common methods of modelling complex defects involve either modelling the defect with a stepped approximation [52], untying adjacent nodes [53], or using unstructured meshes in the location around the defect [54][55]. Each of these methods has its advantages and disadvantages, however, in the context of an automated programme which runs without runtime/meshing errors it is much more suitable to not change the structure of the mesh and instead change the material properties of the elements within the boundary of the defect. It was found that the most common error type was a meshing error when using unstructured or free meshing. By simply identifying the relevant elements and changing their density to zero it is possible to create a stepped stress-free boundary.

2.5 Summary

A background to the basic principles of bulk wave and guided waves has been presented in this chapter, which will form the basis of the ultrasonic techniques covered in the following chapters. Bulk waves (shear and longitudinal) form the basis of all elastic wave theory. However, they are only able to be easily analytically modelled when propagating in a homogenous and isotropic infinite elastic medium (or away from the boundary of a semi-infinite medium), which is not useful for the purposes of defect/corrosion detection.

Chapters 3 and 4 evaluate the ability of guided waves to detect and characterise corrosion in pipes. The dispersive properties of the SH1, A0 and S0 guided wave modes are investigated further along with the non-dispersive SH0 mode. Chapters 6 and 7 make use of bulk waves reflecting off hemispherical defects. In all four chapters 3D finite element analysis is performed to model the interaction of bulk waves with complex defects. Chapters 4, 6, and 7 make use of an automated FEM programme which allows many simulations to be performed without runtime errors. The method by which this was achieved has been outlined in section 2.4.1.1.

Chapter 3

Extraction of Pipe Wall Average Thickness using Circumferential Shear Horizontal Guided Waves

3.1 Introduction

As was discussed in chapter 1, the current in-service technology (spot UT or long range guided waves) sit at either end of the sensitivity/coverage area spectrum. Therefore, when choosing a suitable NDE technique there is a trade-off in sensitivity between the highly sensitive yet highly localised spot thickness measurements and the low sensitivity/high coverage LRGW screening techniques. The objective of this chapter is to analyse a technique which is more sensitive to thickness changes than LRGWs as well as having a much larger coverage area than spot measurements. This chapter will evaluate the potential of a single guided wave transducer to characterise the wall thickness around the circumference of a pipe. The setup is shown in Figure 3.1 which consists of a single transducer placed on a pipe, which transmits a dispersive guided wave around the pipe's circumference and receives it at the same location. As was discussed in chapter 2, the dispersion property of a guided wave pulse relates the frequency-thickness product (MHz.mm) to the phase or group velocity of the pulse. Therefore, any change in thickness along the pulse's path will result in an effective velocity change which can be inverted to give a value of average thickness along the path (see section 3.3.1). The SH0 and SH1 modes are evaluated in this chapter and used to interrogate a range of different sized and shaped defects.

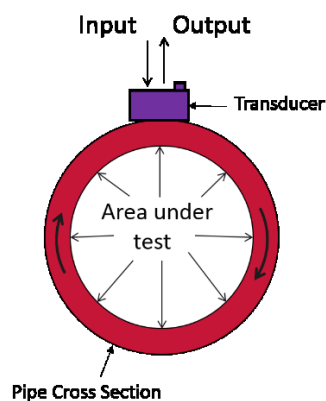


Figure 3.1 Guided wave travelling around the circumference of a pipe

This chapter begins with a literature review of guided wave techniques used for thickness evaluation. This is followed by a description of the ‘temperature compensated thickness extraction method’, using the SH modes, and experimental validation of the method. The method is then further tested using the finite element method to model the effect of thinned notches, part thickness holes and Hann profile defects on the SH guided wave pulses and the subsequent thickness measurements. Conclusions about the suitability of the setup shown in Figure 3.1 are then drawn.

3.1.1 Literature Review

3.1.1.1 Guided Wave Measurements for Thickness Evaluation

The first theoretical piece of work to be conducted on guided waves was in 1876 by Pochhammer, on guided waves in rods [56]. Rayleigh, in 1885, then proceeded to develop the theory behind surface waves of a semi-infinite medium [57]. Finally, Horace Lamb derived the mathematical formulation for the propagation and dispersion relations of guided waves in 1889 [58]. It was only in the late 1940s when it was first possible to test these theories experimentally on metal samples [42]. In the early 1980s the idea of using guided waves for detection of defects in plates was first tested [59], [60]. The use of dispersive guided waves for the characterisation of material properties [61]-[63] was developed in the late 1980s. In 1990 Jansen et al. [64] considered the use of the dispersive properties of guided waves for imaging/tomographic purposes in aluminium plates. This led to a large body of work on the idea of imaging [65]-[68] in the subsequent decade. In 1998 Zhu et al. [69] investigated the use of Lamb waves for detecting hidden corrosion in the skin of an aircraft between two transducers (a transmitter and a receiver). This study used a range of different Lamb wave modes (A0-2, S0-3) and investigated four Lamb wave properties: change in group velocity, higher-order mode cut-off frequencies, transmission and reflection coefficients. The study used both BEM (boundary element modelling) and experiments to evaluate each of these characteristics on samples with defect depths of 1% to 20% of plate thickness, although all results presented are for 5% defect depths and higher. The change in phase velocity was explicitly not measured because the oblique incidence and reflection of waves within the wedge transducers made it "difficult to measure accurately the phase velocity changes". Zhu et al. does successfully show that four Lamb wave characteristics (change in group velocity, higher-order mode cut-off frequencies, transmission and reflection coefficients) are affected by the presence of a defect. Numerical results are presented for specific samples; however, no globally applicable sensitivities are given.

Jenot et al. [70] concentrates on the group velocity change of the S0 mode in thin (<1mm) copper sheets, which were chemically corroded over time. The study compared the

calculated thickness loss against actual thickness loss of copper samples. The results show that there was good correlation between the two up to a wall thickness loss of 64%, however, beyond that there was reduced correlation since the thinning was too varied. In terms of sensitivity the minimum detectable thickness change given (for a 2.19MHz S0 pulse in a 0.45mm thick copper plate) is 0.35% (or 1.57m), which corresponds to a time shift of 30ns.

Instanes et al. [71] exploited the principle of the dispersion of the A0 mode for the purposes of pipeline erosion monitoring. Laboratory based tests were able to detect a 1% general wall thinning between two transducer. This system operates at the constant group velocity point (CGV) which is stated to be the most sensitive frequency at which to operate. At the CGV point the group velocity will not change much relative to the phase velocity of the wave packet. The operation of this setup is further expanded upon in Nagy et al. [72]. A wave packet operating at the CGV point is shown to have the greatest sensitivity to changes in the plate thickness. The sensitivity is calculated analytically to give a normalised sensitivity function expressed in radians (i.e. phase shift). This paper also states that operating at the CGV point "assures the thermal stability of the measurement without external temperature compensation" since a temperature change will not result in a significant change in the maximum value of the normalised sensitivity function (as there is a 'plateau' around that point). This results in the CGV point being "effectively independent of temperature". The paper states that for small thickness change approximations hold for $\Delta d \ll d$, where d is the plate thickness. An example is given stating that for $z/d = 30$ (i.e. the thickness to transducer separation ratio), a 1% change in wall thickness will result in a 13° change in the true phase, which they state as being "fairly easily measurable".

The sensitivity of Lamb wave group velocity dispersion for corrosion monitoring of Aluminium plate was discussed in Gao et al. [73], using both numerical and finite element solutions to calculate the most sensitive frequency to thickness changes. Most importantly the A0 and S0 modes were not at their most sensitive below the higher order mode cut-off. This is somewhat irrelevant for the study presented in this report since the mode purity will affect the sensitivity of the thickness extraction algorithm. Nurmalia et al. [74] studied the effect of mode conversion of SH0 and SH1 modes when interacting with a defect/area of thinning. They concluded that the group velocity of the SH1 mode is reduced by an area of thinning, as well as confirming that the SH0 mode is mostly constant regardless of the thickness. If the defect is greater than twice the plate thickness at the point where the SH0 mode exits the thinned area mode conversion to SH1 occurs.

3.1.1.2 Guided Wave Tomography

Tomography uses many wavepaths through an object (e.g. a defect) and the effective change of velocity/attenuation to reconstruct an image of the object [64], [75]. The first guided wave tomography studies presumed that Lamb waves could be modelled as rays travelling between any given pair of transducers, this is known as ray tomography/tracing [64], [76]. Ray tomography is only correct for defects with a width/diameter larger than the wavelength and the first Fresnel zone [52], otherwise scattering and diffraction effects dominate. Diffraction tomography is the method devised to construct an image from the scattering and diffraction of the incident Lamb wave [67], [68], [77]. Belanger et al. [52], [76], [78] investigated simple defects with either ray theory and diffraction tomography using the Born Approximation, which limits the contrast of the image since only small changes in phase are permitted.

Huthwaite et al. [79] have combined the ray tracing (in the form of bent ray tomography, which calculates every possible ray within the area under investigation [68] instead of the direct path) with the diffraction tomography. Effectively the bent ray tomography is used to produce a low contrast image of the defect. Therefore, the phase distortion of the scattering can be accounted for and the Born approximation is valid again. An iterative algorithm was also developed which further improves the contrast of the image.

Guided wave tomography is the best method for constructing a thickness map of a pipe or plate without taking individual thickness measurements. However, it requires complex acquisition and processing and hence why this project looks to investigate monitoring along a line using a single ray path.

3.2 Measurement Principle

Figure 3.1 shows the measurement principle whereby a single transducer is used to send and receive a directional guided wave that propagates around the circumference of a pipe. To simplify the simulations the pipe was unrolled and represented as a flat plate, as shown in Figure 3.2. In the plate setup, the guided wave signals are sent from one transducer (transmitting - Tx) to the another (receiving transducer - Rx). This is the equivalent of sending a pulse around the circumference of the pipe and detecting it at the same location, using a circumferentially directional transducer [80]. The propagation distance between the two transducers is 500mm and a plate thickness of 10mm was used throughout the study. These dimensions are typical of 6-8" pipes which have a diameter of 150mm-200mm (500mm circumference = 159.2mm diameter). For the large diameter to thickness ratio presented

here, the assumption that the circumferential and plate dispersion curves are good to within 1% of the group velocity (as calculated by DISPERSE [2]) [81].

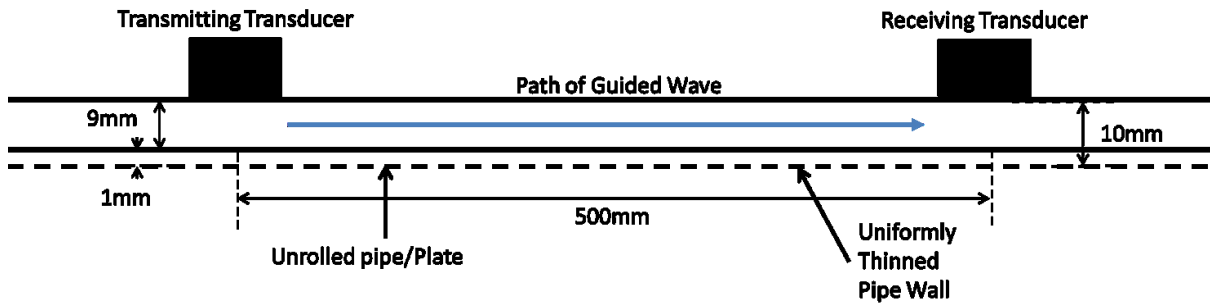


Figure 3.2. Shows a schematic of a cross-section of an unrolled pipe (i.e. a plate), with two transducers 500mm apart with a uniform wall thickness thinned from 10mm to 9mm.

Figure 3.3 shows the analytically calculated output SH0 and SH1 time traces produced by the Figure 3.2 setup using a 5 cycle Hann windowed pulse with a 250kHz centre frequency over 0.5m in a 10mm thick plate. This was achieved by using the equation for SH phase velocity (see equation 2.22). The SH0 (red) and SH1 (green) are temporally separated and therefore able to be easily windowed to perform signal processing separately on either mode. The windowing process for the SH0 mode is trivial since it is non-dispersive and therefore the wave packet does not distort or change temporal location as the thickness changes. The SH1 mode is dispersive and therefore distorts as it propagates. As a rule of thumb the SH1 windowing performed in this study attempted to window as much of the SH1 pulse as possible. Typically, the SH1 windowing started 1.5 cycles after the SH0 toneburst ended and was 28 cycles long (1 cycle or period = $1/f = 4\mu\text{s}$). Both modes were separately analytically calculated and superimposed over one another, therefore, neither attenuation or preferential mode excitation were considered in the analytical propagation, and therefore the SH0 mode is much greater in amplitude than the SH1 mode. In reality, one mode would be excited to a greater extent than the other. The input signal has been included in the Figure 3.3a signal (in blue) and can be seen in more detail in Figure 3.3b as well as its frequency spectrum in Figure 3.3c.

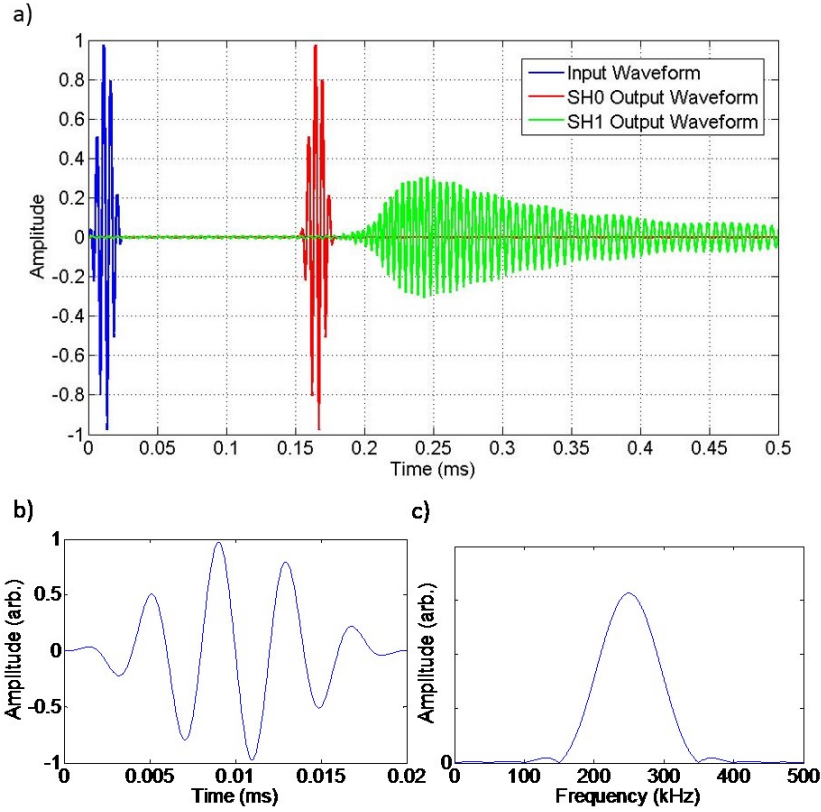


Figure 3.3. a) The input signal to the transmitting transducer (blue), which is a 250kHz 5 cycle Hann windowed pulse ($c_s = 3235\text{m/s}$), and the resultant analytically calculated time trace received by the receiving transducer (0.5m separation in a 10mm thick plate): SH0 (red) and SH1 (green) b) Expanded input signal, and spectra c).

3.3 Temperature Compensated Average Thickness Extraction Method

3.3.1 Effective Group Velocity Extraction Method using SH Guided Waves

The SH1 mode is dispersive, unlike the SH0 mode, meaning that the group (and phase) velocity of the wave is dependent on the frequency-thickness of the plate in which they are propagating. If an SH1 wave packet is sent between two transducers and a change in thickness occurs, then that change in the thickness of the plate will result in a measurable change of the effective group velocity of the wave packet that is travelling between the two transducers. The setup described, in combination with the algorithm/method below, has been designed to extract a value of the average thickness between two points on a plate or around the circumference of a pipe. As this method determines the *average* thickness (not remnant thickness) it is possible for different corrosion profiles, along the propagation path, to have the same value of average thickness. One corrosion profile could be uniformly thinned by 1mm over 0.5m propagation path in a 10mm plate, compared to another corrosion profile, which has 2mm of thinning over 0.25m propagation path. Both would have an average thickness of 9mm over the total propagation path of 0.5m. Any timing delays due to transducer design or equipment setup have been assumed to be constant.

The group velocity curve of the SH1 (c_g) is shown in Figure 3.4 and can be expressed as an analytical equation, which is dependent only on the frequency (f), thickness (b) and shear velocity (c_s):

$$c_g(fb) = c_s \sqrt{1 - \frac{(c_s/2)^2}{(fb)^2}} \quad (3.1)$$

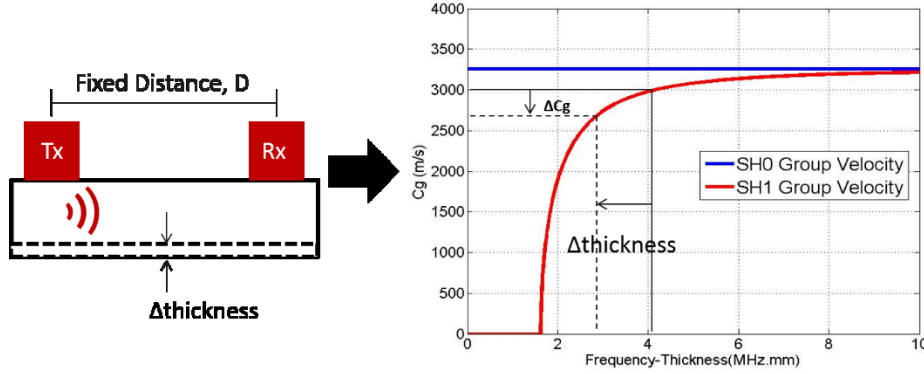


Figure 3.4. Shows the group velocity curves for the non-dispersive SH0 (blue) and dispersive SH1 (red) modes in steel ($c_s = 3235\text{m/s}$) produced in DISPERSE [2]. The effect of a change in the thickness of a plate using a pitch catch SH guided wave setup is shown, as well as the resulting change in the group velocity (at a single frequency-thickness value)

3.3.2 Average Thickness Extraction Algorithm

Group velocity can be extracted from two spatially and temporally separate wave packets as demonstrated by [82] using the zero phase slope method. The zero-phase slope extracts the slope of the phase as a function of frequency of two windowed signals (with a common time frame). The difference between the two phase slopes is inversely proportional to group velocity (see appendix 9.1 for full derivation). In the case of the pipe setup described in this study, an input pulse will be propagated around the circumference of the pipe and detected at the same location, giving the output pulse. In the case of the plate, the input signal is the signal excited by the transmitting transducer and the output signal is the signal received at the receiving transducer. The zero-phase slope of input and output is calculated over the spectra of the pulse and the effective group velocity can be determined using the following equation:

$$c_g(\omega) = \frac{D}{\frac{d\phi(\omega)_{in}}{d\omega_{in}} - \frac{d\phi(\omega)_{out}}{d\omega_{out}}} \quad (3.2)$$

where D is the separation distance between the two transducers, ω is the angular frequency of the spectral component, and $\frac{d\varphi_{in}(\omega)}{d\omega_{in}}$ and $\frac{d\varphi_{out}(\omega)}{d\omega_{out}}$ are the phase slopes of the input (Figure 3.5 - blue) and output signals (Figure 3.5 - green) respectively. SH1 pulse in the output signal must be windowed to extract the effective group velocity of the SH1 mode (Figure 3.5). In the finite element models, the input signal is known and therefore does not have to be windowed, however, in reality the frequency response of the electronic equipment may alter the input signal and therefore it would have to be detected by another means (e.g. a current sensor - see Figure 3.9).

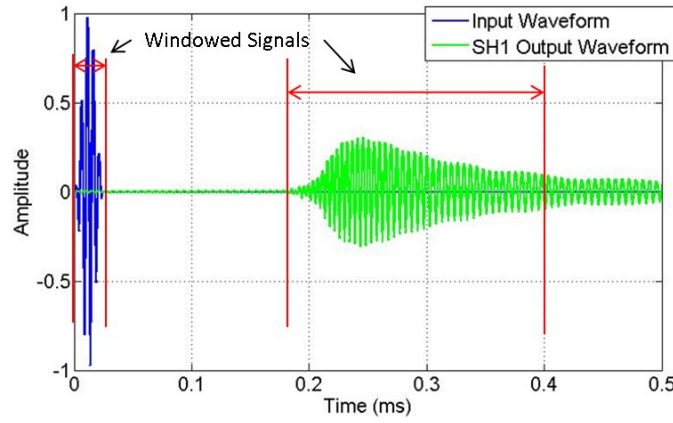


Figure 3.5. Windowing of the input and output SH1 signal in Figure 3.3.

The analytical equation for SH1 group velocity, equation 3.1, depends on frequency, thickness and shear velocity. As the frequency and shear velocity of the metal are constants (in a stable environment), the analytical group velocity can be fitted to the extracted effective group velocity by varying the thickness, b (see Figure 3.6). This is implemented by minimizing the residuals between the extracted group velocity and the analytical group velocity over the spectra of the wave packet.

$$\min \left(\sum_{\omega_{low}}^{\omega_{high}} |c_{g,extracted}(\omega) - c_{g,analytical}(\omega, b)|_{c_s} \right) \quad (3.3)$$

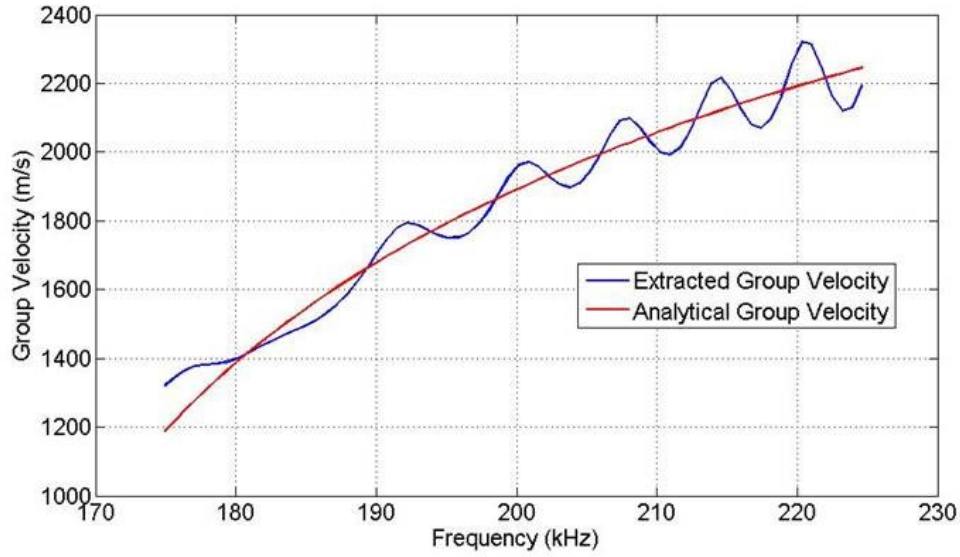


Figure 3.6. Analytical group velocity curve fitted to an experimentally extracted group velocity curve, for a 200kHz 5 cycle Hann toneburst over 0.5m in a 10mm plate with 40dB SNR

3.3.3 Temperature Compensation

The thickness extraction method above depends on the shear velocity of the plate being constant (see equation 3.1); however, the shear velocity of the metal plate is proportional to the temperature of the plate [41]. If not accounted for, this would induce an error in the extracted thickness. Figure 3.7 shows the SH1 group velocity curve plotted using two values of the shear velocity, c_s , at -20°C and 20°C . These temperature values were chosen as a suitable annual variation in a continental climate and the values of c_s were found in [83]. Over a 40°C temperature range there is a 24m/s change in group velocity at 2MHz.mm and that equates to a 0.1mm change in extracted average thickness over a 1m propagation distance.

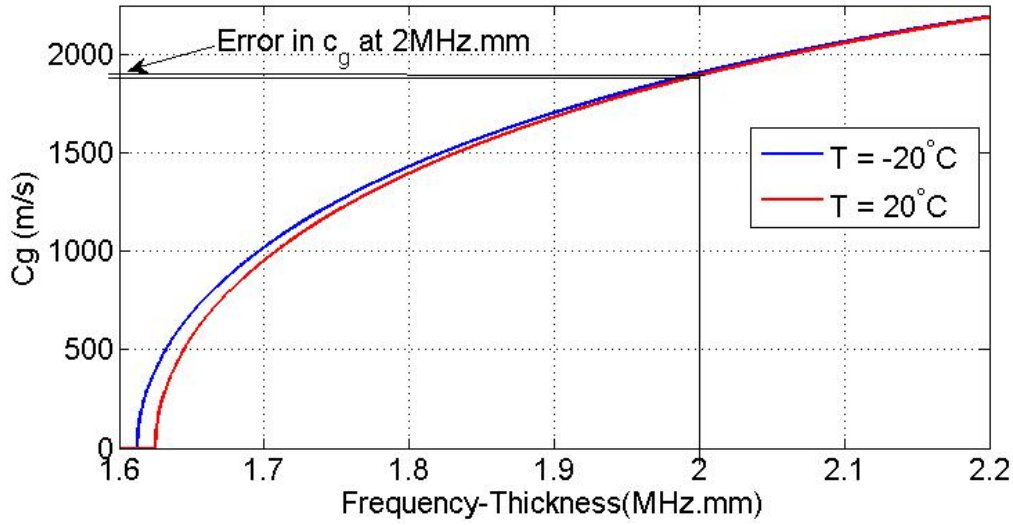


Figure 3.7. Two SH1 group velocity curves with $c_{s,-20^{\circ}\text{C}} = 3236\text{m/s}$ and $c_{s,20^{\circ}\text{C}} = 3260\text{m/s}$

A mechanism was therefore devised to compensate for changes in temperature, exploiting the fact that the group velocity of the non-dispersive SH0 mode is equal to the shear velocity of the metal. The SH0 mode is non-dispersive and its group and phase velocity is equal to the shear velocity of the elastic medium. By propagating both the SH0 mode and the SH1 mode, the SH0 mode can be windowed (shown in Figure 3.8) and the shear velocity can be extracted using the group velocity extraction described above (in equation 3.2). This value can then be used in equation 3.1 and 3.3 to calculate the average thickness.

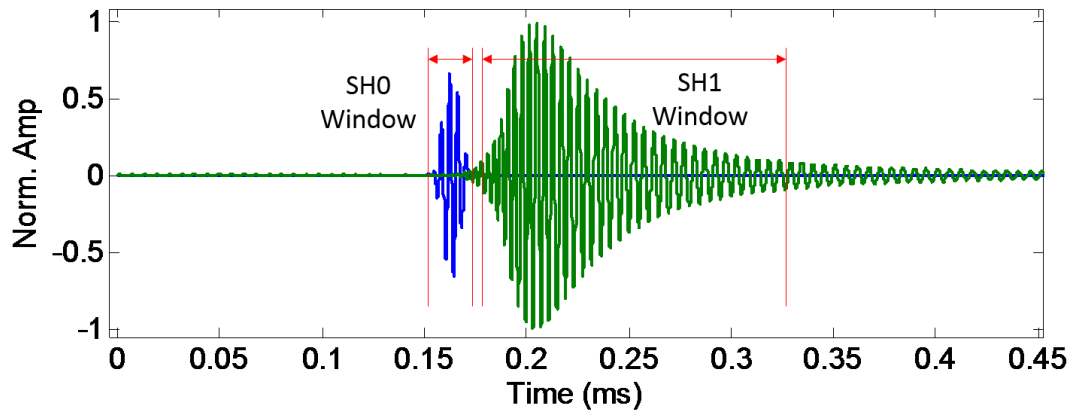


Figure 3.8. Windowing of the FEA SH0 and SH1 modes with a 250kHz 5 cycle Hann windowed over a 500mm propagation distance in a 10mm thick plate ($c_s = 3260\text{m/s}$)

3.4 Experimental Validation of Temperature Compensated Thickness Extraction Using the SH Wave

To validate the temperature compensated thickness extraction method, a pitch-catch measurement was performed. Two shear horizontal electromagnetic acoustic transducers

(EMATs) were placed at a fixed separation distance (0.367m) on a 10mm thick aluminium plate, in a configuration so that edge reflections were minimised (Figure 3.9). A 5 cycle Hann-windowed toneburst at a centre frequency of 200kHz¹ was propagated between the transducers, this excited both the SH0 (non-dispersive) and SH1 (dispersive) modes. The SH0 and SH1 modes had a wavelength of approximately 16mm and 27mm respectively.

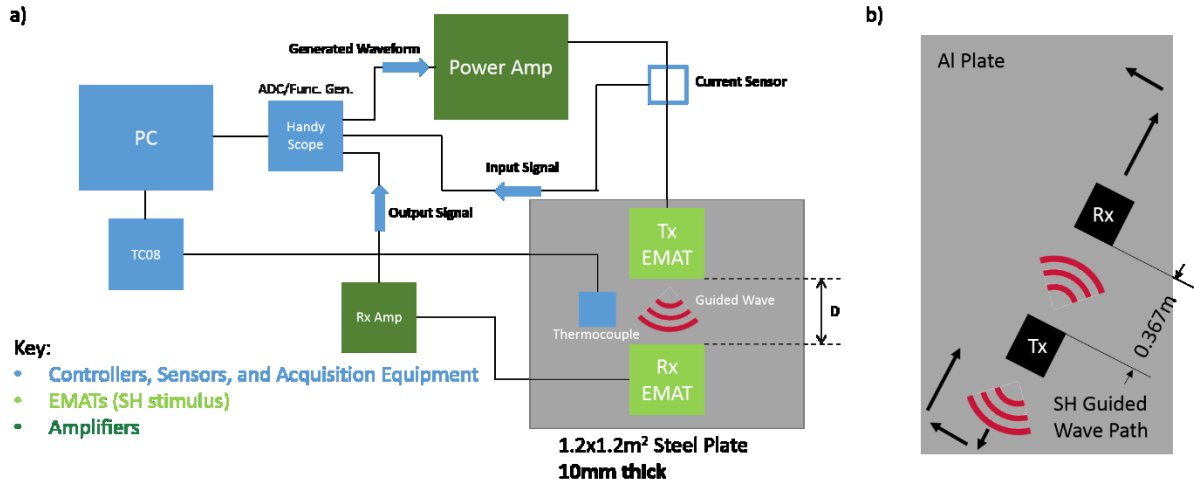


Figure 3.9. a) Schematic of the experimental setup, b) configuration of Tx and Rx EMAT transducers on an aluminium plate to reduce edge reflections

The toneburst was generated using a HandyScope HS3 Function generator/ADC (TiePie Engineering, Sneek, NL) connected to a laptop running MATLAB. The toneburst was input into a Yamaha AS500 Power Amplifier (Yamaha, Iwata, JP), which in turn drove the transmitting (Tx) EMAT. The guided wave packet excited by the Tx EMAT propagated to the receiving (Rx) EMAT. EMATs were custom built by the Imperial NDE group for the excitation of SH0 and SH1 at 200-300kHz. The signal detected by the Rx EMAT was amplified and fed into the HandyScope, which passed the resulting time trace on to the MATLAB code for post processing. The input signal was also collected, by the HandyScope, using a current sensor which consisted of a coil of wire through which the power amplified Tx EMAT signal passed. Multiple time traces of both the input (Tx) and output signals (Rx) were collected per measurement and averaged.

3.4.1 EMAT Construction, SH Signal and Beam Shape

EMATs (Electromagnetic Acoustic Transducers) are non-contact transducers which are able to generate and receive ultrasonic guided waves in electrically conductive media. EMATs generate ultrasonic waves via one of two methods: Lorentz forces or magnetostriction [84].

¹ The centre frequency value was nearing the frequency response limit of the power amplifier, Yamaha AS500 Power Amplifier (Yamaha, Iwata, JP). The finite element simulations used a 250kHz, centre frequency thereby moving further away from the SH1 cut-off.

This project used PPM (permanent periodic magnet) EMATs which exploit the Lorentz force to excite the required guided wave modes in the plate.

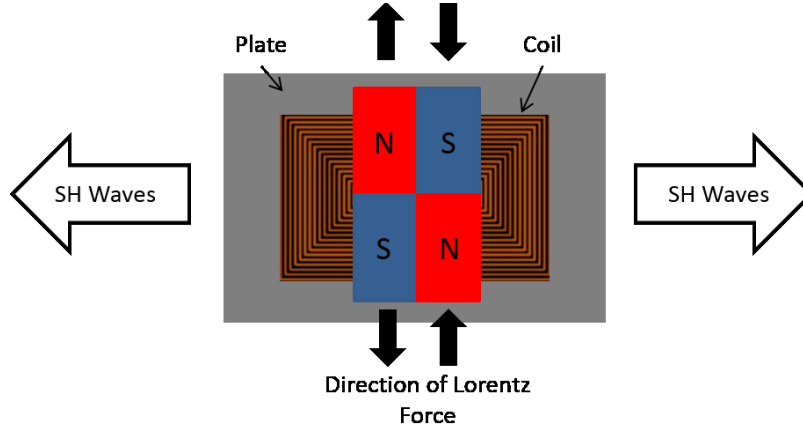


Figure 3.10. PPM EMAT schematic from above showing the direction of the Lorentz force created and SH wave propagation direction

The Lorentz force is produced by inducing an eddy current J in the conductive material by using an alternating current flowing through a coil. When a static magnetic field, B , interacts with the eddy current the Lorentz volume force arises, F , whose magnitude and direction is governed by [85]:

$$F = J \times B \quad (3.4)$$

Figure 3.10 shows a schematic of the EMAT used for generating the SH modes in the experiments. It consists of a static magnetic field placed in the centre of a racetrack coil, with the static magnetic field perpendicular to the current in the wires. In this setup, the Lorentz force excites the SH0 and SH1 modes and the transducer creates a collimated beam propagating from either end of the EMAT. Figure 3.11 shows the simulated beam profile over a distance of 0.5m, which was constructed using a Huygen's model of wave propagation with a 50mm array of point sources (with 5 sources per SH1 wavelength, i.e. every 2mm). Figure 3.12 is an example of a time trace experimentally produced by the EMAT showing the windowed SH0 and SH1 signals.

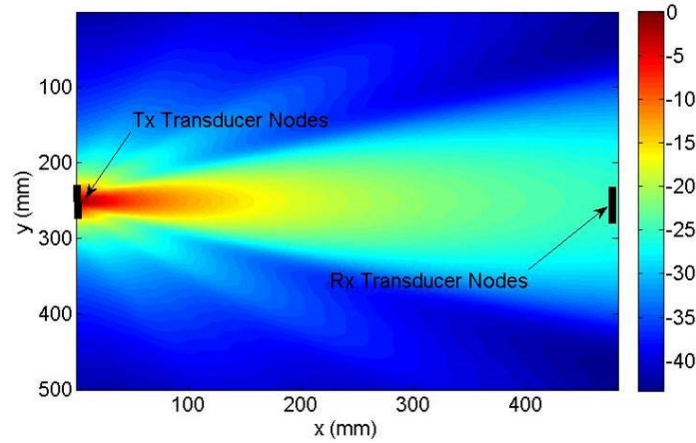


Figure 3.11. Amplitude distribution (dB, relative to max) of the wavepacket emitted by a 50mm wide SH source when excited at 200 kHz with a 5 cycle Hann windowed toneburst with a shear velocity of 3260 m/s.

The width of the transducer is 50mm and all SH wave simulations and experiments were carried out for a 50mm wide transducer unless otherwise stated. Ideally the transducer's beam would have a constant width with as little spreading as possible, however, that would require a large aperture (i.e. large EMAT width) which increases size of the near field region and the beam width. A trade-off is therefore required between size of the near field, width of the beam and beam spread.

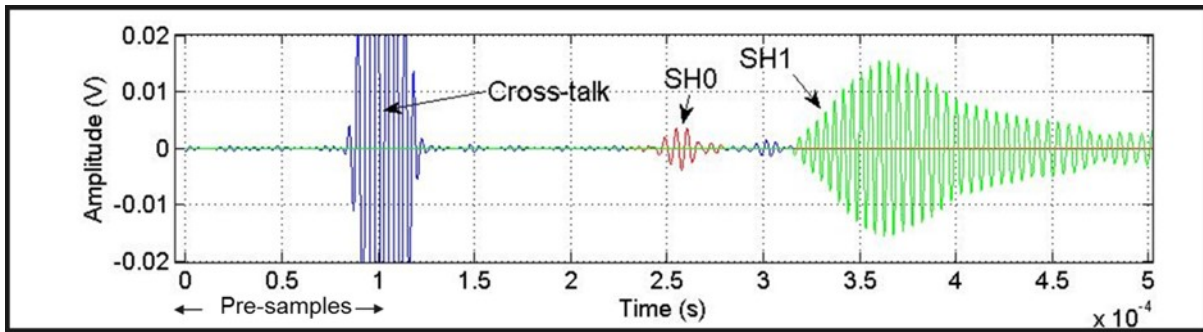


Figure 3.12. Experimental time trace produced by a single measurement with the SH transducer, showing the gated SH0 (red) and SH1 (green) modes. This was produced using a 200kHz 5 cycle Hann toneburst over a propagation distance of 500mm in a 10mm thick plate

3.4.2 Temperature Compensation Results

The experimental setup described above was placed in an environmental testing chamber (Vötsch VT3/VC3 - Temperature and Climate Test Chamber. Vötsch, Lindenstruth, DE). The chamber was heated to the required temperature and kept at that temperature for at least 30 minutes to ensure that the plate was in thermal equilibrium with the chamber. The environmental chamber was then switched off to improve the sensitivity of the measuring equipment whilst the thickness measurement was performed. Two hundred measurements were taken in quick succession (within 2 minutes), and averaged. Measurements were taken

at approximately 10°C intervals between 30°C-90°C, plus a measurement at room temperature (26°C).

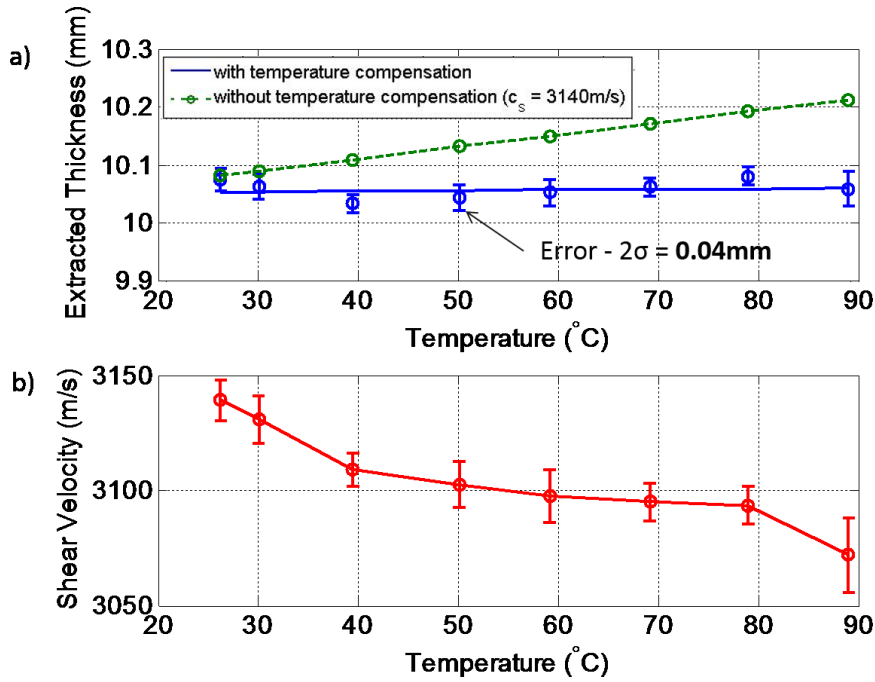


Figure 3.13. The effect of temperature on a) the extracted thickness (blue) and the extracted thickness without temperature compensation is shown in green ($c_s = 3140\text{m/s}$), b) the measured shear velocity (red) using the group velocity thickness extraction methods with SH waves in an aluminum plate. Error bars are 95% range in the extracted thickness values.

Figure 3.13b shows that as the temperature of the plate increased, the shear velocity of the metal decreased, as expected [41]. When the thickness extraction algorithm was applied, the expected thickness was approximately constant over the entire temperature range. In fact the extracted thickness (with temperature compensation) has significantly deviated away from the extracted thickness without temperature compensation (calculated by fixing the shear velocity value at 3140m/s). The mean error in the individual temperature compensated thickness measurements was found to be 0.04mm (95% range). The finite window width of the thickness algorithm means that the absolute value of extracted thickness is not exactly 10mm.

3.5 Finite Element Modelling

A finite element model was created to simulate the effect of different defect sizes and shapes on SH guided waves. This is to test the ability of the thickness extraction algorithm to extract a value of the average thickness between two points with different defects. The base model, to which defects were added, was solved in the time domain using explicit time steps ($\Delta t = 4 \times 10^{-8}\text{s}$), performed by either the open source POGO software package [86] or

ABAQUS [87]. The model of the plate is 500x200x10mm³ and consisted of either 10 elements through the plate thickness. This corresponds to either a 1x1x1mm³ element size. The finite element model used a 5 cycle 250kHz Hann windowed input toneburst. The wavelength of the SH0 mode at 250kHz is 13mm and the SH1 mode is 17mm. Therefore, using 10 elements through the plate thickness satisfies the 10 elements per wavelength considered sufficient to accurately model the behaviour of elastic waves [50]. Absorbing boundaries were placed along the longest side of the model. These used the Absorbing Boundaries using Increasing Damping technique (ALID) in which adjacent vertical layers of elements have an increased damping factor trapping any elastic energy within the ALID region. The mass proportional damping factor is defined as:

$$\alpha = Kl^3 \quad (3.5)$$

Where l is the fraction of distance through the layer, and K is a constant (in this case $K = 1 \times 10^6$) [49].

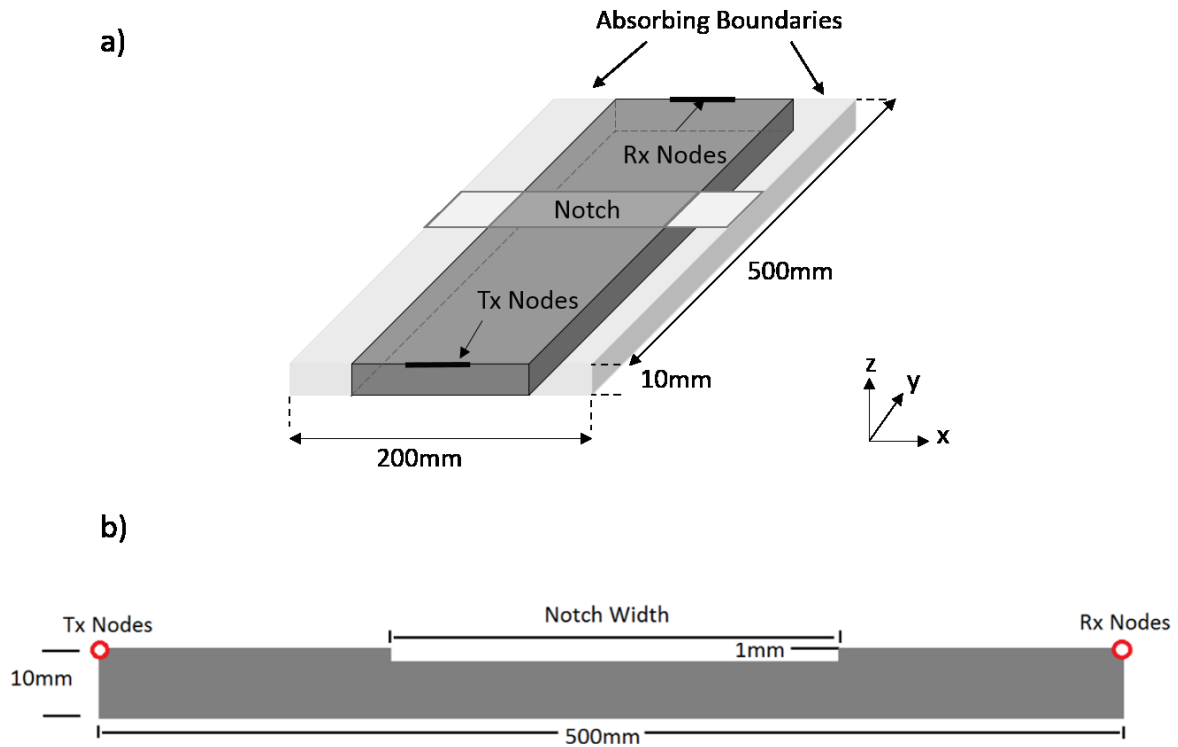


Figure 3.14. a) The finite element model containing a notch, b) is a cross-section of the notch, which has a variable width and fixed depth of 1mm

The meshing was performed by a custom C++ code which generated the node positions and identified the nodes within each linear brick element. For a notch defect the appropriate number of elements were removed to create the notch with the desired width. The notch

defects had a constant depth of 1mm and only the width was variable (Figure 3.14b). The interaction between SH1 guided waves and finite width elements is also considered. Two contrasting defect types were placed in the finite element model: a) a circular Hann profile defect (Figure 3.15b) and b) a circular part thickness hole (Figure 3.15c). The Hann profile defect has no sharp edges from which reflections are likely to occur [88], whereas the part thickness hole has one stepped edge and sudden thickness changes. However, corrosion is much less likely to manifest itself in this way. In order to create the part thickness hole the appropriate elements within the volume of the hole were removed, thereby approximating a circle (Figure 3.15d). For the Hann profile defect the height (z component) of all the nodes through the thickness were scaled to form the desired profile, therefore for a 5mm deep defect the element size in the z-direction was 0.5mm at the defect's deepest point. The width and depth of both defect types were variable.



Figure 3.15. a) Illustration of the finite element model, containing a circular shaped defect. b) Cross-section of the Hann profile defect c) is a cross section of a part thickness hole d) plan view of part thickness hole.

For the results presented in this chapter, all the finite width defects had a diameter of 60mm and the depth was varied between 1mm, 2mm and 5mm. A collimated guided wave beam was generated (in the SH wave case) by applying a 5 cycle Hann toneburst (with 250kHz centre frequency) on a 50mm wide linear array of nodes at one edge (on the 200mm edge). A similar array of nodes on the opposite edge was used for receiving the elastic wave. Both the time traces of the input and output nodal arrays were recorded to be used in the group velocity thickness extraction algorithm. The nodes were placed on the surface of the plate ($z=0.01\text{m}$) since the SH1 mode has zero displacement at half thickness.

3.5.1.1 Simulation of B-Scans using the Finite Element Model

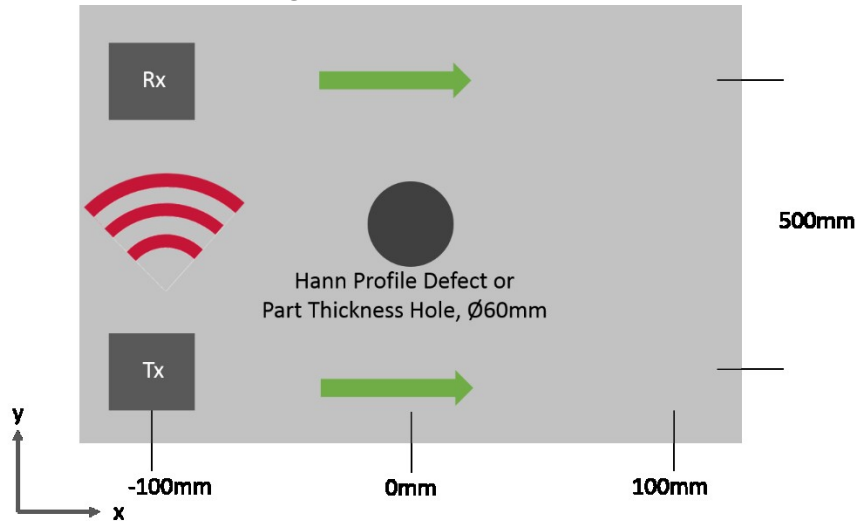


Figure 3.16. Schematic of a B-scan performed over 300mm which has been simulated by the FE simulation. The guided wave is sent between the Tx and Rx over a propagation distance of 500mm

Finite width defects are unlikely to occur directly along the path between the Tx and Rx transducers therefore a B-scan of the defects were performed. The defect was always modelled equidistant from both transducers to save on computational overheads. B-scans, illustrated in Figure 3.16, of all defect sizes were performed to examine the effect of defect location in the x direction on detectability. Simulations were performed at regular intervals (every 5mm) over a 200mm range, 100mm either side of the defect, thereby producing a thickness profile of each mode and defect. The B-scans were modelled by repositioning the defect in the finite element model and only half of the simulations were performed since the scan is symmetric either side of the defect.

3.5.2 Finite Element Convergence using Uniformly Thick Plate

Figure 3.17 shows the extracted thickness value against the number of elements, as the number of elements increases the extracted thickness value tends towards a stable value of thickness. Therefore, the number of elements through the plate thickness chosen for any particular finite element simulation is a trade-off between the computational speed and accuracy of the model. This error can be minimised by comparing relative difference between similar models, i.e. to compare wall thickness loss between a model with a defect and one without a defect. The absolute value of thickness does not tend towards the correct value of 10mm in this case, due to the effect of having a finite window width over the distorted SH1 pulse.

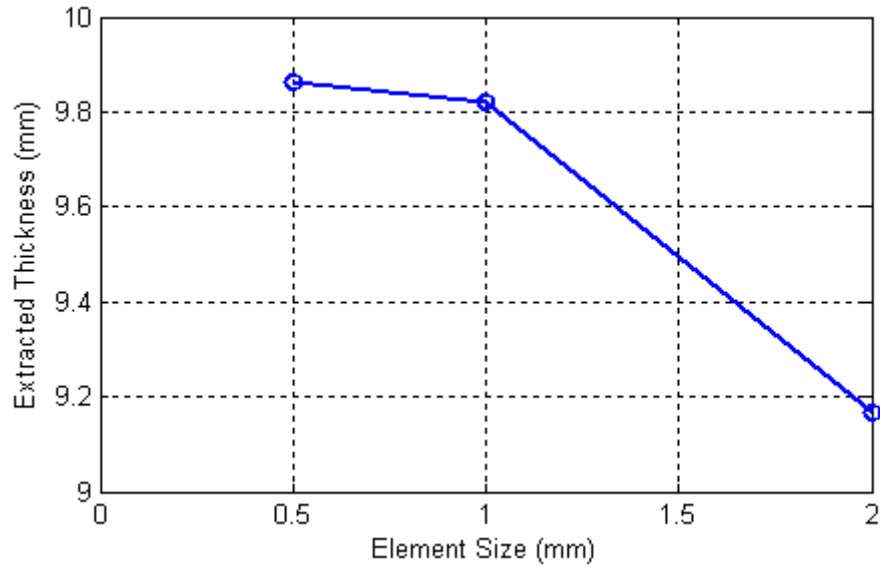


Figure 3.17. Extracted thickness using the group velocity method of a 10mm thick plate from three finite element models with different element sizes, modelled in POGO

3.5.3 Notch Defect of Variable Width

To test the ability of the thickness extraction algorithm to quantify the average thickness between two transducers, a 10mm plate with 1mm notch of variable width was modelled. The notch width was varied between 0.125m (25% of the propagation distance) to 0.5m (100% of the propagation distance). The length of the notch is effectively infinite since it extends across the entirety of the plate and into the absorbing boundaries. A cross section of the plate is shown in Figure 3.14b.

Figure 3.18 shows a good relationship between the expected and extracted change in thickness. There is a slight deviation from the expected thicknesses. This is probably due to numerical error caused by the finite element model. Figure 3.18 shows that the average thickness algorithm is able to successfully detect and measure small changes in the average thickness due to the presence of a notch. The average thickness reading of a 0.125mm width notch is 0.25mm which is significantly above the 0.04mm error shown in Figure 3.13a. If the linear relationship between thickness change and notch width holds then it suggests the SH1 guided wave setup studied is able to resolve 20mm wide notches (which have a depth of 1mm), i.e. a 0.04mm thickness change equates to a 20x1mm notch.

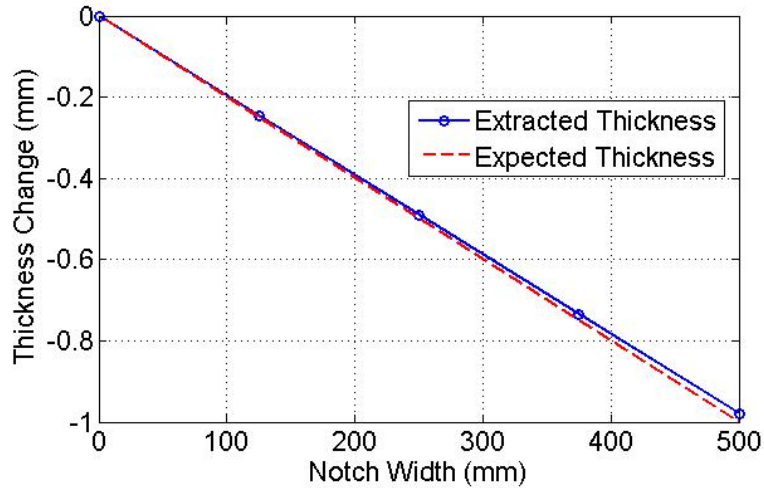


Figure 3.18 The extracted thickness using the group velocity method from a 10mm thick FE plate model containing a notch of variable width using SH waves at 250kHz with 20 elements through the plate thickness, performed in ABAQUS

3.5.4 B-Scan of Finite Width Defects

3.5.4.1 In-depth Example B-scan Result from a 60x1mm Hann Profile Defect

The B-scan of a finite width defect was carried to explore the expected response from with a more realistic defect. The Hilbert enveloped time traces from the B-scan of a 60x1mm Hann profile defect is shown in Figure 3.19a, plotted vertically against defect position in a waterfall plot. The SH0 mode is minimally affected by the presence of the defect, whereas the SH1 mode is substantially attenuated over the width of the defect, but has not completely disappeared. The SH1 cut-off frequency in a 9mm plate is 187kHz, therefore most of the SH1 pulse is able to pass directly through the deepest point of the 60x1mm defect. In this case the reduction in amplitude is due to scattering of the SH1 wave. The lobes at ± 25 mm suggest the SH1 mode has been diffracted by the defect and constructively interferes at Rx, when the defect is in that position. Figure 3.19b shows the result of the thickness extraction algorithm having been applied to the time traces of Figure 3.19a. Clearly the extracted thickness (blue) does not correlate with the expected thickness (red). As the transducers approach the edge of the defect, the extracted thickness decreases from around the ± 80 mm position reading a minimum value at ± 25 mm. However, over the width of the defect the extracted thickness increases reaching a maximum at the centre of the defect.

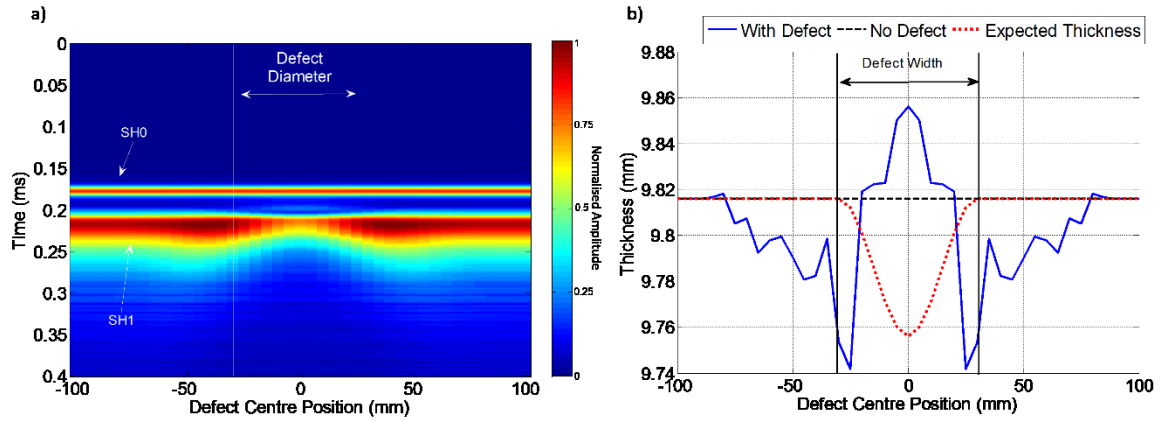


Figure 3.19. a) The waterfall plot of Hilbert enveloped signals of the B-scan performed in POGO, using a 250kHz 5 cycle Hann windowed input pulse, b) shows the thickness extracted (blue) from the B-scan. The expected thickness (red) is also shown.

3.5.4.2 Finite Element Results of a Wide Range of Defect Dimensions

This section compliments Figure 3.19 by showing the effect of an array of different part thickness hole or a Hann profile defect dimensions on the amplitude and thickness measurements using a SH0/SH1 guided wave. Figure 3.20 and Figure 3.21 show the amplitude waterfall plots and the extracted thicknesses, respectively for both the Hann profile defect (top row) or the part thickness hole (bottom row). The defect sizes shown are all 60mm in diameter (which corresponds to 3.5λ at the centre frequency, 250kHz) with maximum depths of 1mm, 2mm, and 5mm. The 60x1mm results in Figure 3.20 are the same as Figure 3.19.

As the Hann profile defect deepens in Figure 3.20a the scattering of the SH1 wave at ± 50 mm remains stable, however, in the centre of the defect (> -25 mm and < 25 mm) the SH1 mode is substantially attenuated as depth increases. This is because the SH1 has a frequency-thickness threshold and the effect of the cut-off frequency can be clearly seen. As the thickness of the plate decreases the frequency cut-off increases. The cut off frequencies in a 1mm, 2mm, and 5mm plate are 187kHz, 212kHz, and 340kHz. Therefore, no frequencies are able to pass through the deepest point of the 60x5mm Hann profile defect (see Figure 3.3c).

The cut-off frequencies also have a very large influence on the part thickness hole results. The Hann profile defects taper to a maximum depth, whereas the part thickness holes are the same thickness over their entire width and consequently the effect of frequency cut-off can be clearly seen at the > -30 mm and < 30 mm position (i.e. over the diameter of the part thickness hole), with the defect being blocked completely in the 5mm case. Another effect is also clearly shown in the part thickness hole images: mode conversion from SH1 to SH0 [74], [89]. When an SH1 is incident on a thickness with a cut-off frequency greater than its

spectral content the pulse is converted to the SH0 mode over the thinner area. Some of the energy is then mode converted back if the thickness increases. The SH0 mode however has a faster group velocity than the SH1 and therefore a low amplitude SH0 pulse can be seen at the central position (0mm) at 0.2ms in all images with defects >2mm in depth.

The SH1 mode is scattered by a part thickness hole in a much more chaotic manner compared to the Hann profile defect. It is worth noting in Figure 3.20b that the SH0 mode has been substantially attenuated in the region of the hole due to the reflection of the SH0 wave packet from the edges of the hole [90]. This phenomenon will be investigated in chapter 4 as a possible method of defect detection.

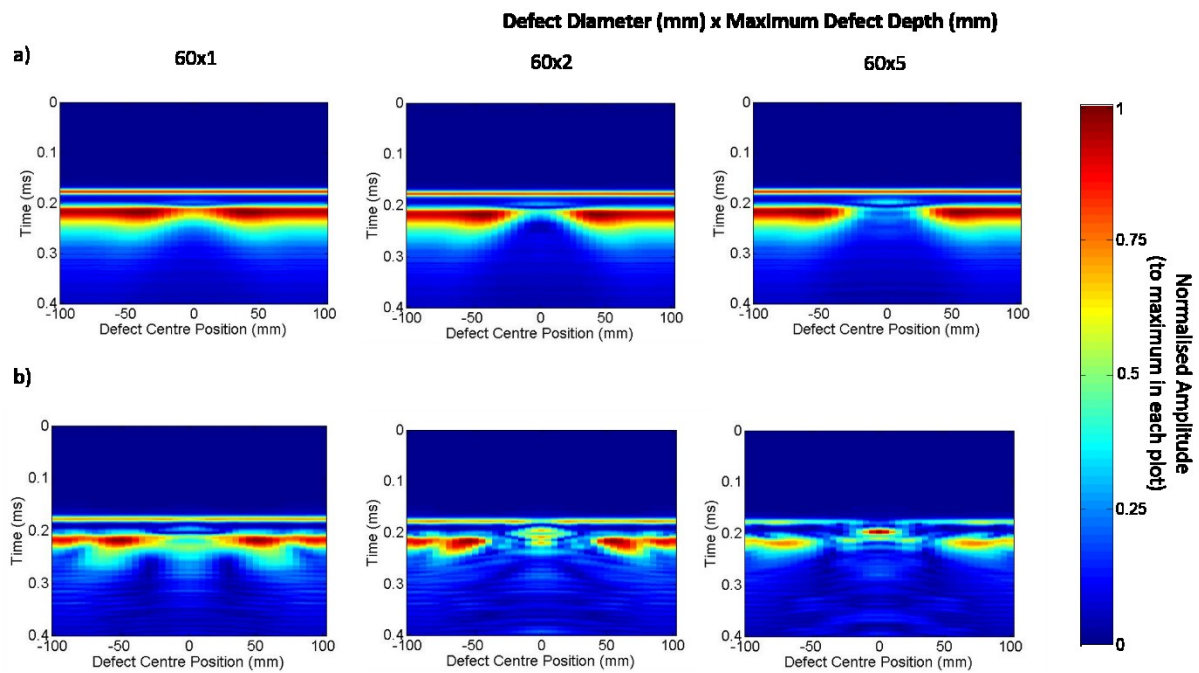


Figure 3.20. Finite Element B-Scans of 3 defects, a) Hann profile defect with SH waves b) Part-thickness Hole with SH waves using 250kHz 5 cycle Hann windowed toneburst over 500mm propagation in a 10mm thick plate

The presence of either a Hann profile defect or a part thickness hole has a distortive effect on the extracted thickness, and there is no case when the extracted thickness neatly follows the expected thickness curve. In the case of the Hann profile defect the extracted thickness starts to decrease well outside the width of the defect (<-30mm, >30mm) and increases in thickness over the width of the defect (>-30mm, <30mm). The part thickness hole results show a similar effect outside the defect width, but over the width of the defect there are large swings in thickness, especially in the 2mm and 5mm case. In the 5mm part thickness hole results all the SH1 wave pulse is blocked by the cut-off frequency and the SH0 mode is heavily attenuated as well, therefore the windowing algorithm will be simply measuring either noise and/or the mode converted SH1->SH0 pulse.

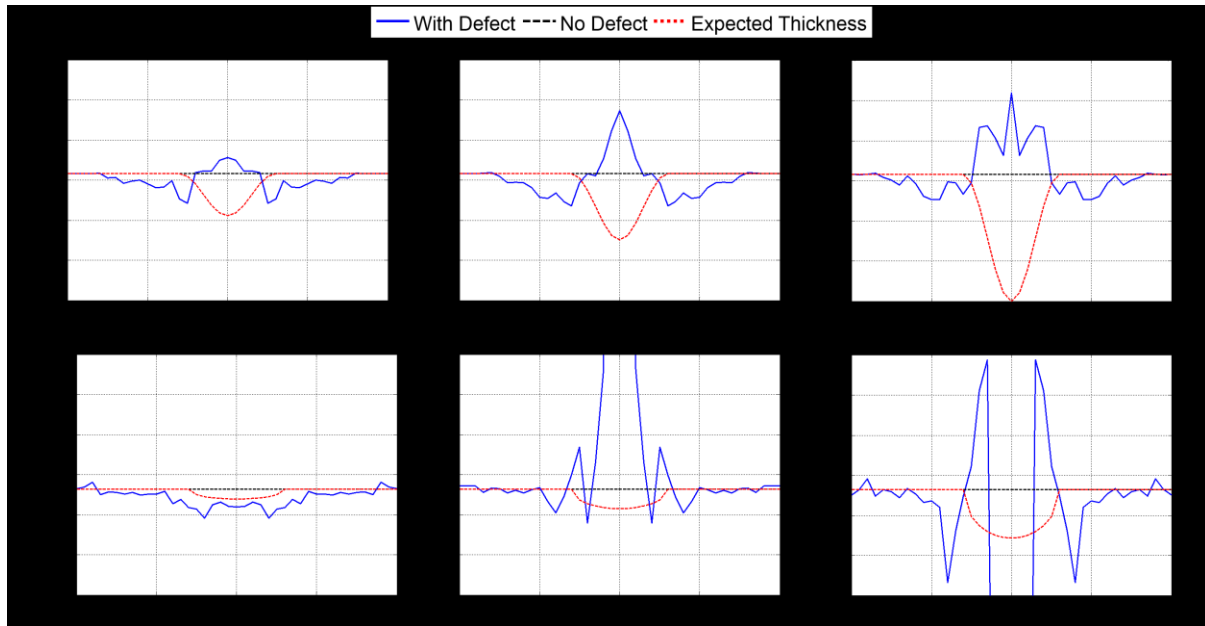


Figure 3.21. Extracted average thickness B-Scans of 3 defects, a) Hann profile defect with SH waves b) Part-thickness Hole with SH waves using 250kHz 5 cycle Hann windowed toneburst over 500mm propagation in a 10mm thick plate

3.5.5 Discussion on Interaction of Finite Width Defects and SH Waves

Two conclusions can be drawn about the result shown Figure 3.19, Figure 3.20 and Figure 3.21. Firstly, this technique cannot be used as a reliable single measurement, because the location of the defect heavily influences the extracted thickness. For example, in the case shown in Figure 3.19b if a single measurement was taken at approximately 20mm then no thickness change would be detected. Therefore, the risk of a false positive is high, and that is before secondary effects like noise or defect roughness are included. To reduce that risk either a second or multiple measurements must be carried out to mitigate against the complex interaction between the SH guided wave and the defect. This makes the use of a single sensor unsuitable as a permanently installed monitoring device, which would operate in a similar way to existing wall thickness sensors. If multiple measurements, in the form of an array or as part of a scan performed by an operator, were used then the method may be of use, although thickness inversion would rely on knowledge of the complex SH-defect interaction.

Following on from this the second conclusion is that the thickness profiles in Figure 3.19b and Figure 3.21 could be used as a qualitative method of defect detection/screening, especially since in Figure 3.19b the peak-to-peak value of the extracted thickness profile (0.11mm) is greater than the expected thickness profile (0.06mm). In this way a sensor could monitor for any changes in the extracted thickness, using the temperature

compensating algorithm. If the thickness changed by a certain amount, then the plant operator would be alerted to the issue and can go to the sensors location to perform a more routine inspection. The fact that the defect has an influence on the extracted average thickness outside the width of the defect also suggests that the sensor is sensitive to the presence of a defect over a much wider area coverage. Chapter 4 will look at the sensitivity of guided waves to a variety of defects for the purpose of defect detection.

It is worth stressing that the thickness algorithm present here has been shown to successfully extract the thickness loss of a uniformly thin plate and with an (effectively) infinitely wide notch placed along the beam's path. The question remains, however: how wide does a finite width defect have to be for the average thickness extraction algorithm to extract a valid thickness change? Further simulations need to be performed on the subject but appendix section 9.2 shows some preliminary figures showing the transition between the two. The extraction of the absolute average thickness in uniform plates is susceptible to systematic errors due to the finite windowing of the SH1 mode.

3.5.5.1 Experimental Validation of B-Scans

The simulations were compared against experimental results obtained with an existing sample (10mm thick steel plate) containing a defect (60x5mm Hann profile defect machined into a 10mm thick steel plate [79]). The same equipment setup was used as the temperature chamber experiment, however, in this case multiple measurements were performed at different locations (100mm either side of the defect, readings taken every 10mm). Unlike the simulations, the symmetry of the B-scan could not be presumed since the tolerance of a plate is approximately $\pm 10\%$ of the pipe/plate thickness [91]. The only indication of the obvious difference between wall thicknesses extracted either side of the defect is that the error bars are larger at positions $< -25\text{mm}$. The experiment here used a 250kHz 5cycle toneburst, unlike the 200kHz used in the temperature compensation experiment above.

Figure 3.22 below shows the extracted thicknesses from the experimental data and the finite element model for both SH. There is a good correlation between the two data sets, outside of the defect, showing that the finite element model is valid in that region. Inside the width of the defect the general pattern of increasing thickness is displayed by both data sets although they do not correlate as well as the data from outside the defect. This is to be expected since in the central region of the defect ($> -30\text{mm}$ and $< 30\text{mm}$) the SH1 mode is blocked by the cut-off frequency, and therefore unable to be transmitted through. In this case the SH1 mode is converted into the faster SH0 mode. The windowing algorithm then windows the temporal space where the SH1 wavepacket should be, but instead detects noise

and/or a SH0 pulse mode converted from SH1. This will cause large discrepancies in the extracted thickness value.

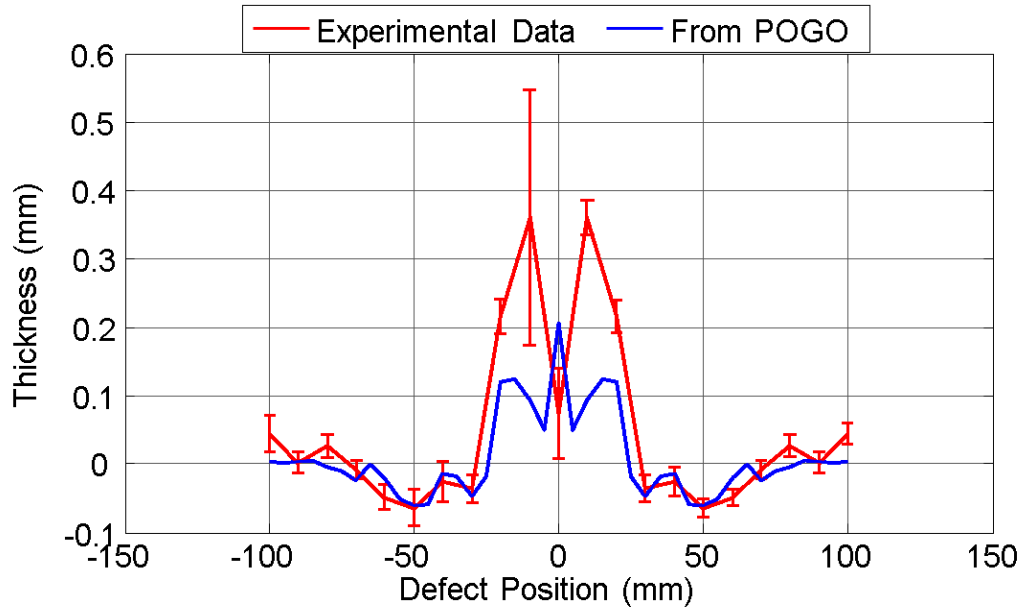


Figure 3.22. Extracted thickness from experimental data (red) and the FE model (blue) of a 60x5mm Hann profile defect using SH waves using a 250kHz 5 cycle Hann windowed toneburst.

3.6 Conclusion

This chapter has evaluated the performance of dispersive SH guided wave thickness measurements along a line of a plate, representing the propagation around the circumference of a pipe. The temperature compensated group velocity thickness extraction algorithm has been shown to be able to precisely determine the average thickness of a uniformly thick plate between two transducers, using SH guided waves. The experimental data showed that the temperature compensated thickness value had an associated error of 0.04mm and the average thickness along the line could be determined to that precision. When the same thickness extraction algorithm was applied to simulated signals from plates which contained flat bottomed notches spanning the whole width of the plate, an accurate value of the average thickness could be extracted.

When testing the thickness extraction algorithm on signals that had passed through finite width defects (Hann profile defects and part thickness holes), it was clear that the presence of the defect distorted the received signal significantly and that the thickness extraction algorithm was unable to extract the correct value of the average thickness. The interaction of the wave with the defect led to an increase in the measured thickness at the centre of the defect and measured decreases outside the defect width. If the corrosion patch is much wider than the beam width and is relatively flat, then the proposed corrosion monitoring

method appears to be sound. However, for the proposed method to be useful in the field, defects of different sizes and profiles must be detectable and ultimately measurable. As the B-scan simulation of the finite width defects has shown, the presence of a defect elicits a detectable/qualitative response. Although, this method could provide a means of screening a pipe for defects or corrosion, it would be difficult to implement as a quantitative monitoring system.

Chapter 4 will describe a parametric study using guided waves to quantitatively evaluate the sensitivity to defects in reflection and transmission. Two analogous setups are studied: monitoring and screening. The study, thereby, will look to quantify the detection ability of guided waves, but not the ability to characterise defects.

Chapter 4

Detectability of Corrosion Damage with Circumferential Guided Waves

4.1 Introduction

Chapter 3 presented a method, using short range guided waves, to estimate a temperature compensated value of a pipe or plate's average thickness, over a given propagation distance. It was concluded that the method presented gave inaccurate measurements when a finite width defect was placed within the path of the guided wave. The value of the estimated average thickness is also highly sensitive to the position of the defect due to scattering of the guided wave and subsequent interference effects. It would therefore be possible to measure no thickness change even if a (large) defect is positioned within the width of the beam.

If, however, adjacent measurements are analysed concurrently then the method presented could serve as a qualitative indication that a defect/region of wall loss exists within a pipe, either as a permanently installed monitoring system (using an array of transducers) or a defect screening system (which scans axially along a pipe). Compared to other multi-measurement scanning methods (e.g. c-scan using a raster scanner) the main benefit of this device is the increased coverage area at each measurement. This chapter, therefore, continues to explore the spectrum of area coverage between the spot ultrasonic measurements and long range guided wave techniques as illustrated in Figure 1.5.

This chapter quantifies the idea of using circumferential guided waves as a means of detecting (as opposed to characterising) wall loss due to corrosion. Temperature correction is not considered, and a simple thickness extraction algorithm is used enabling fair comparison between several modes. The potential for defect detection using reflections from the defects will also be considered alongside the transmission method (average thickness estimation). Specifically, this chapter will evaluate and compare the sensitivities of three guided wave modes optimised for either measurement modality (reflection or transmission) to a range of defects.

Similarly, to chapter 3, the single transducer setup used in Figure 4.1a forms the basis of this study, which propagates a guided wave pulse around the circumference of the pipe and

detects it at the same location. However, to fully evaluate the sensitivity of the guided waves (in either reflection or transmission) several assumptions must be explicitly stated: The transducer is able to:

- a) preferentially excite a guided wave in one direction around the circumference of a pipe, this is a reasonable expectation since directional transducers have been successfully demonstrated in the laboratory [80] and in the field [27].
- b) separate out the transmitted and the reflected signals from one another and treat them independently. This enables a fair comparison between the two measurement modalities.
- c) operate at a wide range of input toneburst parameters, allowing optimisation of input toneburst characteristics in either transmission or reflection.

In this chapter the two analogous setups in Figure 4.1b and c were investigated. In Figure 4.1b a monitoring setup is shown that consists of an array of transducers each of which transmit a dispersive guided wave around the circumference of the pipe, extracting both: a value of the average thickness around the circumference from the through transmitted signal; and a value of the reflection coefficient from the reflected signal. In Figure 4.1c a rapid screening setup which uses a single transducer which is axially scanned along the pipe extracting the average thickness and reflection coefficient. All the fundamental guided wave modes were evaluated (A_0 , S_0 , and SH_0) as well as the first shear horizontal mode (SH_1). Both setups have an associated pitch - distance between adjacent measurements indicated in Figure 4.1b and c - which governs the coverage area and therefore the sensitivity.

In contrast to the single transducer setup explored in chapter 3 the monitoring and scanning setups combine multiple measurements with varying spatial distribution, depending on the measurement pitch. Therefore, the pitch must be taken into account when assessing the ability of a setup to detect a defect. This chapter uses the concept of the probability of detection (POD) as the metric to assess the sensitivity of a setup.

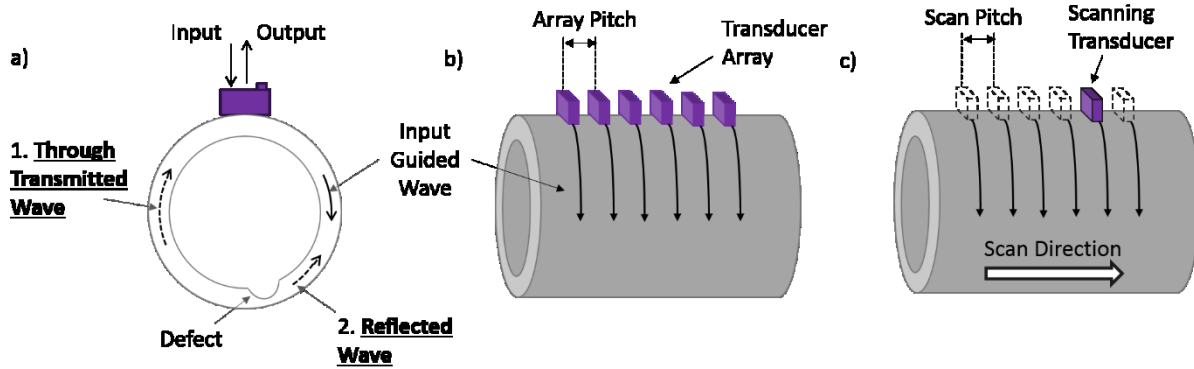


Figure 4.1. a) The single transducer setup studied in this chapter, which inputs a directional guided wave pulse at a single location. b) The proposed array setup. c) The proposed short range guided wave rapid scanning or screening setup

This chapter first describes the finite element simulations, followed by a detailed explanation of the two measurement methods used. The selected input toneburst characteristics as well as the reasons for them are then presented. Some example FE simulation results are then shown, before a description of the POD methods, which is used to quantify the sensitivity. The POD results and discussion are then given before conclusions are drawn.

4.1.1 Overview of Guided Wave Reflection Literature

The literature discussed in chapter 3 covers the existing knowledge on the use of dispersive guided waves, whereas the following gives an overview of the literature on the reflection of guided waves, specifically for the purposes of defect detection and characterisation, propagating either circumferentially around or axially along a pipe wall or in a plate. There is also commercial interest in circumferential guided wave systems [92]. The use of circumferential guided wave reflections for the detection of cracks in pipes has been studied by Valle et al. [93] and Fletcher [94], as have through holes [95], part thickness holes [48], [96] and axial slots [97]. Many finite element and experimental studies have simplified pipe geometry to that of a flat plate to further study more complex defects such as irregular defects [36], [98], part thickness ellipses [90] as well as to characterise the effect of sharp edges on defects [88]. Full, albeit very coarse, 3D FE simulation of guided waves have been commonplace since the early 2000s [99], however, current GPU FE software allows for both high fidelity and fast processing of many different defect sizes [100]. It is these recent developments that has allowed this study to model and subsequently probabilistically analyse a large range of defect sizes to ascertain the sensitivity of guided waves to wall thinning.

4.2 Overview of Model Setup

Figure 4.1a illustrates the measurement principle of using a single transducer to send and receive a dispersive guided wave that travels around the circumference of the pipe. The pipe was modelled as a flat plate as is described in section 3.2, and shown in Figure 3.2, to simplify the model's geometry. The same guided wave propagation distance of 500mm and plate thickness of 10mm were used as well, in keeping with typical dimensions of a 6-8" pipe.

4.2.1 Finite Element Model

A finite element (FE) model, similar to the model in chapter 3, was created to simulate the effect of different defect sizes and shapes on a range of guided wave modes, thereby testing their ability to detect the presence of corrosion-like defects using either reflections or extracted thickness changes. The base model was a structured mesh, to which defects were added. The base model has similar characteristics to the experimentally validated FE model presented in [46], with much higher elements per wavelength in the case of the A0 and S0 modes. Again, the open source POGO software package [86] was used to explicitly solve the model in the time domain. The model of the plate, which is larger than the one in chapter 3, is either 1000x400x10mm³ or 700x400x10mm³ (Figure 4.2a and b) for the transmission and reflection measurements respectively². Both consist of 10 elements through the plate thickness, this again corresponds to a 1x1x1mm³ element size. Two 50mm wide absorbing boundaries were placed along the longest side of both models whereas the reflection model has additional 100mm absorbing boundaries on the shortest sides. As in chapter 3, these boundaries used the 'Absorbing Layers with Increasing Damping' technique (ALID), in which adjacent vertical layers of elements have an increased damping factor attenuating any elastic energy within the ALID region. The transmitting and receiving node sets were 50mm in length. The Tx nodes were situated either at half thickness (A0, S0 or SH0 modes) or at the top and bottom of the plate (SH1) to achieve pure mode excitation (see Table 4.1). The Rx modes were situated at either end of the model and on the top surface since this is the area where a transducer would be sensitive. The meshing was performed by a custom C++ code, as described in chapter 2, which generated the node positions and identified the nodes corresponding to each linear brick element.

² The reason for the switch between model sizes was computational efficiency.

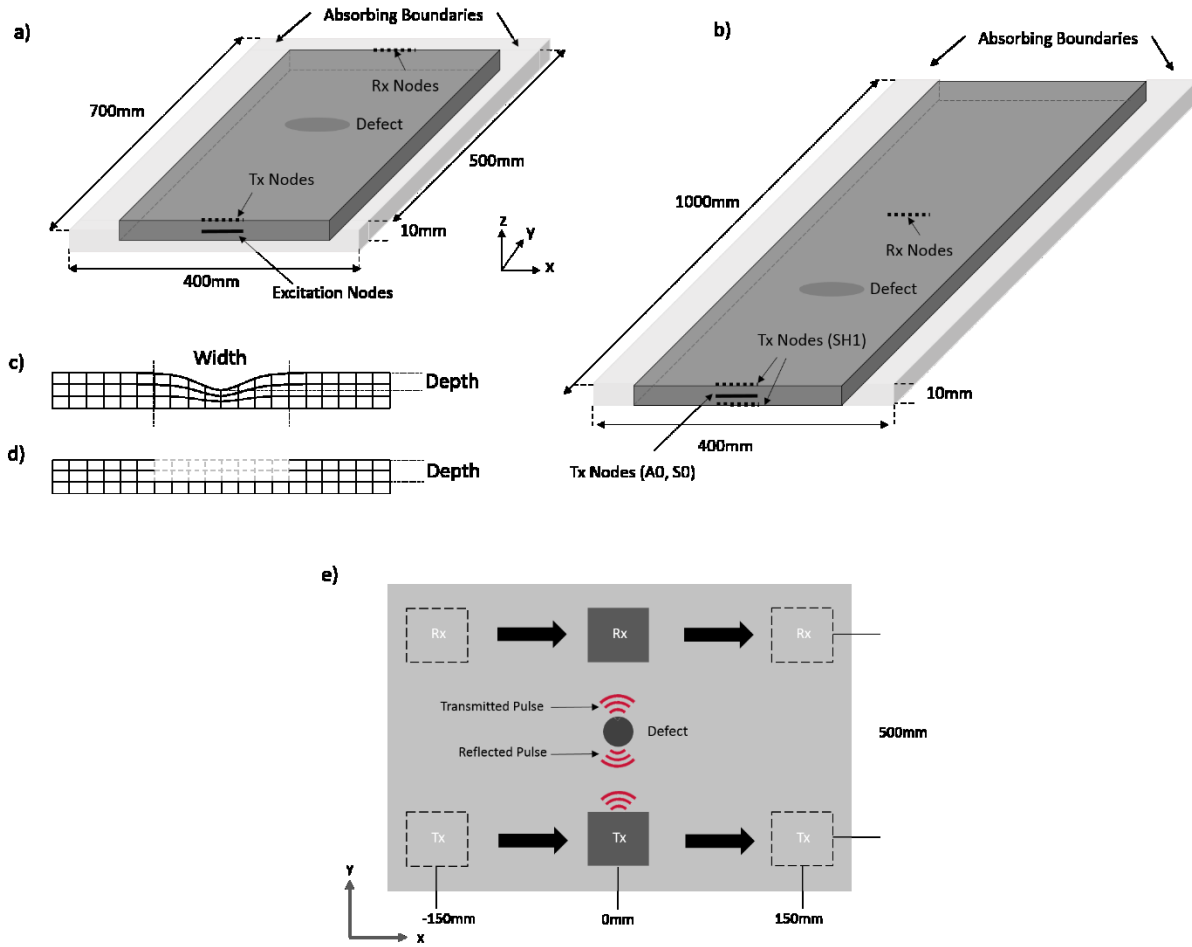


Figure 4.2. a) Reflection and b) transmission finite element model, containing a circular shaped defect. c) Cross-section of the Hann profile defect or d) a part thickness hole. e) Schematic illustration of a B-scan performed over 300mm which has been simulated by the FE simulation with a 1mm³ element size.

4.2.2 Defect Profiles and Dimensions Modelled in the Finite Element Model

The Hann profile defects and part thickness holes were modelled in the same fashion as described in chapter 3. Unlike chapter 3, a greater range of defect dimensions have been modelled: defect diameters from 10mm to 90mm (in 10mm steps) and the defect depths ranges from 1mm to 5mm (in 1mm steps), which is 10% to 50% wall loss in a 10mm plate. Defects of dimensions 120x1mm, 120x2mm, and 120x5mm (diameter x depth) were also modelled using the transmission measurement mode. Previous studies were used as a guide for the defect dimensions. The upper diameter bound was inferred from previous dispersive guided wave studies (whereby the defect diameters ranged from 1λ to 3λ + [46], [101]). Similarly the lower diameter bound was inferred from previous guided wave reflection studies which were interested in defects with diameters around or just below one wavelength [36], [90]. The wavelengths of the toneburst centre frequency of the guided waves used are given in Table 4.1 and Table 4.2. B-scans of the defects were performed

from -150mm to 150mm every 5mm (Figure 4.2e), enabling the incorporation of measurement pitch from the monitoring and scanning setups in Figure 4.1b and Figure 4.1c.

4.3 Guided Wave Measurement Modalities and Selection of Input Toneburst Parameters

Section 4.1 stated that the reflection and transmission measurement modalities will be treated as separate measurements, which are independent from one another. That said however, some nomenclature which is common to both have been defined in Figure 4.3.

The signals are defined relative to either the transmitting (Tx) or receiving (Rx) transducer. Both measurement modalities make use of the baseline Tx and Rx signals, which are produced in a defect free plate of constant nominal thickness (10mm). In this case there will be no reflection present in the signal at Tx, $s_{Tx,baseline}$ in Figure 4.3a. All signals, $s[n]$, are a function of samples, n , and are Hilbert enveloped, $|\hat{s}[n]|$, for the purposes of signal processing. This is because: a) in transmission any changes in thickness will result in a change in the group velocity, which results in a change in the temporal position of the wavepacket; and b) in reflection amplitude changes indicate the presence of a defect.

When the defect is described as being in the central position the defect lies equidistant and directly along the line between the Tx and Rx transducers (Figure 4.3g). The defect position, p , is the distance of the defect away from the central line between the two transducers along the locus between the two transducers. Therefore, unless otherwise stated the defect will lie approximately 250mm away from either transducer, which in the pipe setup shown in Figure 4.1a fixes the defect position at the 6 o'clock position.

Baseline subtraction can be performed to clearly see the reflected signal when a defect is present in the plate. Although the FE model contains ALIDs the baseline subtraction approach was used to remove the input stimulus and other artefacts that may occur within the time trace, leaving just the reflected signal, Figure 4.3d. The baseline subtracted signal at Tx, $s_{Tx,p}$ is defined as:

$$s_{Tx,p}[n] = s_{Tx,p,raw}[n] - s_{Tx,baseline}[n] \quad (4.1)$$

where, $s_{Tx,p,raw}$ is the signal at Tx (Figure 4.3a) with the defect at position p , and $s_{Tx,baseline}$ is the baseline signal at Tx (Figure 4.3b). Baseline subtraction was not performed on the transmission signal, $s_{Rx,p}$, (Figure 4.3f).

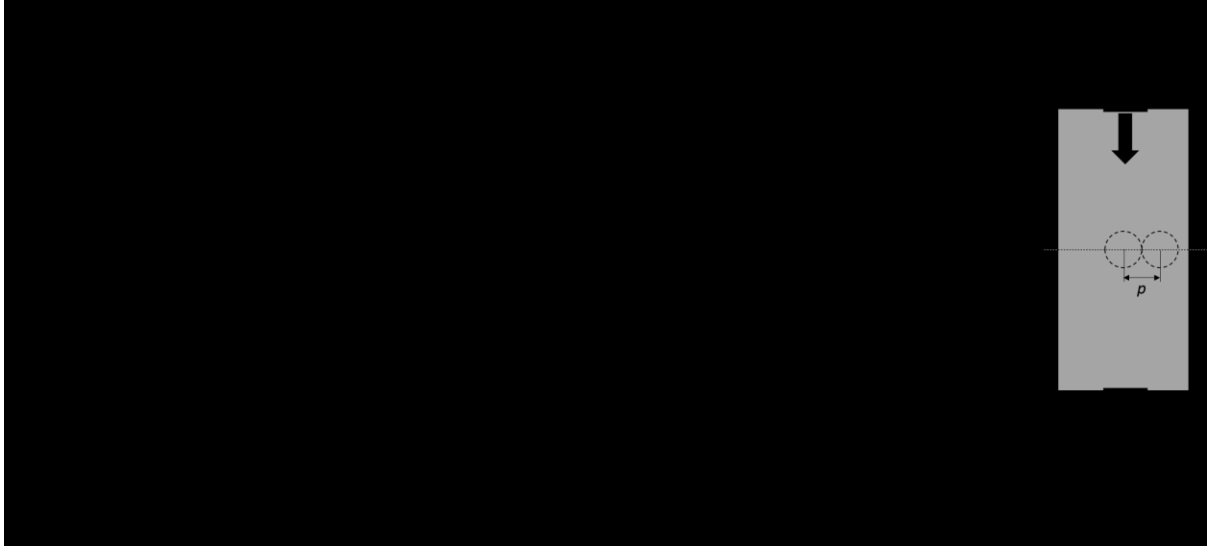


Figure 4.3. Illustrative Hilbert enveloped signals of a) baseline signal at Tx, b) baseline signal at Rx, c) raw signal at Tx with the defect at p, d) baseline subtracted signal at Tx with defect at p, e) signal at Rx with defect at p.

4.3.1 Estimating the Average Thickness from A-Scan Data

The average thickness of the plate, between the sending and receiving transducers, can be estimated from the arrival time of a pulse propagated between them [46]. As was discussed in section 3.2 it is possible for two or more defects to have the same average thickness value.

The average thickness of a plate between two transducers can be extracted using the a priori knowledge of the group velocity curves, shown in Figure 4.6a and b for the Lamb and SH wave modes respectively. The group velocity dispersion curve is expressed in terms of frequency-thickness product. While there are many more advanced algorithms available in the literature [46], [101], [102], as well as the method presented in chapter 3, a simple thickness inversion method based on the change in measured group velocity³ was used in order to provide a comparison of the three guided wave modes. The group velocity, c_g , of the waves is extracted by simply using:

$$c_g = \frac{D}{T} \quad (4.2)$$

where, D is the distance between the two transducers and T is the travel time between the input and output signals. The travel time, T , is calculated by first cross correlating the Hilbert envelopes of the input and the output signals, each of which have N samples.

³ Time of flight is proportional to slowness, s , which is the reciprocal of velocity, $s = 1/c$ [159]

$$C[k] = \sum_{n=0}^{2N-1} |\hat{s}_{Tx,baseline}[n]| |\hat{s}_{Rx,p}[n+k]| \quad (4.3)$$

where $|\hat{s}_{Tx,baseline}|$ and $|\hat{s}_{Rx,p}|$ are the sampled Hilbert envelopes of the input and output signals respectively, n is the index of the signals, and k is the lag between the two signals.

The cross-correlation function of the two signals, $C[k]$, is a maximum at T therefore:

$$T = \frac{2N - 1 - k_{peak}}{f_s} \quad (4.4)$$

where f_s is the sampling frequency of the signals and k_{peak} is the sample at which $C[k]$ is at a maximum. The maximum of $C[k]$ was interpolated using the quadratic peak interpolation [103] to improve the accuracy of T , ensuring the distortions of even the smallest defects were observed.

Once c_g has been established the corresponding frequency-thickness value, F_{Thick} , can be determined from the known group velocity curves, shown in Figure 4.6. The thickness, b , can be extracted using the known centre frequency of the input pulse, f_{centre} ,

$$b = F_{Thick}/f_{centre} \quad (4.5)$$

4.3.1.1 Expected Thickness of Direct Path between Transducers

As was shown in chapter 3, the two-dimensional model presented in Figure 3.2 does not accurately represent realistic measurement setups. In more realistic 3D scenarios both a finite transducer and defect width will need to be accounted for. Nonetheless, it is important to have a simple model that gives an idea of the expected wall thickness measurements, against which the simulation results can be compared. Therefore, a ray based model was used to indicate the expected measured wall thickness variation across the defect. This is illustrated in Figure 4.4. This simplified model assumes that the transducer has a finite width and that straight rays travel from the transmitter to the receiver through the plate (and defect) medium without scattering. Furthermore, it is assumed that the resultant average travel time of all the rays will be the average travel time of the received signal. Therefore, at a given transducer and defect position the expected thickness can be estimated and compared against the results calculated using the method in section 4.3.1.

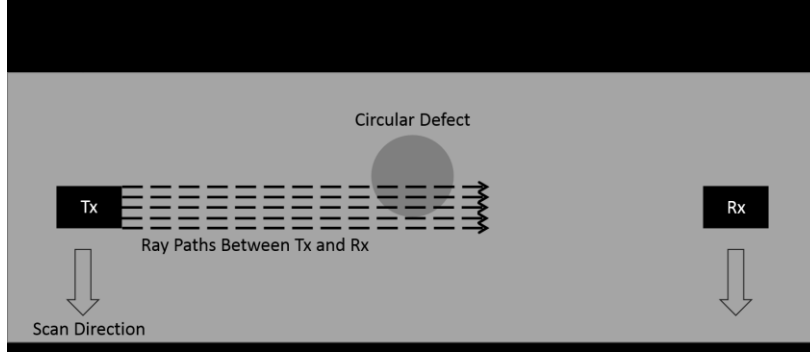


Figure 4.4. A plan view of the plate showing, the transmitting transducer Tx, the receiving transducer Rx and the multiple ray paths through an off-centre defect. The direction in which the two transducers are being scanned is indicated

4.3.2 Defining Normalised Reflection Amplitude

The method by which the normalised reflection amplitude is calculated must be defined to compare the results from adjacent measurements as well as different modes.

Using the baseline subtracted signal shown in Figure 4.3e the normalised reflection amplitude was defined as the ratio of the maximum amplitude of the reflected wavepacket to the maximum amplitude of the baseline through transmitted wavepacket. The normalised reflection amplitude is therefore defined as:

$$A_{Tx,p} = \frac{\max(|\hat{s}_{Rx,p}[n]|)}{\max(|\hat{s}_{Tx,baseline}[n]|)} \quad (4.6)$$

where $|s_{baseline,Rx}[n]|$ is the Hilbert envelope of the through transmitted baseline signal, and $|s_{Rx,p}[n]|$ is the Hilbert envelope of the through transmitted signal with the defect at position p , both at Rx. When the defect is in the central position both the reflected and through transmitted signal will have propagated over the same distance. As the position, p , is varied the adjacent reflection amplitudes are therefore directly comparable with the defect in the centre position, $p=0$. Furthermore, the noise level and decision thresholds (used in section 4.5) are defined in relation to the maximum amplitude of enveloped baseline through transmitted signal (Figure 4.3c):

$$A_{noise} = \frac{\max(|\hat{s}_{Rx,baseline}[n]|)}{10^{\frac{SNR}{20}}} \quad (4.7)$$

where A_{noise} is the maximum amplitude of the filtered noise (over the same bandwidth of the input toneburst) and the SNR is the desired signal-to-noise ratio (in dB).

4.3.3 Selection of Input Toneburst Parameters

To maximise the sensitivity of the various modes the operating characteristics (such as the pulse's centre frequency and toneburst width) must be carefully selected. The parameters

of the input tonebursts will depend on the guided wave mode used as well as the measurement mode (transmission, reflection). For transmission measurements the fundamental anti-symmetric and symmetric (A_0 and S_0) Lamb wave modes as well as the first dispersive shear horizontal (SH) mode, SH_1 , are considered. The non-dispersive SH mode, SH_0 , along with the fundamental Lamb wave modes (A_0 and S_0) were investigated with respect to the reflection measurement modality.

4.3.3.1 Transmission Input Toneburst Parameters

Table 4.1 displays the wave pulse input parameters for each of the guided wave modes that were used in thickness extraction simulations. These were chosen based on a number of considerations as will now be discussed. In chapter 3 a relatively narrowband 5 cycle 250kHz SH_1 toneburst was used, which was heavily scattered by the presence of defect distorting the measured average thickness value. Even though this is an indication that a defect has occurred it is not a fair method by which to assess and compare the three guided wave modes using the transmission measurement modality. In the chapter 3 scenario the dispersive effects are not being isolated/measured but instead a combination of effects are measured. This leads to one of two choices:

- a) use a similar bandwidth and accept a level of dispersion and distortion since that is still an indication that a defect has occurred or,
- b) attempt to improve the measured thickness value, limit scattering and diffraction, and therefore isolate the dispersive effects.

Option b) was chosen since it allows for the maximum level of control over the model's bounds and enables better understanding of the problem. The model presented is already complex, containing more than 4-dimensions/parameters (defect depth, defect diameter, GW mode, noise etc.), and the desire to have defined parameters is crucial. Therefore, the three guided wave modes have been chosen for detection using just the simple method discussed in section 4.3.1. Work investigating other guided wave detection mechanisms using wider bandwidths, such as the use of the SH_1 cut-off, have been investigated by Clough et al. [48]

The guided wave toneburst's centre frequency must be situated on a sloped part of the group velocity dispersion curve to maximise sensitivity to thickness changes (Table 4.1). It was decided that the toneburst should be as narrowband as possible to limit the distortion of the dispersive wavepacket as it propagates. This is because the fewer spectral components in the wavepacket the narrower spread of velocities of those components. This greatly aids the thickness extraction algorithm in section 4.3.1, since it relies on the

wavepacket maintaining its shape as it propagates. The scattering by different spectral components is also reduced.

The A0 mode's operational centre frequency has been chosen as 50kHz, as this is considered a good trade-off between mode sensitivity to thickness changes and excessive mode attenuation due to fluid loading (37 dB/m) as suggested by [79]. The fluid layer was modelled as a layer of water in DISPERSE. The toneburst length was limited to 10 cycles to avoid the overall pulse length exceeding the total length of the propagation path between transmitter and receiver, (i.e. one circumference of the pipe if the plate were rolled up again). A centre frequency of 200kHz and a window width of 25 cycles was selected for the S0 mode. These parameters are a trade-off between attenuation due to fluid loading (29dB/m), sensitivity to wall thickness changes, dispersiveness of the wavepacket as well as overall pulse length exceeding the propagation path length in an 8'' pipe. Heeding the conclusions in chapter 3, the SH1 mode has a centre frequency of 300kHz and a window width of 25 cycles. The selection of the centre frequency is a trade-off between high enough dispersion and being far enough away from the SH1 cut-off point (at 1.7MHz.mm, which corresponds to a minimum remnant thickness of 5.67mm at the 300kHz centre frequency). The input pulses for all three modes can be seen in Figure 4.5.

Centre Frequency (kHz) Window width (Number of cycles) Bandwidth (FWHM%) (kHz) Wavelength at centre frequency (mm) Total Attenuation, inc fluid loading (dB/m) Slope of c_g dispersion curve at centre freq. ($\text{mms}^{-1}/\text{MHz}.\text{mm}$)	Guided Wave Modes		
	A0	S0	SH1
	50	200	300
	10	25	25
	45kHz - 55kHz-(20%)	193kHz - 207kHz-(7.5%)	289kHz-311kHz-(7.5%)
	40	25	13
	37	29	4
	0.46	-4.00	0.13
	FE Pure Mode Generation Method		
Location of Excitation Nodes in the FE Model	Half Thickness	Half Thickness	Top and Bottom Plate Surface
Excitation Direction	$\pm Z$	$\pm Y$	$\pm X$ (top), $\mp X$ (bottom)

Table 4.1. Summary of the characteristics of the wave pulses which were used in the transmission finite element analysis.

All the guided wave modes that are considered here are dispersive. The average thickness of a plate between two transducers can then be estimated using the a-priori knowledge of the group velocity curves of the Lamb and SH wave modes, shown in Figure 4.6a and b.

Pure Mode Generation, Transducer Size and Beam Shape

It has been shown that specially designed transducers can produce pure A0 or S0 modes [80], [104], whereas it is much more difficult to produce a pure SH1 mode. In reality the non-dispersive SH0 mode is also excited, however, provided the propagation distance is sufficiently large these two modes are distinguishable from one another [105].

To enable a comparison of the capabilities of the different guided wave modes it has been assumed for this study that a perfect transducer for excitation of a pure mode can be built. A transducer width of 50mm has been chosen as this is a practical size. A simulation of the radiated fields for the three different guided wave modes based on Huygen's principle is shown in Figure 4.5. The shape of the radiated field is highly dependent on wavelength, and the smaller the wavelength the narrower the beam and the smaller the attenuation of the pulse due to beam spread. This study is mainly interested in the straight line between the two transducers, however, the relative width of the main beam may influence the sensitivity to defects of different sizes.

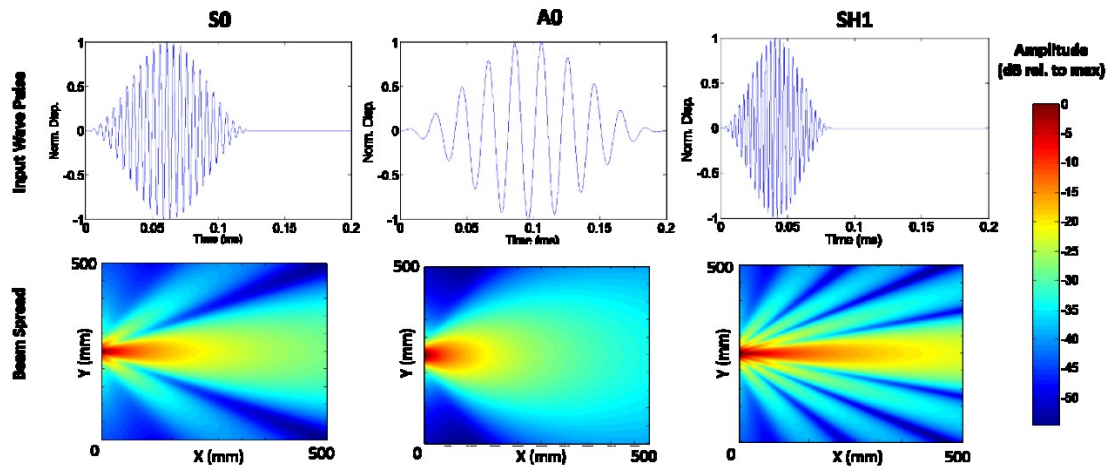


Figure 4.5. The top row illustrates the time traces of the three different input wave pulses used for the simulations with each guided wave mode. The bottom row illustrates the radiated wave field for each transducer and guided wave mode based on a Huygen's model simulation.

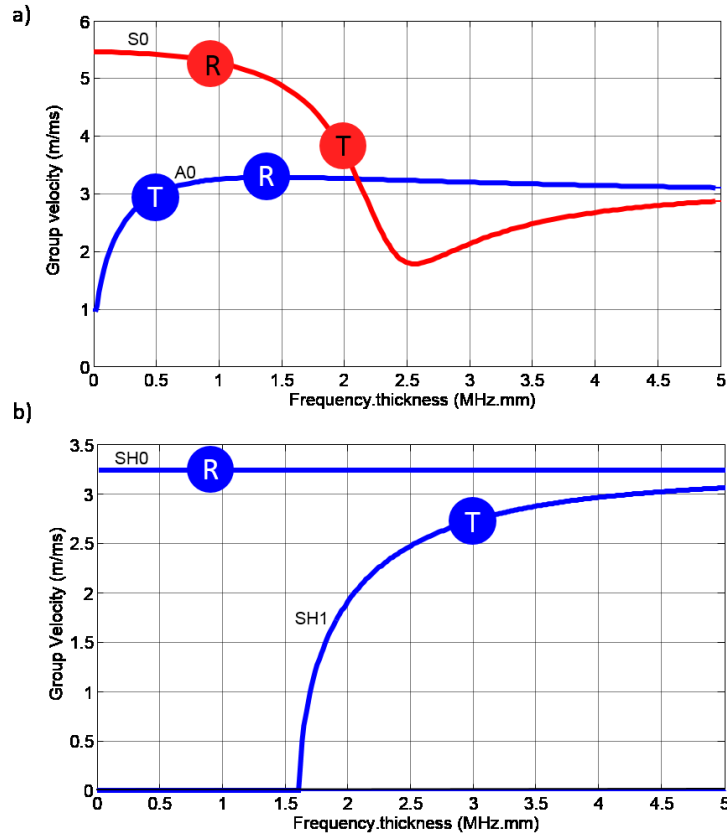


Figure 4.6. a) Group velocity dispersion curves for both the symmetric and anti-symmetric Lamb wave modes in a steel plate ($c_s = 3235\text{m/s}$, $c_l = 5960\text{m/s}$) b) Group velocity curves for the non-dispersive SH0 and dispersive SH1 modes in steel ($c_s = 3235\text{m/s}$) produced with DISPERSE [2]. The centre frequencies of the three modes studied are indicated by the marker on the curves for both the average thickness (T) and reflection (R) methods

4.3.3.2 Reflection Input Toneburst Parameters

A similar input toneburst parameter selection procedure needed to be performed for the reflection measurements. As was stated in the introduction the hypothetical system studied is able to operate over a wide range of frequencies, thereby allowing different input toneburst parameters for transmission and reflection. Previous studies on the reflection of guided waves use a wide range of bandwidths and centre frequencies, each tailored to the requirements of the study. Appendix 9.4 shows a summary of the operating parameters used by a selection of studies and the ranges are included in Table 4.2. The operating parameters used in these studies varied from large wavelength, low dispersion and wide bandwidth [106]-[108] to small wavelength, highly dispersive and with a narrow bandwidth [109], [110]. Other factors were also taken into account such as mode, mode shape, attenuation (with or without fluid loading) and higher order mode cut off. Due to the spread of operating parameters in the literature, the present study needed to perform its own independent analysis, specifically focussing on maximising the sensitivity and detectability.

In contrast to the transmission study, the less dispersive the wave the better. This is because the wave packet distorts as it propagates (see SH1 mode in Figure 3.3), which in turn reduces

the amplitude of the pulse. Dispersion correction is one possible solution to this issue [102]. The non-dispersive SH0 mode was used (in place of the dispersive SH1 mode) and the A0 and S0 operated in a low dispersion regime. This study looks to maximise probability of detecting a defect in reflection by balancing the trade-off between low dispersion and a wide bandwidth, whereby the wavepacket has a greater spectral content, which is important since wavelength has been shown to be a critical factor in guided wave reflections [88]. Therefore, a wider bandwidth could improve sensitivity.

For the A0 and S0 modes a graphical approach, shown in Figure 4.7, was taken to select feasible operating parameters for a guided wave mode in a 10mm thick plate. In each of the figures shown in Figure 4.7 different limits are applied to the two Lamb wave modes:

- a) Phase velocity curves: A1 and S1 Mode Cut Offs provide an upper boundary to prevent the excitation and/or mode conversion to higher order modes.
- b) Group velocity curves: The A0 mode group velocity curve is relatively flat (non-dispersive) above 80kHz and has a peak at 140kHz [72]. The S0 is the least dispersive at low frequencies. Choosing a low centre frequency would, however, decrease sensitivity to small defects, due to a large wavelength, and limit the bandwidth.
- c) Attenuation due to fluid loading: For both monitoring and screening to be practically viable they must be able to be conducted when the pipes are full of fluid. The operating frequency ranges selected by steps a) and b) both have acceptable levels of attenuation, although the S0 mode significantly out performs the A0 mode.

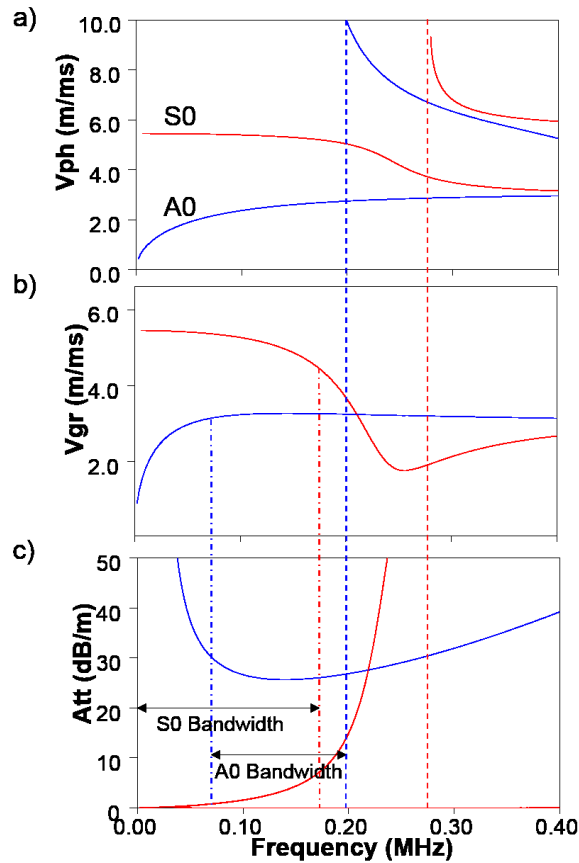


Figure 4.7. Illustration of the method used to select the operating frequency range of the input signals for the A0 and S0 modes by applying limits to the a) phase velocity curves b) group velocity curve and c) total attenuation inc. fluid loading, produced using the DISPERSE software package [2].

Mode	Centre Freq (kHz)	Maximum BW (kHz)	Wavelength (mm) at centre freq.	Excitation Direction (from Figure 4.2)	Range of centre freq from literature (MHz.mm)
A0	140	80-220	60	Z	0.8 - 1.75
S0	90	0-180	18	Y	0.1 - 1.7
SH0	90	0-170	36	x	0.1 - 1

Table 4.2. The selected reflection operating parameters of the A0, S0 and SH0 modes.

From Figure 4.7 the suggested most suitable operating parameters are shown in Table 4.2. Figure 4.8a and b shows the A0 and S0 mode propagation over 500mm. Due to the desire to limit dispersion, the bandwidth of the pulse has been limited to 3 cycles, even though 2 cycles could potentially be used if attenuation is not a large problem (e.g. no fluid loading).

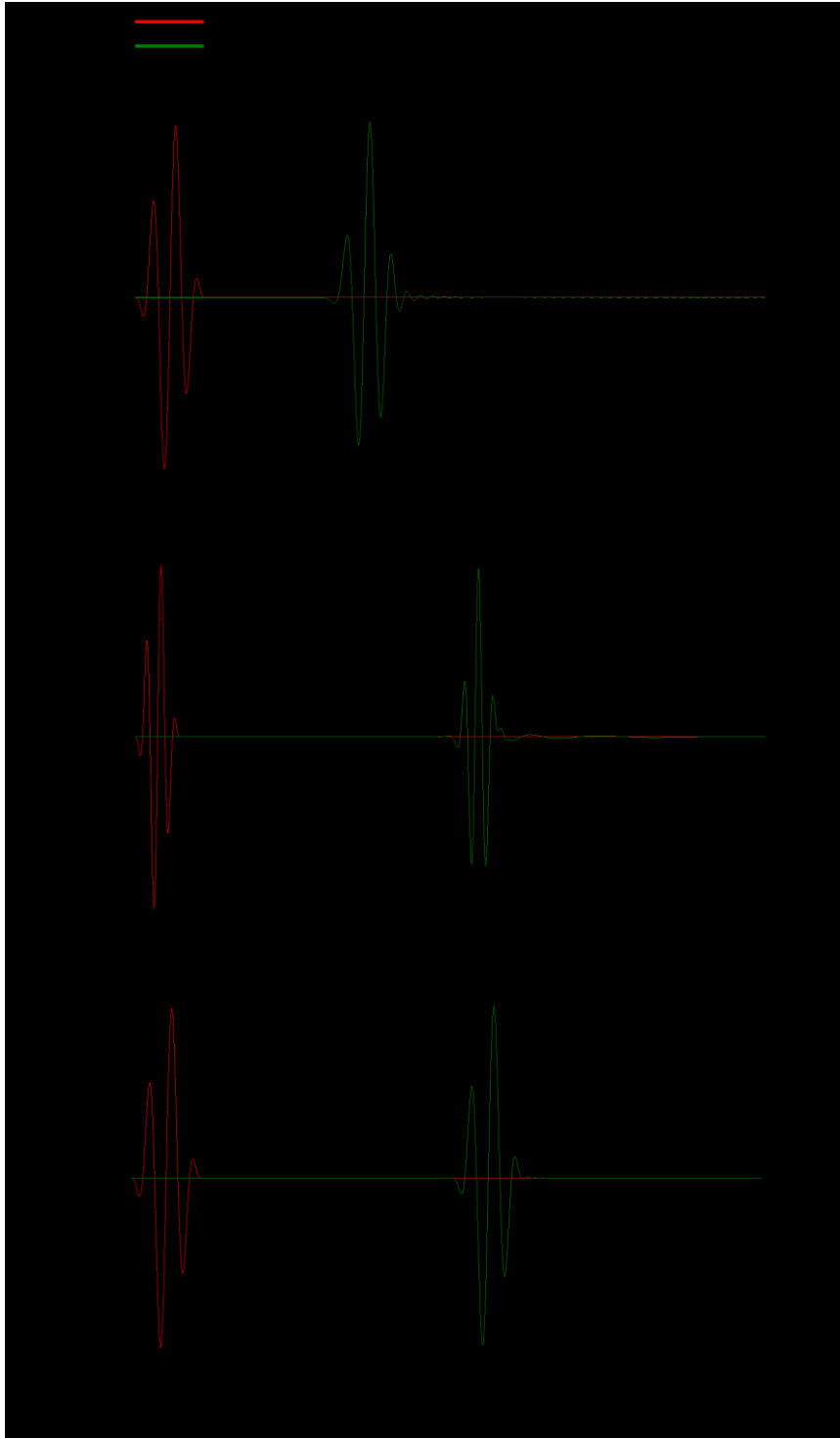


Figure 4.8. Time traces of the input and output waveforms of the a) S0, b) A0, and b) SH0 modes over a 500mm propagation distance in a 10mm thick plate, produced using the DISPERSE software package [111], using the input toneburst parameters from Table 4.2

For the transmission modality measurement mode the SH1 mode was studied alongside, however, it is highly dispersive and therefore unsuitable for use with reflections. The SH0 mode is the fundamental shear horizontal wave mode and in a plate it is not dispersive. In order to prevent exciting the SH1 mode there is an upper frequency limit of 1.7MHz.mm,

and total attenuation is less than 2dB/m for frequencies below the SH1 cut-off. A centre frequency of 90kHz was chosen to maximise the possible bandwidth. The input and output wavepackets that are expected/modelled before and after propagation around a 500mm circumference pipe with a wall thickness of 10mm is shown in Figure 4.8. In a pipe the SH0 is dispersive, however, the effect is <0.5% change in group velocity over all spectral components and no dispersive effects are visible in Figure 4.8.

4.4 Overview of a Sample of Thickness and Reflection Profiles

B-scan simulations were performed for all defect dimensions described in section 4.2.2 using both the reflection and transmission measurement mode. For the sake of brevity only a handful of either thickness or reflection profiles are shown. These profiles illustrate the effect the defect has on either the normalised reflection amplitude or the extracted average thickness value.

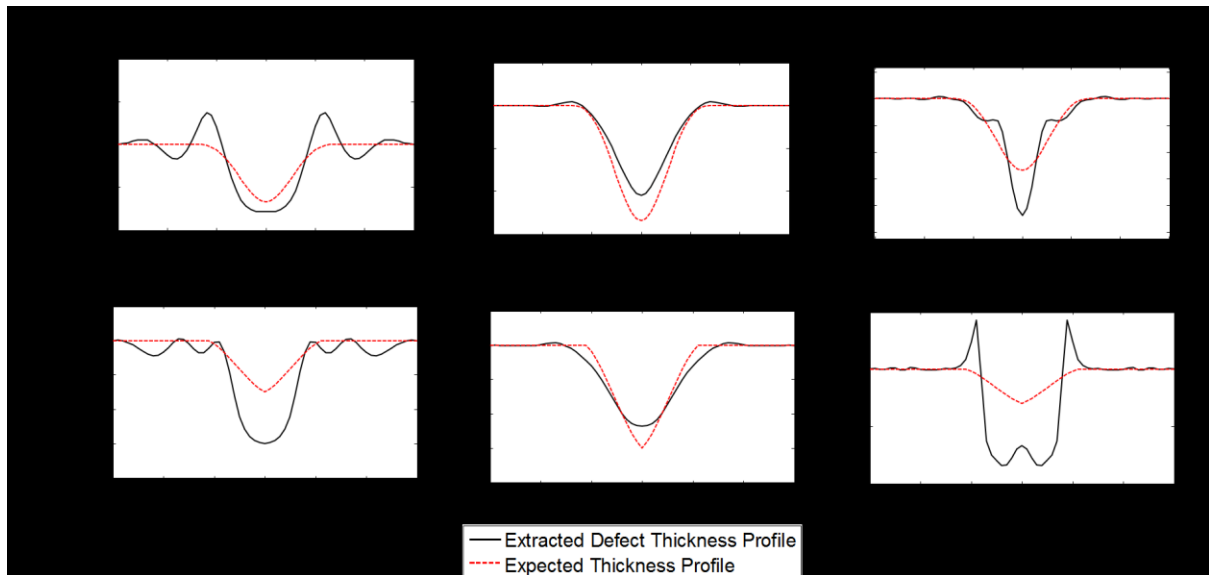


Figure 4.9. Extracted average thickness change profiles from finite element B-scans of three centrally located (250mm propagation from transducer) 90x2mm Hann profile defects (top row) and three centrally located 90x2mm part thickness holes (bottom row) using the, A0, S0, and SH1 modes, with operating parameters shown in Table 4.1.

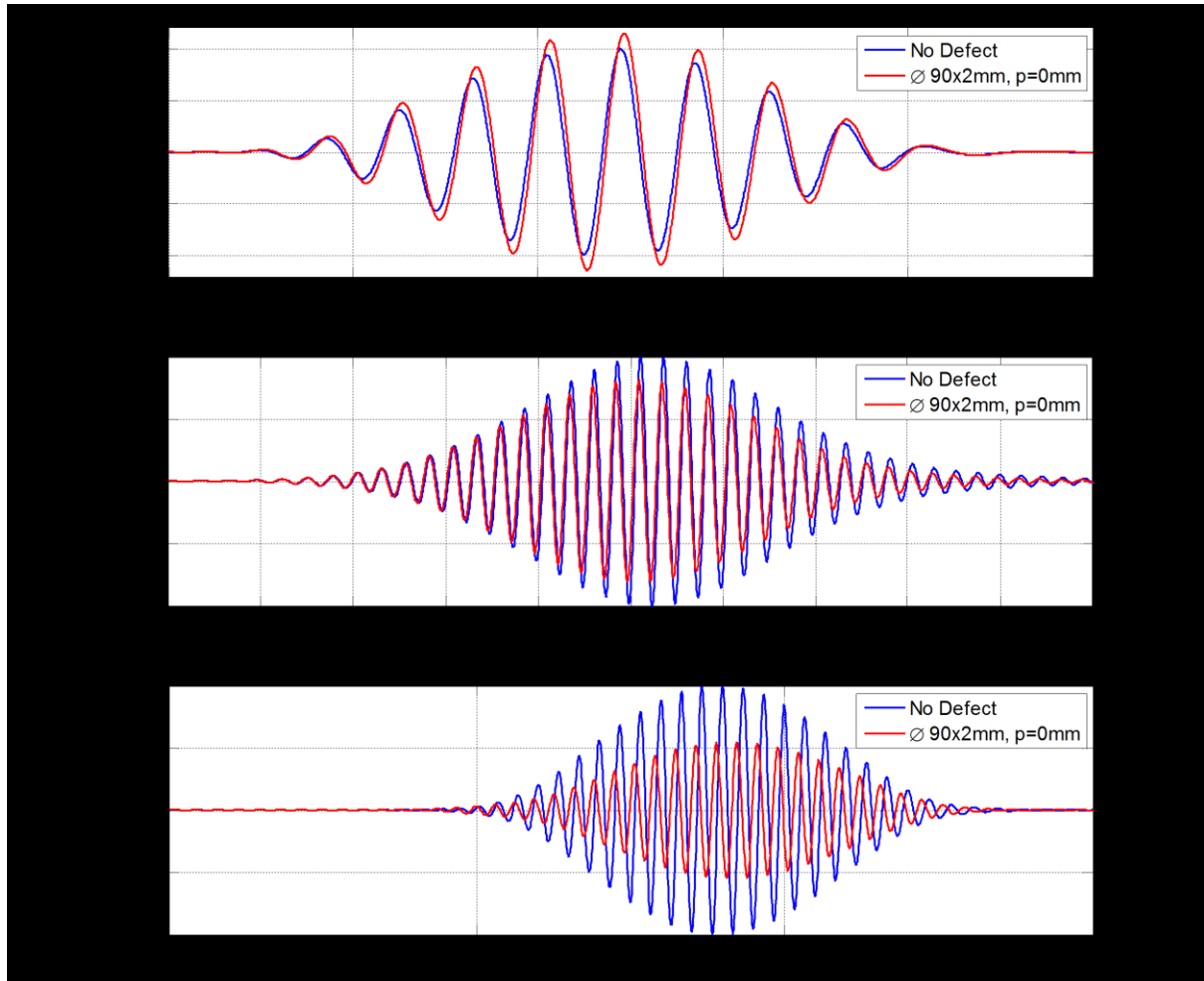


Figure 4.10 Time traces of the A0, S0 and SH1 modes for a plate with no defect (blue) and with a 90x2mm Hann profile defect. The propagation distance was 500mm and the nominal thickness was 10mm.

The thickness profiles for the 90x2mm defects are shown for both the Hann profile defects and the part thickness holes in Figure 4.9. To make it easier to compare the results the mean plate thickness of 10mm has been subtracted from all of the results so that only the measured thickness change is shown. Figure 4.10 shows example time traces of the three modes in a defect free plate and a plate with a 90x2mm defect present, with the defect in the central position ($p=0\text{mm}$).

Figure 4.9a and Figure 4.9d clearly show that for the A0 mode the simple thickness extraction method yields very different results compared to the ray model for both defect types. It is clear that there is significant distortion and scattering of the guided wave as it passes through and around the defect. This leads to large variations in the signal at the receiving transducer and hence large variations in extracted thickness. However, when the axial position of the transducers lies inside the diameter of the Hann profile defect (Figure 4.9a) the extracted thickness profile does approximate to the expected thickness reasonably well.

The extracted thickness profiles from S0 signals (Figure 4.9b and Figure 4.9e) much more closely resemble the predictions of ray theory. In both the S0 thickness profiles the extracted thickness outside the defect diameter is close to the expected thickness (i.e. zero thickness change). When the transducers are aligned with the defect edges, for both defect types, there are slight increases in the extracted thickness; however, the peak value of this thickness increase is small in comparison to the extracted thickness inside the diameter of the defect. Both defects show a reasonable estimation of the minimum thickness but they underestimated it by approximately 20%. The underestimation is most likely due to the S0 phase velocity tending towards a constant value at low frequency-thickness products.

The SH1 mode is unable to neatly track the expected thickness profile of the Hann profile defect for either of the defects shown in Figure 4.9c and Figure 4.9f. Compared with the results in chapter 3 (which is a 60mm diameter as opposed to a 90mm diameter) the thickness profiles are much smoother and in the Hann profile defect case the minimum average thickness is approximately within 50% of the expected value. The effect of scattering in the chapter 3 results (i.e. large extracted thickness outside the width of the defect) have reduced and the thickness change is only sensitivity to the presence of the defect over the width of the defect (>-45mm and <45mm).

The S0 mode approximates the expected thickness profiles much more accurately than the other two modes. This effect can be explained with Snell's law, which governs the relationship between the angle of incidence, θ_i , and transmission, θ_T , when a wave passes through a boundary between two media [112]:

$$\frac{\sin\theta_i}{\sin\theta_T} = \frac{v_1}{v_2} \quad (4.8)$$

where v_1 and v_2 are the wave speeds in the first and second media, respectively. Therefore, if $v_1 > v_2$ then $\theta_i > \theta_T$ and the beam converges, and if $v_1 < v_2$ then $\theta_i < \theta_T$, and the beam diverges. As the plate thins the group velocity of the S0 mode increases, unlike the SH1 and A0 modes (see Figure 4.6). Therefore, the S0 beam will diverge. On the other hand, the SH1 and A0 beams will converge and the defect will act like a convergent lens focusing the guided wave beam. The resulting constructive and destructive interference will heavily distort the extracted thickness value. In the case of the S0 mode there will be no constructive and destructive interference over the width of the defect, because the divergent ray paths will be unable to interfere with one another. The only place where interference could occur is where the divergent beam crosses the part of the beam which

does not pass through the defect (i.e. at the edge of the defect). A small increase in the extracted thickness due to the resulting interference can be observed in the S0 profiles in Figure 4.9 at the edges of the defects (at $\pm 60\text{mm}$ defect position in the Hann profile defect and $\pm 90\text{mm}$ in the part thickness hole).

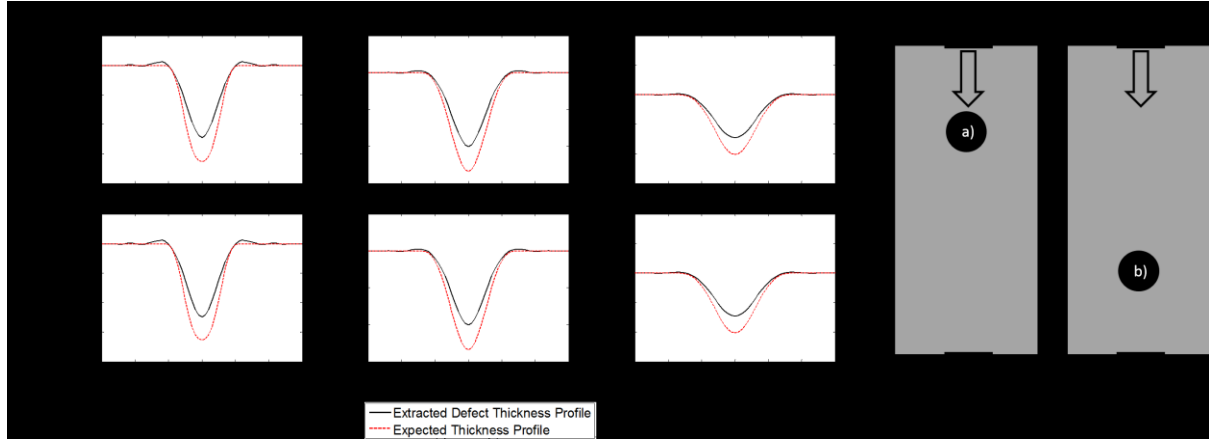


Figure 4.11 Top row - extracted thickness profiles for three defects (60x2mm, 90x2mm, and 120x2mm) defects using the S0 mode with the defects placed 125mm away from the Tx nodes. Bottom row - same setup as top row but with the defect placed 375mm away from the Tx nodes.

Figure 4.11 shows the effect of the S0 thickness profiles of moving the defect nearer (125mm) to or further away from (375mm) the Tx nodes. This corresponds to the defect being either at 3 o'clock or 9 o'clock in the pipe setup shown in Figure 4.1a. There is no large effect on the extracted thickness due to moving the defect around the circumference of the pipe in the case of the S0 mode.

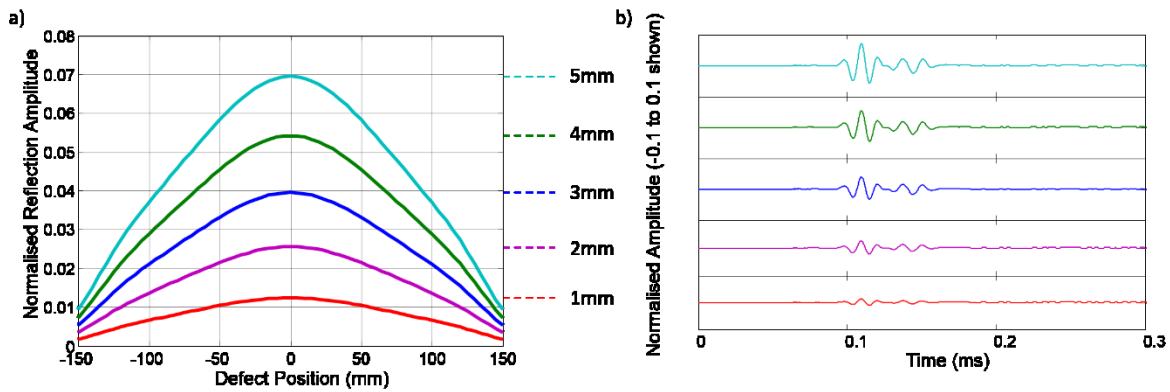


Figure 4.12. a) Reflection coefficient profiles of the S0 mode from five 30mm diameter Hann profile defects with varying depth, using a 90kHz 3 cycle Hann windowed toneburst. The corresponding reflection signals with the defect in the central position are also shown in b). As defined by equation 2, a normalised amplitude range of -0.1 to 0.1 is displayed.

Figure 4.12a shows five normalised reflection amplitude profiles for five 30mm Hann profile defects with different depths (1, 2, 3, 4, and 5mm), interrogated with a 90kHz 3 cycle Hann windowed S0 toneburst. The corresponding signals with the defect in the central position

are also shown. The larger peaks in Figure 4.12b are from the reflection signals from the defect, the secondary peaks are due to edge reflection which have been attenuated but not removed through the use of ALIDs. This does not affect the results as equation 4.6 uses the maximum of the signal. The defect depth increases the peak reflection amplitude in a linear fashion and the reflection amplitude is maximised, for a given defect depth, when the defect is at $p=0$. As the defect position moves away from $p=0$ the reflection amplitude decreases. This is due to a) the incident and reflected wave travelling further, therefore attenuation increases; and b) the incident beam having a finite width, therefore at large defect positions the wave incident on the defect will be significantly less intense than at the central position.

In reflection, the defect is effectively at the furthest point away from the transducer. This is because if the proposed guided wave system successfully took advantage of a directional transducer then it would be able to send directional waves either clockwise or anticlockwise around the pipe. Therefore, the maximum travel distance of the incident and reflected pulse occurs when the defect is at the 6 o'clock position in the pipe.

While the simulated defect thickness profiles did not all conform to expected profiles as calculated by the ray model, they all showed considerable deviations from the baseline average thickness (i.e. the situation with no defect present). Similarly, in reflection there is a (potentially) detectable response depending on noise level, whilst the profile is also much wider than the width of the defect measured. The magnitude of these measurements will have implications on sizing, however, when considering just detection then a substantial difference from the baseline thickness value or the presence of a reflected pulse is an indication that a defect is present. The magnitude of the measurement will dictate the sensitivity when compared to a baseline noise level. Therefore, a method needs to be devised to quantify this magnitude of the measurement compared to different noise levels, as well as including adjacent measurements to derive an overall measure of sensitivity to different sized defects.

4.5 Models of Probability of Detecting a Defect Incorporating Measurement Pitch

4.5.1 Overview of Probability of Detection

This section presents a method to quantify the detection capabilities of the different modes with the aim of quantifying the minimum defect size that can be detected for a given setup and mode. The methods of extracting the probability of detection (POD) and probability of

false alarm (PFA) are similar to approaches that are reported in the literature [113]-[115]. This study is interested in the two setups illustrated in Figure 4.1b and c which have variable pitches between adjacent measurements.

Two probability distributions must be derived, $p(\text{measurement}|\text{baseline})$ and $p(\text{measurement}|\text{defect})$, to calculate the POD and PFA for a certain defect. The distributions describe either the probability distribution of an arbitrary measurement given there is either no defect (baseline) or a defect present. In the case of this study the measurement would either be a value of the reflection amplitude or the extracted average thickness. These two distributions can be overlaid as shown in Figure 4.13. An arbitrary threshold has to be chosen to call a defect, therefore if a change in measurement exceeds this threshold a defect is called. The values of the POD and PFA can then be calculated from the areas under the probability distribution curves which are above or below the threshold as follows [113], [116], [117]:

$$POD = \text{Sensitivity} = \frac{TP}{TP + FN} \quad (4.9)$$

$$PFA = 1 - \text{Specificity} = 1 - \frac{TN}{TN + FP} = \frac{FP}{TN + FP} \quad (4.10)$$

where the true positive (TP), false positive (FP), true negative (TN) and false negative (FN) represent the integrals of the two measurement distributions either side of the threshold, as shown in Figure 4.13.

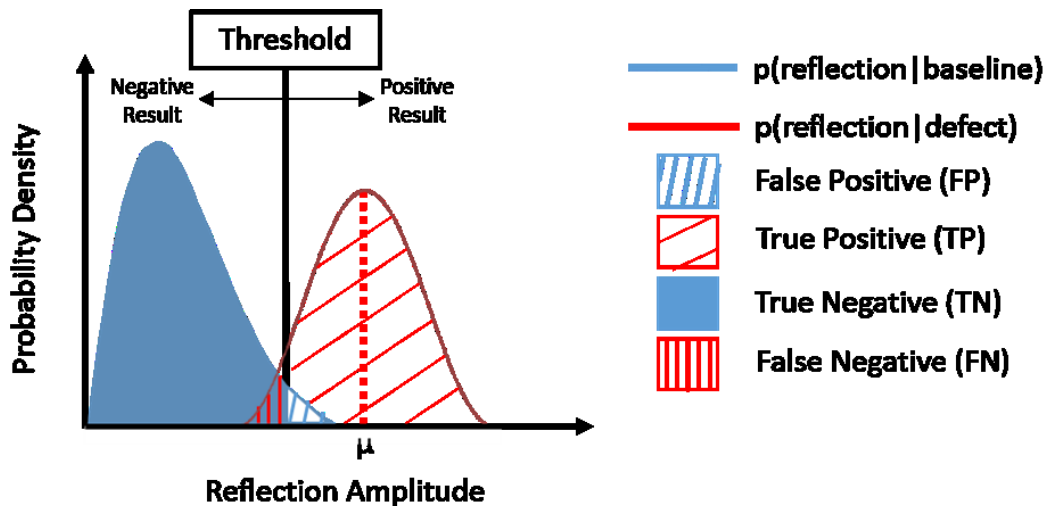


Figure 4.13. Illustration of the TP, FP, TN and FN areas used in the calculation of the POD and PFA in equations 4.9 and 4.10.

In this study the call threshold is defined as 3σ of $p(\text{measurement}|\text{baseline})$, which means if the measurement change exceeds the mean baseline measurement by 3σ then thinning (i.e. a defect) is detected. Therefore, in this study the PFA has been fixed at 0.0027 (0.27%). To calculate the POD and PFA methods to derive $p(\text{thickness}|\text{defect})$, $p(\text{thickness}|\text{baseline})$, $p(\text{reflection}|\text{baseline})$ and $p(\text{reflection}|\text{defect})$ need to be determined. The methods by which these four distributions are derived are outlined in sections 4.5.2 and 4.5.3. Although methods for deriving $p(\text{thickness}|\text{defect})$ and $p(\text{reflection}|\text{defect})$ differ they do both follow the same overall methodology:

- If a defect is present in the plate the distribution of the measurement does not solely depend on the shape and size of the defect but also on the noise level (SNR) and the defect's position relative to the transducers in the array (Figure 4.1b or Figure 4.1c).
- Therefore, for a given defect size and shape (e.g. a 60x1mm Hann profile defect) the distributions in measurement values (i.e. $p(\text{thickness}|\text{defect})$ or $p(\text{reflection}|\text{defect})$ ⁴) are a combination of the distributions due to the noise level and defect position, $p(\text{measurement}|\text{noise})$ and $p(\text{measurement}|\text{defect position})$
- $p(\text{measurement}|\text{defect position})$ is dependent on the defect's position relative to the transducers in the array, which in turn depends on the pitch between the individual transducers.

4.5.2 Method for Determining Probability Distribution from Transmission Measurements

4.5.2.1 Variability Due to Noise in Transmission

The Hilbert enveloped guided wave signal, $|\hat{s}_{Rx,baseline}[n]|$, from the FE simulations of a defect free plate of constant baseline thickness (10mm) were used to extract the probability distribution of baseline thickness measurements due to a particular noise level, $p(\text{thickness}|\text{baseline})$. To simulate the different noise levels, filtered noise with the corresponding signal to noise ratio (SNR) was added to the received and transmitted signals. The noise was scaled to the desired amplitude using equations 4.7.

The baseline average thickness was then extracted using the noisy received and transmitted thickness signals. This process was repeated; building up a distribution of baseline average thickness values. The baseline thickness probability distribution, $p(\text{thickness}|\text{baseline})$, can

⁴ Strictly speaking set notation dictates that these probability distributions are given written as $p(x|\text{defect dimensions, pitch, SNR})$, which reads as 'the probability distribution of x conditional on the defect dimensions (shape, diameter and depth), measurement pitch, and noise level'

be represented by a normal distribution (of unit area) with a mean of zero and an associated standard deviation.

The standard deviations of the extracted average thickness for a range of SNRs (20, 30, and 40dB) of the three guided wave modes - propagating over 500mm in a 10mm thick plate - are displayed in Table 4.3. The S0 and SH1 modes have significantly lower standard deviations in comparison to the A0 mode since they are operating at higher frequencies - 200kHz and 300kHz, compared to 50kHz. The A0 mode was excluded from further analysis due to the larger variance in extracted average thickness.

Standard Deviation of Average Thickness (mm)			
Mode	SNR (dB)		
	20	30	40
A0	0.34	0.169	0.0499
S0	0.0358	0.0113	0.0036
SH1	0.0885	0.029	0.0092

Table 4.3. The standard deviation in the extracted thickness for the three guided wave modes over a propagation distance of 500mm in a 10mm thick plate for three different signal to noise ratios (20, 30, 40dB), using the input characteristics shown in Table 4.1

4.5.2.2 Variability Due to Defect Position in Transmission

Figure 4.9 shows a sample of the thickness profiles extracted from FE simulations. The defects were equidistant between the transmitting and receiving transducer, as the transducers scan the defect - in 5mm steps between -150mm and 150mm. The variability due to defect position is determined from these thickness profiles, which will be represented as a function $b(x)$, where x is the defect position with an associated sample interval q . It was found that upsampling all thickness profiles by factor 100 resulted in a smooth curve that aided subsequent data processing. The upsampling by factor 100 was performed using linear interpolation, therefore $q = 5\text{mm}/100 = 0.05\text{mm}$.

For defect detection purposes it is assumed that the maximum absolute thickness deviation, $|b(x)|$, from the baseline is used. Figure 4.14a shows an example absolute value of the thickness change profile. An array or scan of pitch, X , only measures a thickness of the profile every X mm, therefore an array of individual measurements is represented by sampling the thickness profile every X mm. The sampling process can be represented by $|b(nX)|$, where n is an array of integers between $-\infty$ and $+\infty$ (for an infinite array or scan), indicating a discrete array of individual measurements. In practice, however, the sample range has a finite width, therefore the range of n values must ensure that it spans the width

of the thickness profile, as shown in Figure 4.14a. The maximum value, m , of that sample is then used to determine whether a defect was present. That is, a defect is called if m is larger than the threshold. The maximum of the sample can therefore be expressed as:

$$m = \max(|b(nX)|) \quad (4.11)$$

An array of maximum values, m_k , for different positions of the defect relative to the transducer array can be produced by first: adding a value k , which incrementally increases by q from 0 to $X-q$, to the argument of equation 4.11; and then by taking the maximum of each sample at each value of k . Figure 4.14b shows the same sampling process as in Figure 4.14a but at a different location. m_k - illustrated in Figure 4.14c - is represented by:

$$m_k = \max(|b(nX + k)|), \text{ for } k = 0, q, \dots, X - q \quad (4.12)$$

The m_k array extraction process was performed numerically in MATLAB and since the array is composed of discrete variables, a histogram can be created representing the occurrences within each thickness bin, illustrated in Figure 4.14d. The histogram divides the m_k values into $X/10q$ bins, between the maximum and minimum values in m_k . The probability mass function (PMF) of the variability caused by the defect position can be determined by normalizing the histogram to unit area. The PMF is taken to represent $p(\text{thickness}|\text{defect position})$.

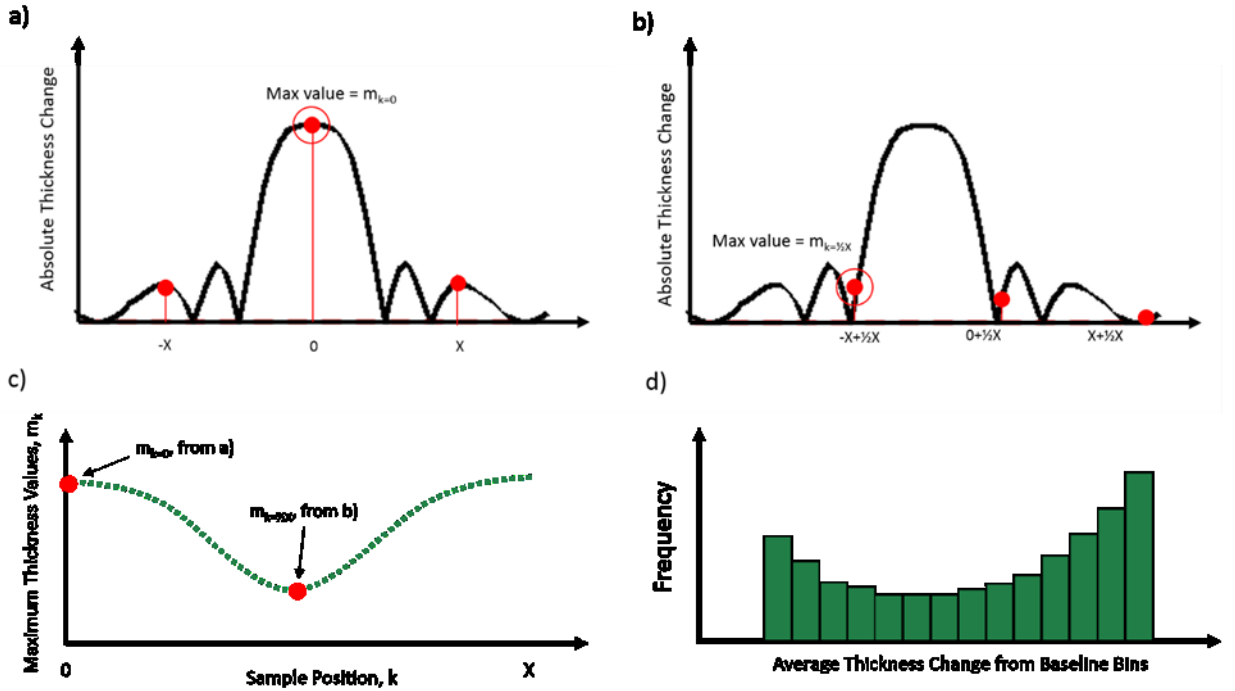


Figure 4.14. Determination of $p(\text{thickness}|\text{defect position})$. a) An example of a highly sampled absolute thickness profile which is being sampled at the first position where $n = -1, 0, 1$ and $k = 0$. b) The same absolute

thickness profile which is being sampled at a different array/sample position where $k = 0.5X$, c) The maximum values of the thickness profile, m_k , d) An example histogram of the thickness change values of the m_k .

The POD depends on both the position of the defect and the noise dependent repeatability of the measurements. Noise is added to the $p(\text{thickness}|\text{defect position})$ by convolving it with a normal distribution with a standard deviation of the associated noise level (from Table 4.3) since the variability due to defect position and noise are independent of one another [118].

Figure 4.15 shows five $p(\text{thickness}|\text{defect})$ distributions for a 60x1mm Hann profile defect interrogated with a 200kHz 25 cycle Hann windowed S0 toneburst with 30dB SNR for five different transducer pitches (50, 75, 100, 125, and 150mm). As the transducer pitch increases a greater range of thickness change values are incorporated into $p(\text{thickness}|\text{defect})$. All five distributions have a peak or local maximum near 0.026mm due to the increased density of points near the maximum thickness change. As the pitch increases there is a greater density of values with near zero thickness change. The wider pitches (100mm, 125mm, and 150mm) have a further peak at zero thickness change, due to the inclusion of more thickness values with little or no thickness change, which lie either side of the defect. These correspond to measurements where the transducer array or scans are made in such a way that the direct wave propagation path does not pass through the defect and hence no change is detected.

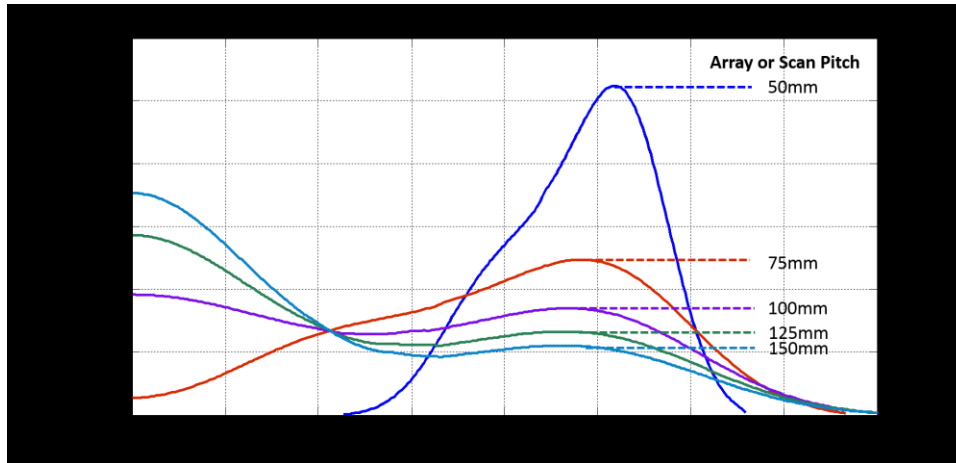


Figure 4.15. $p(\text{thickness}|\text{defect})$ distributions, with unit area, for a 60x1mm Hann profile defect with 30dB SNR using different transducer pitches (50mm, 75mm, 100mm, 125mm, 150mm), with the defect centrally located in the plate and a guided wave propagation distance of 500mm in a 10mm thick plate, using a 200kHz 25 cycle Hann windowed S0 guided wave pulse.

4.5.3 Method for Determining Probability Distributions from Reflection Measurements

4.5.3.1 Baseline Probability Distribution Due to Noise without a Defect Present

To simulate the noise an array of normally distributed random numbers, which had the same number of samples as $s_{Tx,p}[n]$, was generated. The array was filtered in the frequency domain so that it had the same bandwidth as the input toneburst, scaled to the desired amplitude using equation 4.7 and Hilbert enveloped. The amplitude at an arbitrary sample in the noise array, $s_{noise}[n]$, was logged. When performing a pulse echo measurement an operator searches for a reflection within a window in the time trace. However, it is not possible to incorporate all possible window widths within a value of the POD. Therefore, the amplitude of a single sample was logged since a single sample is the most conservative ‘window width’ possible. In this study, for computational convenience, the value at n_{max} was logged (see equation 4.13). This process was repeated 1000 times and $p(\text{reflection}|\text{baseline})$ is then approximated from a histogram of noise amplitudes values. The amplitude variations of enveloped acoustic signals follow Rician distributions [115], [119]. Rician distributions can be approximated to Rayleigh distributions or Gaussian distributions at low or high signal to noise ratios respectively [120], [121].

4.5.3.2 Variability Due to Noise with a Defect Present.

In the presented model noise is added to the Tx baseline subtracted signal (see equation 4.1) with the defect in the central position ($p=0$), $s_{Tx,0}[n]$. The amplitude spread due to noise at the central position is used to approximate the spread due to noise at all defect positions. First the position, n_{max} , of the maximum amplitude in $s_{Tx,0}[n]$ without noise is located:

$$n_{max} = \operatorname{argmax}(|\hat{s}_{Tx,0}[n]|) \quad (4.13)$$

Again, a single sample at the location of the reflection, n_{max} , was used since this is the most conservative ‘window width’ possible. To simulate the different noise levels, filtered noise, $s_{noise}[n]$, with the corresponding signal to noise ratio (SNR) was added to $s_{Tx,0}[n]$.

$$s_{0,noise}[n] = s_{Tx,0}[n] + s_{noise}[n] \quad (4.14)$$

The noise was scaled to the desired amplitude using equation 4.7. Once noise has been added the normalised amplitude, $A_{Tx,0}$, at n_{max} can be logged.

$$A_{Tx,0} = |\hat{s}_{0,noise}[n_{max}]| \quad (4.15)$$

This process was repeated 1000 times, with the value of $A_{Tx,0}$ logged each time. The standard deviation of the $A_{Tx,0}$ set, σ_0 , was then calculated.

4.5.3.3 Variability Due to Defect Position in Reflection

When a defect is present the distribution of the measured reflection amplitude does not solely depend on the SNR and on the type and size of the defect, but its position relative to the transducer(s) as well. The method by which the defect position is incorporated into the POD is illustrated in Figure 4.16, using the reflection profiles, A_{Refl} , such as the examples shown in Figure 4.12.

The full reflection profile, $A_{Refl}[p]$, covers all the defect positions simulated in the finite element model, where p is -150mm to 150mm in 5mm steps. However, for a setup with a particular pitch, X , the reflection profile of interest is much narrower $A_{Refl}[\beta]$, where β is $-X/2$ to $X/2$ in 5mm steps, since we are only interested in the values with the largest normalised reflection amplitude values. Any transducer measuring a reflection outside that region will have a smaller response than the transducer within the central pitch, and is therefore ignored. $A_{Refl}[\beta]$ is cubically upsampled by a factor of 100 to increase the density of points, this is not shown in Figure 4.16.

The assumption is made that the spread in amplitudes due to noise between $-X/2$ to $X/2$ in $A_{Refl}[\beta]$ is the same as at $p = 0$ mm, but with a different value of the mean. Therefore, a Gaussian distribution was presumed at each data point in $A_{Tx,p}$, each with a mean equal to the reflection amplitude at each data point and with the spread equal to σ_0 , as shown in Figure 4.16. This assumption agrees with literature on high SNR signals [120]. While running validation simulations, it was found that at low signal to noise ratios this assumption will start to break-down but only when the reflection amplitude, $A_{Tx,p}$, is much less than the noise level.

By summing the individual Gaussian distributions (Figure 4.16b), the variability due to defect position is taken into account, giving the probability distribution of the continuous reflection amplitude variable, A_r , for a certain defect, $p(\text{reflection}|\text{defect})$, Figure 4.16c.

$$p(\text{reflection}|\text{defect}) = \sum_{\beta=-X/2}^{X/2} e^{-\frac{(A_r - A_{Refl}[\beta])^2}{2\sigma_0^2}} \quad (4.16)$$

The POD can then be calculated using equation 4.9, which does not require the area of $p(\text{reflection}|\text{defect})$ to be normalised to unit area. The distributions would only have to be

normalised to unit area only if the integral methods of calculating probability were used [122].

$$POD = \int_{A_t}^{\infty} K \sum_{\beta=-\frac{X}{2}}^{\frac{X}{2}} e^{-\frac{(A_r - A_{Ref}[\beta])^2}{2\sigma_0^2}} dA_r \quad (4.17)$$

where A_t is the 3σ reflection amplitude threshold and K is a constant which normalises the area of equation 4.16 such that:

$$\int_{-\infty}^{\infty} \sum_{\beta=-\frac{X}{2}}^{\frac{X}{2}} e^{-\frac{(A_r - A_{Ref}[\beta])^2}{2\sigma_0^2}} dA_r = 1 \quad (4.18)$$

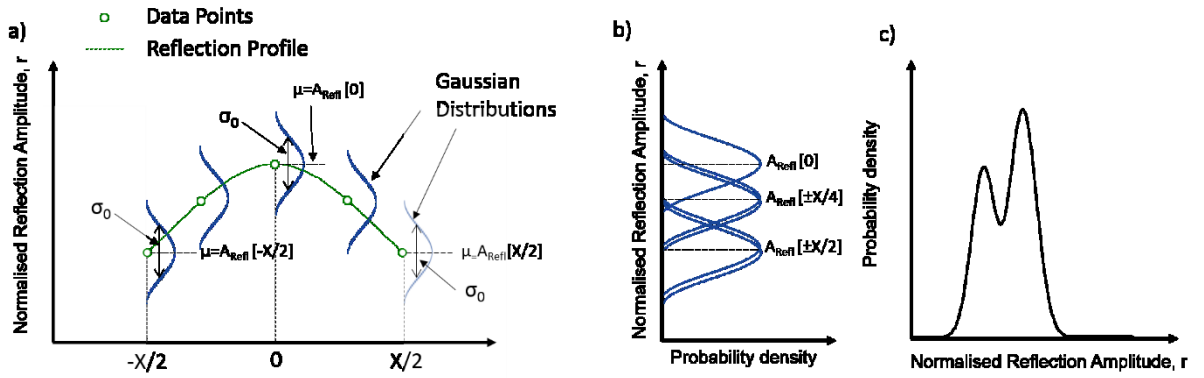


Figure 4.16. Gaussian summation method, a) the assumed spread due to noise is applied to all data points in the reflection amplitude profile, b) the individual Gaussian distributions with the same spread and different means c) the summation of all the Gaussian distributions gives the probability distribution due to noise, defect and pitch.

4.6 Results and Discussion of Probability of Detection Study

In this section the effect of array or scan pitch is presented and discussed first, for both the transmission and reflection measurement modalities. The sensitivity of guided waves, in either measurement modality, to a wide range of defect dimensions is then assessed allowing for generalised conclusions to be drawn.

4.6.1 Effect of Measurement Pitch

Figure 4.17a-f show the POD curves as a function of array or scan pitch for a circular Hann profile defect with a varying diameter (20, 30, 60, 90, and 120mm) and constant depth (1, 2, and 5mm) for both S0 and SH1. Figure 4.17g-l show the POD curves as a function of array

or scan pitch for both modes for circular part thickness holes with a varying diameter and constant depth. All the POD curves are displayed even if the defect is not detectable (i.e. POD is zero for all pitches). To be able to successfully monitor a defect the sensitivity of an array of transducers must increase as the defect increases in size. If the trend in the POD - with increasing defect diameter or depth - does not increase then as a defect becomes increasingly large in size the chances of detecting it decreases.

As a general comparison between the POD curves (as a function of pitch) of the two defects, the Hann profile defects curves are nearly always the same shape. Especially in the case of the S0 mode whereby as the defect increases in depth the POD curve simply shifts upwards. This is in sharp contrast to the part thickness holes curves, where the curves are much less smooth as well as containing local maxima and minima suggesting a much more complex relationship between POD and measurement pitch.

In most cases in Figure 4.17a-f as the pitch decreases (note the axes have been reversed) the POD increases for both the S0 and SH1 modes. As the diameter of the Hann profile defects increases the POD increases at nearly all pitches, demonstrating the desired increase in POD with increasing defect dimensions. The exception is the 120x5mm Hann profile defect using the SH1 mode (Figure 4.17f) which has a lower POD than the 90x5mm defect below a pitch of 80mm.

For the part thickness hole (Figure 4.17g-l) results there is generally much less correlation between increasing diameter and increasing POD for both modes. This is believed to be due to scattering at steep edges of the hole which distorts the transmitted field. This effect is less prominent for Hann profile defects as there are no sharp features, therefore the guided wave pulses are scattered less. There are a few part thickness hole results where the desired correlation between increasing defect dimension and POD occurs over an extended range of pitches; such as at pitches greater than 30mm pitch with 1mm deep defects using the SH1 mode (Figure 4.17j).

When comparing the sensitivity of the two modes, in general the S0 mode is more reliable at detecting both Hann profile defects and part thickness holes with a diameter equal or greater than 60mm compared to the SH1. For example, at pitches greater than 50mm the S0 mode has a higher POD over all defect sizes greater than 60mm except 120x1mm part thickness hole. The SH1 mode, however, is able to detect a far greater range of narrower defects (20mm and 30mm diameter), whereas the S0 is only sensitive to the 30x5mm part thickness holes at very narrow pitches.

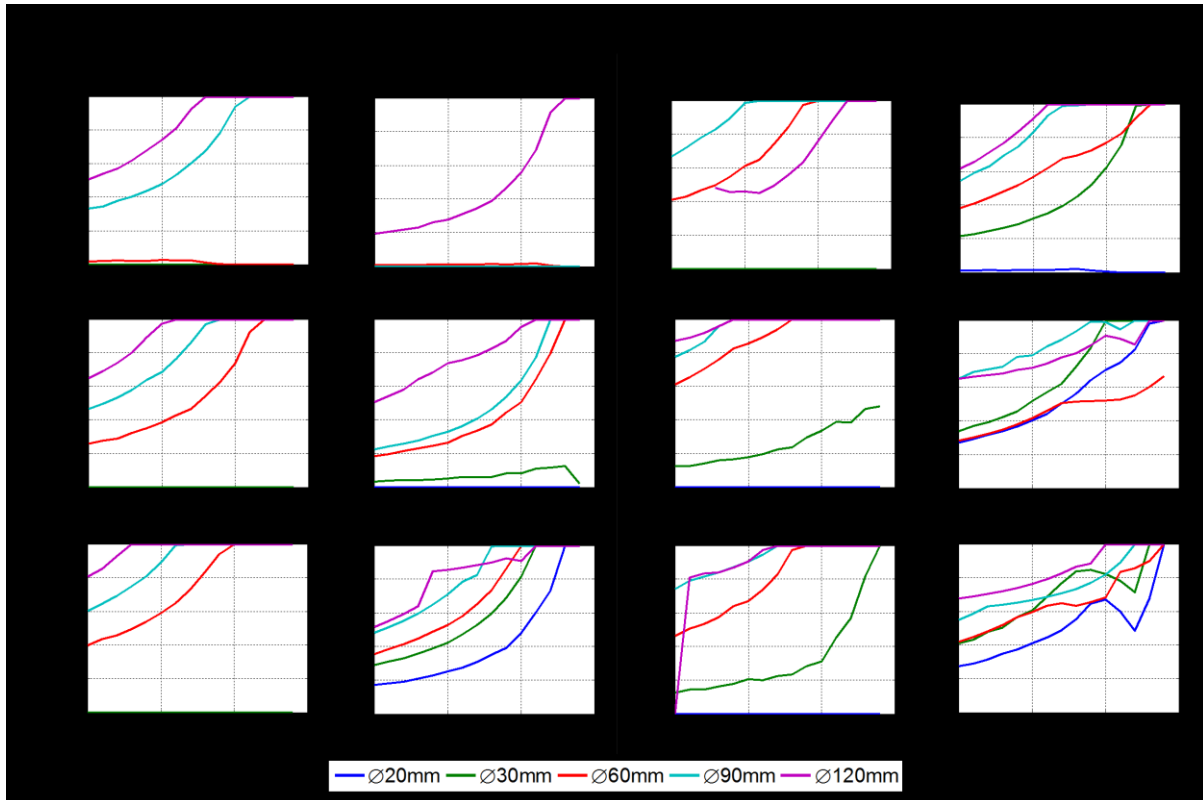


Figure 4.17. Twelve POD curves as a function of transducer array or scan pitch illustrating the sensitivity of the S0 and SH1 modes to changes in defect diameter, 20mm (blue), 30mm (green), 60mm (red), 90mm (light blue), and 120mm (purple), for defects of depths of 1, 2, and 5mm with an SNR of 30dB. The guided waves were propagated over 500mm in a plate with 10mm baseline thickness.

Figure 4.18 shows the relationship between the measurement pitch and the POD using the reflection measurement mode for 5mm deep defects with a range of defect diameters of Hann profile defects. The part thickness hole results are not shown for brevity but they are much more detectable than the Hann profile defects. Only a selection of defect diameters for each guided wave mode are shown, and if a certain diameter is not shown then it will have effectively zero POD across all pitches. In all cases as the pitch decreases (again note the pitch axes have been reversed) the POD increases, which is expected since we have already seen in Figure 4.12 that as the defect moves away from the central position the reflection amplitude reduces.

All three guided wave modes display the same effect, that as defect diameter increases the POD (across all pitches) increases and then decreases as the diameter continues to increase. In Figure 4.18a and c, the A0 and SH0 modes both have the largest POD values (across all pitches) at 20mm diameter, having risen from 10mm diameter before falling back with 30mm and 40mm diameters. The S0, however, shows an increased sensitivity over a wider range of defects (10mm to 80mm) with the POD values increasing from 10mm diameter which has a peak sensitivity of just over 0.2 POD at 10mm pitch, up to the 30-60mm diameter defects all of which have a detectability of at least 0.98 POD at 150mm pitch (shown in

detail in Figure 4.18d). Although these four defect diameters show a small amount of discrepancy between one another they are all comparable in terms of sensitivity. This effect of maximum detectability at a certain defect diameter is in marked contrast to the transmission measurement modality results in Figure 4.17, whereby the POD increases as defect size increases. This effect is explored further in the next section, however, only the Hann profile defect results will be considered.

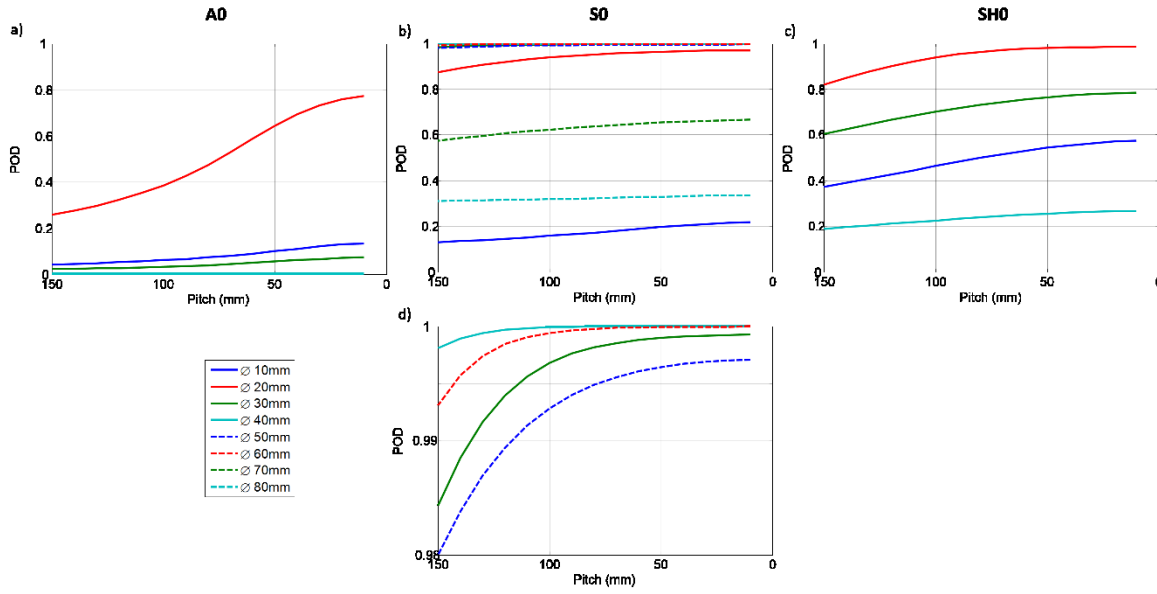


Figure 4.18. POD curves in reflection mode as a function of array or scan pitch for three guided wave modes with a noise level of 30dB SNR (a) A0, b) S0, c) SH0) for a range of Hann profile defects with diameters of 10 to 80mm and a fixed depth of 5mm. d) shows an exploded view of b) in the 0.98 to 1 range of PODs.

4.6.2 Probability of Detecting Hann Profile Defects using Guided Waves

The POD of a particular guided wave mode with a particular array or scan pitch can be displayed in an image format, as shown by way of an example in Figure 4.19a, where the POD has been plotted for all defects depths (1-5mm) and defect diameters between 10mm and 60mm, with a pitch of 50mm and a noise level of 30dB SNR. All probability images presented in section 4.6 have been interpolated since this allows for easier visual interpretation of the data. The example Figure 4.19b is a third order cubic recursive interpolation of Figure 4.19a. The sensitivity of a particular pitch and mode can therefore be assessed quickly by evaluating the ‘sensitivity coverage’ of the probability image. That is, what proportion of the defects modelled are detectable using the particular setup (SNR, measurement pitch, propagation distance).

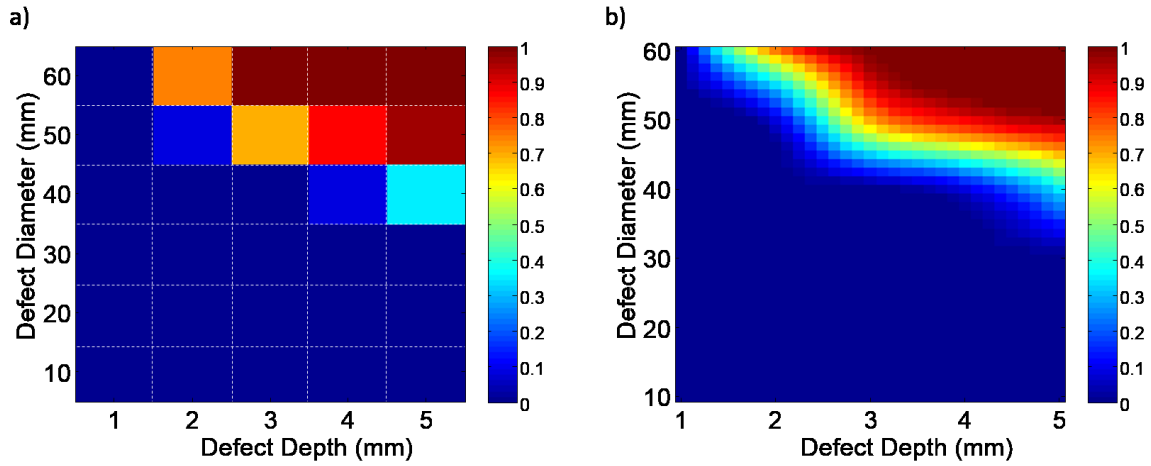


Figure 4.19. Example probability image used to display the POD results for a range of defect sizes. b) a recursively interpolation of a) by using a third order cubic interpolation. The example shown here shows the POD using S0 mode, via the average thickness method presented, for a range of defects with a pitch of 50mm.

The probability images for the transmission measurement mode are shown in Figure 4.20, for the S0 and SH1 guided wave modes with pitches of 10, 50 and 100mm. As the pitch increases the sensitivity of both guided wave modes decrease, because more guided wave beam paths, which either pass through the thinner sections of the defect or miss the defect entirely, are incorporated into the calculation of the POD.

When comparing the two guided wave modes it is clear that the SH1 mode has a much higher sensitivity coverage than the S0 mode for the range of defects shown. The S0 modes is unable to detect any defect below 40mm in diameter, whereas the SH1 can still detect defects under half that. At defect depths below 1-2mm, however, the SH1 mode is unable to detect any defect.

These results complement those in Figure 4.17 where the SH1 outperforms the S0 at narrower defect diameters (e.g. <60mm). Figure 4.20 also highlights the lower bound in sensitivity (in terms of defect diameter) for each guided wave mode.

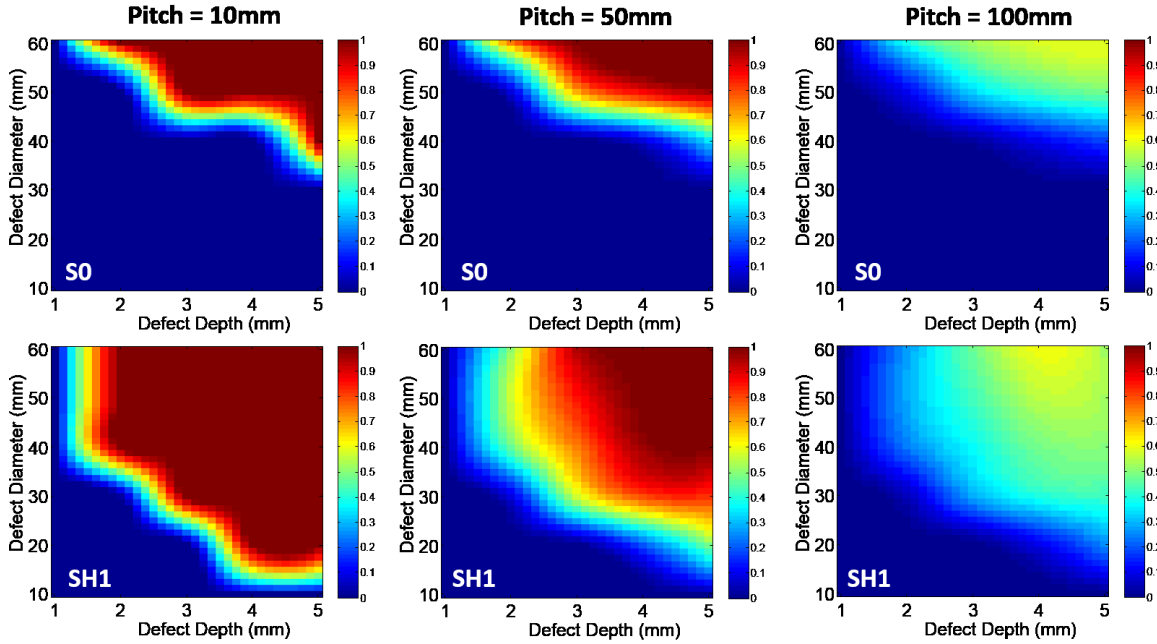


Figure 4.20. Probability of detection in transmission for the S0 mode (top row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of defect diameters (10-60mm) and depths (1-5mm)

Figure 4.21 shows the probability images using reflections to detect Hann profile defects, again with array or scan pitches of 10mm, 50mm, and 100mm. Across all guide wave modes, as the pitch increases there is little effect on the POD at all defect dimensions. This is due to the defects acting as point scatterers with the reflected wave radiating in all directions.

The S0 mode has the greatest sensitivity coverage to the defect dimensions simulated in this study. Using 0.95 POD as a threshold, the S0 mode can detect defects with a minimum depth of between 3 and 4mm and an associated diameter of 30mm as well as defects with a minimum diameter of 20mm and an associated depth of 5mm. The SH0 has less coverage; however, it does have a higher sensitivity to narrower defects, being able to detect 20x4mm Hann profile defects with 0.95 POD. The A0 is unable to detect many defects and the only defect it can detect with $POD > 0.5$ is the 20x5mm defect. It is therefore excluded from any further analysis. As expected, the probability images for the part thickness holes show a much higher sensitivity for all modes and are shown in Appendix 9.5.

The results also show in reflection that guided waves are sensitive to a finite range of defect diameters. Reflections of any waves occur when there is a change in acoustic properties in a material. With a Hann profile defect this effect is much more gradual than with either a step, notch or part thickness hole. For defects with large diameters the change in acoustic properties will be very gradual and as a consequence little energy will be reflected, thereby providing an upper bound to reflection sensitivity [88]. As the defect diameter shrinks the gradient in acoustic properties will become more pronounced (increasing the reflection

amplitude). At smaller diameters the defect size as a percentage of the beam width will become very small. At these defect diameters little energy will be incident on the defect, greatly reducing the amplitude of the reflected pulse.

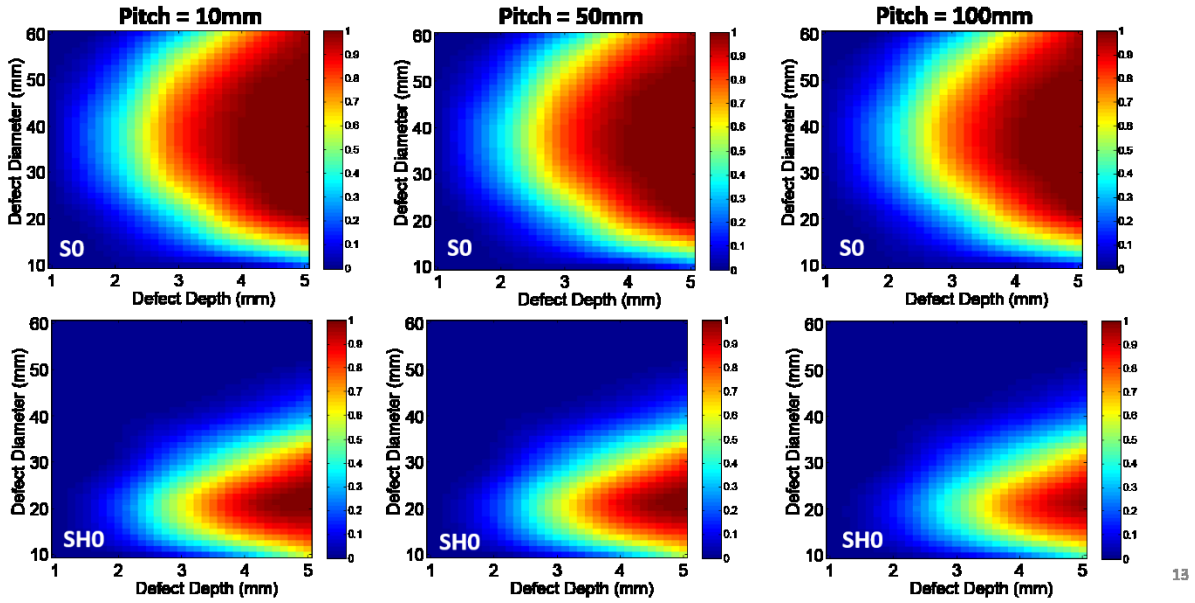


Figure 4.21. Probability of detection in reflection for the S0 mode (top row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of defect diameters (10-60mm) and depths (1-5mm)

4.6.2.1 Wavelength Normalised Probability Images

It is important to note that each of the reflection probability images for the two guided wave modes have a similar shape, with each having a peak in sensitivity at 0.5-0.6 wavelengths, λ_{refl} (This is the wavelength at the toneburst centre frequency using the reflection input toneburst operating characteristics, S0 - 60mm, SH0 - 36mm). The contoured plot of the probability image, Figure 4.22a, shows the equivalent of the S0 and SH0 10mm pitch colour probability images but highlights lines of constant probability (in this case 0.5 and 0.95 POD). The defect diameter is expressed in terms of the wavelength at the input toneburst's centre frequency. At depths of 5mm both modes are sensitive to $0.2\lambda_{\text{refl}}$ and $1-1.2\lambda_{\text{refl}}$ diameter defects at 0.5 POD. Figure 4.22a further demonstrates that guided waves in reflection are only sensitive to a range of finite width defects (e.g. patches of corrosion). In general, these defects (relative to wavelength) can be classed as narrow and deep defects.

Figure 4.22b shows contoured probability images for the through transmission detectability, with the defect diameter normalised to λ_{trans} (This is the wavelength at the toneburst centre frequency using the through transmission input toneburst operating characteristics, S0 - 25mm, SH1 - 13mm).

The through transmission contours of the S0 or SH1 modes are comparable in shape, with either 0.5 or 0.95 POD. At diameters greater than $1.5\lambda_{\text{trans}}$ with 5mm depth both modes are 95% sensitive (0.95 POD) to defects, whereas below that threshold there is no sensitivity. As the defect depth decreases the 0.5 and 0.95 POD contours for each mode correlated well to one another. Both modes have a 0.95 POD at defect depths around 2mm defects with $2.5\text{--}3\lambda_{\text{trans}}$ diameters. In combination with the findings of chapter 3, it is therefore possible to state that relative to wavelength, guided waves in transmission are suitable for detecting wide areas of wall thinning, either shallow or deep.

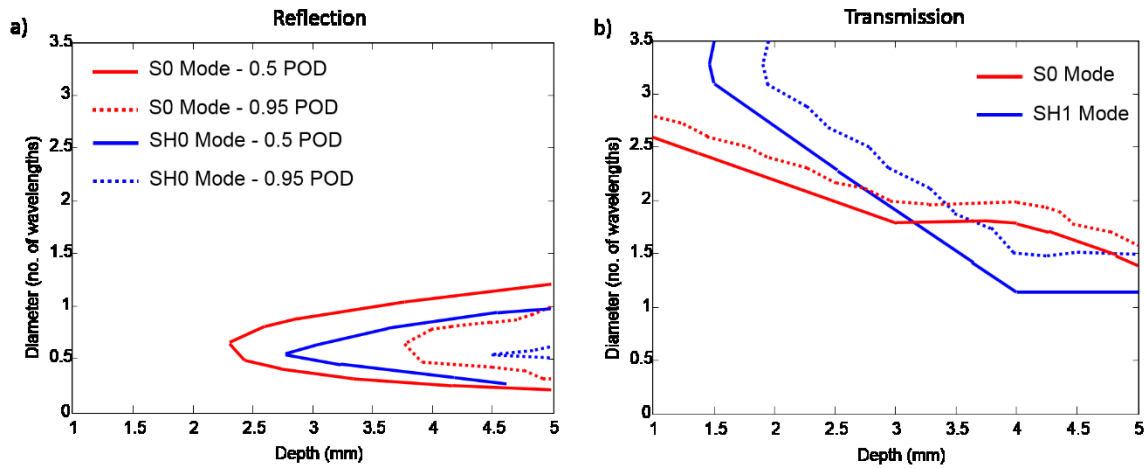


Figure 4.22. Contour plots of the POD as a function of defect depth and diameter showing both the S0 mode and the SH hybrid for both measurement methods (a - reflection, b - transmission), with the defect diameter normalised to the wavelength of the centre frequency of the input toneburst. Contours are for 0.5 and 0.95 POD, the pitch is 10mm and SNR is 30dB.

4.6.2.2 Design Implications and Discussion on the Limitations of Short Range Guided Waves
Figure 4.22 highlights the similarities in the sensitivity of the S0 and SH0/1 modes using either measurement method when the defect diameter is normalised for wavelength. It also shows the limits of sensitivity of both measurement methods as a function of wavelength.

Although the results in Figure 4.22 suggest that one could optimise the setup by changing the wavelength to increase the sensitivity to a given defect, it is not that straight forward. That is because at different frequencies guided waves have different characteristics (especially dispersiveness and attenuation due to fluid loading) which will dramatically reduce the sensitivity for either measurement method.

A rigorous approach in section 4.3.3 was taken to choose the most suitable operating characteristics and consequently it is believed that the results presented here are close to the maximum sensitivity potential of short range guided waves, with a 6-8'' pipe and 30dB SNR.

Figure 4.22 shows that through transmission detects wide, shallow defects, whereas reflection is better suited to detecting narrow deep defects. Even at a pitch of 10mm neither method can detect narrow ($<2\lambda_{\text{trans}}$) and shallow defects ($<2\text{mm}$). By combining the results of the two measurement methods for either mode the maximum theoretical sensitivity of both modes can be found. This is based on the assumption that it is possible to build a transducer able to generate both the input operating parameters optimised for either measurement method.

4.6.3 Increasing Sensitivity through the Data Fusion of Probability Images

There are many possible ways to combine multiple data sets [123]-[125]. In this case the transmission (Figure 4.20) and reflection (Figure 4.21) probability image data sets were fused using a simple OR-logic gate method which takes the larger value of the commensurate data points from the two probability image data sets. The SH0 reflection data is combined with the SH1 through transmission data, forming a hybrid SH mode.

Figure 4.23 shows the data fused probability images for Hann profile defects with scan pitches of 10, 50, and 100mm with the S0 and SH hybrid modes. The A0 mode is not shown since in both reflection and through transmission its sensitivity to Hann profile defects is much less than the S0 and SH modes.

At 10mm pitch the SH hybrid has a higher sensitivity coverage than the S0, due to the high sensitivity of the dispersive SH1 mode to thickness changes. This pitch is more representative of a rapid screening or inspection tools, such as in Figure 4.1c, since only a single transducer would be required and could slowly scan a pipe axially. At larger pitches of 50 and 100mm then sensitivity of the SH hybrid reduces significantly, and although the S0 does likewise, the greater coverage of the S0 in reflection compensates for this loss. A monitoring setup would take advantage of these larger pitches, such as in Figure 4.1b, because fewer sensors would be required, thereby reducing the cost and complexity of the overall system.

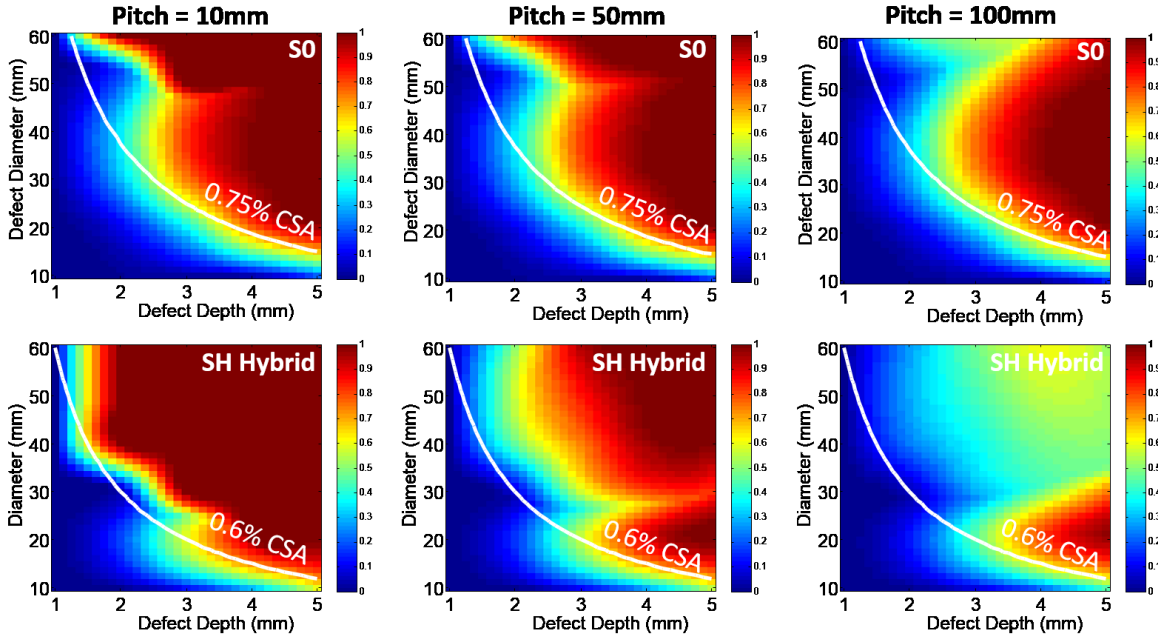


Figure 4.23. Data fused probability images for Hann profile defects using the S0 mode or hybrid of SH0 and SH1 modes for 10, 50 and 100mm pitches at 30dB SNR over a propagation distance of 500mm in a 10mm thick plate. Lines of constant cross sectional area (CSA) are overlaid.

4.6.3.1 Comparison of Data Fusion Results with Long Range Guided Waves

By way of comparison between short and long range guided waves (LRGWs) it is possible to convert the defect into a value of cross sectional area (CSA). When viewing a cross section of the pipe through the deepest part of the defect, the CSA is defined as the area removed by the defect as a percentage of the entire cross section of the pipe. LRGWs are an established screening technique whose physical implementation is tried and tested in the field. The LRGW setup also has the benefit of 100% coverage.

In Figure 4.23 two contours which approximately bound the maximum sensitivity coverage of either modes are overlaid onto the data fused probability images (S0 - 0.75% CSA, SH - 0.6% CSA).

Long range guided wave techniques had a quoted sensitivity in 2001 of 5% CSA [27], however, recent strides have lowered this value to as low as 0.5-1% [30] when monitoring an area for an extended period of time. The measurement methods presented in this study are relatively simple compared with the more advanced methods studied with LRGWs, therefore it is reasonable to assume that appreciable gains could be made by employing more advanced signal processing.

In section 4.1 several assumptions had to be made about the short range guided wave setups, shown in Figure 4.1, regarding the operation of the transducers. Depending on the physical implementation of the setups this could potentially reduce the sensitivity of the system. If

overcome, however, in specialist/select scenarios then the setups and techniques presented may provide a new and commercially viable way of monitoring or screening of pipeline corrosion.

4.7 Conclusion

The suitability and sensitivity of three circumferential guided wave modes for detecting wall thinning defects has been studied. The guided wave modes were evaluated using two measurement modalities: 1. using the reflected signal; and 2. using the through transmitted signal. The A0 mode was excluded early in the study as it had a much lower sensitivity compared with the other two modes.

The selected input characteristics were chosen for each guided wave mode to boost sensitivity in either transmission or reflection. Results for the SH1 mode showed that it was sensitive to a much greater range of defects than the S0 mode in transmission, whereas in reflection the S0 mode was able to detect a greater range of defects compared to the SH0 mode.

Once the defect diameter was normalised to wavelength the sensitivity coverage was effectively independent of the guided wave mode. It was shown that in reflection the guided wave modes are more sensitive to narrow and deep defects but over a finite range of diameters. This contrasts with the transmission results where guided waves are sensitive to wider defects (either shallow or deep) and only have a lower bound of sensitivity. Neither measurement modality could detect narrow and shallow defects using the setup described in this chapter: propagation distance, 500mm; nominal wall thickness, 10mm; and SNR, 30dB.

The guided wave operating frequency/wavelength is constrained by physical factors (such as dispersion, higher order mode cut-offs and fluid loading attenuation), which restricts the ability to frequency sweep and thereby design a system to be optimally sensitive to certain defect dimensions. The data fused SH hybrid results show a higher sensitivity to a wider range of defects at 10mm pitches compared to the data fused S0 mode results, whereas the S0 mode has a higher sensitivity at pitches of 50mm and 100mm. At 10mm pitch the sensitivity of the data fused short range guided waves have a limit of 0.6% CSA and 0.75% CSA for the SH hybrid and S0 mode respectively. This is comparable with long range guided waves, which have a quoted sensitivity in monitoring mode of 0.5-1% CSA. The results shown in this chapter will aid the future design of a short range guided wave system, detailing the

defects to which the guided waves are most sensitive as well as highlighting some of the design implications which must be considered.

Chapter 5

Quantification of the Coverage Area of Bulk Wave Spot Measurements for the Detection of Pitting due to Corrosion

5.1 Introduction

The previous two chapters focussed on evaluating the ability of guided waves to detect wall thinning due to corrosion. It has been demonstrated that although guided waves are able to detect wide areas of wall thinning they are unable to pick up small pits, which are typically less than one quarter of the wavelength of the pulse's centre frequency. Using the parameters described in chapter 4⁵ guided waves were unable to detect realistic Hann profile defects with a 10mm diameter of any depth or 20mm diameter defects with depths less than 2mm.

At these small dimensions corrosion is usually known as pitting. It is generally accepted [40], [126]-[128] that pitting occurs because of a chemical or physical heterogeneity on the surface of the metal (e.g. a breakdown of the passive/oxide layer, mechanical damage, or inclusion). This results in accelerated corrosion of the underlying metal at the location of the heterogeneity.

To detect pits of this order of magnitude a bulk wave setup is required in the form of spot ultrasonic measurements. As figure 1.5 shows there is a trade-off between coverage and sensitivity and spot measurements sit at one extreme, providing highly localised but sensitive measurements. However, the question remains: how sensitive and localised are spot measurements? This analysis will enable a comparison with guided waves.

This brief chapter introduces spot measurements as well as modelling and quantifying the coverage area and sensitivity of spot measurements to pit defects, before discussing and drawing conclusions from the results.

⁵ Propagation distance - 500mm, plate thickness - 10mm, SNR 30dB

5.1.1 Introduction to the use of spot measurements for the detection of corrosion

Spot measurements are most often used to detect, inspect, and monitor for corrosion by wall thickness gauging or amplitude analysis [129]. These analysis methods can be carried out in either A, B, or C-scans forms. A schematic of each method and how the data is displayed is shown in Figure 5.1a, b, and c. Wall thickness gauging involves transmitting an ultrasonic pulse into the sample and measuring the time difference between the sent and received pulses. The time of flight (TOF - Figure 5.1aii) between the two pulses multiplied by the sound speed of the material under test estimates the distance travelled by the pulse. Half that distance estimates the thickness of the sample. As the pipe wall thins the remnant thickness can be tracked. Amplitude analysis is carried out either by windowing/gating (Figure 5.1aiii) the first backwall reflection time trace and analysing the maximum amplitude within the window or viewing all the time traces side by side in a B-scan waterfall/colour map plot (Figure 5.1biii). As the amount of reflected energy changes, due to scattering or attenuation from the corroded back wall surface, the amplitude will change indicating the presence of damage or a defect. B-scans and C-scans are usually carried out by equipment that logs the transducer's position; whereas, A-scans are generally carried out by manual inspection or a permanently installed sensor at a fixed location.

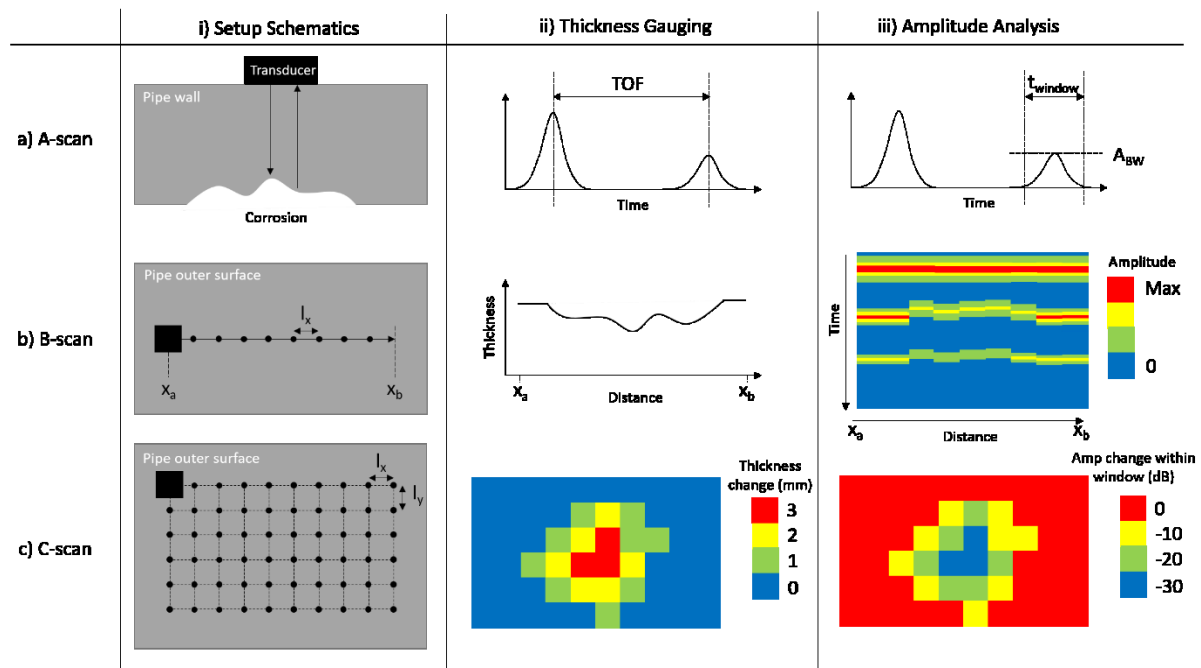


Figure 5.1. Schematics of spot measurement data collection (i) and display conventions (ii, and iii) for A-scan (top row), B-scan (middle row) and C-scan (bottom row) methods.

5.2 Quantitative Estimation of Area Coverage of Spot Measurements

In chapter 4 the coverage of the guided wave setups (either in monitoring mode or scanning mode) was defined via the measurement pitch. In the case of spot measurements, the monitoring array (Figure 5.2a) or C-scan (scanning mode, Figure 5.2b) also has a measurement pitch, which governs the area of the unit cell, i.e. the area around each transducer which is closest to it. If the distribution of transducers or measurements is a square array then the width of the unit cell will equal the pitch. Using a simplified model of probability of detection, the relationship between POD, defect width, and unit cell area/pitch can be estimated.

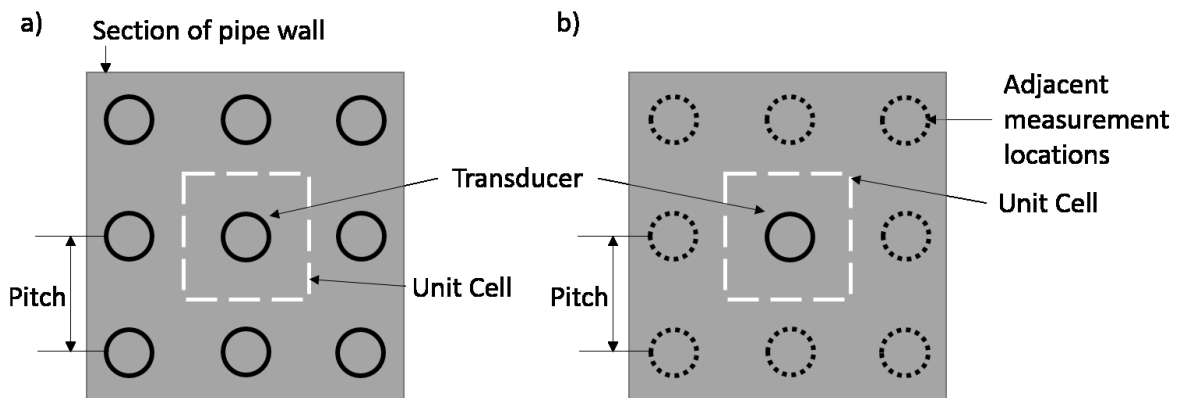


Figure 5.2. Schematics of a) a monitoring setup using bulk wave transducer array, b) a scan using bulk wave transducers. The unit cell of the central transducer is indicated.

5.2.1 Spot Measurement Coverage Model Using Area Approximation Method

The approach taken approximates the POD as a ratio between the area of a unit cell and a 'detectable area', which is a theoretical area under the transducer. It is assumed that if a defect were to be positioned in the 'detectable area' then the transducer would detect it.

The model assumes the spot measurement sensor is perfect i.e. that if any part of a defect of any depth is located directly under the sensor then the sensor can detect it. The defect is assumed to be uniformly distributed within the unit cell, i.e. it has equal probability of being located anywhere within the unit cell.

Figure 5.3a shows the unit cell with a circular defect located at either position A or B. At position A the defect is not located under the transducer and therefore has not been detected. At position B the defect is located under the transducer and has been detected. Figure 5.3a illustrates the parameters used in the model: D_T , the transducer diameter; w_{UC} , the unit cell's width; and D_D , the defect diameter. Figure 5.3b shows the area beneath the sensor where the defect can be detected (with diameter $D_T + D_D$, i.e. the 'detectable area').

The estimated POD is then simply a ratio between the area whereby the defect can be detected and the area where the defect can exist (i.e. the unit cell):

$$POD = \frac{\frac{\pi}{4}(D_T + D_D)^2}{w_{UC}^2} \quad (5.1)$$

For the results presented in this chapter the transducer diameter, D_T , is fixed to 10mm. The notion of transducer diameter is taken to mean the diameter of the active aperture, which generates ultrasound in a sample. For most piezo-electric transducers the diameter of the transducer housing is similar to the active area/aperture. However, other transducer types, such as EMATs can have active apertures significantly smaller than the diameter of the housing.

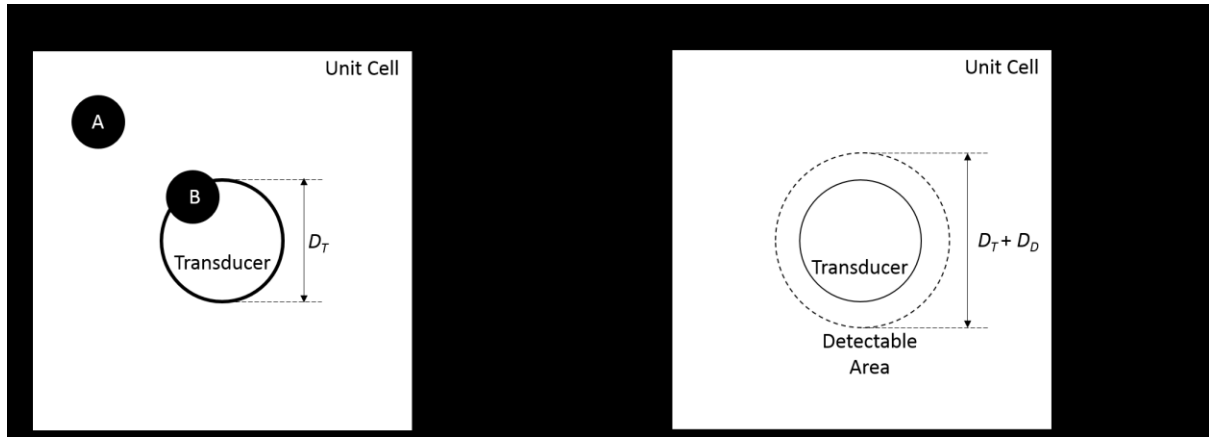


Figure 5.3 Schematic of the a) parameters and setup used in the spot measurement coverage model with an example undetectable (A) and detectable defect (B) defect, b) method used to calculate coverage using the area method described in equation 5.1

5.2.2 Approximate Spot Measurement Coverage

Figure 5.4a shows a probability image showing the POD as a function of unit cell width and defect diameter. The transducer width has been fixed at 10mm. Figure 5.4b is the equivalent contour plot with lines of constant POD at 0.1-1 POD in 0.1 steps. From these plots the effective coverage of spot measurements can now be quantified.

As would be expected when the unit cell is smaller than the defect size the defect is always detectable (POD of 1). Therefore, to always detect a 10mm defect using a 10mm transducer a unit cell of 10mm is required, which is the equivalent of completely covering a pipe with spot transducers (i.e. 100% transducer coverage of the pipe surface). At a unit cell width of 20mm (25% transducer coverage of the pipe surface) the detectability of a 10mm diameter defects is 0.78 POD. A 20mm diameter defect is 100% detectable up to a unit cell width of 26.5mm, this quickly falls to 0.5 POD at a unit cell width of 37mm. The drop off in POD at

all defect widths is severe and beyond a unit cell width of 40mm the POD is less than 0.4 for all defect widths shown in Figure 5.4.

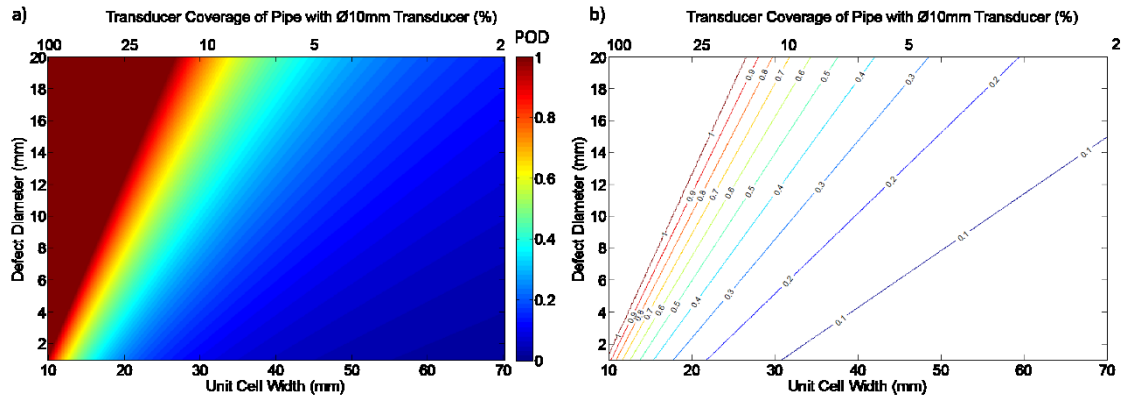


Figure 5.4. a) Probability image of the POD for a 10mm wide transducer using the area approximation method (equation 5.1) b) contour plot of the probability image in a) with lines of constant 0.1-1 POD.

5.2.3 Discussion and Implications for Spot Measurement Uses

The results in Figure 5.4 demonstrate that to achieve a high probability of detection using near perfect spot transducers a high density of measurements or transducers is required. This complements the work conducted by Cawley et al. [35] on the relationship between spot (point) measurements and area measurements. Cawley et al. conclude that the main factor governing the spot measurement POD is pit location and/or distribution and not transducer sensitivity.

For a monitoring array to detect a 20mm wide defect with only 0.5 POD requires a 10mm wide transducer every 37mm, which would require 7 transducers to monitor a 100x100mm² area. This number of transducers increases the physical requirements of the system, in terms of battery power and multiplexing between transducers compared to currently available permanently installed transducers. The implementation of a permanently installed monitoring array system may be feasible using low power electronics and careful design, however, the gains in detection sensitivity are not significant compared to guided waves. For example, to detect a 20x3mm pit with 0.5 POD would require a guided wave transducer array with a transducer every 50mm (20 per m) arranged axially along the pipe (see Figure 4.1); whereas a spot measurement array would require 700 transducers per m² to have the equivalent POD.

It must be emphasised that all the results presented here assume that the transducers can detect all defects regardless of depth and surface profile, so long as they are positioned

under the transducer. This is obviously an overestimate of an individual spot transducer's detection capabilities and therefore all PODs are overestimates as well.

In scanning mode, it is possible to have measurement pitches below the transducer width and subsequently much higher PODs are possible. Commercial scanners have a quoted measurement pitch of the order of 0.5mm [130], which under the parameters of the simple model presented here would have 100% detectability.

5.3 Summary and Possible Use of Spot Measurements as Pit Monitoring Solution

This chapter contained a brief investigation to quantify the coverage of bulk wave sensors to detecting defects with widths less than 20mm. This was achieved using a simple analytical area based model using an idealised transducer. It has been shown that an array of permanently installed bulk wave transducers are unsuitable for detecting pits.

It is possible, however, that spot measurements will be able to monitor sub-critical defects if the location of the defect is already known. That is, if a defect was identified during a C-scan a sensor could be placed over the defect, thereby monitoring and tracking its progress until it becomes critical. Then the pipe section could be removed and replaced and the sensor reused at another location. This technique is considered in chapter 7.

However, before investigating this idea further and designing any new NDE technique, a greater understanding of the interaction between bulk waves and pits is required. In the model above it was assumed that the spot transducer could detect any defect of any depth if it was directly under the transducer. However, this is unlikely to be the case and therefore the interaction between bulk waves and pitting due to corrosion needs to be understood further. As will be elaborated upon in the next chapter there is a dearth of literature on this subject.

Chapter 6

Phenomenological Study of the Interaction between Bulk Waves and Pitting Corrosion

6.1 Introduction

The previous chapter showed that bulk waves are unsuitable for monitoring large areas of a pipe's surface for the purposes of detecting isolated pits, since a high density of sensors would be required. This was even the case whilst assuming that the transducer was 'perfect', i.e. that it could detect any defect so long as any part of the defect was directly under the transducer.

It was suggested, however, that spot measurements could be used to monitor individual sub-critical pits, which have already been detected by other means (such as a c-scan). Before this analysis can take place a greater understanding of the interaction of bulk waves with pits must be gained. As is discussed in section 6.1.1 there is a paucity of literature on this subject and although inferences can be drawn as to the possible behaviour of bulk waves when reflecting off pits, an in-depth phenomenological study was conducted to gain greater knowledge and understanding.

The analysis will focus on evaluating several transducer setups, with a particular focus on 0-degree shear wave transducers. Further analysis on the potential design, implementation and operation of an individual pit monitoring system will be discussed at the start of chapter 7. Even though the outcomes of this chapter have been designed with a single pit monitoring system in mind, the results of the current chapter will still be applicable to a wide range of bulk wave NDE techniques. For example, it will aid in the understanding of how pitting under transducers can influence and distort the desired measurements of wall thickness monitoring [8] or c-scanning techniques [130].

This chapter will first review the literature on spot measurements of pits, and introduce the transducer setups that were evaluated. A description of the finite element models used to simulate the interaction between bulk waves and pitting is then given, followed by the details of the signal processing methods. Simulation and experimental validation results are then presented, before conclusions are drawn.

6.1.1 Review of Literature on Bulk Wave Reflections from Non-Planar Surfaces

The first recognisable ultrasonic bulk wave NDE method was the ‘Supersonic Reflectoscope’ developed by Firestone in 1946 [131]. A quartz crystal, placed on the surface of a sample, was excited with a high frequency voltage inducing ultrasonic pulses in the sample. The pulses reflected off any boundaries or flaws within the sample, with the received signal displayed on an oscilloscope. The fundamental operation of ultrasonic bulk waves has changed little since, and although the data acquisition methods and equipment have been continually updated most bulk wave NDE methods still rely on piezo-electric materials to excite a longitudinal ultrasonic pulse (known as piezo electric transducers, PZTs). Recent developments in electromagnetic acoustic transducers (EMATs) technology has enable their use in a wider range of bulk wave inspection and monitoring techniques. EMATs are more convenient to excite shear waves compared to PZTs, which require a fluid couplant and therefore are mainly limited to longitudinal waves when 0-degree inspection is required.

The study of longitudinal and shear bulk wave scattering and reflection from a multitude of features (cracks, voids, inclusions etc.) is one of the most prevalent topics within NDE research; and although there is a general understanding that pitting is an issue for ultrasonic sensors [35], [132] there has been little research conducted to explore this further. The research which has been done analytically explores the interaction between longitudinal waves and hemispherical pits [133], [134]. The research which does exist mainly concentrates on flat bottomed holes (FBHs); however, corrosion is highly unlikely to manifest as a FBH and existing research suggests that a hemispherical pit (and distortions thereof) is a much more accurate representation of corrosion [40], [126], [135], [136].

Jarvis et al. [3], [137] studied the effect of a conical pits and flat-bottomed holes on shear waves. The experimental study of conical pits, which were laser micromachined into a 9.88mm mild steel plate, showed that 500µm deep pits had very little effect on the signal from existing spot thickness sensors. The FBH study using larger defects (3mm in diameter and depths from 0.1-3mm) showed that reflections occur from the back-wall as well as from the top surface of the defect. Constructive and destructive interference between the backwall and pit reflections were also observed. Figure 6.1 and Figure 6.2 explain these findings in more detail. Figure 6.1 categorises four scenarios with pits of varying size and depth:

Case 1: A bulk wave reflects off a flat backwall surface. In this case a simple time of flight method (TOF) can be used to estimate the wall thickness.

Case 2: If the defect is much smaller than the beam width then back wall reflection dominates the received signal since only a small percentage of the pulse's energy is incident on the FBH. However, as Figure 6.2a shows the pit can still distort the pulse width and amplitude due to constructive and destructive interference effects between the backwall and pit reflections.

Case 3: As the FBH increases in depth the pulse reflected from the top surface of the FBH becomes temporally separated from the backwall pulse, as shown in Figure 6.2b.

Case 4: As the FBH's diameter widens a greater percentage of the pulses energy will be reflected by the top surface of the FBH. When the diameter exceeds the beam width then all the pulse's energy will be reflected by the FBH and conventional TOF can be used to track the thickness.

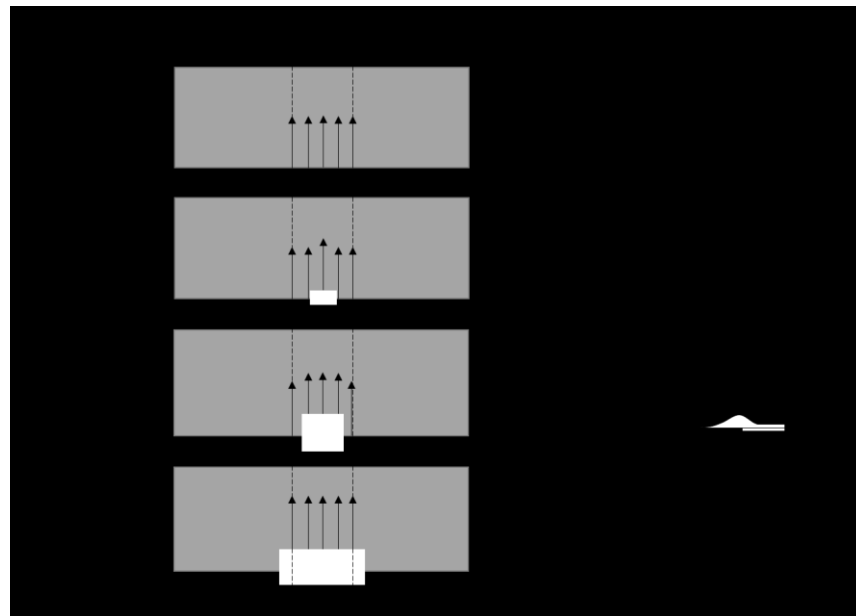


Figure 6.1. Schematic of bulk wave interactions with different flat-bottom hole defects inferred from the existing literature and illustrations of the associated signal envelopes

Figure 6.2 is a reproduction of some signals acquired by Jarvis et al. [137] using a high temperature waveguide placed above two 3.2mm diameter FBHs, with depths of 0.4mm (a) and 3.2mm (b). The plate was 10mm thick. It is clear that the shallow hole (a) significantly reduces the backwall amplitude with no pit signal present (case 2). Whereas the deeper hole (b) has a reduced backwall amplitude with a clear pit reflection present (case 3). This shows that defect depth has an important effect on the detected response.

If the simplified explanation of bulk wave-FBH behaviour (shown in Figure 6.1, case 3) was applicable to all defect shapes then the ratio between the pit amplitude and the backwall amplitude would be approximately equal to the ratio between the transducer and pit area.

However, this completely ignores other factors such as beam characteristics (i.e. beam spread and shape, as well as mode conversion and scattering at the defect). Furthermore, the use of different transducers will mean that there are many different beam characteristics which need to be taken into account. Pit shape will also heavily influence the pit reflection amplitudes. This is analogous to the studies on the reflections from plates with rough backwall morphologies [16], [17], [41], [138], whereby the reflected signal is heavily attenuated by non-planar surfaces.

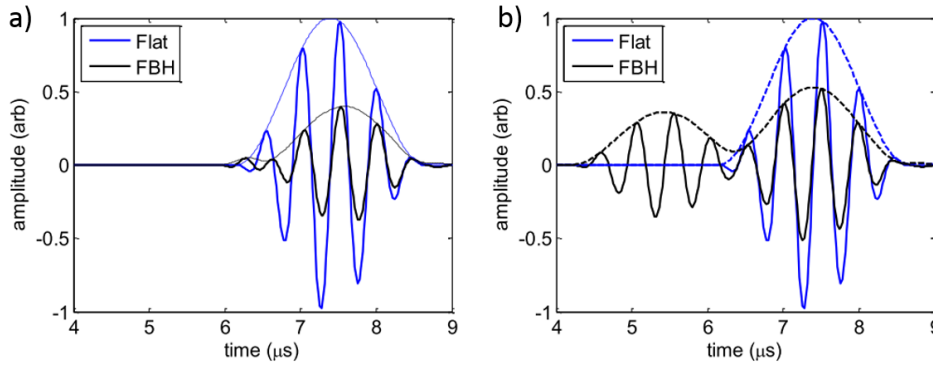


Figure 6.2 Reproduction of part (c) and (d) in figure 6.1 from [3]: Comparison of simulated backwall reflection signals when the inner surface is flat and has a FBH located directly beneath the wall thickness sensor with a diameter of 3.2mm (2λ) and a depth of (a) 0.4mm ($\lambda/4$) and (b) 3.2mm (2λ). Dashed lines represent the Hilbert envelopes of the associated signals.

6.2 Configuration and Validation of the 3D Finite Element Models

The base finite element model used to simulate the interaction between bulk waves and pitting is shown in Figure 6.3a. The model is a structured mesh whose dimensions are 36mm x 36mm x 10mm (Xmm x Ymm x Zmm). The element size is 0.1mm. A 6mm thick ALID boundary was placed around the sides of the model. The meshing was performed by a custom C++ code and the model was solved explicitly use the POGO GPU solver [139].

Various transducers can be modelled by placing different distributions of excitation nodes on the top surface of the model. The two input tonebursts used in this study can be seen in Figure 6.3bi and ci, 3 cycle Hann window tonebursts with 2MHz and 5MHz centre frequency respectively. Both these tonebursts can be filtered to 5 cycle tonebursts for comparison with experimental results. This base model was manipulated as required, the methods of which are covered in the relevant sections (6.4 and 6.5). The 2MHz shear wave and the longitudinal 5MHz validations are detailed in 6.2.2 and in appendix 9.8 respectively.

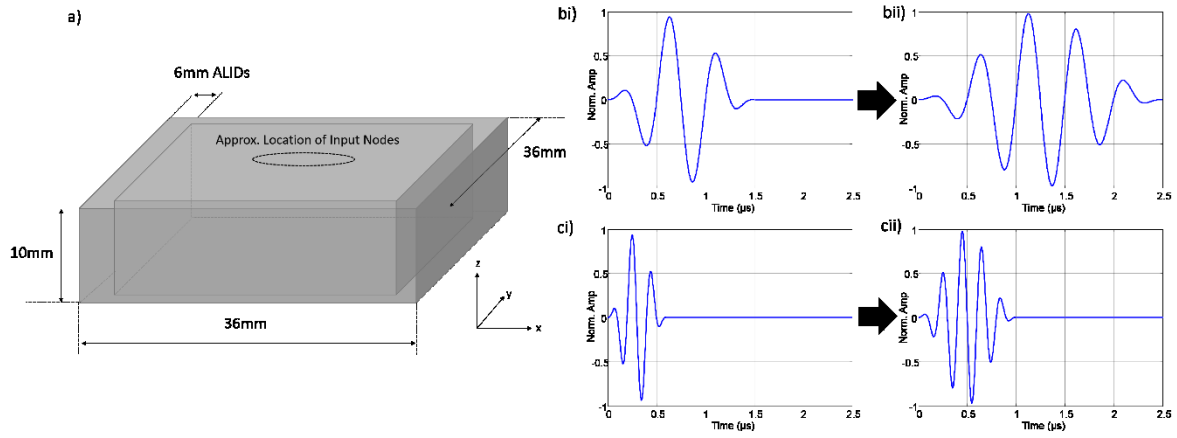


Figure 6.3 a) The base $36 \times 36 \times 10 \text{ mm}^3$ FE model to which different defects or geometries can be added and different nodal inputs to model different transducer types. b) 2MHz centre frequency Hann windowed toneburst: 3 cycles (i) and 5 cycles (ii). c) 5MHz centre frequency Hann windowed toneburst: 3cycle (i) and 5 cycle (ii)

6.2.1 Overview of the Bulk Wave Transducer Setups Studied

Three transducer setups have been evaluated in this chapter: high temperature wall thickness sensor, shear electromagnetic acoustic transducers, and pitch catch compressional PZTs.

6.2.1.1 High Temperature Wall Thickness Monitoring Sensor

The geometry of the high temperature wall thickness sensors is shown in Figure 6.4, whereby two stainless steel waveguides operate in pitch-catch mode sending a pulse down one waveguide (Tx) and receiving the surface wave signal and backwall reflection signal via the other (Rx) [140]. The transduction elements and electronics are situated at the top of the waveguides enabling use at high temperatures. Permanently installed waveguides have been used for many years as wall thickness monitoring devices, using a modified time of flight method (TOF) utilising the surface wave (Figure 6.4b and c) travelling between the Tx and Rx waveguides to extract a value of remnant thickness. This is explained in depth in section 6.3.2.

The Tx and Rx nodes were $12 \text{ mm} \times 1 \text{ mm}$ (Figure 6.4d) representing the area of contact of the waveguides with the pipe surface. There was a 1mm separation distance between the waveguides. The input pulse was a 3 cycle Hann windowed toneburst with a 2MHz centre frequency (wavelength 1.6mm) which was excited in the y direction (principle shear direction, S1). The first backwall reflection amplitude field (in the same direction as the shearing vector, S1) is shown in Figure 6.4e. This plots the maximum amplitude of the first backwall reflection at each point on a clean backwall (in a 10mm thick plate). The method to derive this image is described in the appendix 9.7. The highest amplitude occurs directly under the Tx input nodes at approximately $y = \pm 2.5 \text{ mm}$ and not at $y = 0 \text{ mm}$. The field is also

much wider in the x direction, this effect is explained in Figure 6.4f which shows the displacement field $2\mu\text{s}$ after excitation (produced in ABAQUS) of the $y=0$ plane. In this orientation the beam has a circular wavefront like that generated by a point source which propagates over a wide area. In the $x=0$ plane (Figure 6.4g) the beam is much more collimated and has linear wave fronts of 12mm width, therefore limiting the beam spread in the y direction.

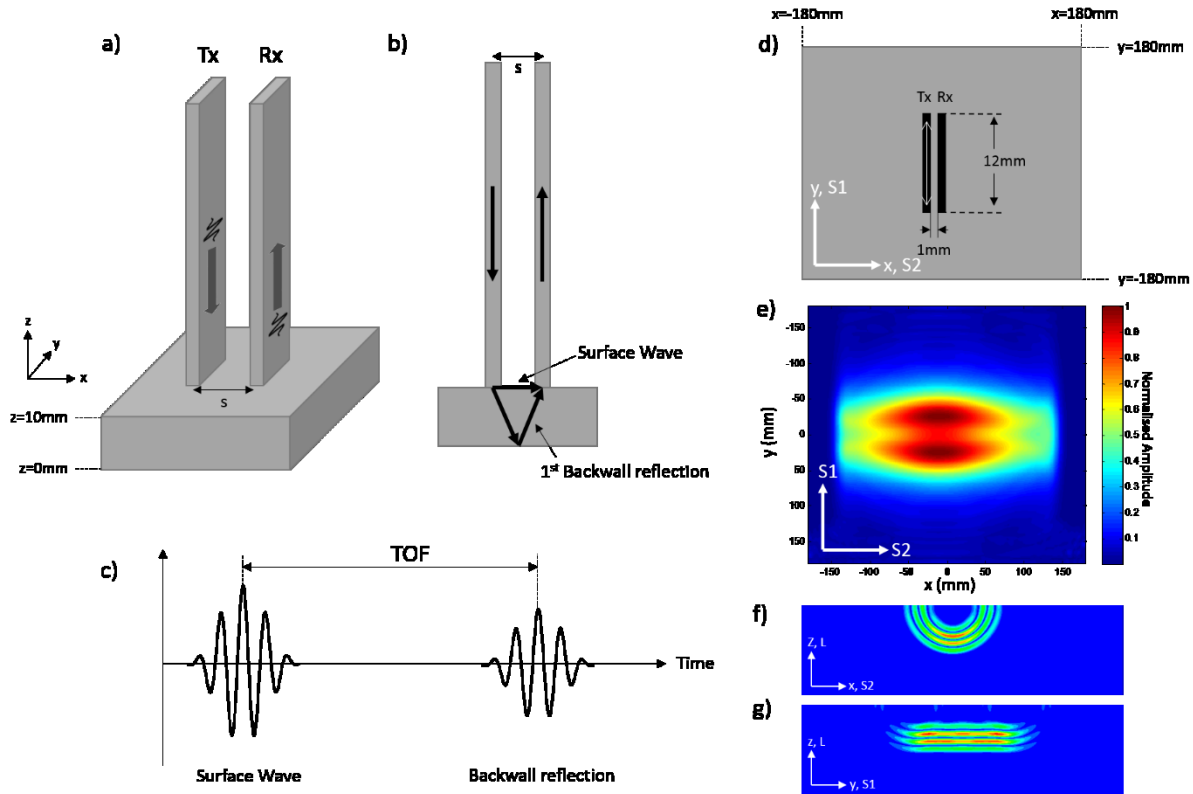


Figure 6.4. a) Geometry of the high temperature waveguide sensor, b) paths taken by the surface wave and the 1st backwall reflection, and c) a typical time trace d) Node configurations of a waveguide with a 12mmx1mm transmitting (Tx) and receiving (Rx) sets, e) magnitude of the enveloped first backwall amplitude field, and the pulse's displacement field at 2×10^{-6} s in the $y=0$ plane (f) and $x=0$ plane (g). e-g were obtained with a 3 cycle Hann windowed toneburst at 2MHz centre frequency.

6.2.1.2 Shear Electromagnetic Acoustic Transducers

In the past EMATs were not available as permanently installed wall thickness monitoring devices, this has now changed. Therefore, there is a need to understand their capabilities and limitations. The main advantage of using an EMAT over a waveguide is that they are non-contact, therefore no couplant is required. This also allows them to be easily moved/reused. The mechanism by which EMATs induce ultrasound in a metal is explained in chapter 3. Unlike the guided wave EMATs which were modelled as a single line of nodes, a bulk wave EMAT will induce ultrasound over an area (i.e. aperture), this area has initially been assumed to be the same size as the footprint of the magnet (10mmx10mm - Figure 6.5c). Section 6.2.2 will test whether this aperture is an accurate representation of real

EMATs that were used in experiments. A 3 cycle Hann windowed toneburst at 2MHz centre frequency (wavelength 1.6mm) was excited in the y direction (principle shear direction, S1).

The bulk wave EMAT setup is shown in Figure 6.5a and b. Figure 6.5b shows a plan view of the inside of the EMAT, which uses a coil and magnet arrangement [141]. The resulting shearing direction is perpendicular to the direction of the coils under the magnet. The wall thickness can be estimated using a simple time of flight method (section 6.3.2).

The first backwall reflection amplitude field of an EMAT with a 10x10mm aperture is shown in Figure 6.5d, with peak amplitudes occurring under the corners of the EMAT and not in the centre of the EMAT. This is due to the backwall being so close to the transducer than only the near field is being measured. The $y=0$ and $x=0$ plane displacement field at $2\mu\text{s}$ (Figure 6.5e and f) shows that the beam is relatively collimated. The edge effects of the EMAT are much more apparent in the $y=0$ plane this is because the shearing direction is in the y-direction.

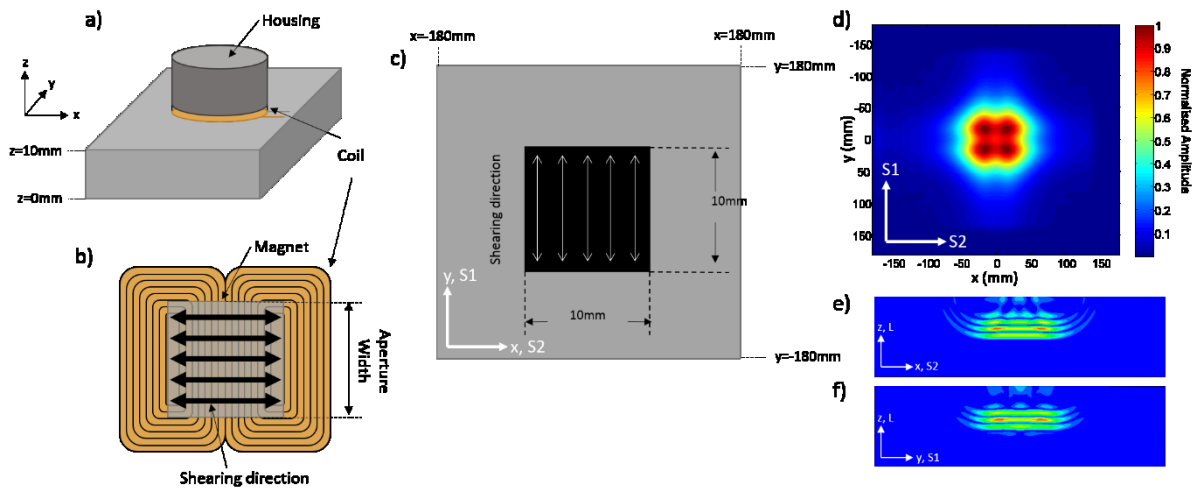


Figure 6.5 a) Illustration of an EMAT, b) illustration of a butterfly coil and magnet inside an EMAT, c) a typical EMAT time trace, d) node configurations of an EMAT with a 10mmx10mm aperture, e) magnitude of the enveloped first backwall amplitude field, and the magnitude of the pulse's displacement field at $2 \times 10^{-6}\text{s}$ in the $y=0$ plane (e) and $x=0$ plane (f). d-f were obtained with a 3 cycle Hann windowed toneburst at 2MHz centre frequency.

6.2.1.3 Semi-Circular Compressional Piezo-electric Transducers

The final transducer setup evaluated is a pitch-catch piezo-electric transducer (PZT), which is a compressional transducer, exciting a longitudinal bulk wave. This will be used as a comparison against the two shear transducer setups. The parameters of the transducer are based on a commercially available permanently installed monitoring system [142]. The Tx and Rx elements are semi-circular in shape and each have a radius of 5mm. They are

arranged as shown in Figure 6.6b. A 3 cycle Hann windowed toneburst at 5MHz centre frequency (wavelength 1.2mm) was excited in the z direction (longitudinal, L).

The first backwall reflection amplitude field is shown in Figure 6.6c which has a maximum amplitude near $x=2\text{mm}$ and $y=0\text{mm}$. The displacement field at $2\mu\text{s}$ after excitation in the $y=0$ plane (Figure 6.6d) shows curved wavefronts since the width and length of Tx are not equal, whereas in the $x=0$ plane (Figure 6.6e) the beam has linear wavefronts. The wavefronts in Figure 6.6d and e are similar to those of the waveguide setup in Figure 6.4f and g, due to the asymmetric nature of the Tx node's dimensions. Appendix 9.8 details the validation of the longitudinal FE model.

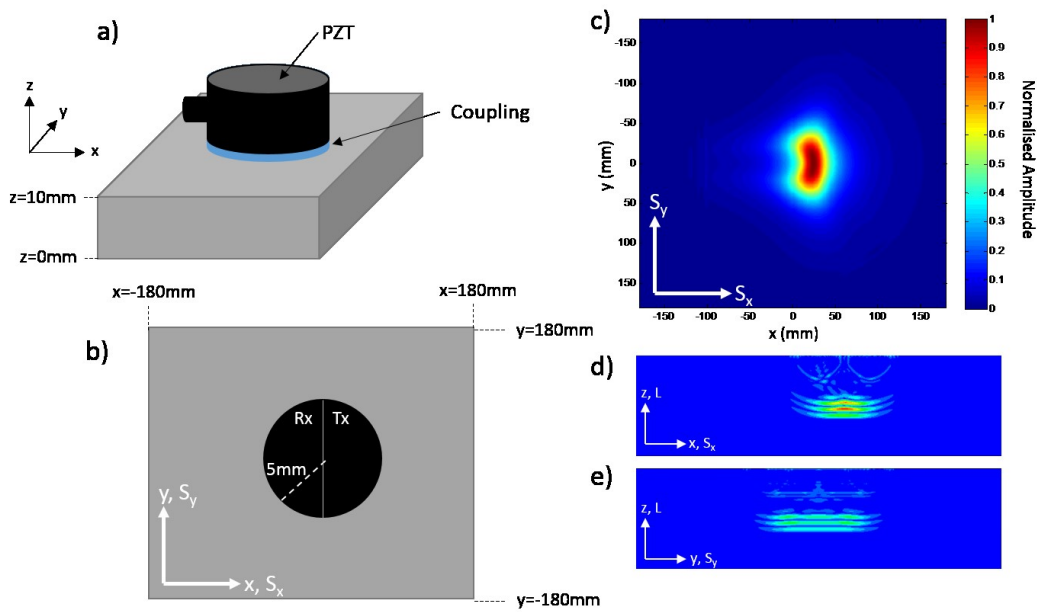


Figure 6.6 a) Illustration of a dual element PZT transducer, b) the segmentation and input nodal configuration of a pitch catch PZT, c) magnitude of the enveloped first backwall amplitude field, the pulses' displacement field at $1.2 \times 10^{-6}\text{s}$ in the $y=0$ plane (d) and $x=0$ plane (e). c-e were obtained with a 3 cycle Hann windowed toneburst at 5MHz centre frequency.

6.2.2 Validation of Finite Element Model and Determination of the Effective EMAT Aperture

As stated in section 6.2.1.2 the $10\text{mm} \times 10\text{mm}$ EMAT aperture only represents the physical size of the EMAT's coil. In reality, the shape of the magnetic field will produce a more complex shearing force on the surface of the metal, which will affect the beam width. To ensure that the FE model is simulating the correct response a representative/effective square aperture was found which correctly simulates a real response. The models were compared against experimental pulse echo time traces from an EMAT placed above a 2mm deep $\varnothing 7\text{mm}$ flat bottomed hole (FBH) in a 1" plate.

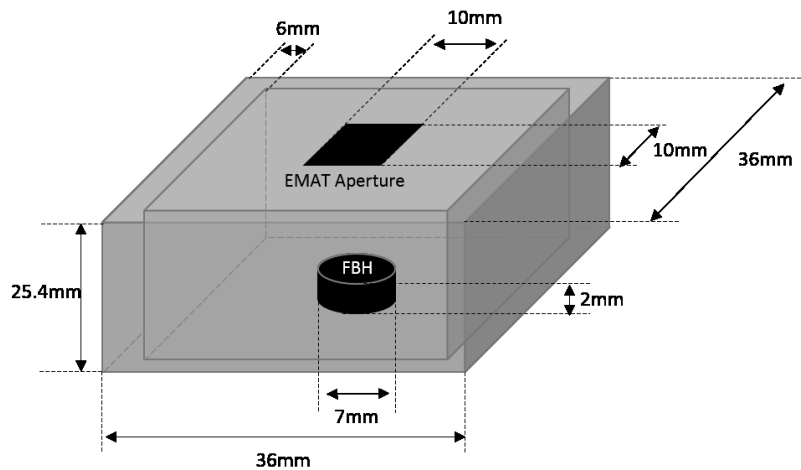


Figure 6.7. Illustration of the FE model used to verify the EMAT aperture using a 7mmx2mm deep flat bottomed hole (FBH).

6.2.2.1 EMAT Validation Experimental Setup

The experimental rig used to validate the EMAT setup used proprietary equipment developed at Permasense Ltd, UK, which included the transducer, the EMAT driver as well as the DAQ software. The input toneburst had a centre frequency of 2MHz and a window width of 3 cycles. Care was taken to site the EMAT over the FBH. There were 1000 acquisition samples in each signal and 500 measurements were taken and then averaged. The results were filtered from a 3 cycle to 5 cycle in post processing using a cross correlation algorithm.

6.2.2.2 Validation against Existing Experimental Data

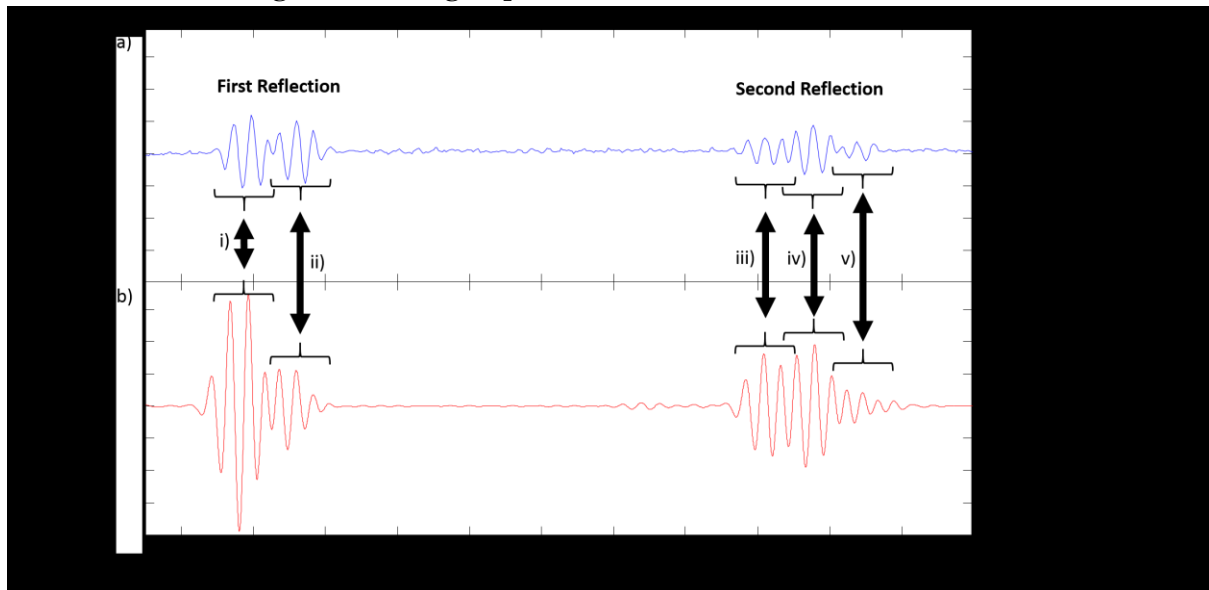


Figure 6.8 a) Experimental signal using an EMAT with a 2MHz 5 cycle Hann windowed toneburst reflecting off a 7x2mm part thickness hole, showing the first (i,ii) and second reflections (iii,iv,v) off the backwall or defect, b) the simulation of a) using a EMAT with a 10mmx10mm aperture.

The result of the experimental acquisition is shown in Figure 6.8a, which clearly shows the first and second backwall reflections (BW1 and BW2, respectively).

In the BW1 signal it is possible to identify the reflection from just the backwall (i, peaking at $17\mu\text{s}$) and the top of the flat-bottomed hole (ii, at $14.5\mu\text{s}$). The BW2 signal contains three double reflections: a double reflection from the backwall (v, $33\mu\text{s}$); a double reflection from the top of the defect (iii, $30\mu\text{s}$); and one reflection from the top of the defect and one from the backwall (iv, $31.5\mu\text{s}$). Figure 6.8b shows the simulation result for the $10\text{mm}\times 10\text{mm}$ aperture EMAT (referred to as the 10mm EMAT from now on), whereby the backwall reflection in BW1 has been scaled to the same height as in Figure 6.8a.

The major difference in Figure 6.8b, compared to Figure 6.8a, is that the defect reflection (i) is much greater than the backwall reflection (ii), suggesting the beam is too narrow. Several apertures were modelled. Figure 6.9 shows the results from an aperture of $12.5\text{mm}\times 12.5\text{mm}$. This has a much better fit with the experimental data, in both a) raw and b) enveloped form. Both 10mm and 12.5mm EMATs are used in the FE simulations, to provide a further comparison in analysis.

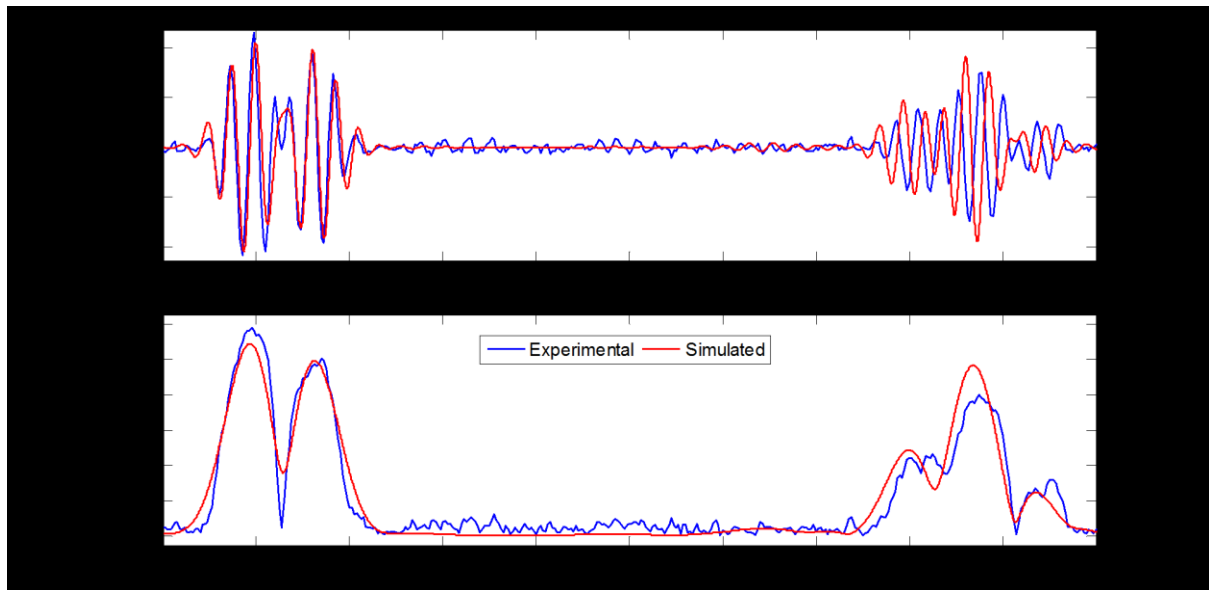


Figure 6.9 a) Comparison of signals from an experimental pulse echo measurement of a $7\text{mm}\times 2\text{mm}$ part thickness hole (blue line) with an FE model (red line) simulation of an EMAT with a $12.5\text{mm}\times 12.5\text{mm}$ aperture with a 2MHz 3 cycle input toneburst (simulated signal is filtered from 3 to 5 cycles in post processing), b) Hilbert enveloped of the signal in a)

The first backwall reflection amplitude field of a 12.5mm EMAT is shown in Figure 6.10a. This can be compared to the backwall amplitude field of a 10mm EMAT (Figure 6.5d). In both cases the amplitudes peak at the corners of the EMAT apertures, however, the 12.5mm EMAT setup has a much lower relative amplitude in the centre of the aperture. The

displacement field at $2\mu\text{s}$ in Figure 6.10b and c have similar shapes to the 10mm EMAT case albeit slight wider beam width, as would be expected.

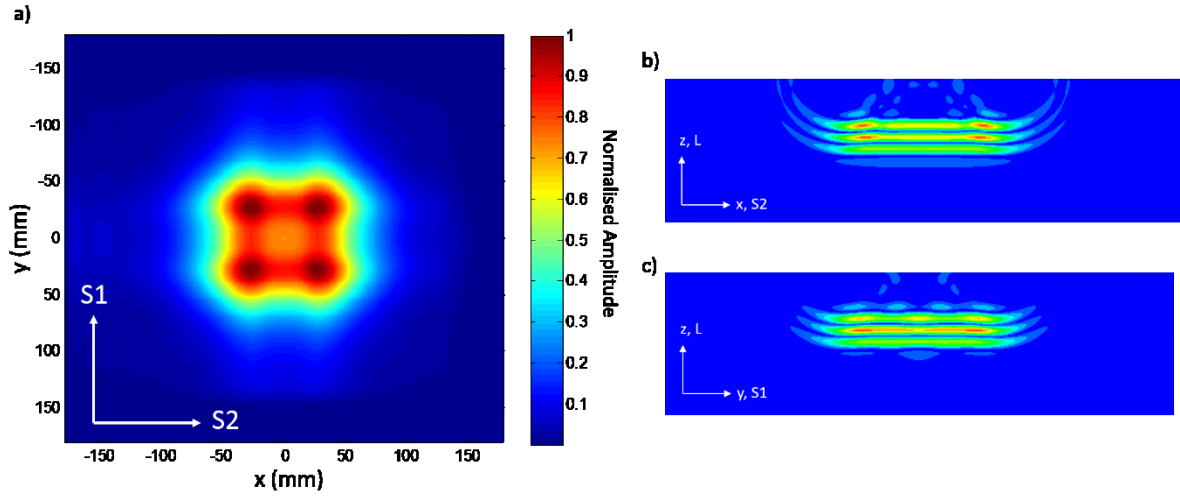


Figure 6.10. a) magnitude of the backwall amplitude displacement field of the first backwall pulse in the same direction (S1) as the input toneburst for a EMAT with a $12.5\text{mm} \times 12.5\text{mm}$ aperture. The pulses's displacement field (in S1 direction) along the $y=0$ plane (b) and $x=0$ plane (c) at $2 \times 10^{-6}\text{s}$ using a 3 cycle 2MHz Hann windowed toneburst.

6.3 Signal Processing Methods

Three characteristics of the received signals from the FE models will be analysed: the amplitude of the first backwall signal (BW1), the amplitude of the pit signal (PS) and the extracted wall thickness (WT). BW1 and pit signal phase changes have not been considered.

6.3.1 Normalised Amplitude Definitions

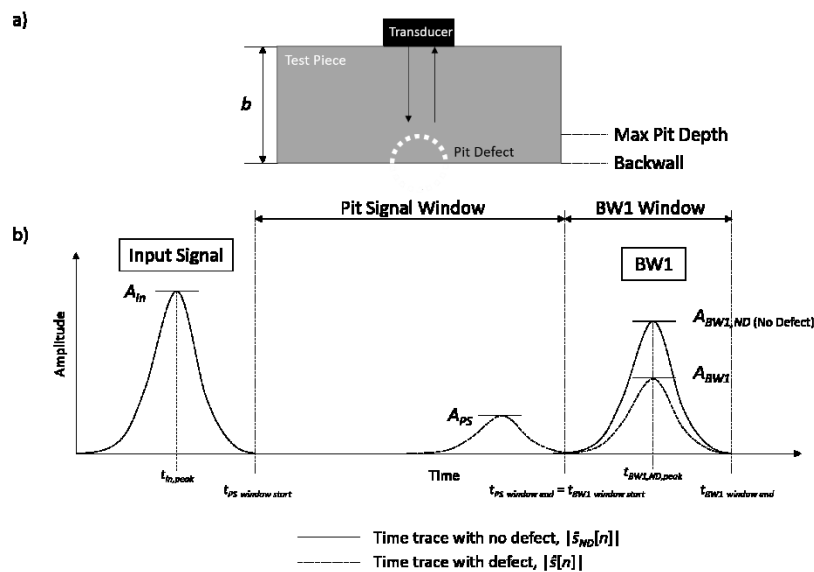


Figure 6.11 a) Schematic of a spot measurement setup b) illustration of the windowing used in the method to determine the backwall and pit amplitudes

An overview of the method to determine the backwall and pit amplitudes is illustrated in Figure 6.11b, whereby the time trace is segmented into two windows covering the 1st backwall echo (BW1) and the pit signal. The maximum amplitudes within either the BW1 or pit signal window is taken as the A_{BW1} amplitude or the A_{PS} pit signal amplitude respectively. Both of the amplitude values are calculated (in dB) relative to $A_{BW1,ND}$, i.e. the 1st backwall echo without a defect present. The Hilbert envelope of the raw time traces, $s_{env}[n]$, are used to calculate the amplitudes. The following outlines the methods which were used to define the BW and pit signal windows as well as how the BW1 amplitude or the pit signal amplitudes, A_{BW1} and A_{PS} , are calculated. One drawback of using the windowing method is that it creates ‘deadzones’, see appendix 9.6 for more details.

6.3.1.1 Determination of the First Backwall Amplitude

First, the peak location of the BW1 without a defect is determined using the known nominal thickness, b :

$$n_{BW1,ND,peak} = \underset{n}{argmax} \left(s_{env,ND} \left[\left(\frac{b}{c_g} \right) f_s < n < \left(\frac{3b}{c_g} \right) f_s \right] \right) \quad (6.1)$$

where $s_{env,ND}[n]$ is the enveloped signal with no defect present, c_g is the group velocity, f_s is the sampling frequency and $\left(\frac{b}{c_g} \right) f_s$ is a threshold which occurs approximately at the midpoint between the input signal and the BW1 echo. The start of the BW1 window can then be defined:

$$n_{BW \text{ window start}} = n_{BW1,ND,peak} - N_{input \text{ toneburst}}/2 \quad (6.2)$$

where $N_{toneburst}$ is the sample width of the input toneburst and is equal to $\frac{N_{cy} f_s}{f_{cen}}$, N_{cy} are the number of cycles and f_{cen} is the centre frequency. Similarly, the end of the BW1 window is determined:

$$n_{BW \text{ window end}} = n_{BW1,ND,peak} + N_{input \text{ toneburst}}/2 \quad (6.3)$$

The limits of the BW1 window are then used to find the maximum value of $s_{env,ND}[n]$ and $s_{env}[n]$ which occur within the BW1 window. The relative value of the BW amplitude is given in the dB scale:

$$A_{BW1} = 20 \log_{10} \frac{\max(s_{env}[n_{BW1 \text{ window start}} < n < n_{BW1 \text{ window end}}])}{\max(s_{env,ND}[n_{BW1 \text{ window start}} < n < n_{BW1 \text{ window end}}])} \quad (6.4)$$

6.3.1.2 Determination of the Pit Signal Amplitude

The window used to define the pit signal starts where the input signal ends and ends when the BW1 signal without a defect begins. First, the peak location of the input toneburst using the known nominal thickness, b , is determined.

$$n_{in,peak} = \underset{n}{\operatorname{argmax}} (s_{env,ND}[n < (b/c_g) f_s]) \quad (6.5)$$

Next the start of the pit signal window is located using the known width of the pulse:

$$n_{PS \text{ window start}} = n_{in,peak} + N_{input \text{ toneburst}}/2 \quad (6.6)$$

The end of the pit signal window is equal to the start of the BW1 window:

$$n_{PS \text{ window end}} = n_{BW \text{ window start}} = n_{BW1,ND,peak} - N_{input \text{ toneburst}}/2 \quad (6.7)$$

Then using the limits of the pit signal window the maximum value of $s_{env}[n]$ which occurs within the pit signal window is determined. The relative value of the pit signal amplitude is given in the dB scale, relative to the BW1 echo with no defect.

$$A_{PS} = 20 \log_{10} \left(\frac{\max(s_{env}[n_{PS \text{ window start}} < n < n_{PS \text{ window end}}])}{\max(s_{env,ND}[n_{BW1 \text{ window start}} < n < n_{BW1 \text{ window end}}])} \right) \quad (6.8)$$

6.3.2 Time of Flight Method to Estimate Wall Thickness

In this study cross correlation is used to extract a value of wall thickness. An overview of the method is shown in Figure 6.12. First a threshold, $n_{WT \text{ threshold}}$, where the input toneburst ends is defined, see Figure 6.12a.

$$n_{WT \text{ threshold}} = n_{in,peak} + N_{input \text{ toneburst}}/2 \quad (6.9)$$

$n_{in,peak}$ is determined using equation 6.5. Two new signals are created, one of which contains the signal before the threshold (input toneburst signal, $s_{in}[n]$, Figure 6.12b), and another which contains the signal after the threshold (BW1 signal and a potential pit signal, $s_{BW1}[n]$, Figure 6.12c). The removed part of the signal is replaced with zeroes:

$$s_{in}[n] = s[n > n_{WT\ threshold}] = 0 \quad (6.10)$$

$$s_{BW1}[n] = s[n < n_{WT\ threshold}] = 0 \quad (6.11)$$

The two time traces are cross correlated with the input toneburst, $s_{tone}[n]$ ⁶, which is used to generate the FE toneburst⁷:

$$C_{in}[k] = \sum_{n=0}^{2N-1} s_{in}[n]s_{tone}[n+k] \quad (6.12)$$

$$C_{BW1}[k] = \sum_{n=0}^{2N-1} s_{BW1}[n]s_{tone}[n+k] \quad (6.13)$$

The arrival times of the input toneburst, t_{in} , and the BW1 echo, t_{BW1} , are found using the $argmax()$ function:

$$k_{in,max} = argmax_k(C_{in}[k]) \quad (6.14)$$

$$t_{in} = \frac{k_{in,max}}{f_C} \quad (6.15)$$

$$k_{BW1,max} = argmax_k(C_{BW1}[k]) \quad (6.16)$$

$$t_{BW1} = \frac{k_{BW1,max}}{f_C} \quad (6.17)$$

where f_C is the sampling frequency of the cross correlations (C_{in} and C_{BW1}). If the sampling frequency of $s_{tone}[n]$ is the same as $s[n]$ then $f_C = f_s$. The method of calculating the wall thickness will change depending on the transducer setup being modelled. If the same set of

⁶ To simplify the cross correlation $s_{tone}[n]$ is resampled to have the same sampling frequency as $s[n]$

⁷ The input signal is effectively auto-correlated and therefore $t_{in} = 0$; however, there are certain setups where this is not a given (such as the waveguide setup) therefore the method has been described in full.

nodes generates and receives the signal (i.e. pulse-echo) then the wall thickness, b , can simply be calculated using:

$$b = c_g \cdot \frac{t_{BW1} - t_{in}}{2} \quad (6.18)$$

When the transducer setup under investigation has a different set of Tx and Rx nodes (i.e. pitch catch) then the distance travelled by the pulse must take account of the separation, d , between the Tx and Rx node sets [143]:

$$b = \frac{1}{2} \left(\sqrt{c_g(t_{in} - t_{BW1})(c_g(t_{in} - t_{BW1}) - 2d)} \right) \quad (6.19)$$

Furthermore the input signal, s_{in} , will not necessarily be represented in the signal received at the Rx nodes. In the case of the waveguide setup the surface wave between the Tx and Rx node sets will produce t_{in} [143].

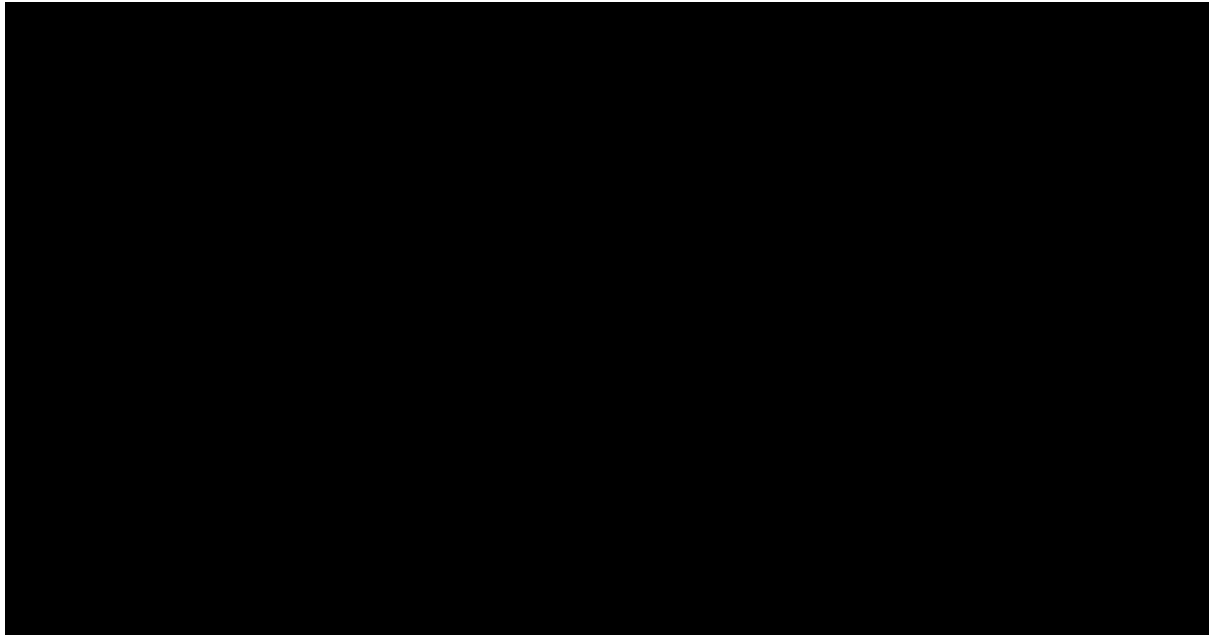


Figure 6.12. Illustration of method used to extract wall thickness, using a time trace a) which is divided into two: b) the input signal in the time trace is cross correlated with the input toneburst² to find a first time value and c) the first backwall signal is cross correlated with the input toneburst to find the second time value.

6.4 Effect of Sloped Backwall with Variable Gradient

A FE model with a sloped backwall was created to observe and understand the interaction between bulk waves and sloped surfaces, as well as understand the relationship between the relative orientation between the shearing direction of a pulse and a sloped surface. This simplified setup will be able to isolate any phenomena relating solely to sloped surfaces.

The model (Figure 6.13) has a constant thickness of 10mm in the centre of the plate. The backwall is sloped between 0° - 20° . The slope vector is defined by the lines of constant depth (i.e. contours). For the shear transducers, the parallel orientation is defined as when the shearing direction (S1) and the slope vector are aligned. The perpendicular orientation is defined as when the shearing direction and the slope vector are orthogonal. The relative orientation of the semi-circular compression transducer and the slope is defined by the direction of the separation between the two semi-circular halves of the transducer and the contours of the slope.

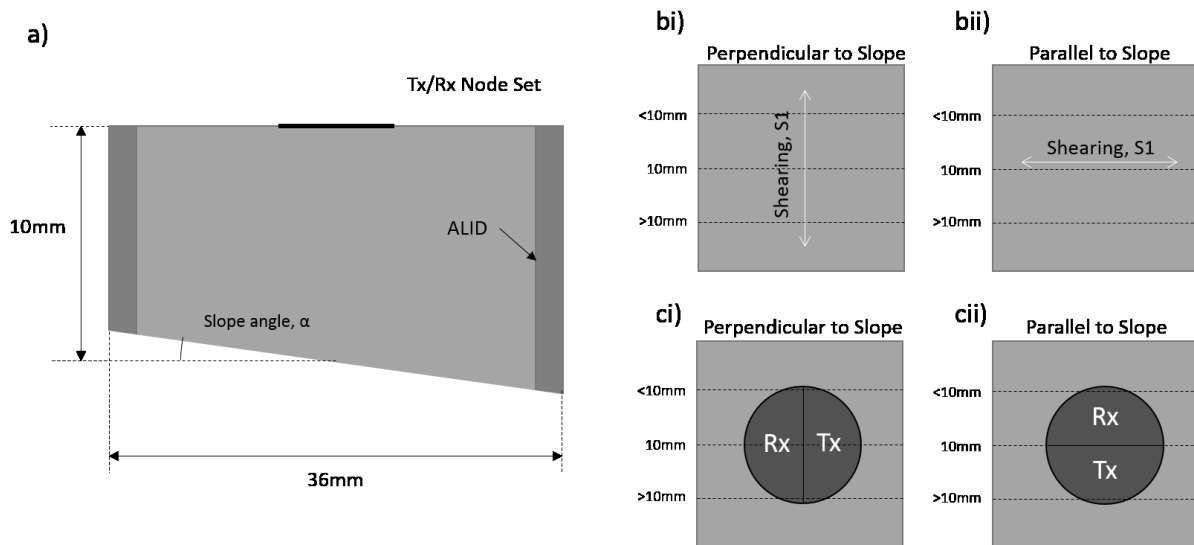


Figure 6.13. Illustrations of the sloped backwall model, a) cut-through of the model, b) projected views of the sloped backwall models with the shear transducers (b) and compression transducer (c) defining the terminology which distinguishes between the two orientations: perpendicular (i) and parallel (ii).

Figure 6.14 shows the backwall amplitudes of all three transducer setups for slope angles from 0° - 20° , when orientated either parallel or perpendicular to the backwall slope. The equivalent waterfall plots for the two shear transducers (Figure 6.15) and the semi-circular compressional transducer (Figure 6.16) enable further analysis of the mechanics behind the effects seen in Figure 6.14.

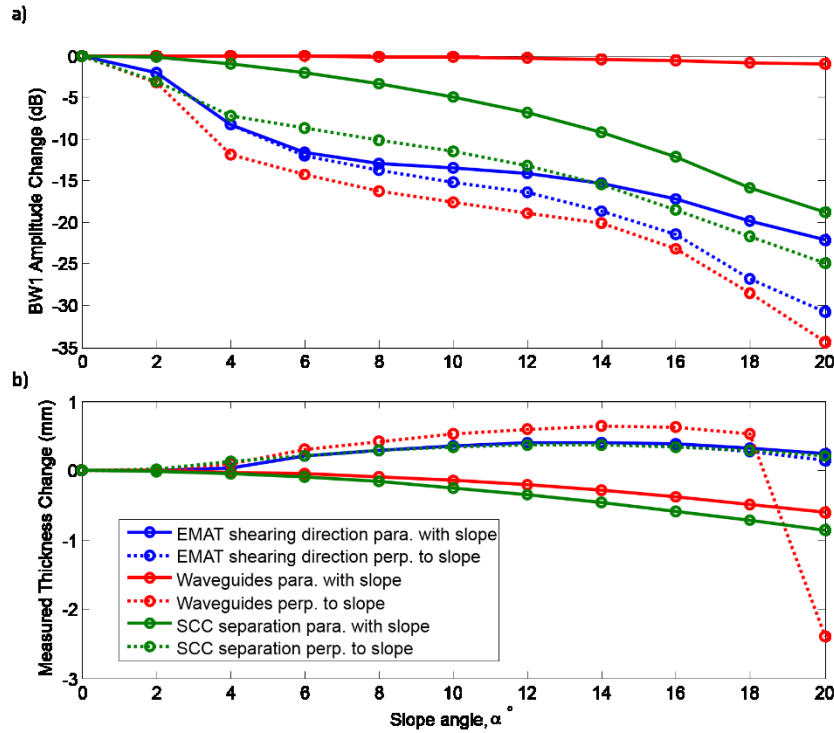


Figure 6.14. a) Back wall amplitudes and b) extracted thicknesses for the three transducers types (blue - EMAT 10mm, red - waveguide, and green - semi-circular compressional) in either the perpendicular (dashed) or parallel (solid) orientations for back wall slope angles of 0°-20°

The backwall amplitude of the 10mm EMAT decreases as the slope angle increases, as the beam is reflected away from the transducer, and is not affected by orientation up to 6° slope (Figure 6.14a, blue lines). Beyond 6° the amplitude is affected by the orientation of the transducer. When the transducer is parallel with the slope it has a marginally higher backwall compared to the perpendicular orientation (8dB difference at 20°). This difference can be explained by mode conversion of the pulse. When the EMAT is parallel to the slope there is no mode conversion to the other shearing direction, S2, or the longitudinal direction, L (Figure 6.15bii and biii). When perpendicular to the slope some of the energy of the shear pulse is converted to the longitudinal direction (Figure 6.15aii - S1-L) thereby reducing the amount detected in the principle shearing direction, S1. The longitudinal component of the S1-S1 pulse detected in Figure 6.15aiii will also decrease the backwall amplitude in the perpendicular orientation since this will not be detected in the S1 direction. The overall decrease in the backwall amplitude is mainly due to the beam being reflected away from the transducer by the sloped backwall (also clearly visible in Figure 6.15ai and bi, i.e. the S1 direction). Both backwall orientation trends exhibit a slight periodicity, due to constructive and destructive interference effects. It is also necessary to note that in Figure 6.15aiii a L-L reflection is observed (this means that a small compressional pulse is excited by the transducer).

There is no difference between the measured thickness of either of the EMAT orientations (Figure 6.14b - both blue lines). The extracted thickness is broadly flat below 4° , after which it increases by nearly 0.5mm, peaking at 14° .

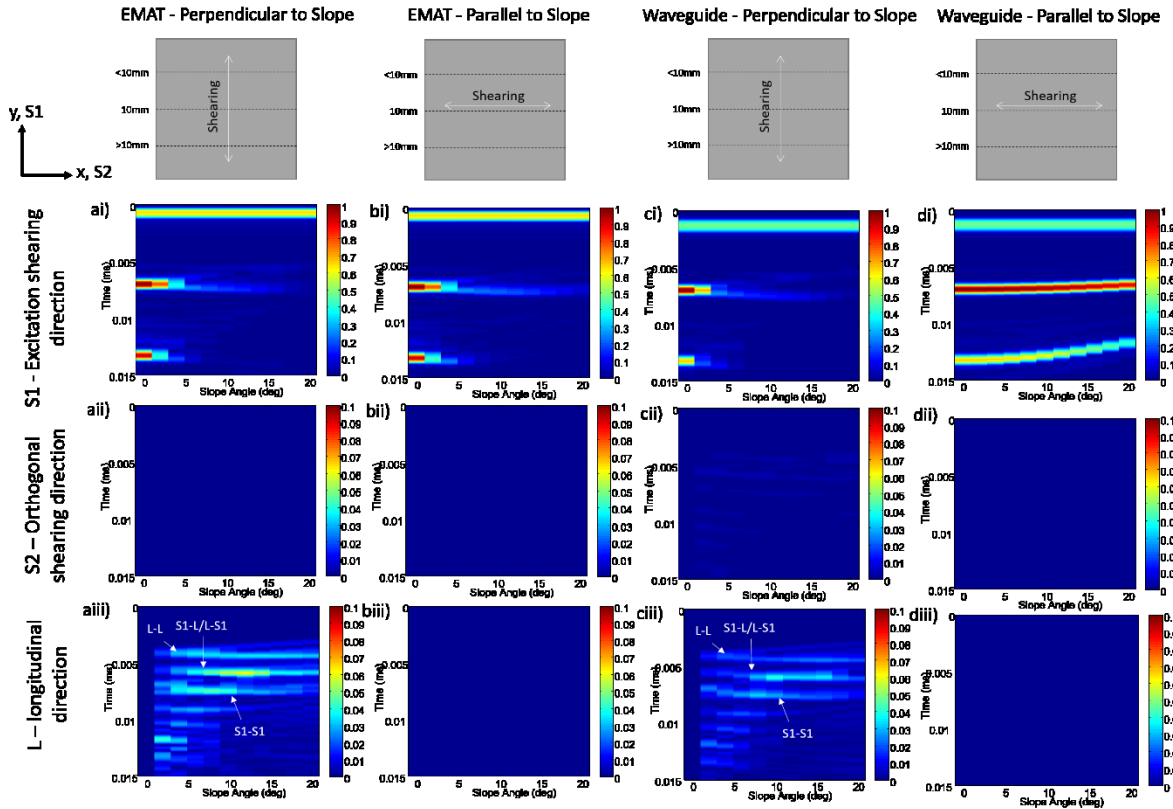


Figure 6.15 Waterfall plots for the two shear transducers (a and b - EMAT 10mm, c and d - waveguide), in the principle shearing component (i), other shear component (ii) and the longitudinal component (iii) in either the perpendicular (a, c) or the parallel orientations (b, d). The ii) and iii) results are -20dB the peak in i)

The waveguide's backwall amplitude exhibits a large difference between the two orientations (shown in Figure 6.14a - both red lines, and difference between Figure 6.15ci and di). When parallel with the slope there is little effect on the amplitude, less than 2dB change over all angles (solid red line). In this orientation ($y=0$ plane) the waveguide acts a point source and the resulting circular wavefront (shown in Figure 6.4f) ensures that a similar amount of energy is reflected from the backwall at any slope angle. No mode conversion occurs in this orientation (Figure 6.15dii and diii). When perpendicular to the slope the amplitude falls by -35dB over 20 degrees, that largest fall in amplitude of any of the transducer setups (dashed red line). In this orientation, the wavefronts are linear (as shown in Figure 6.4g) and therefore the pulse's energy is increasingly reflected away from the transducer at larger and larger angles. A fraction of the beam's energy is also mode converted to the longitudinal direction, S1-L (Figure 6.15ciii). The backwall amplitude also exhibits the same periodicity as the EMAT backwall amplitudes. The L-L and S1-S1 features are also visible in Figure 6.15ciii.

In the parallel orientation the waveguide extracted thickness decreases slightly as the angle increases (solid red line). Whereas the perpendicular case increases slightly, before suddenly falling below the nominal thickness at 20° (dashed red line). This is because the backwall signal at $7\mu\text{s}$ (Figure 6.15ci) splits into two and at 20° slope angle the amplitude of the 1st part of this signal exceeds the 2nd, therefore the wall thickness algorithm uses the temporal location of the 1st peak to calculate the TOF, instead of the 2nd peak.

In both shear wave setups, when in the parallel orientation there is no mode conversion. In the perpendicular cases there is mode conversion from the principle shearing component to the longitudinal direction (S1-L). This effect is visible in Figure 6.15aiii and ci. In these figures there are three bands at $4\mu\text{s}$, $5.5\mu\text{s}$, and $7\mu\text{s}$, which are the L-L reflection (low amplitude longitudinal wave generated by the edge effects of the input node set), S1-L (the mode conversion), and S1-S1 (i.e. the shear energy detected in the longitudinal direction due to reflection off a non-planar surface).

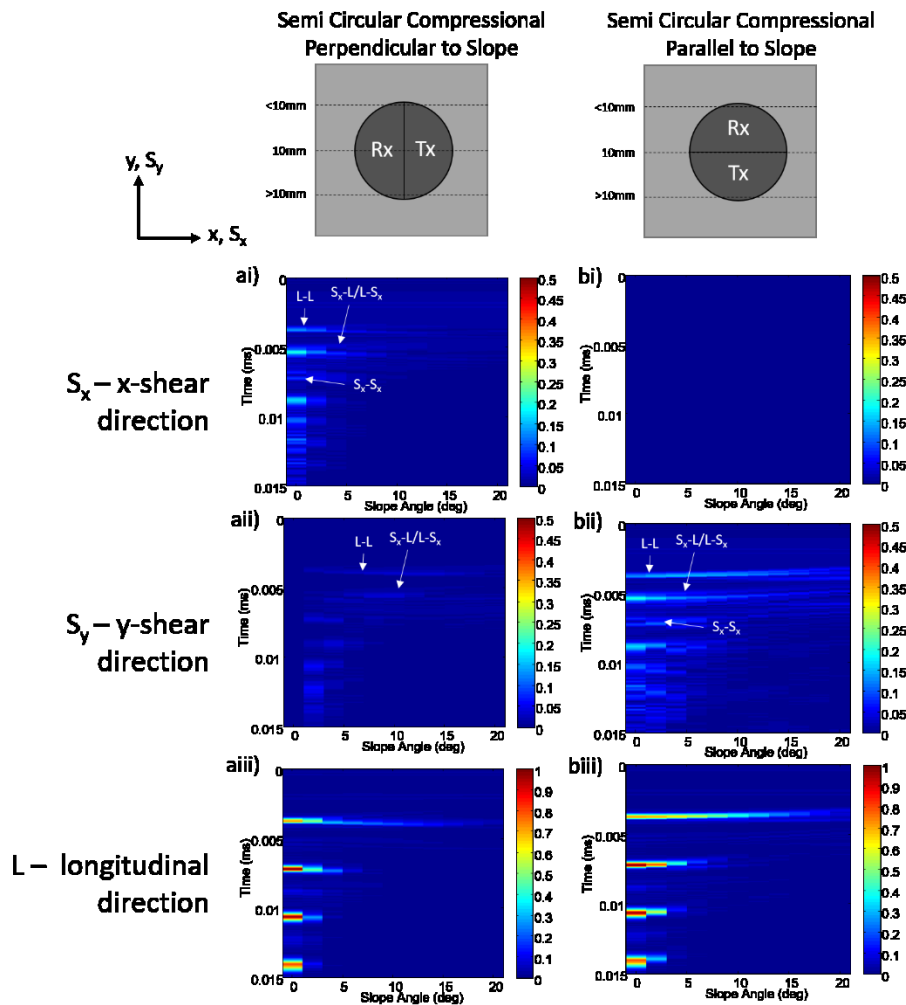


Figure 6.16. Waterfall plots for the semi-circular compression transducer in the x shearing component (i), y shear component (ii) and the longitudinal component (iii) in either the perpendicular (a) or the parallel orientations (b). The ii) and iii) results are -6dB the peak in i).

Figure 6.14a shows that when the semi-circular compression (SCC) transducer is orientated parallel to the slope (green solid line) the backwall amplitude is greater than the perpendicular orientation (green dashed lines) at all angles. This result is also shown in Figure 6.16a(iii) and b(iii) in the difference between the backwall reflections at $4\mu\text{s}$. The asymmetry of the SCC transducer and beam shape is likely to be the main cause. If the transducer is parallel to the slope then the y-z plane wavefronts will be curved/circular (Figure 6.6c(ii)) and therefore, the pulse's energy incident on the backwall will be similar at any angle. If the transducer is perpendicular, then the y-z plane wavefronts will be flat (Figure 6.6c(iii)) and the pulse's energy will be reflected away from Rx. Both of these orientations are analogous to the asymmetry of the waveguide transducer's beam. Mode conversion is also present in the SCC case. There is mode conversion to the S_y direction in Figure 6.16a(ii) and b(ii), although it is more prevalent in the parallel orientation. Interestingly there is always a shear wave reflection at 0° slope (i.e. flat backwall) to the vector component perpendicular to the separation line between the two semi-circles. I.e. in the perpendicular case there is mode conversion to S_x (Figure 6.16a(i)) and in the parallel case there is mode conversion to S_y (Figure 6.16b(ii)) at 0° slope. This is due to the edge effect from the straight edge separating the Tx and Rx generating curved wavefronts. This effect is amplified in the parallel case as the slope increases (Figure 6.16b(ii)).

6.5 Effect of Pitting on Bulk Waves

The section above has shown that the orientation of a transducer with respect to a sloped backwall affects the backwall amplitude. This section will use 3D finite element modelling to explore the interaction between bulk waves and pits using the three transducer setups described above. The enquiry will be twofold, first analysing the effect of a pit directly under the transducer setups and then observing the effect on the bulk waves of pits located at many different locations.

6.5.1.1 Finite Element Model Containing Hemispherical Pits

Pitting rarely manifests as flat bottomed holes and therefore hemispherical pits were introduced into the FE model in Figure 6.3 since they are a good approximation of pitting due to corrosion [40], [126], [136], [144], [145]. The pit can be moved about within the model and its position can either be defined in Cartesian or polar coordinates (as shown in Figure 6.18a and b). The pit is defined by its radius, which also equates to the maximum wall loss. Pit radii of 0.5-8mm (in 0.5mm steps) were modelled with the defect at position (0,0), i.e. directly under the transducers. From these results specific radii of interest were selected to be investigated further by varying the defects position. The radial pit position, r , was varied between 0-5mm (in 1.25mm steps), with simulations performed at 0° , 45° ,

and 90° angular position, θ , only. This takes advantage of the symmetry of the setup and therefore angular positions 90° - 360° are not required. Like the part thickness holes in chapter 4, pits were introduced into the plate by first finding the boundary of the pit and then changing the material density within the pit to zero (Figure 6.17). This method creates a stepped defect but the steps are much smaller than bulk wave wavelength.

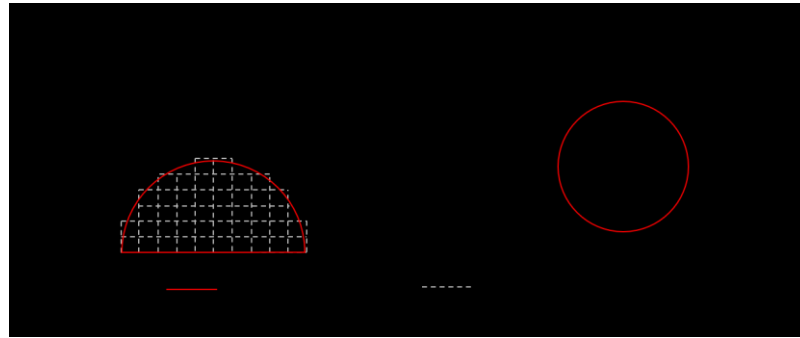


Figure 6.17 Schematic of how the hemispherical defects were defined in the FE model a) central cut-through b) underside view of a hemispherical defect

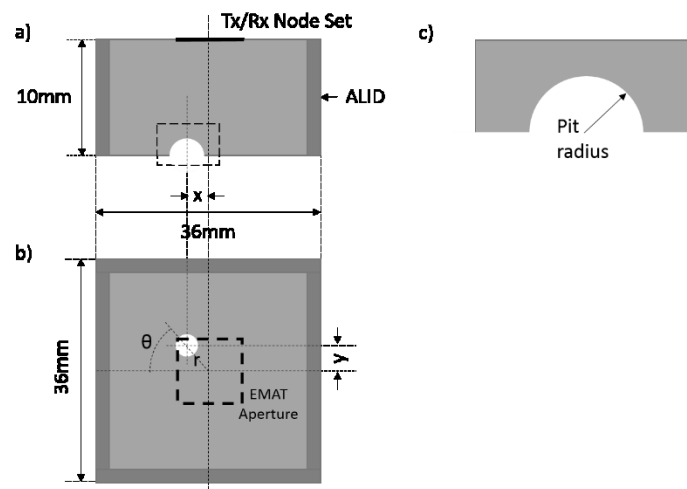


Figure 6.18 Illustration of the hemispherical pit variables which are able to be altered in the FE model: a) cut-through of an off centre hemispherical defect, b) backwall projection, and c) exploded view from inside dashed rectangle in a) of a cut-through of a pit.

6.5.2 Effect of Pitting Directly Under the Transducers

Different pits were placed directly under the transducers to gauge relative sensitivities of the various setups. Figure 6.19 shows the backwall amplitudes, pit amplitudes, and extracted thicknesses for all four transducers setups for pit radii of 0.5-8mm. In all cases as the radius of the defect increases the backwall amplitude (Figure 6.19a) decreases until a certain level when only coherent noise of the model is being measured. The rate at which

the backwall amplitude decreases depends on the transducer setup and beam characteristics. Generally speaking, the larger the transducer footprint the larger a defect has to be to affect the backwall amplitude.

The pit amplitude (Figure 6.19b) increases as the defect radius increases as the tip of the defect gets closer to the top surface. However, the pit amplitude never reaches 0dB meaning that the reflection from the pit is heavily scattered by the curved surface of the pit. This is even the case for the deep defects, for example in the 8mm case, the reflection from the pit will travel only 4mm, compared to 20mm to and from the backwall, yet the pit signal is between -5 and -20dB lower than the backwall reflection with no defect present. Although the pit amplitude curves have similar shapes, the absolute amplitude of each is dependent on the transducer setup.

Figure 6.19c shows the extracted wall thickness. Each trend has two distinct areas: first, a value close to the nominal wall thickness is extracted (all transducers extract the nominal wall thickness up to 3mm defect radius/max wall loss). At a definite point, however, the extracted thickness suddenly switches to the maximum wall loss figure (i.e. the defect nominal - radius). This occurs in each case when the pit signal becomes greater than the backwall signal due to how the wall thickness is calculated in section 6.3.2. In this scenario, the pit signal is picked out as the highest amplitude reflection by the cross-correlation algorithm, whose temporal location is then used to calculate the TOF.

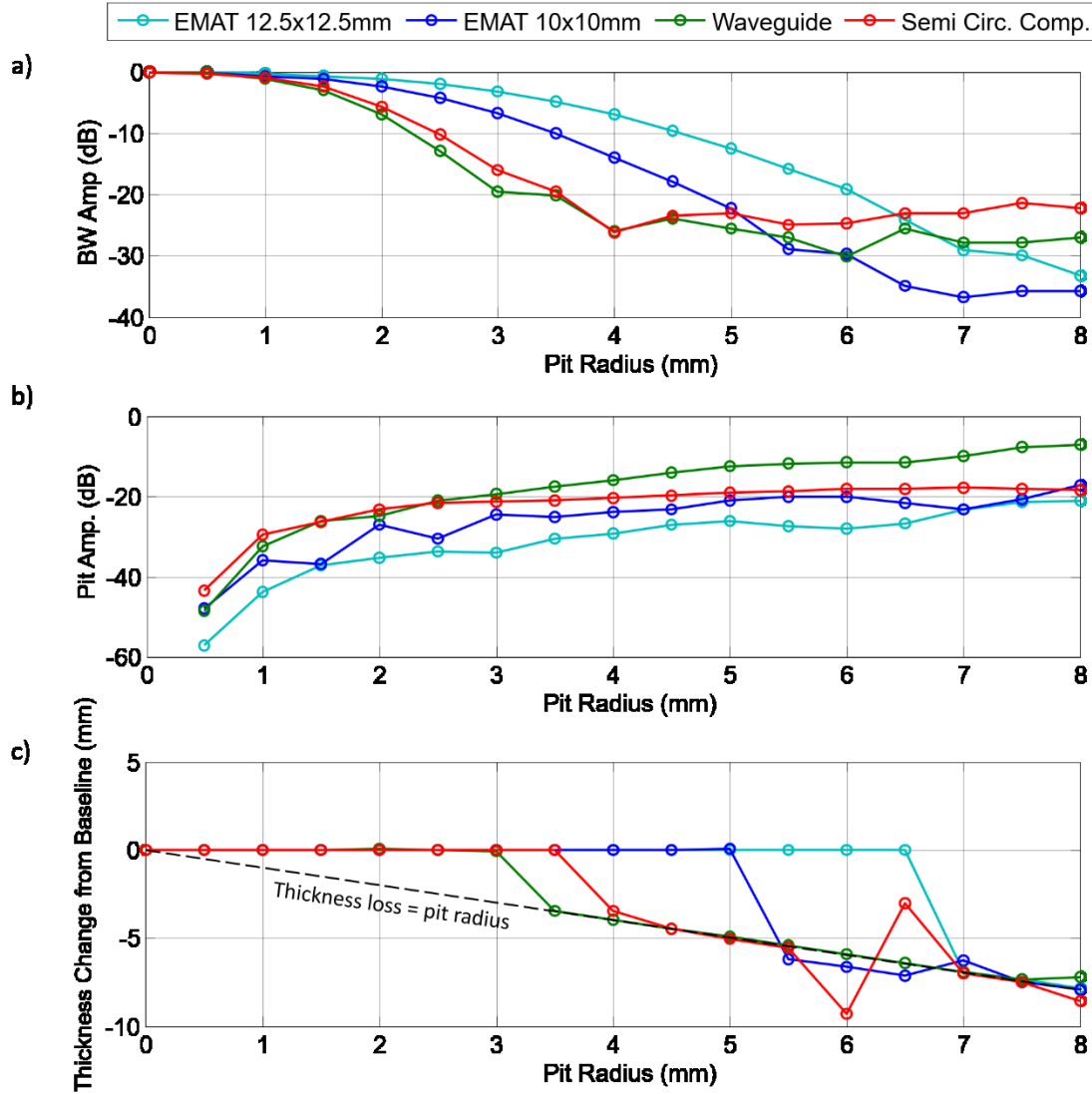


Figure 6.19 a) Backwall amplitudes, b) pit amplitudes and c) extracted thicknesses for the four transducers types (blue - EMAT 10mm, green - waveguide, red - semi-circular compressional, and cyan - EMAT 12.5mm) for pit radii from 0mm to 8mm.

The EMAT transducers have the least sensitivity to the pits. Pits of radius 6mm and 7mm decrease the 10mm and 12.5mm EMAT backwall amplitudes by -30dB, respectively (Figure 6.19a, blue and cyan lines). The pit amplitudes of the EMAT transducers are broadly similar in shape although the 12.5mm EMAT curve has a lower value for most pit radii (Figure 6.19b, blue and cyan lines). The waveguide and the semi-circular compressional transducers have similar results. Neither backwall amplitudes drop below -30dB, but they do hit a coherent noise floor around -25dB (Figure 6.19a, green and red lines). The pit amplitudes are similar until 3mm radius after which the waveguide pit amplitude increases at a faster rate. (Figure 6.19b, green and red lines). The larger the transducer aperture the less sensitive it is to pitting (i.e. the defect has less influence on either the backwall amplitude, pit amplitude or wall thickness), since the defect's diameter as a proportion of the beam width is smaller.

Therefore, the sonified area is greater and a greater proportion of the beam reflects off the backwall, leading to a larger backwall amplitude compared to the pit amplitude. This effect is also exhibited in the validation experiment in section 6.2.2, when modelling the effect of a 7x2mm FBH using either a 10mm or 12.5mm EMAT.

Figure 6.20 is an expanded graph of the extracted thickness between defect radii of 0-3mm, showing that the extracted thickness is not perfectly stable and does vary by $\pm 0.02\text{mm}$.

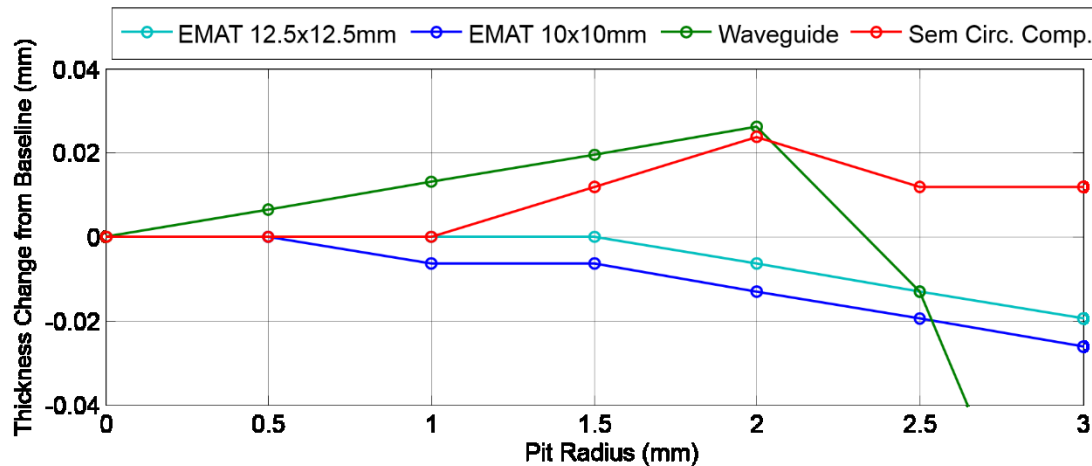


Figure 6.20. Extracted thicknesses for the four transducers types (blue - 10mm EMAT, green - waveguide, red - semi-circular compression transducer, and cyan - 12.5mm EMAT) for a centrally located pit for radii from 0mm to 3mm.

Figure 6.21 are the normalised waterfall plots for the four transducer setups, which display the enveloped signals vertically against the pit radii (x-axis). In each case the input signal, first and second backwall signals are visible, as well as the third and fourth backwall signals in SCC. As the defect radius increases the backwall signals decrease in amplitude in all cases, with the EMAT backwall signals decreasing at a much slower rate than the other two transducers. The pit signal increases as the radius increases, appearing as a diagonal line extending from the first backwall signal (at zero radius) to just behind the input signal at 8mm radius. The amplitude of the pit signal varies greatly depending on the transducer used. The waveguide has a visibly larger pit signal in comparison to the other transducers (Figure 6.21c), and a double pit reflection is also visible.

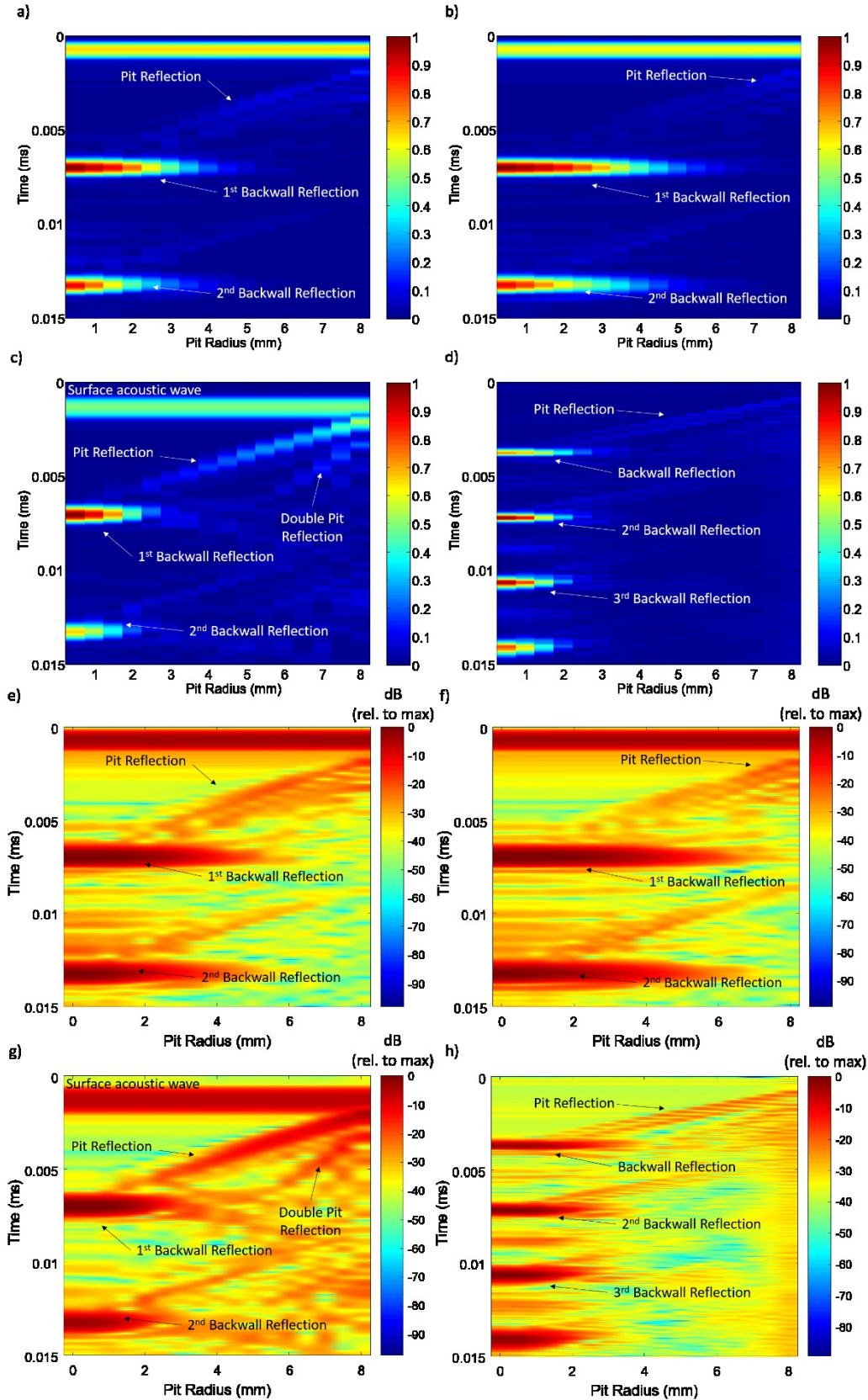


Figure 6.21 Normalised waterfall plots for the four transducers types in the same displacement direction as the input excitation direction (a) EMAT 10mm - S1, b) EMAT 12.5mm - S1, c) waveguide - S1, and d) semi-circular compression - L) for a centrally located defect for pit radii of 0.5mm to 8mm. e-h) are the equivalent log scale waterfall plots, plotting the amplitude relative to the maximum in each.

Figure 6.22 shows eight example time traces from the waveguide and the 10mm EMAT setups with the defect at 2, 4, 6, and 8mm. In both cases as the defect increases the BW signal decreases and the pit signal increases, although not substantially in the EMAT case. Looking at the EMAT in the 6mm (Figure 6.22biii) case the pit signal is clearly shown although it is much smaller than the backwall signal in the 2mm case, even though it has travelled less than one-third of the distance, suggesting the pulse is heavily scattered by the pit. The waveguide by comparison has a much larger pit signal at all pit sizes than the EMAT. However, only by the 8mm pit (Figure 6.22aiv) is the pit amplitude greater than the backwall signal with a 2mm pit, even though it has only propagated one-fifth of the nominal thickness, suggesting the pulse is still heavily scattered. It is worth noting that in the FE simulation setup shown here the input signal is half height since the excitation toneburst fixes the displacement of the nodes over the duration of the toneburst. This therefore doesn't allow the instantaneous reflection off the front wall to be added to the input toneburst, which would double its amplitude.

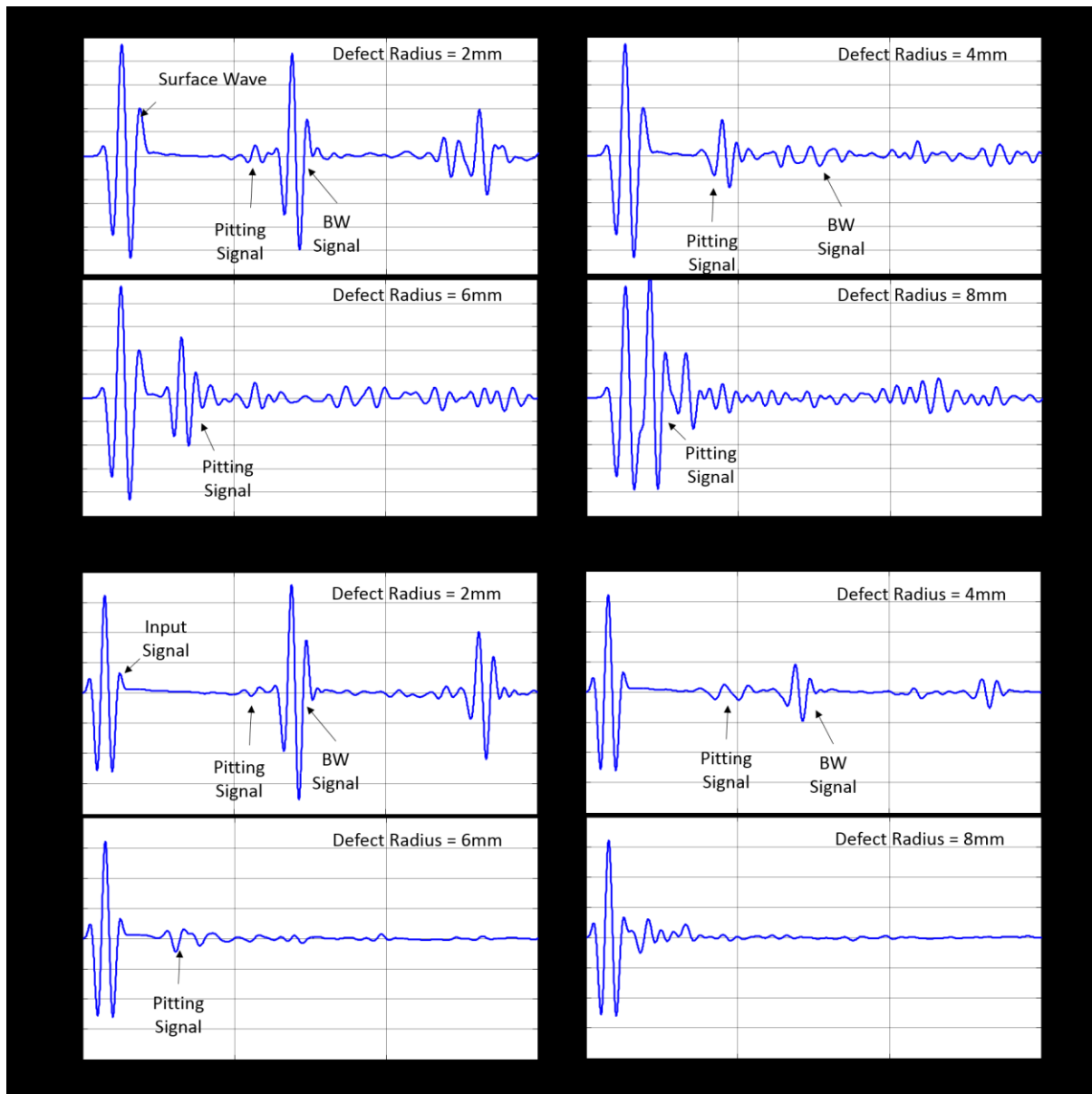


Figure 6.22. Example simulated signals received by a) a Waveguide and b) an EMAT 10mm for centrally located pits with radii of i) 2mm, ii) 4mm, iii) 6mm and iv) 8mm

6.5.3 Effect of Position and Orientation of the Pit Relative to the Transducer

The previous section illustrates the relative sensitivity of the backwall amplitude, pit and measured wall thickness of each of the transducer setups to pits of varying radii located directly under the transducer. However, this is unlikely to be the case in reality and even if an operator is placing a transducer over a known defect there will be a degree of placement/location error.

Figure 6.23 shows what the effect on the backwall amplitude of the 10mm EMAT transducers as defects of 4mm (a), 6mm (b) and 8mm (c) are moved radially from directly under the transducer along different angular paths. Figure 6.23d explains the terminology used to

describe the three relative orientations between the shearing direction (S1 in the y-direction) of the transducer and the pit: parallel, 45° , and perpendicular.

In all cases the backwall amplitude increases as the radial position increases as less and less of the defect is under the EMAT aperture, thereby scattering less of the pulse (Figure 6.23a). In the 4mm case there is little difference in the backwall amplitudes as the radial position increases. An interesting effect is observed in the 6mm and 8mm cases, whereby the backwall reflection depends on the angular position of the defect relative to the shearing direction (Figure 6.23b and c). In both cases when the defect's position is parallel with the shearing direction the backwall amplitude is much lower than the perpendicular orientation (-10dB at 2.5mm for the 6mm defect and -13dB at 3.75mm for the 8mm defect). Furthermore, the back-wall amplitudes in the 45° orientation lies between the parallel and perpendicular orientation. These results illustrate an anisotropic effect, showing that the shearing direction relative to the pit position can have a substantial influence on the sensitivity of a transducer to the presence of a defect.

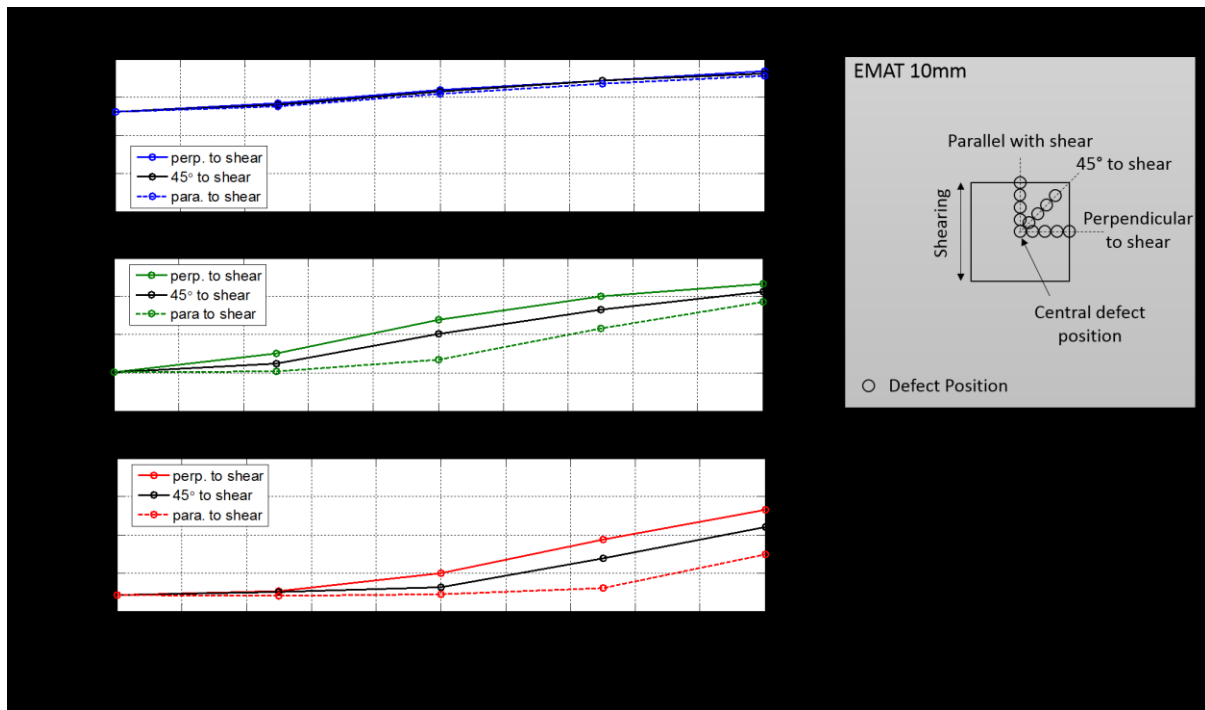


Figure 6.23. Back wall amplitudes for three pit sizes which are moved relative to the EMAT 10mm transducer as shown in d), for a) a 4mm, b) a 6mm, and c) a 8mm pit size

6.5.3.1 Shear Wave Transducers

Figure 6.24 shows in depth results for 10mm EMAT with a 6mm pit. Figure 6.24a is therefore the same as Figure 6.23b. The pit amplitudes are similar in the perpendicular and parallel orientation whereas the 45° orientation has a 5dB higher pit amplitude at radii greater than 3.75mm (Figure 5.28a_{ii}). The extracted thickness change (from the baseline value) shows

another anisotropic effect (Figure 6.24aiii). In the parallel orientation the thickness jumps from -6mm (the minimum remaining thickness) to the nominal thickness for radial distances between 2.5mm and 3.75mm, whereas the perpendicular and 45° orientations that occurs between 1.25mm and 2.5mm.

The waterfall plots explain the anisotropic effect of the backwall signal. In the perpendicular orientation none of the original shear pulse (S1) is mode converted to the other two directions (S2, and L) (Figure 6.24bi,iv,vii). In the 45° orientation (bii,v,viii) there is a large amount of mode conversion to S2 and a small amount to L. When parallel to the shearing direction (biii,vi,ix) there is no mode conversion to S2 but much more to L. This mode conversion causes the reduction in the backwall amplitude in the 45° and parallel orientations compared to the perpendicular orientation. The mode converted reflections will not be detected by the transducer and therefore will not contribute to the backwall amplitude.

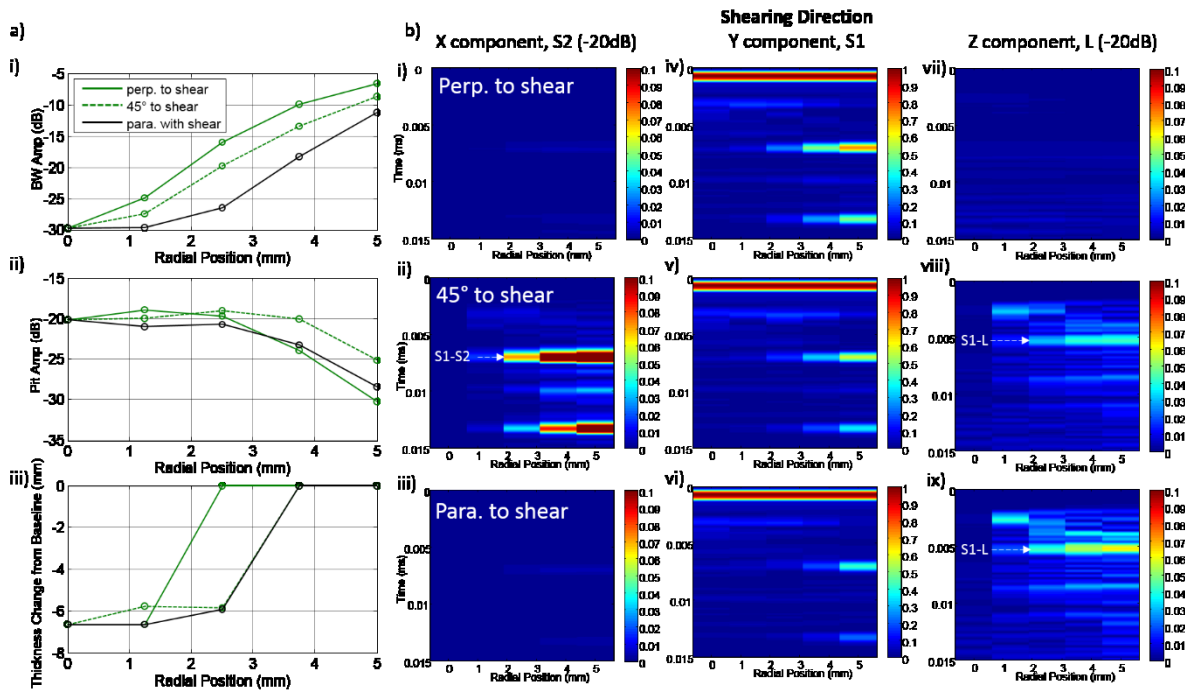


Figure 6.24 ai) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the 10mm EMAT with a 6mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations (parallel, 45° and perpendicular) in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction)

By comparison, in Figure 6.25ai the 12.5mm EMAT with a 6mm defect has less anisotropy in the backwall amplitude. This is because the 12.5mm EMAT has a larger aperture and a therefore wider beam (as shown in Figure 6.19), therefore for the same defect size a greater proportion of the beam will reflect off the backwall. Yet, there is still a visible anisotropic

effect with the perpendicular orientation having a greater backwall amplitude than the 45° or parallel orientation. The waterfall shows the same mode conversion effects as the 10mm EMAT (Figure 6.25b). That is, significant mode conversion to S2 occurs at the 45° orientation (Figure 6.25bii) and to L in the parallel orientation (Figure 6.25biv). The pit signal (Figure 6.25a) shows a small difference between the parallel and perpendicular orientations, whereas in the 45° orientation it has deviated significantly away from the other two orientations above defect radii $> 2.5\text{mm}$. This is due to a higher beam amplitude (see Figure 6.10) at the corners of a square aperture (i.e. along the lines $\theta = \pm 45^\circ$). The measured thickness is undisturbed by the presence of the defect. And only perturbed by $\pm 0.02\text{mm}$. This means that the pit signal is never greater than the backwall signal (Figure 6.25a). This means that the pit signal is never greater than the backwall signal (Figure 6.25a).

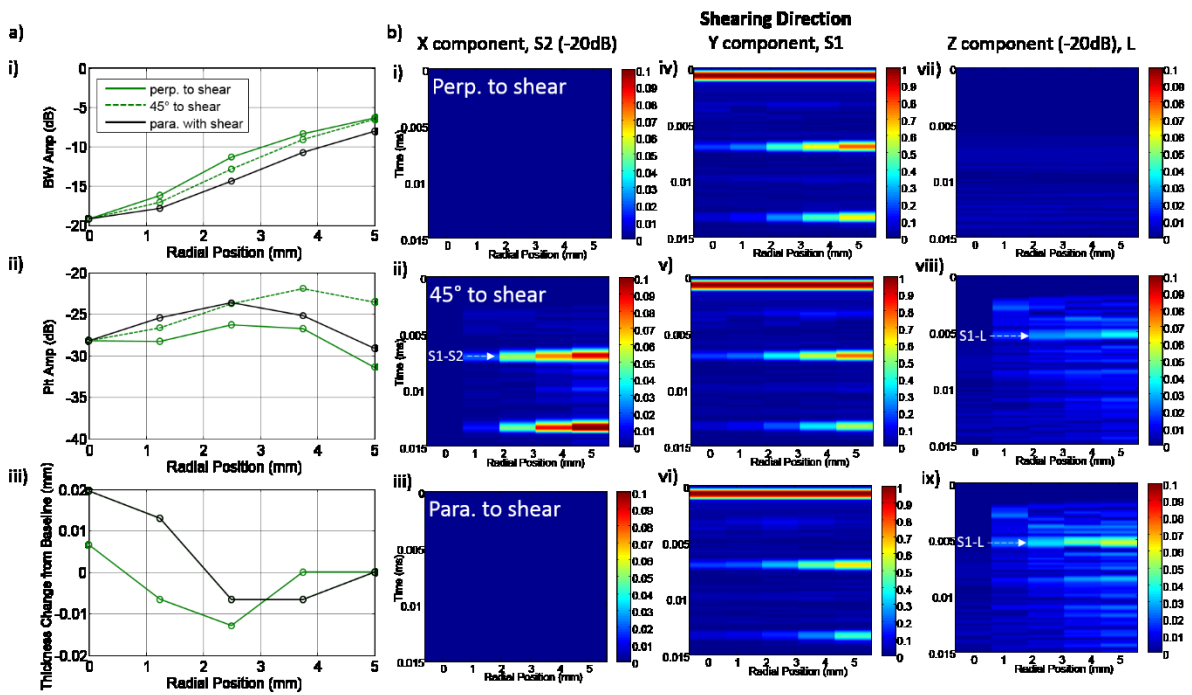


Figure 6.25 a) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the 12.5mm EMAT with a 6mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colour scale for the plots that show responses in the directions perpendicular to the shearing direction)

Figure 6.26 shows the relationship between the orientation of a 3mm defect and the backwall signal, pit signal and extracted wall thickness using a waveguide transducer. A 3mm pit was chosen from results of Figure 6.19a since this is the limit of the backwall reflection's sensitivity. There is a large amount of anisotropy when comparing the parallel and perpendicular case. This is because, as discussed above and unlike the EMATs, the waveguide setup is inherently anisotropic even without a defect present. Adding the mode conversion results will only enhance the anisotropic effect. At radial positions greater than

2.5mm there is a difference of 9dB in the backwall amplitudes between the parallel and the perpendicular orientations (Figure 6.26ai), and by $r=3.75$ mm the perpendicular orientation backwall amplitude is at 0dB, i.e. equal to the backwall amplitude with no defect. The waterfall plots clearly show the difference between the three orientations. There is no noticeable mode conversion in the case of the perpendicular orientations (Figure 6.26bi,vii). However, in the 45° there is mode conversion to the S2 (Figure 6.26bii). Whereas in the parallel case there is mode conversion to L (Figure 6.26biii). These mode converted signals are similar to the EMATs, which is to be expected since they are both 0-degree shear transducers, however, the relative magnitudes of the mode converted signals differ.

The pit amplitudes show an interesting effect whereby there is a peak in the pit signal in the parallel case around 2.5mm (Figure 6.26aii). By looking at the waveguide's backwall amplitude field (Figure 6.4e) it is apparent that there is a peak at $y=\pm 2.5$. Therefore, when the pit is located at this point the highest intensity of the ultrasonic wave will be incident on it resulting in the largest pit signal. As the plate thickness increases the beam shape will change resulting in changes in backwall amplitude field, therefore the maximum amplitude will occur at a different location. The extracted thicknesses are similar to nominal thickness (Figure 6.26aiii).

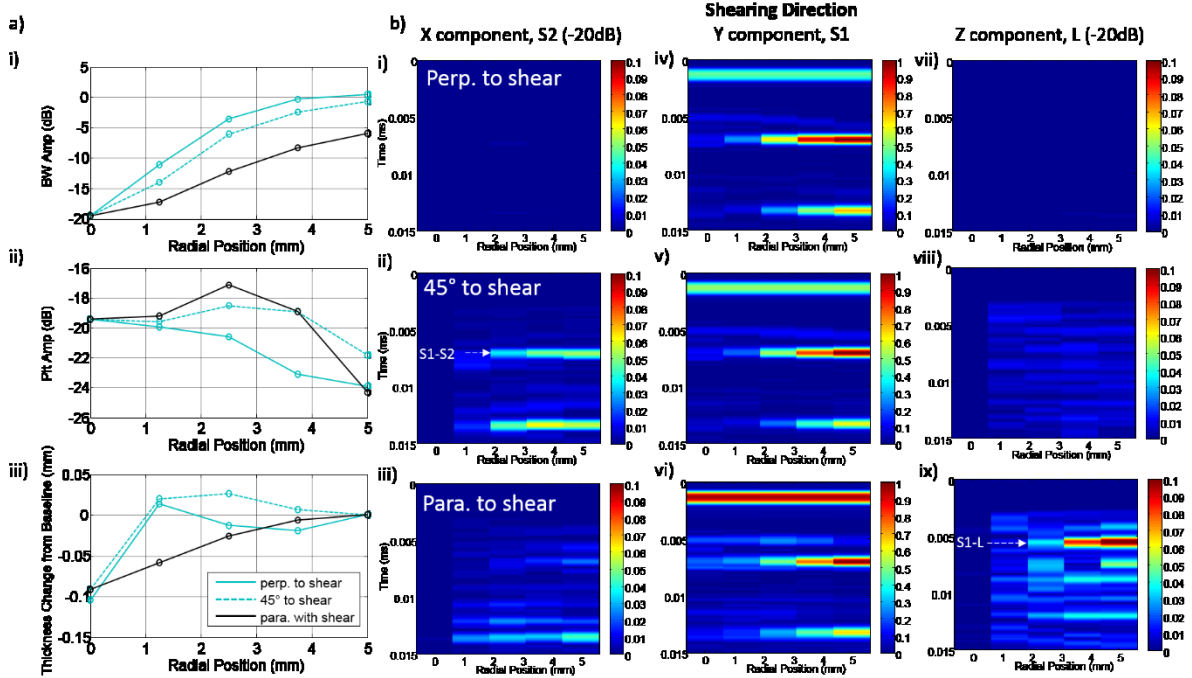


Figure 6.26 ai) Back wall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the waveguide with a 3mm hemispherical pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction)

6.5.3.2 Semi-Circular Compressional Transducer

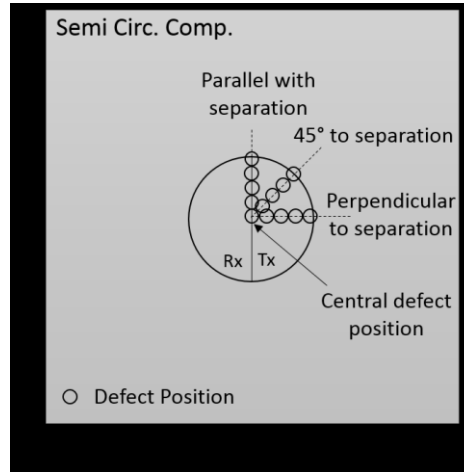


Figure 6.27. The three orientations (parallel, 45° and perpendicular) relative to the separation between the two halves of the semi-circular compression transducer.

The orientation of defects are defined relative to the separation between the two halves of the SCC, see Figure 6.27. The 3mm was chosen since it is the approximate limit of sensitivity of the SCC (from Figure 6.19) and can act as a comparison to the waveguide setup. There is a small amount of anisotropy between the parallel and perpendicular orientations (4dB max) - (Figure 6.28ai). However, this is much smaller than either the 10mm EMAT or the waveguide shear transducers as well as the anisotropy seen in the sloped back wall simulations. There is mode conversion to the x-shear direction (S_x) in all cases, however, as was established in section 6.4 there will always be mode conversion to a shear direction even with a flat backwall due to the edge effects of the semi-circular transducer (see L-L and L- S_x labels in Figure 6.28b). Therefore, the S_x mode is equally apparent in each orientation and increases in amplitude in a similar manner to the z component as the defect moves further from the central position. There are no obvious anisotropic effects in the pit amplitudes or the measured thicknesses (Figure 6.28aii and iii).

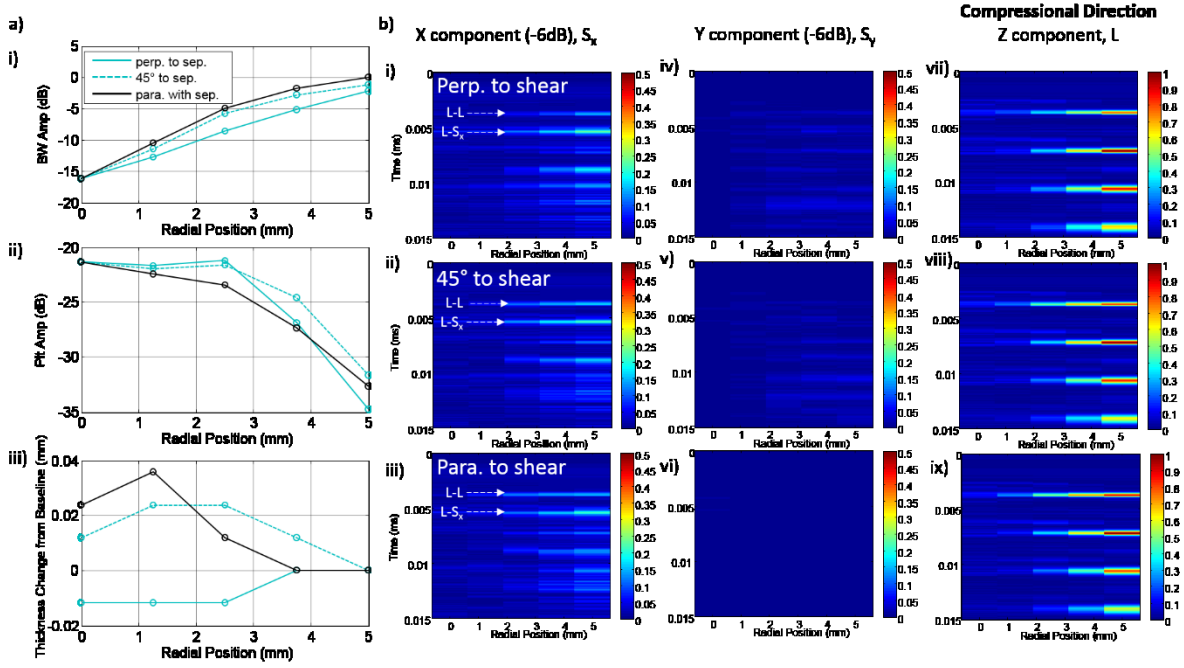


Figure 6.28 ai) Backwall amplitude, aii) pit amplitude, aiii) extracted thicknesses for the semi-circular compression transducer with a 6mm pit which varies its position in three orientations (parallel, 45° and perpendicular); b) shows the associated waterfall plots for the three orientations in the (i-iii) x, (iv-vi) y, and (vii-ix) z component. (Note: difference in colourscale for the plots that show responses in the directions perpendicular to the shearing direction)

6.5.4 Discussion of Observed Phenomena in Shear Wave Results: Beam Shape and Mode Conversion

In the shear setups, there is an anisotropic relationship observed between the shear bulk wave response and the pits. This relationship is due to two observable phenomena: the *beam shape* (which is due to the transducer shape) and *mode conversion*.

Figure 6.29 illustrates these two phenomena and how they influence the backwall and pit amplitudes. More FE simulations were performed to better illustrate the observed phenomena. The results are for a 12.5mm EMAT with a 6mm pit (top row) and waveguide with a 3mm pit (bottom row), and the pit positions were varied from $r=0$ to 10mm and $\theta=0^\circ$ to 90° in 22.5° steps (symmetry was assumed in both cases allowing for 360° images). Backwall amplitudes are displayed in (a) and (d) and pit amplitudes in (b) and (e). The effect of mode conversion due to the presence of a defect is visible in the EMAT backwall amplitude results. The mode conversion varies in accordance with the angular position of the pit relative to the shearing direction resulting in different values of backwall and pit amplitudes for the same radial position. No mode conversion is observed when the defect moves perpendicular to the principle shearing direction, S1. Along the 45° vector there is S1-S2 and S1-L mode conversion, with the former being prevalent. There is little to no S1-S2 mode

conversion in the parallel orientation whereas the S1-L mode is much more prevalent. This effect for both shear transducers is summarised by the overlay in Figure 6.29d.

Beam shape does heavily influence the waveguide's backwall amplitude, since the waveguide aperture has a much higher aspect ratio ($AR = \text{length}/\text{width} = 12$) compared to the EMAT ($AR=1$). This means that the waveguide is inherently anisotropic. Overall sensitivity to different defect radii is heavily dependent on the transducer size/beam characteristics. Generally, the larger the transducer footprint the greater the backwall amplitude at larger defect radii as a greater percentage of the pulse's energy is reflected off the backwall instead of the pit (Figure 6.19a).

The mode conversion and/or the beam shape phenomena are important in the backwall responses whereas the beam shape is the dominant phenomenon in the pit amplitude responses. Figure 6.29c and f show the first backwall reflection amplitude fields (over the same coordinate space as a-d) for the 12.5mm EMAT and waveguide respectively. The amplitude is not highest in the centre of either of the backwall amplitude fields, this is because the near field region of the beam is being measured, which is much more complex than the far field region (if it were able to propagate that far). This result is, therefore, beam shape and, consequently, thickness dependent. The waveguide maxima are also located along $y = -1\text{mm}$ where the Tx nodes are located. Common features to both the pit amplitude images and the first backwall amplitude fields are highlighted in the figures. Peaks in the pit amplitude occur at the same location as the peaks in the first backwall reflection amplitude field, in both the EMAT (A) and waveguide (B). The overall EMAT pit amplitude response is similar to its backwall amplitude field with both showing a local minimum at (0,0), as well as four peaks in the same locations (A). In the waveguide case the two horizontal fringes are visible in the pit amplitude response (B) as well as a horizontal line ($y=0$) of lower amplitude running between the two fringes (see the centre of area C).

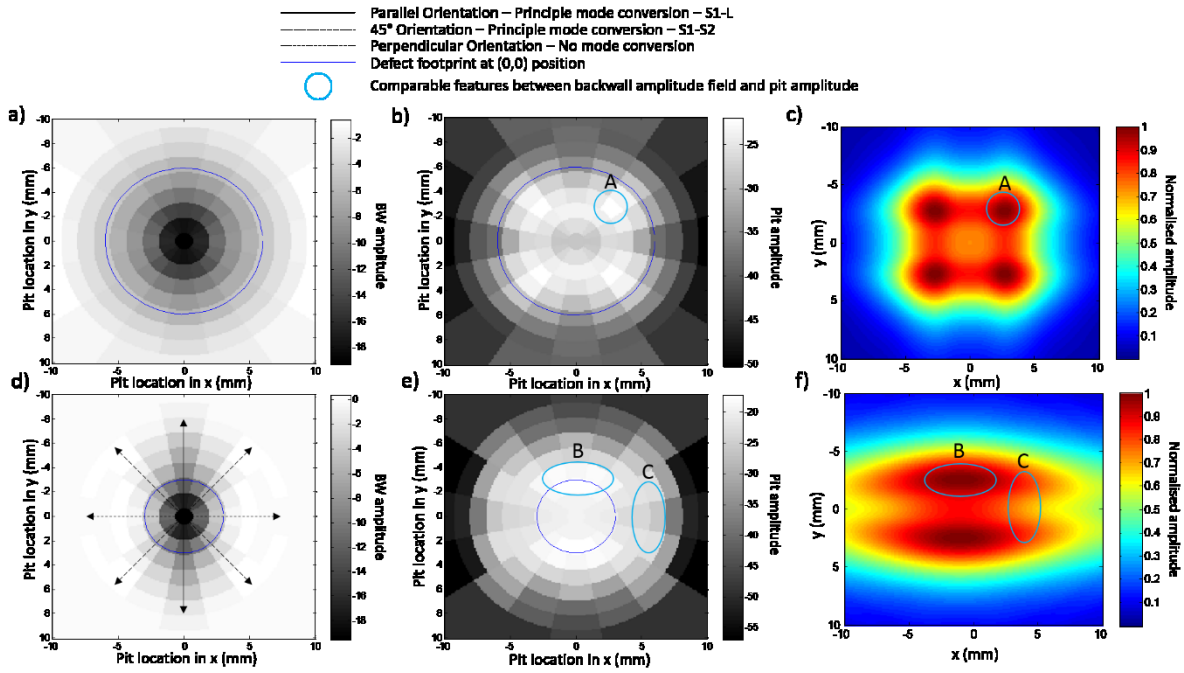


Figure 6.29. The top row are results from a 12.5mm EMAT with a 6mm pit and the bottom row from a waveguide setup up with a 3mm pit. a) and d) are the backwall amplitudes in an image format for defect positions of $r = -10\text{mm}$ to 10mm in 1.25mm steps and θ in 22.5° steps. b) and e) are the pit amplitudes plotted over the same position space as a) and d). c) and f) are expanded versions of Figure 6.10a and Figure 6.4e.

6.5.5 Experimental Validation of the Mode Conversion Phenomenon

An experimental EMAT setup was designed to replicate the simulations as well as to observe the anisotropic effect. The test plate was a 1" (25.4mm) mild steel plate (200mm x 150mm) which had various defects machined into it: four hemispherical pits (4mm, 5mm, 6mm, and 7mm radius), as well as two 2mm deep part thickness holes ($\varnothing 5\text{mm}$ and $\varnothing 9\text{mm}$), shown in Figure 6.30. Figure 6.30c shows the 3D printed jig which accurately controlled the position of the EMAT, allowing the EMAT to perform a B-scan over a defect. A height gauge was used to accurately locate the central positions of the defects on the top side of the test plate. The experiment used a custom made EMAT developed at Imperial College London [141]. The EMAT contains two butterfly coils arranged orthogonally to each other, each of which are accessible by a dedicated connector. This allows two measurements with orthogonal shearing directions to be made at the same location without having to rotate the EMAT. Figure 6.30a also shows a schematic of the experimental setup and a photograph of the setup. A PC interfaced with a HandyScope HS5 (TiePie, NL) which input a toneburst into a custom made EMAT driver. A USB-RLY08B 8 Channel relay module (Devantech, UK) was used to select between the two EMAT coils, allowing the desired coil to excite an ultrasonic pulse in the sample. The EMAT driver then switches to receive mode and amplifies the received signal, which is inputted into the PC via the HandyScope. A dial gauge (British Indicators Ltd, UK) with a 0.01mm resolution was used to accurately measure the position of the EMAT.

A 2MHz 3 cycle Hann windowed pulse was used as the excitation toneburst, with 500 averages per measurement.

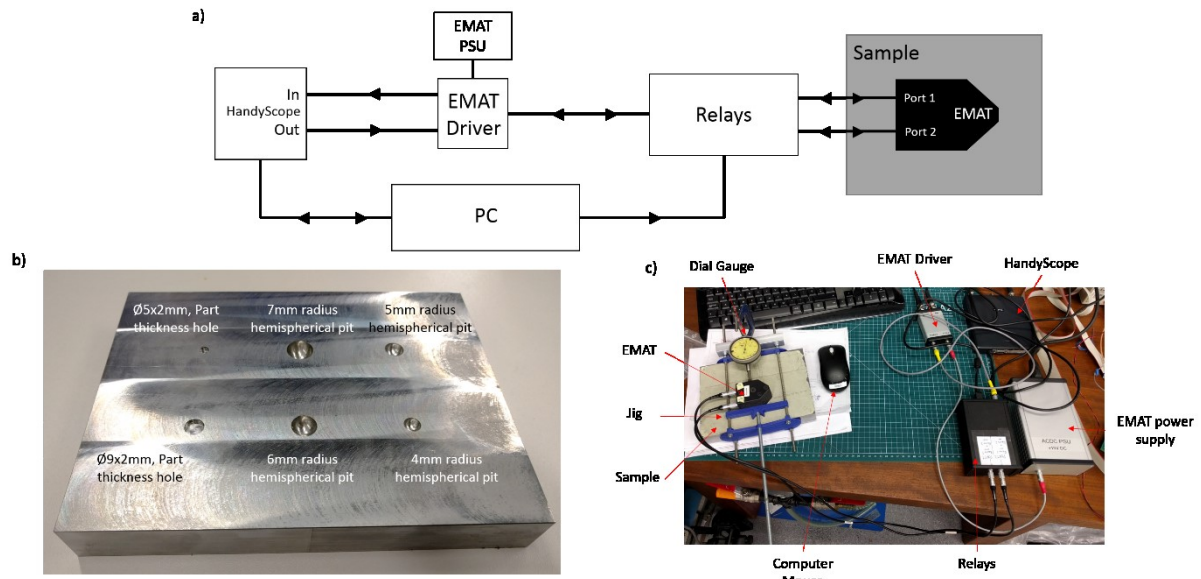


Figure 6.30 a) schematic of the experimental setup, b) photograph of the test plate sample, and c) a photograph of the experimental setup taken in February 2017

Experimental data was gathered over a distance of 15mm in the perpendicular and parallel orientations, starting with the EMAT positioned directly over the 6mm defect. The experimental data was normalised by selecting the point on the raw data set at which the backwall amplitude plateaus. It is at this point when the pit is no longer affecting the measurement. This location can therefore be counted as being a clean back wall signal. All the raw data points were then normalised to the mean of the clean backwall signals. The error bars are calculated by taking the standard error of the backwall amplitudes of the clean signals. FE scans were performed similar to the one in Figure 6.25 using 6mm hemispherical pit and a 1" (25.4mm) thick model. The radial distance of the pit was extended to 10mm. The 6mm results are shown in Figure 6.31. There is a good fit between the simulated and experimental data for both parallel and perpendicular orientations. Furthermore, the anisotropic effect is clearly visible with a -3dB difference between the perpendicular and parallel orientations at a radial distance of 5mm.

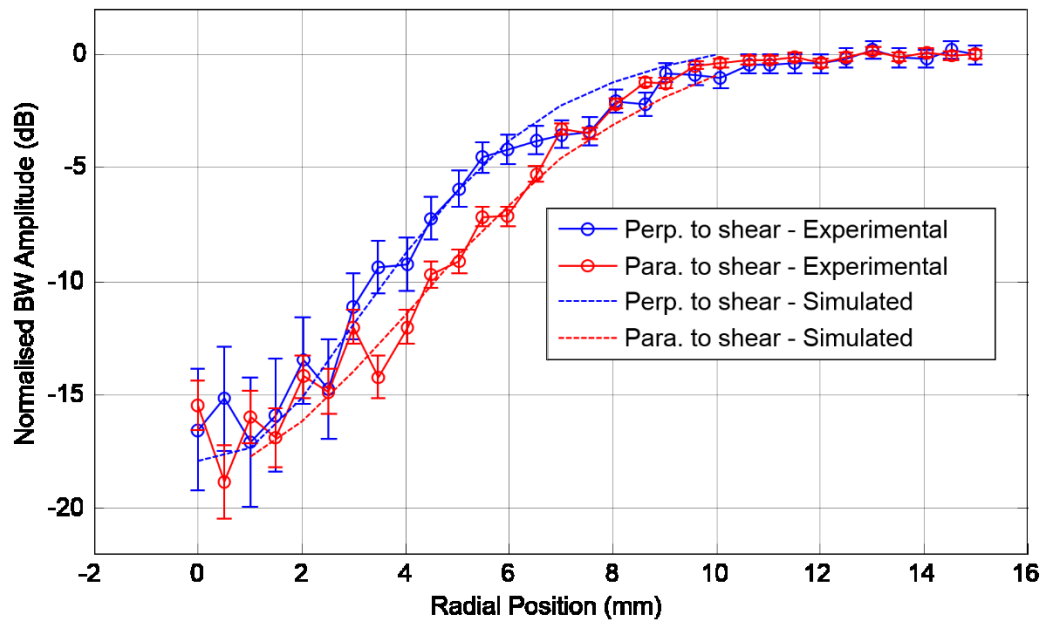


Figure 6.31 Measured experimental backwall amplitude of a 6mm defect with a radial position between 0 and 15mm (solid lines), and the simulated back wall amplitude of an EMAT12.5mm on a 1" plate with a 6mm defect with a radial position of 0 to 10mm (dashed lines). Both the perpendicular (blue) and parallel (red) orientations are shown

A FE and experimental scan of the 4mm hemispherical pit were also performed (Figure 6.32). The results show no discernible difference between the parallel and perpendicular orientations. Therefore, it was concluded that the anisotropic effect observed in Figure 6.31 is real and not due to the discrepancies between the two EMAT coils.

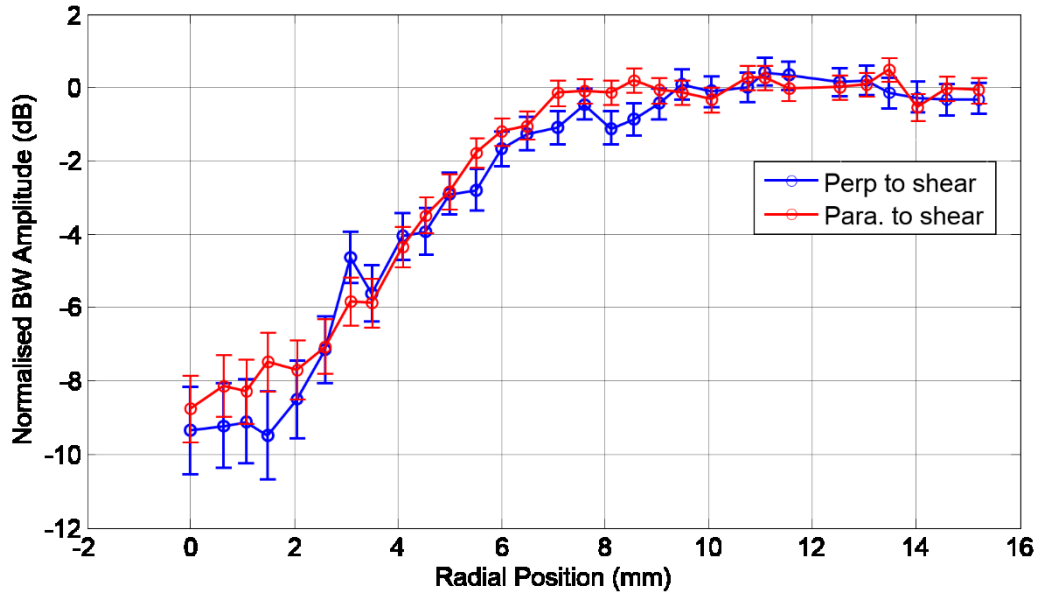


Figure 6.32 Measured experimental backwall amplitude of a 4mm defect with a radial position relative to the centre of the EMAT between 0 and 15mm, both the perpendicular (blue) and parallel (red) orientations are shown

6.6 Future Transducer Design Considerations

It is apparent from these results how the presence of pitting may influence and attenuate backwall reflections and distort wall thickness measurements; however, is it possible to exploit these phenomena further to design a transducer with increased sensitivity to pitting? For example, designing two transducers in one housing which is able to excite a shear wave in two orthogonal directions. Furthermore, by altering the dimensions of the transducer setups can the sensitivity of spot measurements to pitting be increased? The effect of EMAT aperture size has briefly been qualitatively touched on, however, if this were to be considered in transducer design then a quantitative metric of sensitivity would need to be devised.

6.7 Summary

The results above have demonstrated that there are two principle phenomena influencing the bulk wave interactions with corrosion like pits: beam shape and mode conversion. Both phenomena are dependent on the transducer setup used and this has many implications for NDE and spot measurement design. The model presented in chapter 5 assumed a perfect transducer, which could detect any defect which was placed directly under the transducer. As expected, the results not only demonstrate that the perfect transducer assumption is

wrong but also that the anisotropic relationship between the response and pit position means that the resulting sensitivity is much more complicated.

Chapter 7 will explore in detail the idea of using a single spot measurement sensor as a method of monitoring a single known pit. This will involve detecting a sub-critical pit using alternate means (e.g. c-scan) and placing a spot measurement at that location to monitor it. Once the pit has become critical the pipe section can be removed/decommissioned, the sensor removed, and used at a new location. The results from the simulations will enable the evaluation of this concept. Attention will be given to the signal processing, transducer design and the evaluation practical considerations such as locational/positional error.

Chapter 7

Preliminary Evaluation of an Individual Pit Monitoring System

7.1 Introduction to an Individual Pit Monitoring System

In chapters 5 and 6 the idea of using a single bulk wave transducer to monitor a pit was briefly discussed. This involves placing a bulk wave transducer over a pit which has already been detected by another means, such as for example a c-scan. The sensor will then monitor the pit, until it has reached a certain threshold (e.g. depth threshold). When the threshold is reached the operator can be alerted and a decision can be made on how to proceed. Pit monitoring and tracking is commercially available [9], however, as the results in chapter 6 showed there are several factors which will influence the bulk wave reflection from a pit. Furthermore, there is little publicly available information analysing the suitability and reliability of using bulk waves to monitor and/or track pits. This chapter looks at this concept in more detail, not only by further analysing chapter 6's FE model results but also by highlighting potential conceptual and procedural issues.

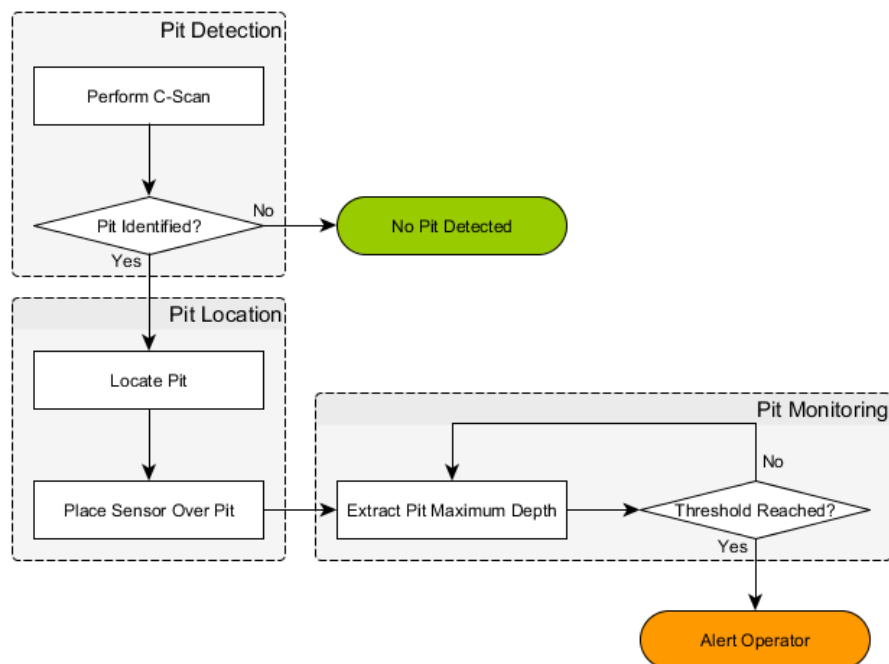


Figure 7.1 Three phases of operation of an individual pit monitoring system (IPMS)

Figure 7.1 shows a flow diagram of the idealised workflow of an individual pit monitoring system (IPMS), which is split into three distinct phases: initial pit detection, pit location and pit monitoring. In this analysis, the initial pit detection methodology will not be considered in detail (phase one). The main focus of this chapter is on the process of pit location (phase two) because any errors at this stage (e.g. unprecise placement of the transducer) may affect the ability of the transducer to monitor the pit successfully (see section 7.1.1.2). Furthermore, a spatial technique (such as ultrasonic c-scans) is able to detect a pit using the relative difference between adjacent measurements, and when presented in a 2D image format changes in amplitude or TOF, for example, due to the presence of a pit will be more easily apparent. However, a single transducer is only able to rely on the information it receives in the reflected signals (A-scans), and a pit must be identified within a time trace before tracking can commence. The setup described here presumes that the information from the pit detection method is not available to be used by the IPMS (see section 7.1.1.1). This study looks to assess whether currently available turnkey solutions are able to be adapted for pit monitoring purposes. Before any consideration can be given to pit tracking and monitoring it must first be determined whether or not a pit can be identified and measured by the IPMS. Elementary conclusions regarding the tracking/monitoring ability of an IPMS will be drawn (phase three - Figure 7.1).

The next section will explain the framework in which this analysis will be conducted, as well as explicitly state any assumptions which are being made. Any known issues regarding the idealised operation described in Figure 7.1 will also be discussed in section 7.1.1. The FE results from the previous chapter will be used in the evaluation and analysis. Section 7.2 will present a selection of representative time traces from certain simulations, providing an initial qualitative analysis of the different responses from the pits. These results form the basis of the detection routines created to quantitatively analyse the different transducers. The quantitative results are then presented followed by discussion and conclusions.

7.1.1 Discussion of Potential Issues and Analysis Framework

Before presenting the raw time trace data in an IPMS context, the framework of the analysis must be explicitly stated as well as any assumptions. Furthermore, any existing issues regarding the techniques and technologies will be discussed here, either from the knowledge gained in the previous chapter or from other sources.

7.1.1.1 The Use of A Priori Information

The complexity and age of modern oil and gas infrastructure means that there are thousands of different components within a single site, many of which were installed decades ago whose individual specifications/technical drawings are no longer available or accessible.

Performing lengthy diagnostics on a component before the installation of a sensor would be expensive and increase the complexity of the system elsewhere (e.g. storage of more data). Therefore, the less information and time required to quantify the integrity of the component the better. The IPMS is envisioned as using the same technology as existing permanently installed wall thickness monitoring systems. The knowledge afforded to these system's post-processing routines is the wave speed, c_s , dimensions of the transducers (i.e. separation between Tx and Rx transducers) and the input toneburst parameters (centre frequency and window width). The IPMS post-processing also can use the fact that the sensor has been placed over a pit. Temperature and environmental effects are neglected in this study. It is entirely possible that when the operator performs the initial defect detection, which locates the defect, the information gained in that scan could be used in the subsequent pit monitoring and tracking. However, for the time being, the least amount of available information has been assumed.

7.1.1.2 Placement Error, Number of Operators, and Compatible Techniques or Equipment

The manner in which the workflow in Figure 7.1 is implemented will affect how precisely the IPMS sensor is placed over the defect, and as the previous chapter has shown the sensitivity to pits of bulk wave sensors is dependent on the relative position between the two. There are two time points during the entire IPMS process where positional errors can arise. The first is at detection, when the operator identifies a pit which will need to be monitored and subsequently notes its position (See 'Locate Pit' in Figure 7.1). The second-time point is when the location of the pit is interpreted, and using that value the operator then places a sensor over where he or she has determined the pit to be located (See 'Place Sensor Over Pit' in Figure 7.1). The contribution of these two errors to the total value of placement error will depend on the way the detection and sensor placement is carried out. In this report the first positional error (detection and location of defect) will be presumed to be equal to the second (sensor placement).

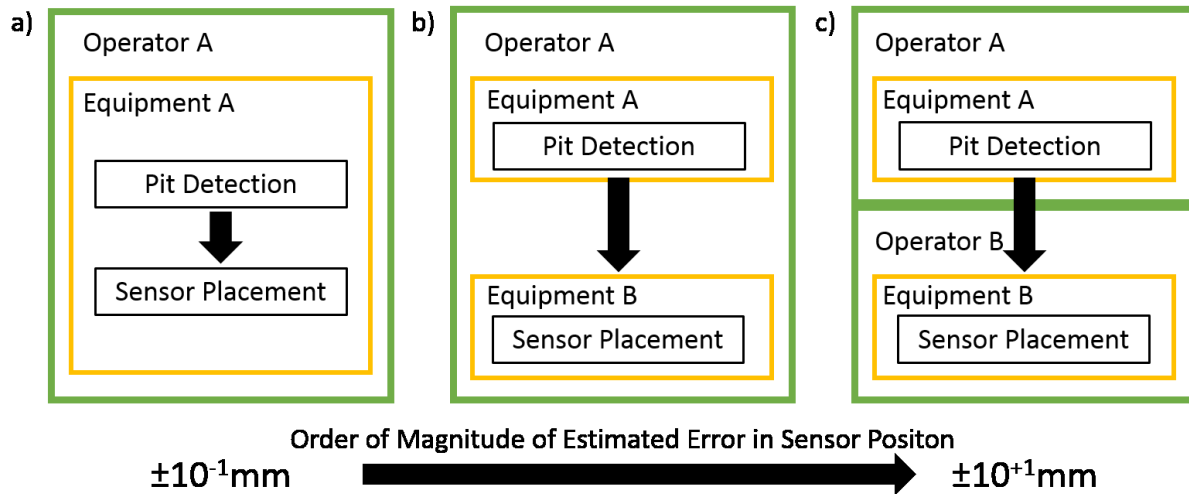


Figure 7.2 Three possible permutations of pit detection and sensor placement during IPMS implementation

Figure 7.2 shows three different permutations of the methodology which depends on the number of operators involved and equipment used. The first permutation (Figure 7.2a) uses a single operator and a single setup/piece of equipment to perform the pit detection and install the sensor. Two potential methods of achieving this are now described, based on simple adaptations to existing NDE technology:

- C-scan raster scan with jig attachment. The scanning head, which houses the c-scanning ultrasonic probe, could also house a jig/guide to precisely place the sensor after a pit has been identified. It would work as follows: perform full c-scan of a specimen; identify any pits within the c-scan image; move scanning head to the location of the pit(s) but with a known offset so that the jig/guide is positioned above the pit; place sensor into jig/guide.
- Tracking of detection transducer (e.g. Optically [146]). By tracking the position of the detection transducer (which could be scanning manually or automatically) will allow the operator to locate the pit using the tracking system's own coordinate system. If the monitoring sensor was integrated into the same positional tracking system (e.g. a reflective element was mounted on the sensors, and tracked by an optical or visual system) then the sensor could be placed over the pit with an accuracy similar to that of the tracking system.

In both of these example systems the positional error would be dictated by the positional error of either the motorised scanning rig (0.5mm [130]) or the optical tracking system⁸ (<0.22mm - [147]).

The second methodological permutation (Figure 7.2b) relies on the same operator performing the pit detection and sensor placement but using different equipment for either tasks. For example, this could involve the pit detection being performed by a c-scan crawler, which scans an area of pipe, and only after the scan has finished does the operator review the c-scan data to locate any defects. In this scenario, the operator may be able to better locate defects since they'll be writing the inspection report and any accompanying technical drawings. It is hard to quantify the error from this method since there are many factors which could influence the error. However, it is reasonable to assume that the placement error would sit between the methods shown in Figure 7.2a and Figure 7.2c.

The third methodological permutation (Figure 7.2c) involves separate operators and equipment being used for detection and placement. In this case a first operator will perform an inspection and write an inspection report which will include information on the location of the pit. The second operator will now be tasked with locating the pit and placing the sensor. It is presumed that the second operator does not rescan the area to find the pit, if he or she does then the error would be similar to either method A or B depending on the equipment used. The reporting of corrosion maps and defects is dependent on the company providing the service, and therefore there is no standard way of locating a pit. Many NDT inspection reports, however, use engineering drawings of the parts to indicate the location of the pit. On this basis the pit's location is defined relative to a datum, then using this information the location of the pit can be determined. The author is unable to find any NDT related studies which quote a sensor placement error value, however, land surveying uses many of the same skills to locate features within an area. Furthermore, these skills are implemented on a similar spatial scale (1m-100m) and in similar environment (i.e. outside of buildings and large man-made structures). The American surveying standards body, ALTA (American Land Title Association), state a maximum allowable positional tolerance of 20mm [148]⁹. This figure will guide the range of defect positions modelled, i.e. $\pm 10\text{mm}$ around the centrally located point under the transducers.

⁸ The NDT specific system referred to previously (Technology Design Ltd, UK) does not quote a value of positional precision, therefore a general optical tracking system tolerance is quoted (i.e. motion capture)

⁹ Modern surveying equipment (if required) can measure down to the tenths of mm range [160]

7.1.2 Finite Element Model

The results presented in this chapter used the signals acquired by the finite element model described in the previous chapter. The results used were from hemispherical pits with 2-5mm and 4-7mm radii which were interrogated with the waveguide setup and 12.5mm EMAT setups respectively. Time traces from the 10mm EMAT interrogating a 6mm pit are also shown. As with the results in chapter 6, the symmetry of the pit positions relative to the transducers was assumed, enabling 360° images to be produced by only modelling the 0°, 45°, and 90° angular positions, like those in Figure 6.29. The switching speed from Tx to Rx is not considered or modelled.

7.2 Analysis of Different Time Traces and Classification Scheme

Example Hilbert enveloped time traces are shown in Figure 7.3 and Figure 7.4 from simulations using either the 10mm EMAT with a 6mm pit and waveguide with a 4mm pit respectively. The figures show the defect located at three different angular positions (0°, 45°, 90°) and five different radial positions (0, 1.25, 2.5, 3.75, and 5mm). The three highest peaks have been indicated on the time traces. All the time traces described in 7.1.2 formed the basis for a classification system which has been devised to classify the different responses from different pit sizes using different transducers. This will then allow for the analysis of how pits can be identified and monitored, as well as form the basis of automated detection routines. In this section, the patterns in the data which do or do not indicate the presence of a defect are discussed and classified in Figure 7.5. It is important to note that noise is not included in this analysis. The analysis is mainly interested in the ‘shape’ or ‘patterns’ within the time traces, which indicate the presence of a defect and not whether those peaks can be identified above a threshold or not. The amplitudes are normalised to the amplitude of the first backwall signal without a defect present.

Figure 7.3 shows the enveloped signal response from a 6mm pit using a 10mm EMAT at various positions relative to the transducer. The top row represents the (0,0) position and is the same figure repeated across the row. A single peak (at 2µs) is prominent, which is the reflection from the top of the pit. The anisotropic response of the shear wave signal is again apparent, especially between the relative difference in amplitude between the pit signal and the first backwall signal (at 7µs) in various time traces. In accordance with the results in chapter 6, their relative amplitudes differ depending on the angular and radial position of the pit. For example, at r=2.5m the backwall amplitude at $\theta = 0^\circ$ is half that of $\theta = 90^\circ$. Also, the backwall amplitude at $\theta=0^\circ$ from r=2.5-5mm is consistently lower than the other

two angular orientations. At $r=3.75\text{mm}$ and 5mm the familiar backwall decay appears, characterised by a series of three evenly spaced peaks which descend in amplitude as TOF increases. The $r=3.75\text{mm}$ time traces (and $r=5\text{mm}$ albeit with reduced pit amplitude) show the pit signal and a backwall decay signal. Interestingly, this result could potentially yield the most information since the nominal thickness of the pipewall is able to be monitored along with the pit depth from a single time trace.

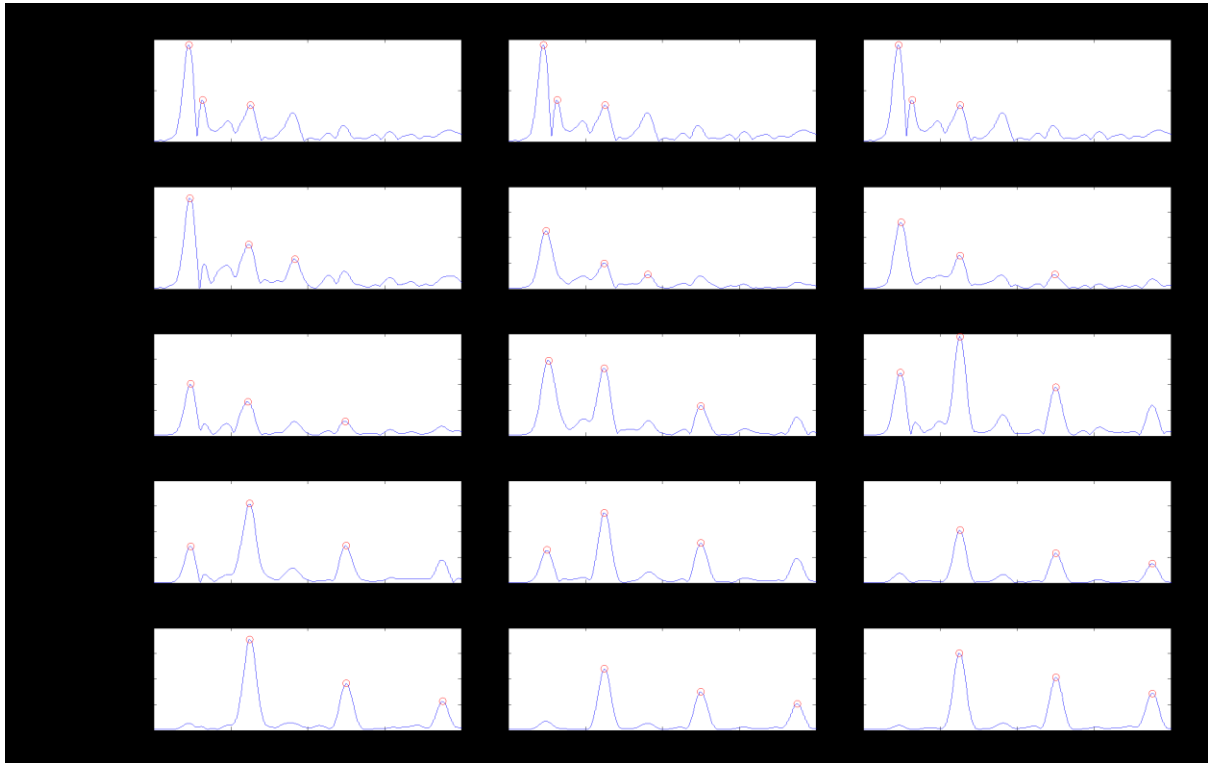


Figure 7.3 Hilbert enveloped time traces from a 10mm EMAT exciting a 2MHz 3 cycle pulse in a 10mm steel plate, sonifying a 6mm radius pit placed a range of locations relative to the transducer.

Figure 7.4 shows the enveloped signal response from a 4mm pit with various radial and angular positions using a waveguide transducer. Again, the anisotropic behaviour seen in chapter 6 is observed here. Especially when comparing the relative backwall and pit amplitudes in the $r=2.5\text{mm}$, $\theta=0^\circ$ and the $r=2.5\text{mm}$, $\theta=90^\circ$ cases. The backwall decay is not obvious in the $r=0-2.5\text{mm}$ cases, and either a single pit signal or twin peaks (pit and backwall signals) dominate. The backwall decay is again visible in the $r=3.5$ and 5mm cases along with the pit signal, whose amplitude depends on the relative orientation of the pit to the transducer.

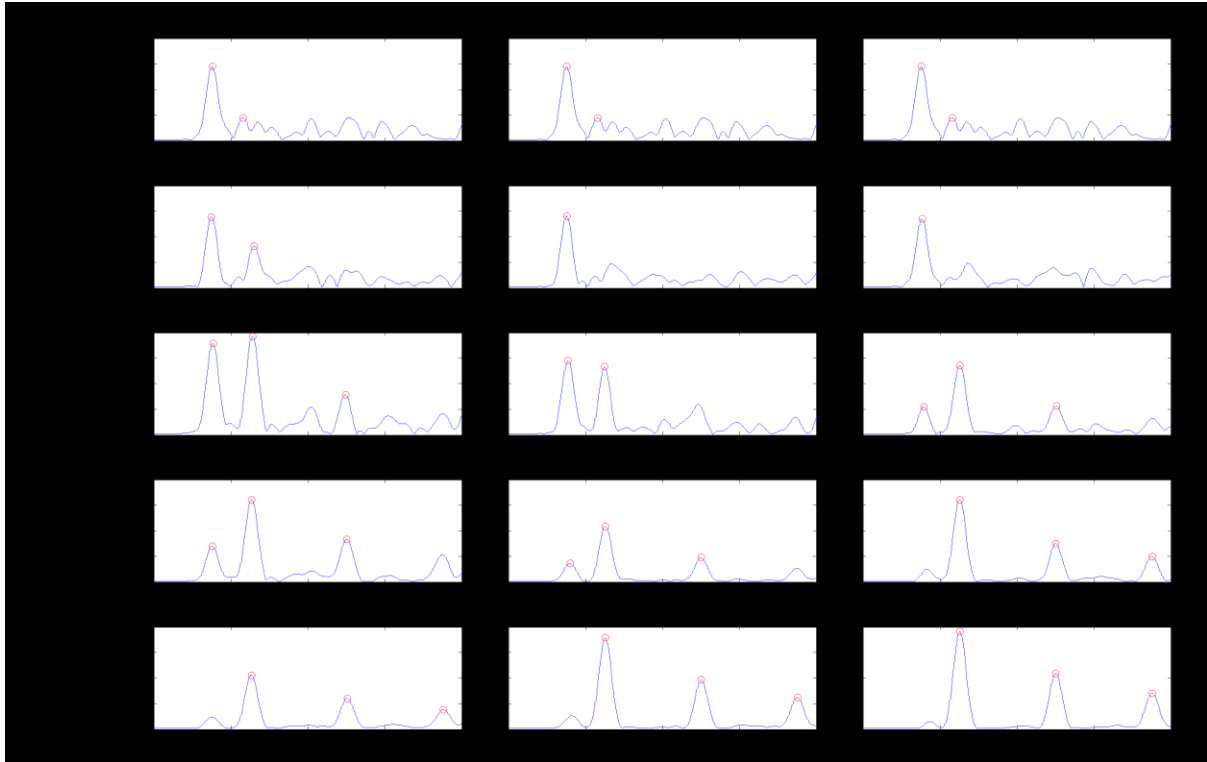


Figure 7.4 Hilbert enveloped time traces from a waveguide transducer exciting a 2MHz 3 cycle pulse in a 10mm steel plate, sonifying a 4mm radius pit placed at a range of locations relative to the transducer.

7.2.1 Classification Scheme

Figure 7.5 shows the classification scheme which has been devised based on qualitative analysis of the time traces generated by the finite element model, of which a representative selection has been presented in Figure 7.3 and Figure 7.4. This analysis will inform the quantitative methods and analysis which are devised and implemented in sections 7.3 and 7.4 respectively. The signals from different pits with various locations have been classified into three classes which broadly represent signals in which: pitting is not detectable (class 1); pitting is detectable (class 2); and where there is insufficient information to perform any analysis (class 3)

Class 1 encompasses signals which are unable to identify a pit since there is no information contained within the signal which relates to a pit. If a defect is not present, the signal received by the transducer is a backwall echo which has defined characteristics (Figure 7.5 - Class 1A), such as regular spacing of reflections and a decreasing amplitude of said reflections over time. Depending on the transducer, if the pit is sufficiently small and/or not located directly under the transducer no pit signal will be detectable, however, the backwall echoes may be attenuated in some manner (e.g. scattered or mode converted). In this case (Class 1B) there is still no information relating to a pit contained within a single time

trace¹⁰ but there is a notable amplitude decay. An example of this time trace is Figure 7.3 $r=5\text{mm}$, $\theta=90^\circ$.

Class 2A signals contain a steep backwall decay as well as a pit signal located before the first backwall echo. In this case, there is information contained within the signal relating to the presence of a pit. The $r=3.75\text{mm}$ $\theta=0^\circ$ cases in Figure 7.3 and Figure 7.4 are examples of this signal.

Neither of the Class 2B or 2C signals contain a backwall decay, however, they do contain either two prominent peaks (pit and backwall signal - Class 2B) or one prominent peak (pit signal only - Class 2C). Unlike Class 1 signals which contained backwall information but no pit information Class 2C contains pit information but no backwall information, in this case we are able to make use of the fact that a transducer is knowingly being placed over a pit and therefore the received signal is due to the presence of a pit. If a Class 2C signal were to be received with no prior knowledge of pipewall condition, this assertion could not be made. Example of Class 2B signals are shown in Figure 7.3 $r=2.5\text{mm}$ $\theta=0^\circ, 45^\circ$ at all angular orientations or Figure 7.4 $r=2.5\text{mm}$ $\theta=0^\circ, 45^\circ$. The two time traces in Figure 7.3 and Figure 7.4 at $r=0\text{mm}$ are examples of Class 2C signals, as well as the $r=1.25\text{mm}$, $\theta=45$ or 90° in Figure 7.4.

There is obviously some cross over between the three Class 2 subclasses. For example, in both Figure 7.3 and Figure 7.4 the $r=2.5\text{mm}$ and $\theta=90^\circ$ cases have two prominent pit and first backwall echoes as well as a visible second backwall echo. However, the third backwall echo is potentially not clear enough to verify a backwall decay. However, this cross-over between subclasses is not as important as any potential cross-over between Class 1 and 2 signals, since this is the demarcation point between not being and being able to identify a pit. Therefore, particular attention will be paid in the next section to designing an algorithm to detect the presence of a backwall decay within the signal.

7.2.1.1 Further Discussion and Inferences from the Time Traces Results

Class 3 signals have been included in the classification system to cover any signal where there is no prominent peak. Since this analysis is yet to incorporate noise then a pit and/or backwall signal will always be observed no matter how low in amplitude¹¹. However, once

¹⁰ If an array of measurements were used then relative differences between backwall amplitudes or decay rates may be an indication that a pit is present.

¹¹ Reverberations around the FE model may cause a form coherent noise in the FE signals, however, in all cases modelled a pit and/or backwall signal was always observed.

noise is added to the time traces prominent peaks may fall below the noise level and become undetectable, depending on the SNR.

Although not directly observed in the examples above, it is possible for false negatives to be present, especially with a half thickness defect (e.g. 5mm pit in a 10mm plate). If multiple reflections were to occur from the deepest point of the pit, then a decay would potentially be visible as the multiple pit and backwall reflections attenuate over time. Obviously, this decay signal would yield a reduction in thickness, however, in the context of a single sensor IPMS (with no a priori thickness information) then this system could presume a clean backwall signal.

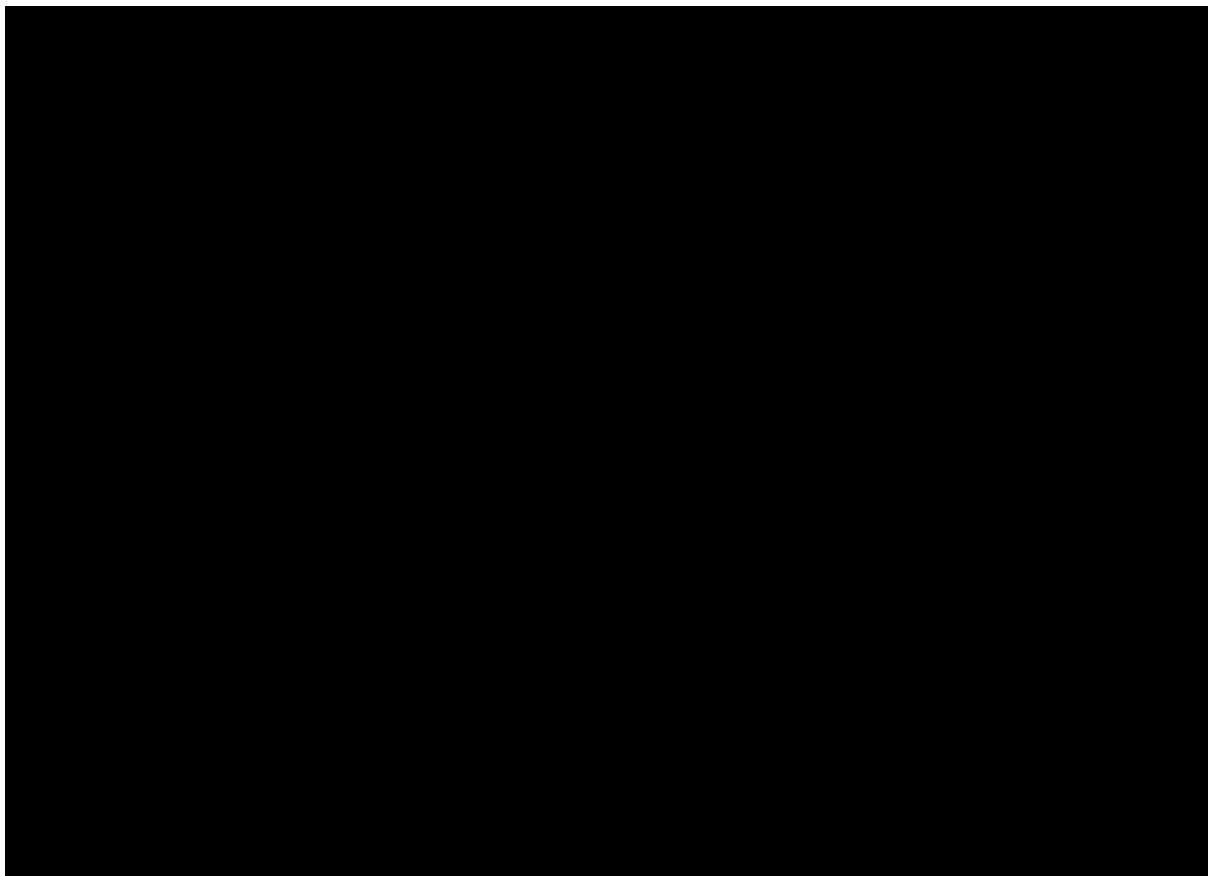


Figure 7.5 Illustrative time traces of the devised classification scheme, showing the class 1 (pit not detected), class 2 (pit detected), and class 3 (ambiguous) time traces - and all sub classes

7.3 Identification Routines

Identification routines have been designed based on the classification scheme above, to automatically classify the time traces produced by the finite element models. The algorithms are based on the order and amplitude of the three highest peaks in the enveloped time trace. There are many different, more advanced and complex algorithms which could be implemented to classify the time traces, however, the routines presented here have

been purposefully designed to be a foundation upon which more complex routines can be written.

7.3.1 Presence of a Backwall Decay: Class 1 Identification

The backwall decay is due to multiple reflections from the top and bottom surfaces of a plate or pipe wall and is a characterisable effect, which primarily consists of two characteristics: multiple reflections descending in amplitude, and the reflections occurring at constant time intervals. The identification routine described in Figure 7.6 is based on determining whether these two factors are present in the first three maxima/peak of a time trace.

First, the Hilbert envelope of the time trace from the finite element model, $|\hat{s}[n]|$ (which is a function of samples, n , with maximum samples, N), is calculated. All the maxima amplitudes, $Max[i]$, of $|\hat{s}[n]|$ were found by finding the samples which satisfied:

$$Max[i] = (|\hat{s}[n]| - |\hat{s}[n-1]| > 0) \& (|\hat{s}[n+1]| - |\hat{s}[n]| < 0), n = 2, \dots, N-1 \quad (7.1)$$

The samples (or indices), n , at which the maxima occur are also logged in $Ind[i]$. $Max[i]$ is then sorted in descending order giving $Max[j] = \text{sort}(Max[i])$, and only the top three values are used, therefore $j = 1, 2, 3$ ¹². The array of indices is also sorted as per $Max[j]$, giving $Ind[j]$.

Using $Ind[j]$ (i.e. the temporal locations of the three highest maxima) the equivalent thicknesses, $T[j]$, are calculated using the transducer separation, d , shear wave velocity, c_s , sampling rate, f_s :

$$T[j] = \sqrt{(c_s Ind[j] / 2j f_s)^2 - (d/2j)^2}, \quad j = 1, 2, 3 \quad (7.2)$$

These three thicknesses can then be compared to the thickness, T , extracted using the standard/generic thickness algorithm described in 6.3.2, to calculate the errors in the three thickness values:

$$\Delta T[j] = |T - T[j]| \quad (7.3)$$

¹² The routine described only considers the relative amplitudes and temporal order of the three highest amplitudes. Further complexity and pit identification fidelity may be achieved by increasing the number of pits analysed, however, this is beyond the scope of this study

If any thickness error value is greater than a predetermined threshold, then the maxima are not evenly spaced and/or descending in height and the time trace is classified as not a class 1. A threshold value of $\pm 0.5\text{mm}$ was used in the analysis unless otherwise indicated.

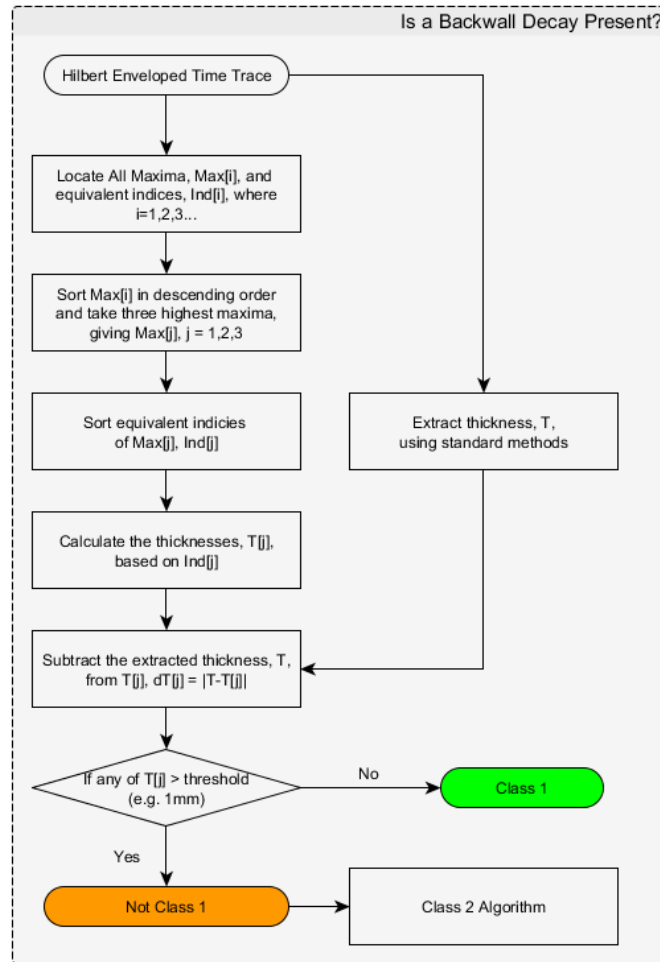


Figure 7.6 Workflow of the class 1 routine

7.3.1.1 Clear Pit Signal: Class 2 Classification

A routine is outlined below which classifies the non-class 1 time traces into classes 2A, 2B, or 2C. Although the boundary between class 1 and 2 designates the whether a particular setup is sensitive to the presence of a defect, further classification of the time trace would aid pit tracking. Also by outlining the method here the bounds of the three sub-classifications are definitively defined. A flow chart of the method is shown in Figure 7.7.

The signal maxima, $Max[j]$, and the corresponding indices, $Ind[j]$, are calculated using the method in section 7.3.1. If the highest maximum is temporally located after either the second or third maxima, then the time trace is classified as a Class 2A. In this case the first backwall echo has the largest amplitude but the first pit echo (and potentially the second pit echo) have larger amplitudes than the second and/or third backwall echoes.

Class 2B and C are differentiated by how prominent the highest maximum is compared to the second. This method uses an arbitrary threshold. If $Max[2] > Max[1]/4$ then the time trace is classified as a Class 2B and if $Max[2] < Max[1]/4$ then the time trace is classified as a Class 2C. Using the FE time traces and identification routines shown here, a time trace will always be classified. This is a valid assumption since the idea behind the IPMS method is to place a transducer over a known pit.

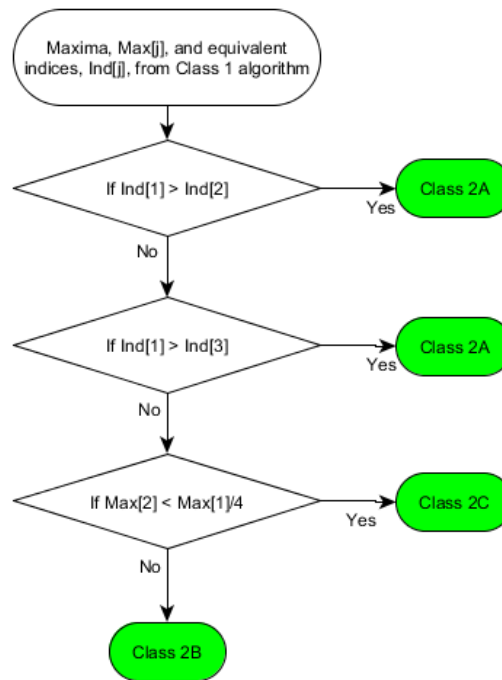


Figure 7.7 Workflow of the class 2 routine

The class 1 algorithm effectively states that if the three highest peaks are evenly spaced and in descending order with time then a class 1 time trace has been identified. However, it is possible for a clear pit signal to be temporally located before the first backwall reflection, but lower in amplitude than the third backwall echo. This step has not been included in either the class 1 or class 2 identification routines as the third backwall signal effectively acts as a threshold. Furthermore, for the analysis of this permutation to be of use the pit signal would need to be compared to a range of noise levels, which is beyond the scope of this initial study.

7.3.1.2 Thickness Algorithms – Generic and Class 2

Two thickness algorithms were used in the study presented in this chapter. The first is the ‘generic thickness algorithm’, and is identical to the method described in section 6.3.2, which effectively identifies the temporal location of the highest amplitude pulse using cross-correlation, from which it can calculate the TOF and thickness. The analysis was performed alongside the pit identification routines since current wall thickness sensors will primarily

report a wall thickness value only. Therefore, by performing this analysis in parallel we can see at what point pit radius and position cause the thickness to deviate away from the nominal thickness.

A pit signal is not necessarily the highest amplitude peak, and by first running the class 2 identification algorithm and identifying the presence of a pit reflection a second thickness algorithm can be used to determine the temporal location of the pit reflection, from which the TOF and remnant thickness can be calculated. This is called the ‘class 2-thickness algorithm’. For the sake of simplicity, the pit reflection’s temporal location was determined by finding the location of the maximum of the reflection’s envelope, and not by cross-correlation.

This also allows for the quick analysis as to whether thickness change could be used as a form of pit identification. If the operator were to know the nominal thickness, then a sudden change of thickness (as was seen in Figure 6.19, when the pit signal exceeded the backwall signal), is an indication of the presence of a pit.

7.3.1.3 Potential Class 3 Identification: Added Noise and No Prominent Peaks

A class 3 detection routine is not possible without the addition of noise to the time traces since all pit sizes and positions will produce either a pit signal or backwall signal which will be classified as Class 1 or 2 signal. It is possible for noise to be added to the signal in the same manner as described in chapter 3, using the defect-free first backwall echo as a reference level. A class 3 classification routine could then be devised and applied to a noisy time trace. Noise levels will also influence the various pit thresholds, described in sections above.

7.4 Results

7.4.1 Waveguide Setup

7.4.1.1 Class 1 and Generic Thickness Algorithm

Figure 7.8 shows the class 1 algorithm images (top row) applied to the waveguide time trace data over a range of different pit positions (x , y) and radii, as well as the generic thickness algorithm images (bottom row) over the same pit parameter space. As the pit radius increases the area over which a backwall decay is not detected increases. The same area in the 2mm and 3mm images have no identifiable backwall decay, whereas the 4mm and 5mm class 1 images show increasing sensitivity to the pit due to the lack of a backwall decay. In each case the area is similar in size to the pit diameter (shown in blue) and suggests that as long as the waveguide is within ($\pm$ pit radius, $\pm$ pit radius) it will be able to identify that a

pit is present. In all cases there is also an anisotropic effect with the waveguide having greater sensitivity to the pit in the y direction (along the same direction as the shear excitation, S1). When the generic thickness algorithm is applied the 2mm and 3mm pits are unable to be measured, since the pit signal is not greater in amplitude than the backwall signal. The 4mm and 5mm pits can measure a thickness change albeit over a smaller area than the pit's footprint. The correct maximum remnant thickness is extracted in both cases. Half the true thickness maps of the pits are superimposed over the images.

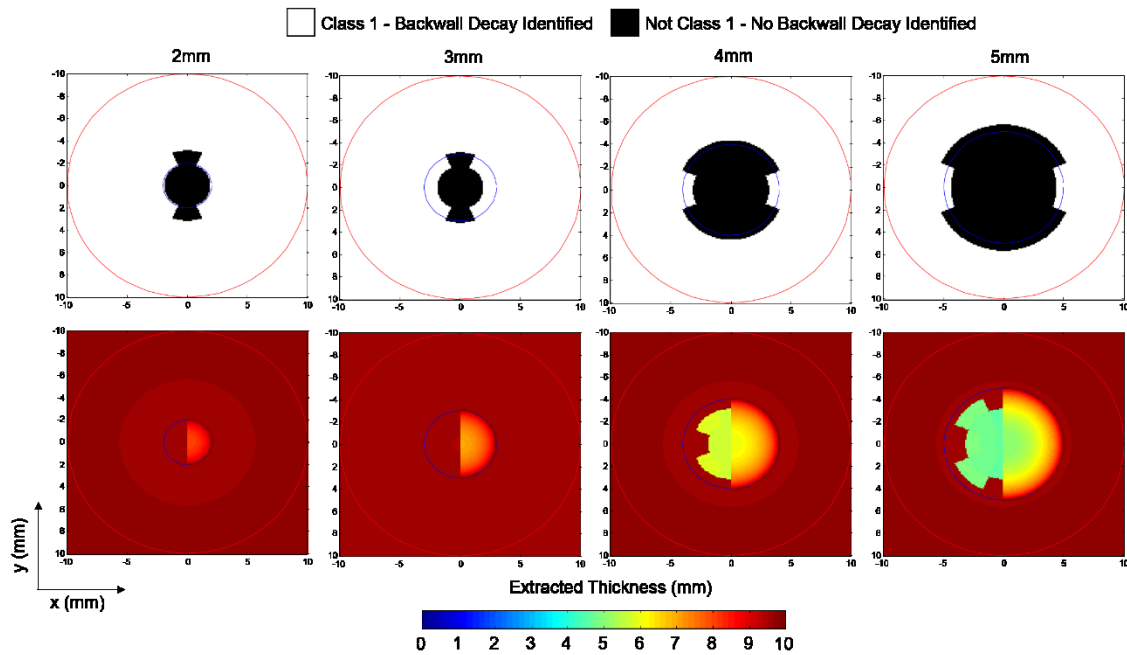


Figure 7.8 Class 1 images (top) and generic thickness images (bottom) applied to the results from the waveguide transducer over the pit position space (radial positions=0-10mm, angular positions=0-360°). The results for four pit radii are shown, 2mm (left) to 5mm (right). The half space thickness maps of each pit are superimposed over the extracted thickness images.

7.4.1.2 Class 2 and Class 2 Thickness Algorithm

Figure 7.9 shows the class 2 images (top row) and class 2 thickness images (bottom row) over the same parameter space as Figure 7.8. Due to the absence of random noise in the FE model a time trace without a decay will always be classified as a class 2A, B or C. In the 4mm and 5mm pit radius cases when the edge of a defect is located under the transducer the algorithm identifies a class 2A time trace and as the defect becomes more centrally located the time trace becomes a class 2B and then 2C (in the 5mm case). The 4mm and 5mm class 2-thickness algorithm images (bottom row) show that a pit has been correctly identified because the correct remnant thickness value has been extracted over the same area as the images in the top row.

The 3mm pit results are more mixed. The class 2 image suggests that class 2A and B time traces have been identified. However, the class 2-thickness algorithm shows that only the

class 2A time traces have successfully identified a peak, since the only change in thickness is located where a class 2A time trace has been identified. In the equivalent location where a class 2B time trace has been identified a thickness of 10mm has been extracted.

This result is seen in the 2mm case as well, where a class 2B algorithm has been identified (top), but does not correspond to a change in the remnant thickness (bottom). Figure 7.10 shows the time trace from the 2mm pit at (0,0) and explains the effect that is occurring. The backwall decay in this instant decays very rapidly and the second, third and fourth backwall reflections are heavily attenuated, therefore the fifth backwall signal becomes the third highest peak. The Figure 7.10 signal does not satisfy the $Max[2] < Max[1]/4$ step in Figure 7.7 and is therefore classified as a class 2B.

In the 2mm and 3mm pit radius images the presence of a pit is still influencing the signal, but in an unexpected manner. However, the results for the 4mm and 5mm pit radii still show that it is possible to successfully identify and extract the remnant thickness of a pit.

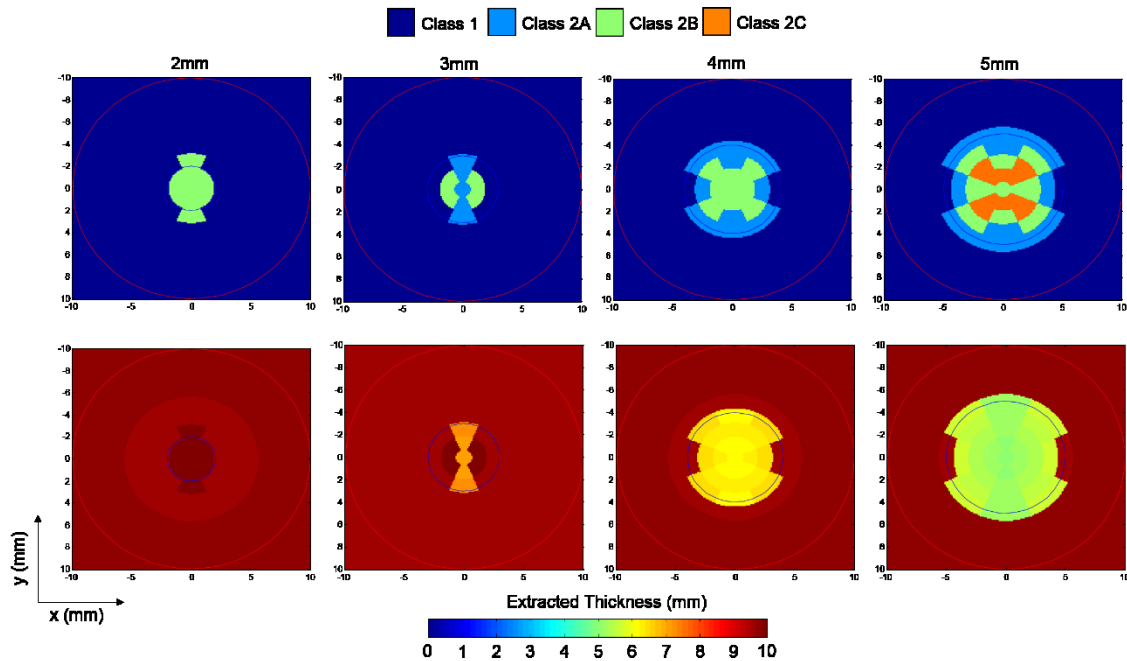


Figure 7.9 In-depth class 2 images (top, showing a breakdown of the black areas in Figure 7.8 top) and Class 2 thickness images (bottom) applied to the results from the waveguide transducer over the pit position space ($r=0-10\text{mm}$, $\theta=0-360^\circ$).

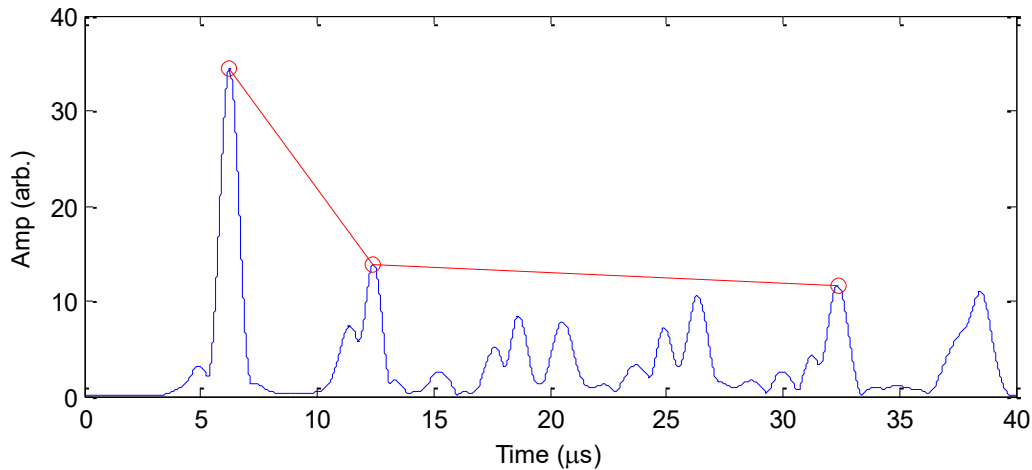


Figure 7.10 Hilbert enveloped time trace from a waveguide interrogating a 2mm radius pit at $(r=0, \theta=0^\circ)$, with the 3 highest peaks indicated

7.4.2 12.5mm EMAT Results

The class 1 algorithm (top) and generic thickness (bottom) results are shown in Figure 7.11 for the 12.5mm EMAT, and the class 2 algorithm (top) and class 2 thickness (bottom) results are shown in Figure 7.12.

With the 4mm and 5mm pit radii, the class 1 algorithm states that a decay is identified over a large portion of the parameter space apart from a few distinct areas at radial pit positions $> 6.25\text{mm}$. The corresponding class 2 results (Figure 7.11 - top and bottom) show that a similar effect as in the 2mm waveguide cases (Figure 7.9) has occurred, whereby the same areas have been identified as class 2B time traces but the class 2-thickness is still 10mm. In the EMAT 5mm pit radius case, the third backwall signal is greater than second. An example time trace from a 5mm radius pit positioned at $r = 7.5\text{mm}$ and $\theta = 0^\circ$ is shown in Figure 7.13, clearly showing the second reflection has a lower amplitude than the third, causing the algorithm to identify a class 2B yet still extract a 10mm thickness.

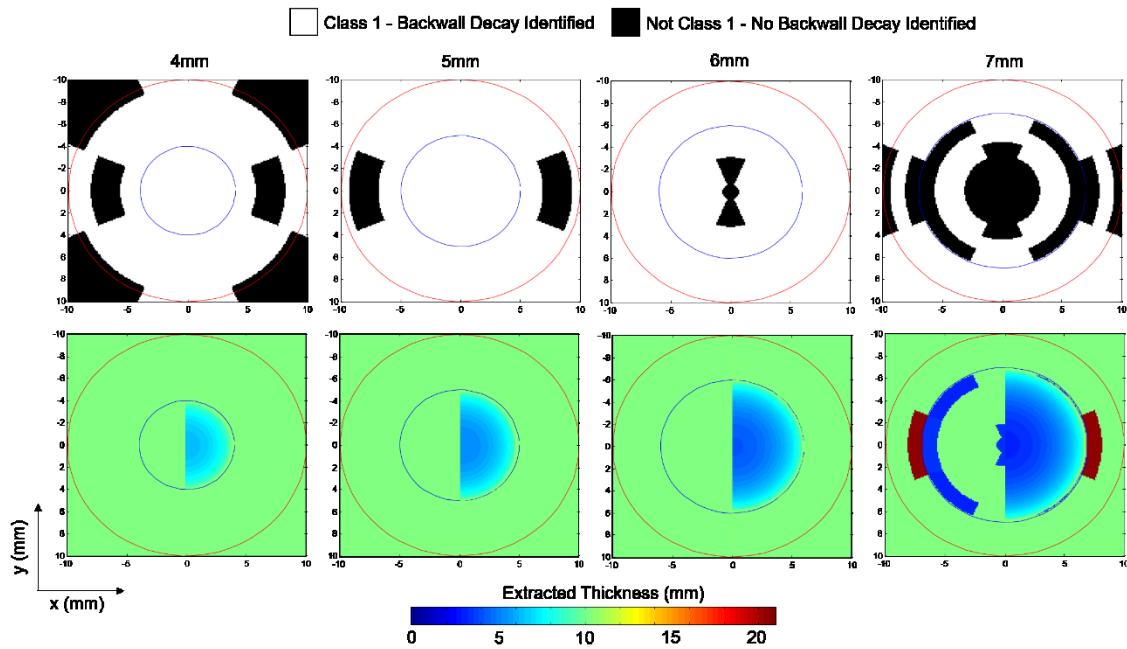


Figure 7.11 Class 1 images (top) and generic thickness images (bottom) applied to the results from the 12.5mm EMAT transducer over the pit position space ($r=0-10\text{mm}$, $\theta=0-360^\circ$). The half space thickness maps of each pit are superimposed the extracted thickness images.

The 7mm pit has an interesting class 1 image (Figure 7.11 - top), whereby the area over which a pit is identified is not contiguous and is split into two distinct features. The first feature is an area around the (0,0) position and the second feature are the fringes at $(0,\pm 6.25\text{mm})$ and $(0,\pm 10\text{mm})$. And when the pit has a radial position between approximately 4mm and 6mm a backwall signal is detected and therefore no pit is identified. A similar fringe pattern is observed in the generic thickness algorithm result (Figure 7.11 - bottom), however, at $(0,\pm 7.5\text{mm})$ a thickness of 21mm is extracted, which is due to the second backwall reflection having a higher amplitude than the first backwall echo. In the class 2 results (Figure 7.12 - top) class 2A and B time traces are identified. Interestingly the fringe at $(0,\pm 6.25\text{mm})$ remains when the class 2-thickness algorithm is applied, suggesting there is a correct identification of a prominent pit signal at that location.

The 6mm pit radius is the only 12.5mm EMAT result where the class 1, class 2 and class 2-thickness images match. The class 1 algorithm identifies no decay over a small area in the centre of the pit parameter space (Figure 7.11 - top). That same area is identified as a class 2A time trace (Figure 7.12 - top) and the correct remnant thickness is extracted using the class 2-thickness algorithm (Figure 7.12 - bottom).

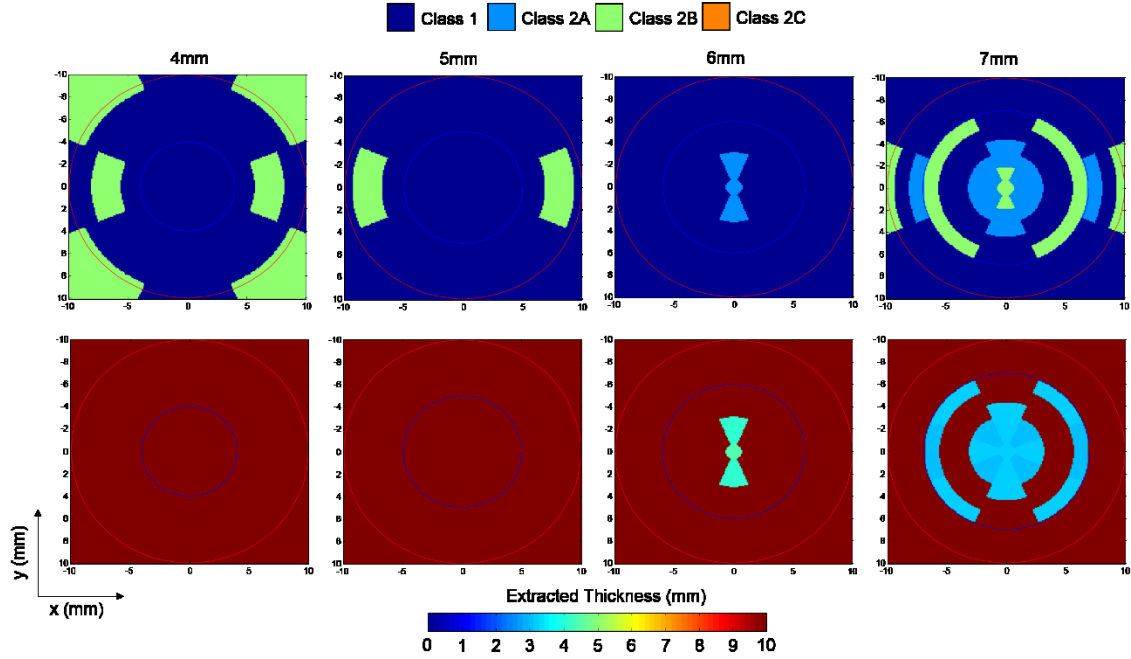


Figure 7.12 Class 2 images (top) and Class 2 thickness images (bottom) applied to the results from the 12.5mm EMAT transducer over the pit position space ($r=0-10\text{mm}$, $\theta=0-360^\circ$).

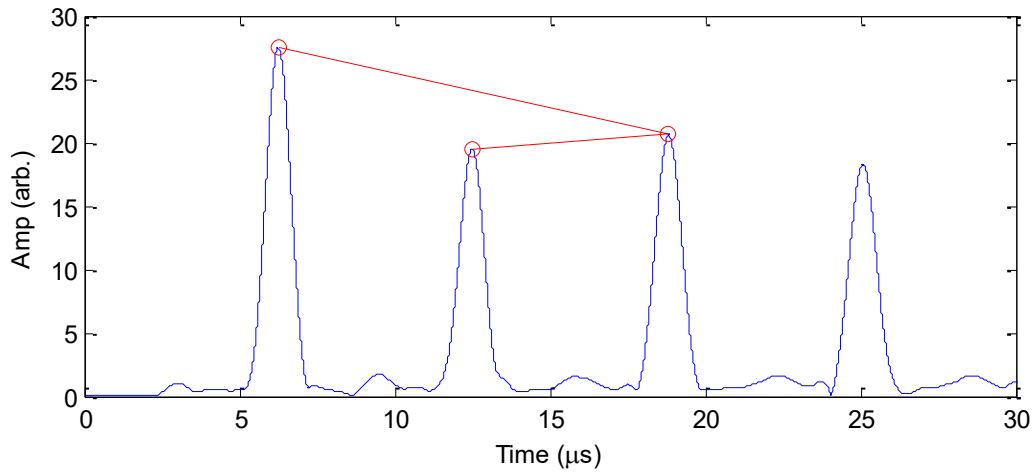


Figure 7.13 Hilbert enveloped time trace from a 12.5mm EMAT interrogating a 5mm radius pit at ($r=7.5, \theta=0^\circ$), with the 3 highest peaks indicated

7.5 Discussion on the Transducer Design Requirements and Capabilities for Pit Identification and Monitoring

The results above give a strong indication of the sensitivity of the two transducers to pitting as well as the required positional precision in the placement of either transducer over a pit.

In comparison to the waveguide the 12.5mm EMAT is much less sensitive to larger defects. This is to be expected as it agrees with the previous chapter's analysis. The response from the 12.5mm EMAT is much more complex as well, whereas the waveguide has a much more

uniform result: the pit's area of influence is approximately the same size as the pit's footprint and the measured remnant thickness is similar to the actual remnant thickness.

Generally, the area over which a pit is identifiable is greater than the area over which the pit can be measured using the generic thickness algorithm (this is summarised for both transducers in Table 7.1). Thus, showing that by first identifying the presence of a pit and then measuring the pit signal using the class 2-thickness routine the area over which the waveguide is able to measure (and therefore track) a pit is expanded. The waveguide, for example, is unable to measure a 3mm pit using the generic thickness algorithm, but once it has identified the pit it is able to measure a 3mm pit if placed at (0, 0 or ± 1.25). Furthermore, the waveguide is able to identify but not measure a 2mm pit. The 12.5mm EMAT is only able to reliably identify and measure pits in excess of 6mm radius, although the 7mm response is non-contiguous and very anisotropic.

The increase in the area (and therefore the allowed placement error) is shown in Table 7.1, where the minimum and maximum allowable placement error ranges are displayed since the sensitivity is anisotropic and is dependent on the relative orientation between the shearing direction and the pit. For example, in order to detect a 4mm pit using the waveguide the centre of the sensor has to be placed within ± 2.5 mm in the x axis (S2, orthogonal to shear) and ± 3.75 mm in the y direction (S1, principle shear) of the central position of the pit. This is very tight error, especially when compared to the 20mm error used in land surveying discussed in section 7.1.1.2, but well within the error of a fully integrated c-scan raster or optical tracking system.

Table 7.1 also lists the pit signal amplitudes at the (0,0) position. As discussed in chapter 6 this is not necessarily the largest pit amplitude (due to local maxima in the near field beam shape), however it is a good indication as to the required SNR levels in order to detect a pit signal. The pit amplitudes and SNRs are given relative to the first backwall reflection amplitude without a defect present. The 12.5mm EMAT would require a SNR of 29.9dB to be 6db above the noise level (23.9dB + 6dB) just to detect a 7mm pit (i.e. a 3mm remnant thickness). Whereas the waveguide requires a SNR of 26.5dB to identify, measure and track a 3mm pit, which is much more feasible. Pits may have a rough morphology, which will increase attenuation. However, the research presented here shows that if the waveguide is able to be precisely placed over pit then it should be able to track and monitor a 3-4mm radius pit as it grows.

	Waveguide - Defect Radius (mm)				EMAT 12.5mm - Defect Radius (mm)			
	2	3	4	5	4	5	6	7
Pit Identifiable	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Min Pos Range (mm)	2.5	2.5	5	7.5	0	0	0	12.5*
Max Pos Range (mm)	5	5	7.5	10	0	0	5	20*
Measurable using the generic thick. alg.	No	No	Yes	Yes	No	No	No	Yes
Min Pos Range (mm)	0	0	2.5	7.5	0	0	0	12.5*
Max Pos Range (mm)	0	0	5	5	0	0	0	15*
Pit amplitude at (0,0) (dB)	27.8	20.5	16.3	12.8	30.1	27.2	28.0	23.9

Table 7.1 Overview of waveguide and 12.5mm EMAT results, showing the minimum and maximum radial pit positions required in order to either identify a pit (Pit Identification) or measure thickness change (using the generic algorithm). The amplitude of the pit signal at the central position (0,0) is, also, given in dB

7.6 Summary

This chapter has introduced the concept and provided a brief analysis of using a single sensor to identify, monitor and track individual pits as they increase in size. A conceptual workflow describing the individual pit monitoring system, IPMS, has been introduced which consists of three phases: pit detection, location and monitoring. The manner in which the entire IPMS operation is implemented was discussed, and it was judged that this will have a substantial bearing on the ability of an operator to locate and place a transducer above a defect (phase two). By integrating the defect location and sensor placement a smaller positional error is much more likely, as opposed to if the two steps are carried out by different pieces of equipment and different operators.

Using a single sensor to detect a pit requires the sensor to first identify the pit. Therefore, using the time traces generated by the FE model in the previous chapter a classification scheme was manually devised, classifying the time traces into either class 1 (backwall decay present - therefore no pit) and class 2 (no backwall decay present - pit identified). Class 2 time traces were sorted into sub categories (A, B, and C). Automated routines were then described which were able to correctly identify the signal classes in most cases. There were a few cases where the incorrect time trace was classified due to unforeseen time trace characteristics. Two thickness algorithms are also described, enabling the tracking and monitoring ability of the transducers to be briefly assessed.

The waveguide setup was much better at identifying the presence of a defect compared to the 12.5mm EMAT. The waveguide was able to measure and detect the pits (radius 2-5mm) over an area similar to the pits diameter. Whereas the 12.5mm EMAT was unable to reliably

detect the pit over a consistent or contiguous area. If the defect was detected then the correct value of remnant thickness was extracted in most cases, either with the generic or class 2-thickness algorithm enabling thickness extraction. The 12.5mm EMAT has been shown to be unsuitable for pit detection due to poor and inconsistent pit identification and low pit amplitude. The waveguide is able to successfully identify, track and monitor pits as well as having a much higher pit amplitude. In terms of waveguide positional error the pit diameter can serve as a proxy for the required sensor's positional precision. Since the input toneburst is identical (2MHz 3 cycle Hann toneburst), the difference between the setups must be due to the transducer shape, which governs the beam shape. The narrow slit aperture (high aspect ratio) performs significantly better than the square aperture (low aspect ratio). This study focused on existing bulk wave wall thickness technology as a starting point, however, future work will be able to use the approaches described above to improve the transducer design for the task of pit monitoring.

Chapter 8

Conclusion

8.1 Thesis Summary

If left unchecked corrosion in pipes can lead to a range of undesirable events from unexpected downtime to catastrophic failure resulting in loss of life. This work is motivated by the desire to detect and monitor pipe corrosion allowing for the safe, continual and cost-effective operation of oil and gas infrastructure. Two ultrasonic NDE approaches have been evaluated in this thesis with the common goal of aiding the management of corrosion in pipes. Chapter 1 introduces the corrosion problem in more detail along with the existing NDE technologies used to perform corrosion diagnostics on pipe work. Efficient monitoring for corrosion is a trade-off between sensitivity of an individual sensor to corrosion and the spatial coverage it provides. From this brief analysis, it was decided to explore the techniques between the two established ultrasonic techniques of spot measurements and long range guided waves. Chapter 2 provides an overview of the theory describing bulk and guided wave propagation and an outline of finite element modelling. The work in this thesis takes advantage of improved finite element modelling speeds allowing for the ultrasonic response from a greater range of defect dimensions to be simulated. It was therefore necessary to devise an automated modelled generation routine to take advantage of the higher solver speeds.

The first ultrasonic NDE approach studied was a circumferential guided wave setup, which was the focus of Chapters 3 and 4. In chapter 3, the simplest implementation of a single circumferential guided wave sensor was studied, whereby a pulse is excited by a single transducer. The pulse travels around the circumference of the pipe and is detected by the same transducer. By approximating a pipe to a plate the setup was modelled in FE using the dispersive SH1 mode to extract a value of the average thickness between two transducers. The non-dispersive SH0 mode was also excited and used to compensate for fluctuations in temperature. The temperature compensated average thickness extraction method was experimentally validated. The method was able to extract the correct average thickness values of a uniformly thick plate and a plate with a notch across the entire width of the plate. However, the method was unable to extract the correct thickness values for a finite width defect (part thickness hole or Hann profile defect), and furthermore slight variations

in the defect position relative to the transducers could result in large variations in the measured/estimated average thickness value, increasing the chance of false negatives.

Chapter 4 introduced the idea of adding a spatial component to the circumferential measurements to reduce the chance of missing a finite width defect. This was achieved by using either an axial array or a series of axial measurements along the pipe. The detection ability of the circumferential guided waves was studied in both transmission and reflection to determine the overall sensitivity of guided waves to corroded areas of pipes. The S0, SH1 and SH0 modes were investigated using a large range of defect dimensions modelled using FEA. The operating characteristics of the transmission and reflection pulses were selected using either knowledge gained from existing literature or from chapter 3 to increase the guided wave's sensitivity to defects. The results were normalised with respect to wavelength, this gave a good indication of the maximum sensitivity of circumferential guided waves. In reflection, the guided wave modes were sensitive to narrow and deep defects, whereas in transmission shallow and wide defects were detectable. Practical constraints, however, limit the suitable range of input toneburst parameters. One suggested way of increasing the sensitivity of circumferential guided waves is to data fuse reflection and transmission results.

Chapter 5 contained a brief study to quantify the limited spatial coverage of a single 'ideal' bulk wave transducer (spot measurement) to detecting pitting corrosion. As expected a pipe would have to be completely covered by bulk wave transducers to detect a pit of comparable size to the transducer itself. It was therefore suggested that a bulk wave system is better suited to monitoring individual pits. Chapter 6 details a phenomenological study which investigated the reflected signal from more complex geometries, such as sloped backwalls and hemispherical pits, to gain a better insight into bulk wave interaction with complex defects. Several transducers were modelled using FEA: a shear waveguide transducer; a 0-degree shear wave EMAT; and a semi-circular compression transducer. The results showed that there is a complex anisotropic response with respect to the relative position of the transducer and the pit. This response depends on the beam shape and/or the mode conversion of the incident pulse.

Chapter 7 discusses an individual pit monitoring system in more detail, whereby a single sub-critical pit, which has already been detected by another means, could be continuously monitored as it grows. Aspects of this system were discussed in detail to provide a stable framework for the analysis using industry relevant parameters. Before the monitoring transducer could measure the pit it first had to be ascertained whether the transducer was able to identify the presence of a pit in a time trace. Using the simulated data from the

previous chapter, a classification scheme was manually devised sorting the time traces into either class 1 (pit not identified) or class 2 (pit identified) time traces - plus further class 2 sub-categories. These classifications formed the basis of simple routines designed to automatically sort time traces, and were applied to the waveguide and EMAT datasets.

8.2 Summary of Main Findings

8.2.1 SH1 Guided Wave Monitoring System

Temperature Compensated Average Thickness Extraction of Uniformly Thick Plates and Infinitely Wide Notches

It is possible for a short range guided wave system, which simultaneously excites both the non-dispersive SH0 and dispersive SH1 guided wave modes, to extract a temperature compensated average thickness value over the propagation distance between the transmitting and receiving transducers. By extracting the group velocity of the SH0 mode, which is dependent on the temperature of the sample, a temperature corrected SH1 dispersion curves for the given temperature can be calculated. The thickness extraction algorithm is also able to correctly extract the average thickness of infinitely wide shallow notches. This was verified in simulation and experiment.

Average Thickness Extraction of Finite Width Defects

A dispersive guided wave system that extracts the average thickness along a line (either around the circumference of a pipe or between two transducers on a plate) is unable to reconstruct the correct average thickness profile for a finite width defect. This is because the guided wave is scattered and diffracted by the defect, and the resulting interference creates a complex waveform with spatially varying arrival times. This setup can be used to given a qualitative indication of wall loss, however, it must be used as part of an array or series of measurements to increase the effectiveness. If this system were to be implemented as a solitary circumferential pipe wall thickness sensor/measurement, then there is a risk of measuring zero thickness change even when a large thickness variation has occurred. By way of example, the axial elongation of a 60x1mm Hann profile defect/notch is required to be $>3\lambda_{\text{trans}}$ for a stable value of thickness is calculated in the centre of the defect, which is equivalent of $>10\lambda_{\text{trans}}$ (at the centre frequency) - see appendix 9.2.

8.2.2 Multimodal Corrosion Monitoring using an Array of Guided Wave Measurements

Wavelength Normalised Defect Detection Ability

The ability of multiple circumferential guided wave sensors/measurements for the detection of finite width defects has been quantified. This setup can either be implemented as an array of permanently installed transducers or a series of measurements in a scan. The S0 and SH1 modes were evaluated in transmission and the S0 and SH0 modes were evaluated in reflection. The A0 mode was also evaluated but shown to be much less sensitive than the others. Once normalised to the wavelength of the centre frequencies, the reflected signals of the S0 and SH0 modes were sensitive to narrow and deep defects (50% wall loss with a defect diameter of $0.5-0.6\lambda_{\text{refl}}$) over a finite range of diameters ($0.2-1.2\lambda_{\text{refl}}$). The transmitted signals were sensitive to wide ($>1\lambda_{\text{trans}}$) defects which are either shallow or deep.

Detection Ability of Circumferential Guided Waves using Common Industrial Parameters

For a given plate thickness, the dispersion curves of the three guide wave modes (S0, SH1, and SH0) restrict parameters and wavelength of the input toneburst, due to associated characteristics, such as dispersiveness and mode cut-off frequencies. One way to increase the sensitivity of the guided waves is to combine the sensitivities (i.e. data fusion). A representative maximum value of sensitivity for the various modes can be calculated using typical industrial parameters: 6-8" pipes (10mm wall thickness and 500mm propagation distance) and 30dB SNR. With a pitch of 10mm between adjacent measurements the S0 mode (when combined in reflection and transmission) is sensitive to finite width defects with a 0.75% CSA and the SH hybrid (SH1 - transmission, and SH0 - reflection) is sensitive to defects with a 0.6% CSA. Representing the detection sensitivity as a value of cross sectional area (CSA) encompasses the inherent trade-off between defect depth and diameter sensitivity. For both methods, deep and narrow (50% maximum wall loss, $\varnothing 12-16\text{mm}$) and wide and shallow (20% maximum wall loss, $\varnothing 60\text{mm}$) defects are detectable in either reflection or transmission respectively. However, neither methods can detect defects with $<20\%$ maximum wall loss and $<\varnothing 30\text{mm}$ (i.e. narrow and shallow defects).

8.2.3 Interaction between Shear Bulk Waves and Pitting Corrosion

Anisotropic Backwall Reflections from Complex Geometries

The reflected bulk 0-degree shear wave signal from a defect of complex geometry is anisotropic with respect to the defect location and the polarisation of the wave-pulse. Two geometries were modelled: sloped backwalls and hemispherical pits. Two main causes of

this anisotropy are the beam shape and mode conversion at the defect. If the aperture of the transducer has a high aspect ratio, then the beam will be inherently anisotropic, leading to an anisotropic backwall response. If the aspect ratio of the transducer aperture is 1, then the anisotropic backwall response is due to mode conversion of the shear wave. Mode conversion of the principle shear wave can be to either the orthogonal shearing direction, longitudinal direction, or both.

Evaluation of an Individual Pit Monitoring System using Current Spot Measurement Systems

The high aspect ratio transducers (waveguide and semi-circular compression transducers) had a higher sensitivity to hemispherical pits than the transducers with an aspect ratio of 1 (EMATs). The difference in sensitivity was clear in both the reduction in the backwall signal amplitude and pit signal amplitude at lower pit radii. This ensures that the waveguide transducer is more suitable for an individual pit monitor system (IPMS), whereby a known sub-critical defect is tracked as it grows. Defects with 3mm radius are shown to be detectable and measurable using a waveguide transducer on a 10mm thick plate, however, the transducer must be placed over the pit with a placement error similar to the diameter of the defect.

8.2.4 Discussion of the Ability of Ultrasonic Techniques to Detect Corrosion-Like Defects

In Figure 1.5 a relationship between sensitivity and area coverage of ultrasonic techniques was introduced, and using values from literature it was shown that spot/point ultrasonic measurements and LRGWs occupy either end of a spectrum. The work covered in this thesis places additional techniques on the quantitative sensitivity-area coverage spectrum. Furthermore, a framework that enables the quantitative analysis of the best case performance of a particular technique in simulation has been devised [P2, P3]. This will enable a more efficient and fair comparison with any future technique.

The term ‘sensitivity’ can refer to either the characterisation ability (i.e. measurement precision - how precisely backwall or pit depth can be measured) or detection ability (i.e. what is the smallest detectable defect). After chapter 3, this thesis has primarily been interested in detection ability. Another point of clarification is the defect type. The values of spot UT sensitivity provided in Figure 1.5 are for uniformly thinned pipe walls, and therefore are not comparable with finite width defects (chapter 7).

It should be noted that each of the three ultrasonic NDE techniques essentially takes a measurement along a different axis of the cylindrical coordinate system: LRGWs - axial; circumferential GWs - polar; and spot UT - radial. This means that different aspects/areas

of the defect are sonified depending on the technique used. This is illustrated in Figure 8.1. It is, therefore, harder to provide a direct comparison in terms of defect 'size' (depth, axial extent, or circumferential extent) between the three techniques, since they measure the same object but are sensitive to different/multiple defect parameters.

The bulk wave spot measurements act in the radial direction sonifying an area directly below the transducer. This sonified backwall area represents the approximate coverage of an individual transducer, which is on the order of 10mm^2 , however, some pits may have to be located within an even smaller area directly under the transducer, to detect smaller pits. For example, the waveguide transducer has the ability to detect 3mm radius hemispherical pits, so long as they are located within an area with a diameter less than or equal to the diameter of the defect.

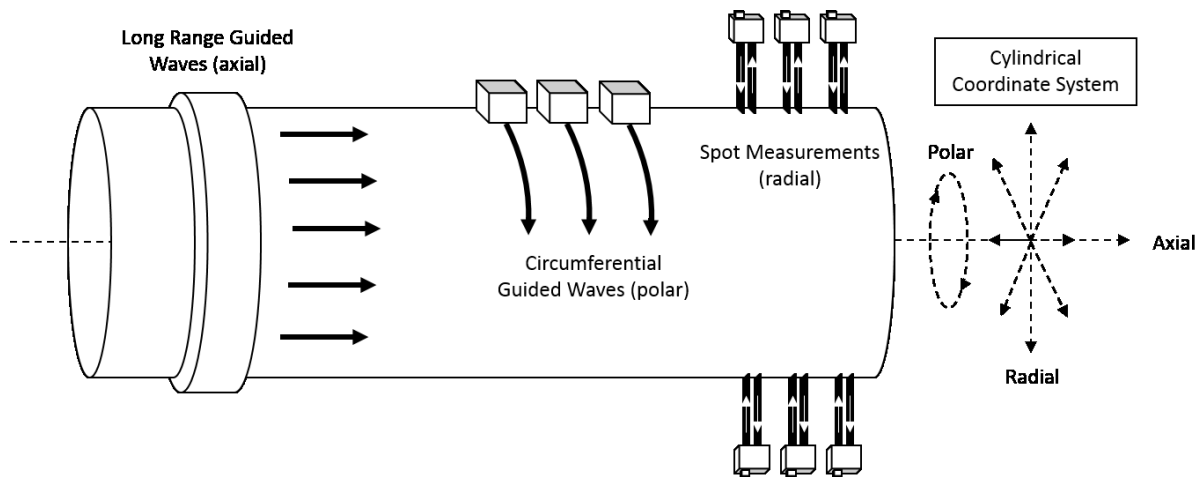


Figure 8.1 The three corrosion monitoring setups compared and their equivalent cylindrical axis along which they act

Circumferential guided waves are incident on the axial and radial (i.e. depth) extents of a defect and their area coverage is potentially equivalent to their beam width. However, in transmission, the complexities caused by scattering ensure that a series of axial measurements (array or scan) are required to successfully detect the defect. The measurement pitch essentially limits the width of the beam, and a value of area coverage can be calculated as the pitch x propagation distance. For the work presented here the area coverage is therefore, $10\text{mm} \times 500\text{mm} = 5000\text{mm}^2$. Another complication is in reflection, whereby circumferential guided waves are only sensitive to smooth Hann profile defects over a range of diameters. Therefore, there is no minimum defect size to which they are sensitive. As shown in chapter 4, however, the data fused results provide a value of cross sectional area (CSA) as the minimum defect size - 0.6% CSA for the SH hybrid mode and

0.75% CSA for the S0 mode over 500mm propagation distance in a 10mm thick plate with 30dB SNR.

LRGWs excite a pulse axially along a pipe and therefore the circumferential and radial extent of the pipe are sonified. There are several existing studies which may provide a comparison with the bulk wave and circumferential guided wave techniques. In 2001, [27] quoted LRGWs as being able to detect 5% CSA defects during screening. A more recent study [33] predicts this value is lower in monitoring mode using baseline subtraction techniques: 0.5%-1% CSA. Both LRGW studies used tapered hole defects which has defined edges, which increases the reflection coefficient over smooth profiles [36] and therefore will increase detectability. The recent LRGW study placed the defects up to 11m away from the transducer in an 8" schedule 40 pipe [33]. This equates to an area coverage of 6.6m^2 ($6.6 \times 10^6\text{mm}^2$). However, in the field the LRGW system can scan either side of the pipe, doubling the area coverage to 13.2m^2 .

8.3 Suggested Future Work

Section 8.2.4 highlights three well explored techniques for the purpose of corrosion detection, each of which have strengths and weaknesses depending on the coverage and the required detection ability. However, of the remaining unexplored space between the three NDE techniques, the coverage gap between the LRGWs and circumferential guided waves is of less interest. This is because a technique which operated over this area (5×10^3 - $13 \times 10^6\text{mm}^2$) would require guided waves, and therefore, the sensitivity of that technique could be extrapolated from the current literature and knowledge. A technique which operated over a 10 - 5000mm^2 area, however, would begin to use either higher frequency guided waves or low frequency bulk waves, which ultimately converge towards each other. The response of such a device could not be extrapolated from existing knowledge, and an in-depth study of its potential would need to be carried out. Another avenue of research would be to expand the area coverage of bulk wave techniques and investigate different transducer apertures or shapes, or spacings between pitch catch transducers.

Chapter 4 made several assumptions regarding the operation of a circumferential guided wave system, thereby allowing a value of detectability close to the theoretical maximum to be calculated. One assumption stated that the transducer was able to excite a broad spectrum of frequencies, allowing for pulses which were suitable for reflection and transmission to be excited. Research into whether a guided wave transducer could be constructed or whether two transducers housed in the same package would be required. In the case of an EMAT, one possibility would be to use the same set of magnets but with

different coils. Further developments of the circumferential guided wave signal processing techniques should concentrate on improving monitoring sensitivity using techniques such as baseline subtraction. In reflection, this would mirror the work done for long range guided waves [33]. The circumferential guided wave techniques studied may also have immediate application in specific corrosion management scenarios within the high value/risk areas of the oil and gas industry.

The ability of the waveguide transducer to identify a pit has been demonstrated, however, its ability to track a pit was only briefly touched upon in chapter 7, which requires a more detailed evaluation. The incident pulse is heavily scattered and distorted by the pit, and the simple thickness algorithm used to calculate the TOF from the pit needs to be improved to extract a more accurate value, possibly using a cross-correlation technique similar to that described in section 6.3.2. Furthermore, as acknowledged in chapter 7 the pit identification algorithm only used the three reflections with the highest amplitude in the time trace to decide whether or not a pit was present. It was therefore possible that the pit signal was still a significant and recognisable peak but only the fourth (or lower) highest in amplitude. Therefore, more complex pit identification algorithms need to be written. This would especially benefit the waveguide transducer due its anisotropic beam shape; since it is possible for a pit to lie away from the point directly under the transducer (which will ensure a strong backwall signal) but be close enough to cause a strong pit signal. In that scenario, the backwall signal will have little decay and the pit signal is unlikely to be greater in amplitude than the third backwall reflection.

Transducer shape, which influences the beam shape, was shown to be the main factor in determining pit sensitivity. Chapter 6 focussed on three existing techniques all of which were designed specifically for extracting values of inner pipe wall thickness, not for detecting and tracking pits. Therefore, there is scope for exploring different transducer designs to optimise the tracking of pits. The high aspect ratio of the waveguide was shown to be superior to the unitary aspect ratio of the EMAT, however, if the EMAT width were to be narrower would that improve the detection ability? Could the spacing between the waveguides improve coverage? Also, there is scope for exploring whether it is possible to exploit the mode conversion effect observed in the 0-degree shear wave transducers, and to determine whether there is any extra diagnostic information contained within mode converted signals.

The ability of fast finite element enabled much of the work presented in this thesis and the automated defect meshing and modelling methods developed for this thesis have shown that a great variety of pit sizes, shapes and positions can be modelled. The same meshing method

can be applied to simulate even more complex defects as well as multiple defects and morphologies. This is not a pressing concern since there is still more knowledge to gather regarding the effect of a single pit. If these conditions are evaluated, however, the study must be relevant and targeted due to the complexity of evaluating more and more dimensions (e.g. number of pits, spacing between pits, pit elongation etc.).

Finally, much of the long range guided wave research has focussed on sharp edged defects, which are known to have a higher reflection coefficient than smooth defects (such as Hann profile defects). Research should be conducted to quantify this effect on LRGW sensitivity and the probability of detection, thereby allowing a fairer comparison of all three NDE techniques.

Appendix

9.1 Zero Phase Slope Method Derivation

The derivation below is taken from the thesis of Frederic Cegla [82]. The zero-phase slope method uses the Fourier transform of a signal to determine the group velocity for each of the spectral components. This is done by using two windowed signals of the same pulse at different points in time, but using a common time frame. The group velocity curve of two signals can be found by determining the phase slope for each spectral component, that is the rate of change of phase with frequency. When each of the windows are aligned with the group arrival time of a frequency component within the signal the phase slope of the frequency component will tend to zero. The following shows the derivation of equation 3.2, which is used to extract the group velocity curve of the guided waves. The derivation makes use of the shift property of Fourier transforms:

$$\begin{aligned}
 F(f(t)) &= \int_{-T}^{+T} f(t)e^{-i\omega t} dt = F(\omega) \\
 F(f(t - t_{shift})) &= \int_{-T}^{+T} f(t - t_{shift})e^{-i\omega t} dt \\
 &= \int_{-T}^{+T} f(t - t_{shift})e^{-i\omega(t-t_{shift})}e^{-i\omega t_{shift}} d(t - t_{shift}) \\
 &= e^{-i\omega t_{shift}} F(\omega)
 \end{aligned}$$

The Fourier transform of a displaced signal of a travelling wave is represented by:

$$F(u(x, t)) = F(\omega)e^{-i(kx)}e^{-i\phi_0}$$

When a time shift, t_{shift} , between the two signals occurs:

$$F(u(x, t))_{shift} = F(\omega)e^{-i(kx)}e^{-i\phi_0}e^{-i\omega t_{shift}}$$

This leads to:

$$F(u(x, t))_{shift} = F_1 e^{-i\phi_e}$$

where F_1 is a constant and ϕ_e is the overall phase angle represented by:

$$\phi_e = -i(kx + \phi_0 + \omega t_{shift})$$

The phase slope is therefore:

$$\frac{d\phi_e}{d\omega} = -\frac{dk}{d\omega}x - t_{shift}$$

where $c_g = \frac{d\omega}{dk}$, therefore:

$$\frac{d\phi_e}{d\omega} = -\frac{x}{c_g} - t_{shift}$$

if the rate of change in the phase between signals is zero then $x \neq 0$ must be true:

$$\frac{d\phi_e}{d\omega} = 0 = -\frac{x}{c_g} - t_{shift} = -T_g - t_{shift}$$

where the group arrival of the signal, $T_g = x/c_g$. If the time frame stays the same then the group velocity of the signal (at x_1 and x_2) can be found using:

$$\frac{d\phi_{e1}}{d\omega} - \frac{d\phi_{e2}}{d\omega} = \frac{x_1}{c_g} - t_{shift} - \left(\frac{x_2}{c_g} - t_{shift}\right) = \frac{x_1 - x_2}{c_g}$$

which leads to:

$$c_g = \frac{x_1 - x_2}{\frac{d\phi_{in}}{d\omega_{in}} - \frac{d\phi_{out}}{d\omega_{out}}}$$

9.2 Average Thickness Extraction of a Half Notch using SH Guided Waves

Figure 3.18 shows the average thickness extraction algorithm successfully extracting the average thickness of a notch which extends across the entire width of the plate. Figure 3.19 show the average thickness algorithm unsuccessfully extracting the correct thickness of several finite width defects. This poses the question: at what defect width will the average thickness algorithm start extracting the correct thickness?

Figure 9.1 shows the cross-sections of the two half notches modelled: a) Hann profile half notch, which has an end profile which has a half Hann profile, and b) a rounded half notch (based on the part thickness hole). In both cases the central position is taken to be the origin of the radii of either half thickness (see Figure 9.1c). The Hann half notch has a Hann profile when viewing it down the notch, whereas the part thickness half notch has a rectangular profile. A B-scan of the half notches was performed over a 400mm range,

ensuring the defect free and full notch average thicknesses were included in the results. The FE model was $400 \times 500 \times 10 \text{ mm}^3$ thick with a $1 \times 1 \times 1 \text{ mm}^3$ element size. A 250kHz 5 cycle Hann windowed toneburst was used.

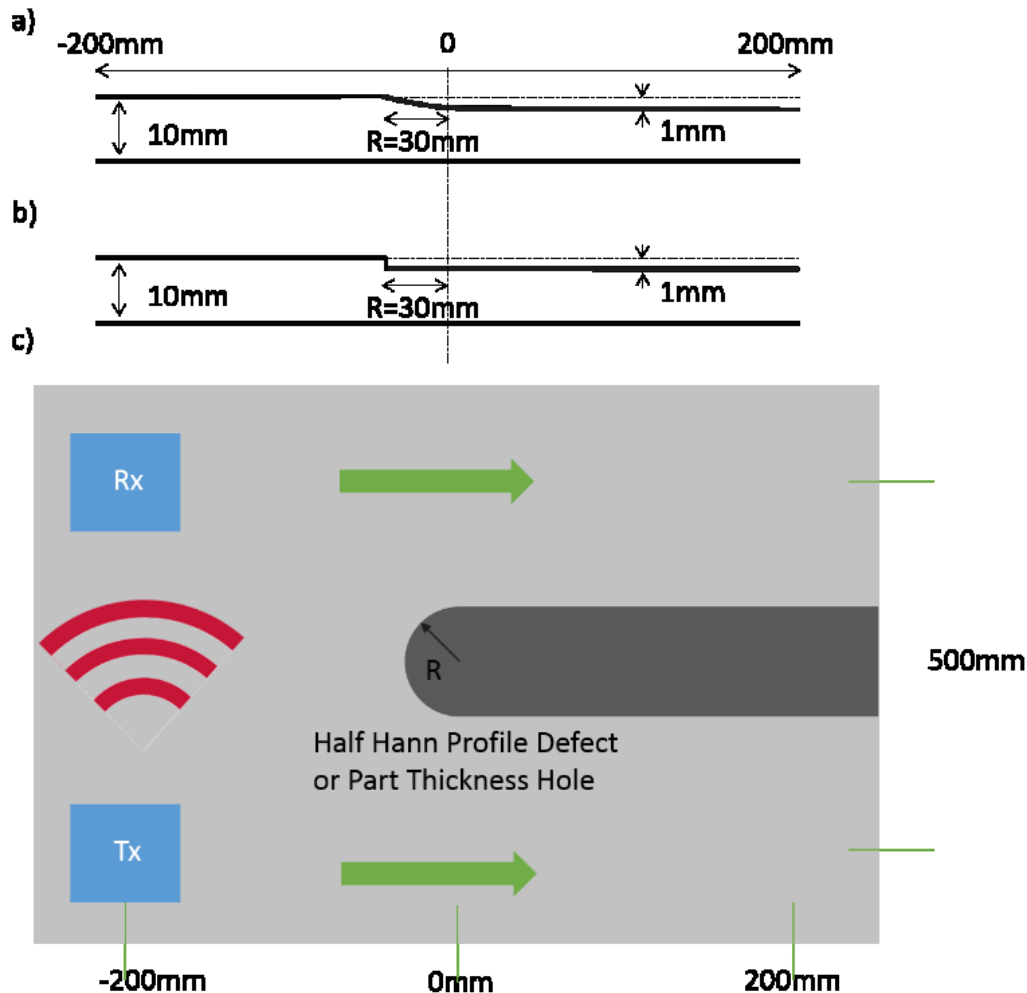


Figure 9.1 Cross sectional profile of a a) 1mm deep Hann profile half notch, b) 1mm deep part thickness hole half notch, c) B-scan schematic of a 60mm diameter half notch

The transition from the baseline thickness value to the notch thickness values can be characterised as the 'transition length'. The Hann half notch (Figure 9.2a) has a transition region around 100mm around the central position, where the thickness dips at -50mm and settles to a steady value at +50mm. The part thickness hole half notch (Figure 9.2b) has a much larger perturbation from -70mm where the thickness decreases until +100mm before a steady state is reached. Over this 170mm range (almost 3ϕ) the extracted thickness values is unstable and not reliable compared to the Hann half notch which has a much narrower transition region (1.5ϕ). Translating this value into an effective finite defect width would mean doubling the transition region since the edge perturbation effects shown would be on both sides of the finite width defect. This suggests that the part thickness hole half notch

would have to be 6σ before a correct/steady thickness value is extracted, compared to a 3σ for the Hann half notch. It is debatable whether these two defects are comparable since they have different values of average thickness, therefore modelling a 60×0.5 mm part thickness hole half notch or 60×2 mm Hann half notch would be needed. Furthermore, more simulations need to be performed to generalise the result.

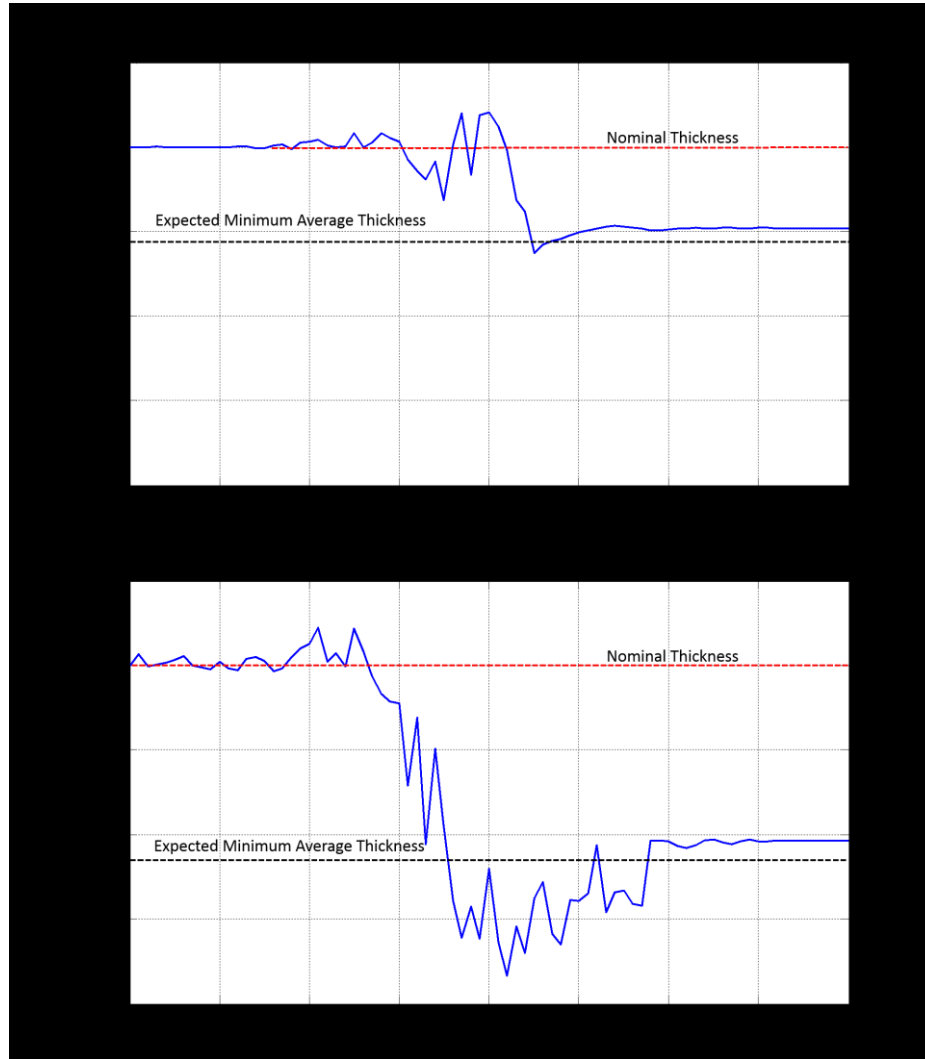


Figure 9.2 Extracted average thickness B-scan, using a 250kHz 5 cycle Hann windowed toneburst over a propagation distance of 500mm in a 10mm thick plate, of a a) 1mm deep 60mm wide half notch with a Hann profile, b) 1mm deep 60mm wide half notch with a rounded end of constant thickness

9.3 Visualisation of SH1 Scattering

Figure 9.3 shows the displacement field (on the top surface of the plate) of the two SH modes as they are transmitted through a Hann profile defect (60x5mm). Just before the SH modes reach the defect, at 0.07ms, the SH0 and SH1 modes are separate and distinguishable from one another. At 0.1ms the SH0 mode has passed through the defect and there is no noticeable difference between the SH0 mode before and after the defect, showing that the defect has little effect on the mode. The SH1 mode, at this time, is in the process of passing through the defect and it is obvious that only a fraction of the modes energy is able to pass through the deepest part of the defect and instead is deflected either side of the defect. After passing the defect the two halves of the SH1 mode diffract (i.e. spread out) around the defect. This shows that the SH1 mode which reaches the receiver will have potentially travelled a longer path by diffracting around the defect. This longer path length explains why the extracted thickness decreases¹³ when the defect is located off centre.

¹³ If the TOF increases the algorithm identifies this up as larger decrease in group velocity, which equates to a greater amount of thinning

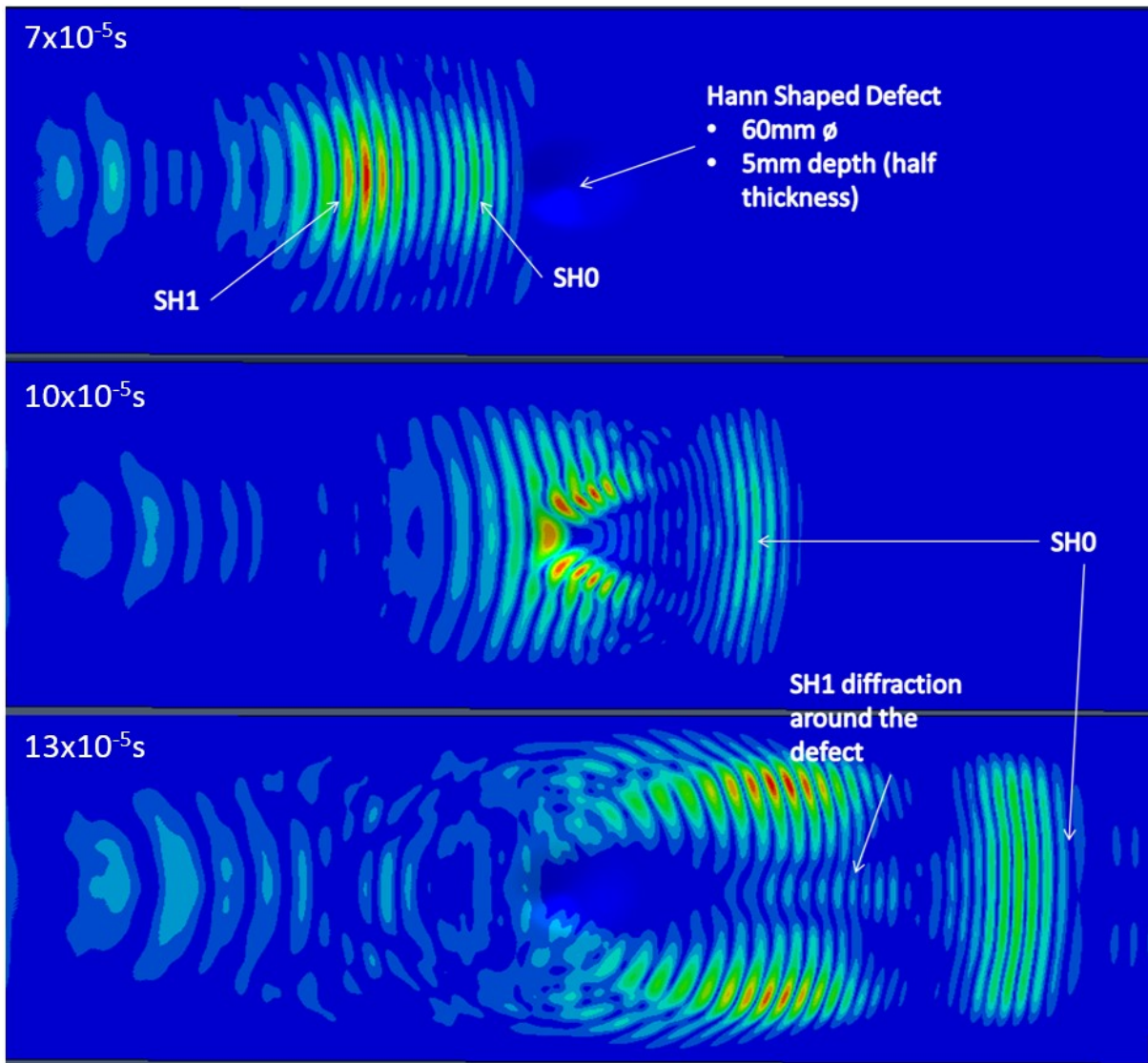


Figure 9.3 Displacement field of the SH0 and SH1 pulses (250kHz centre frequency 5 cycle toneburst width) on the top surface of the plate at 0.07, 0.1, 0.13ms, as the two modes pass through a 60x5mm Hann profile defect placed in the centre of the plate.

9.4 Summary of Input Toneburst Operating Parameters from a Selection of Guided Wave Reflection Studies

S0 Mode		
Citation	Centre Frequency (MHz.mm)	Bandwidth (MHz.mm)
Cho et al. 1997 [149]	0.8	0.1-1.5
Dilgent [150]	0.1	
Fletcher [94]	1.15	0.95-1.35
LeClezio [151]	1.12	
Alleyne [50]	1.35	
Zhao [152]	0.175	
Clarke [153]	0.2	
Moreau et al. [98]	0.96	
Wilcox et al. [154]	1	
Wilcox et al. (Expt.) [154]	0.6	0.4-0.8
Lowe et al. [106]	0.5	
Singh et al. [155]	0.52	
Fromme [110]	2	0.01-4
Leleux et al. [156]	1.7	1.4-2

Table 9.1 Summary of S0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature

A0 Mode		
Citation	Centre Frequency (MHz.mm)	Bandwidth (MHz.mm)
Cho et al. [149]	0.8	0.1-1.5
Lowe et al. [106]	1.5	
Rajagopal [109]	1.75	1.5-3
Alleyne et al. [50]	1.35	
Wilcox et al. [154]	1	

Table 9.2 Summary of A0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature

SH0 Mode		
Citation	Centre Frequency (MHz.mm)	Bandwidth (MHz.mm)
Cho et al. [149]	0.8	0.1-1.5
Rajagopal et al. [157]	0.1	
Demma et al. [158]	0.55	
Zhao et al. [152]	0.21	
Ma et al. [90]	0.6	0.2-0.9
Carandente et al. [36]	0.3	
Fletcher [94]	0.95	0.8-1.1
Nurmalia et al. [89]	0.9	
Wang et al. [97]	1	

Table 9.3 Summary of SH0 input toneburst operating parameters for the detection and/or measuring of defects in pipes or plates from literature

9.5 A0 probability images and part thickness hole probability images

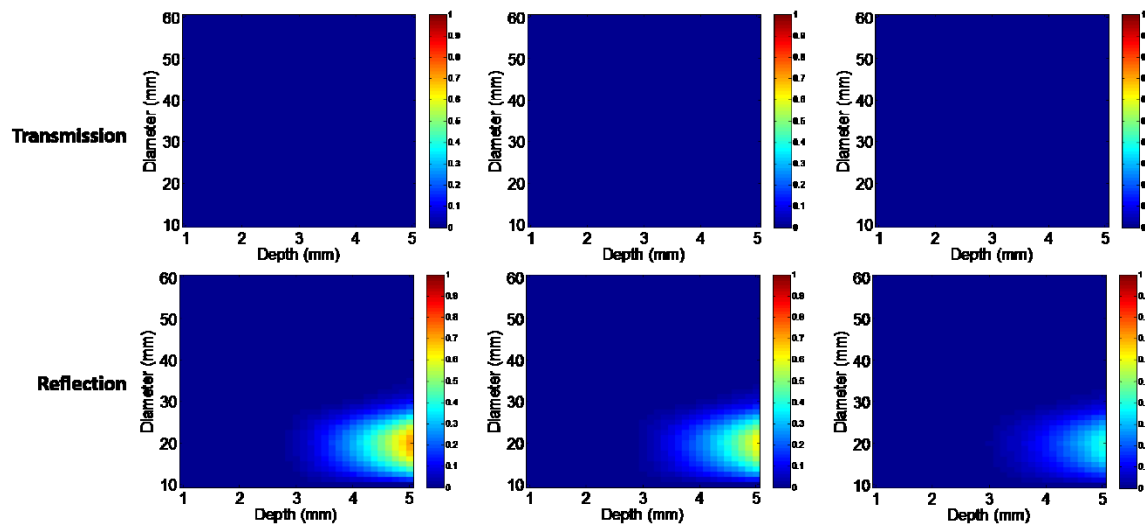


Figure 9.4 Probability of detection for the A0 mode in transmission (top row) and in transmission (bottom row) with pitches of 10, 50 and 100mm, over a range of Hann profile defect diameters (10-60mm) and depths (1-5mm)

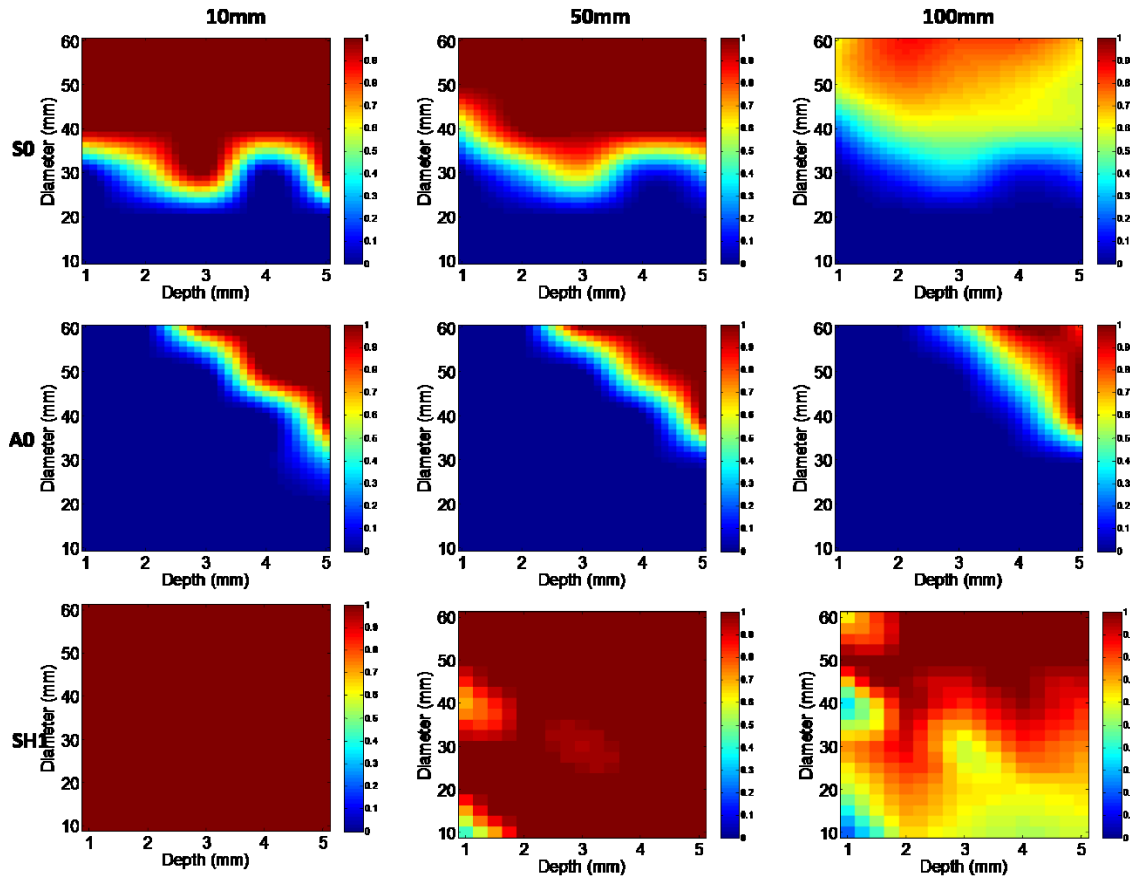


Figure 9.5 Probability of detection in transmission for the S0 mode (top row), A0 mode (middle row) and the SH1 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of part thickness hole diameters (10-60mm) and depths (1-5mm)

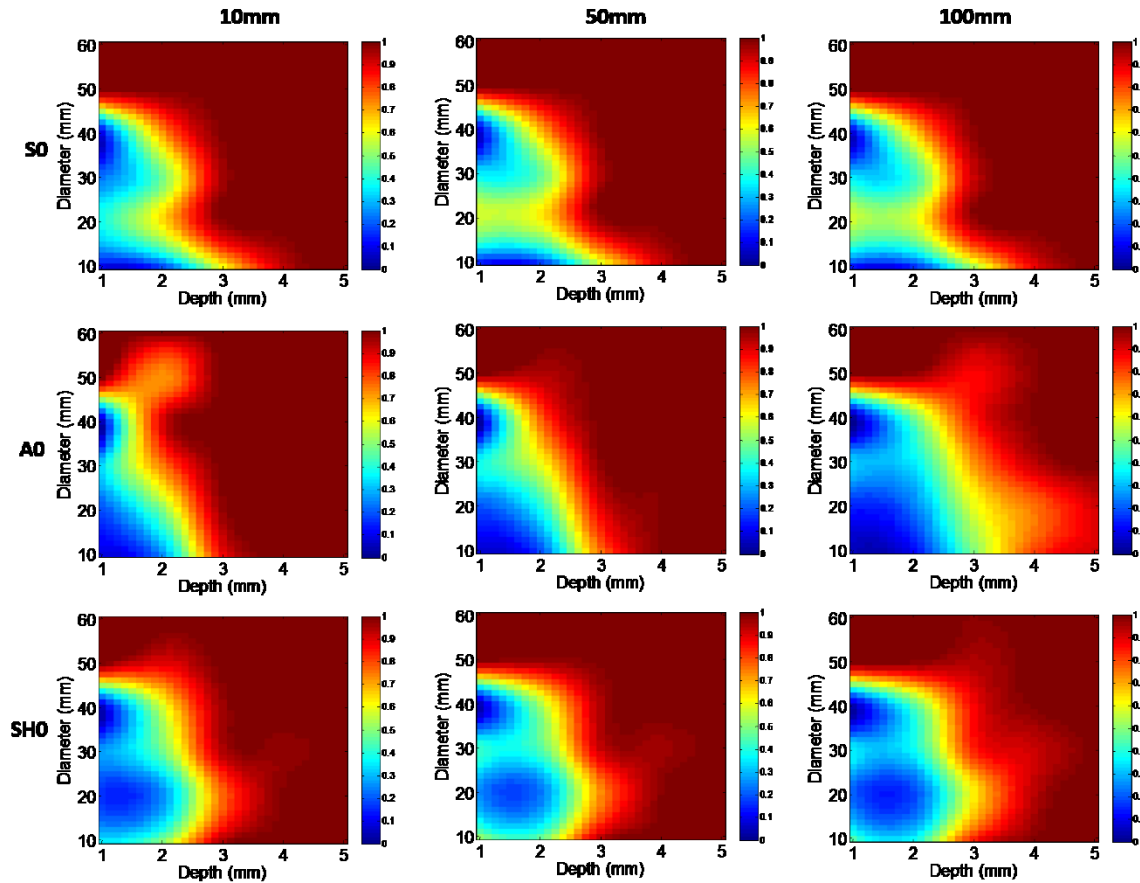


Figure 9.6 Probability of detection in reflection for the S0 mode (top row), A0 mode (middle row) and the SH0 mode (bottom row) with pitches of 10, 50 and 100mm, over a range of part thickness hole diameters (10-60mm) and depths (1-5mm)

9.6 Issue of Deadzones When Using Windowing Techniques

The backwall and pit amplitude methods described here produce a representation of the amplitudes of the backwall and pit signal because there exist scenarios whereby either the pit signal is located outside the pit signal window or the backwall echo no longer exists (as the defect is very deep). Therefore, the measures/definitions presented here aim to facilitate the analysis of the time traces by defining a broad definition of amplitude which can be applied to a wide range of relevant defect sizes. The method to derive the size of the deadzones is described in the appendix.

The use of thresholds creates effective deadzones whereby the amplitude of the pit signal is not represented correctly since it lies outside the pit window (Figure 9.7a). Figure 9.7b and c shows the approximate relationship between the characteristics of the input toneburst (centre frequency and toneburst width) and the deadzone (given as a measure of thickness, b_{deadzone}). As the width of the toneburst increases the deadzone will increase. The method to produce Figure 9.7b and c is given below. The thickness deadzone is either: a) the

smallest pit depth required for the pit signal to occur within the pit signal window; b) or the deepest pit depth possible with the pit signal occurring within the pit signal window. By way of an example, a 2MHz 3 cycle toneburst shear transducer has a deadzone of 1.22mm.

As with the amplitude definitions, the wall thickness extraction method/definition has been intentionally designed to be as broad as possible. The extracted thickness relates directly to the arrival time of the highest peak after the input signal. Thus giving us a measure of when the pit signal would start to interfere with the wall thickness measurement, as well as telling us what the thickness reading is with large defects. The only case when this algorithm/measurement would start to breakdown is when the defects become so large that the pit signal moved below the threshold, $t_{WT \text{ threshold}}$, and merges with the input signal.

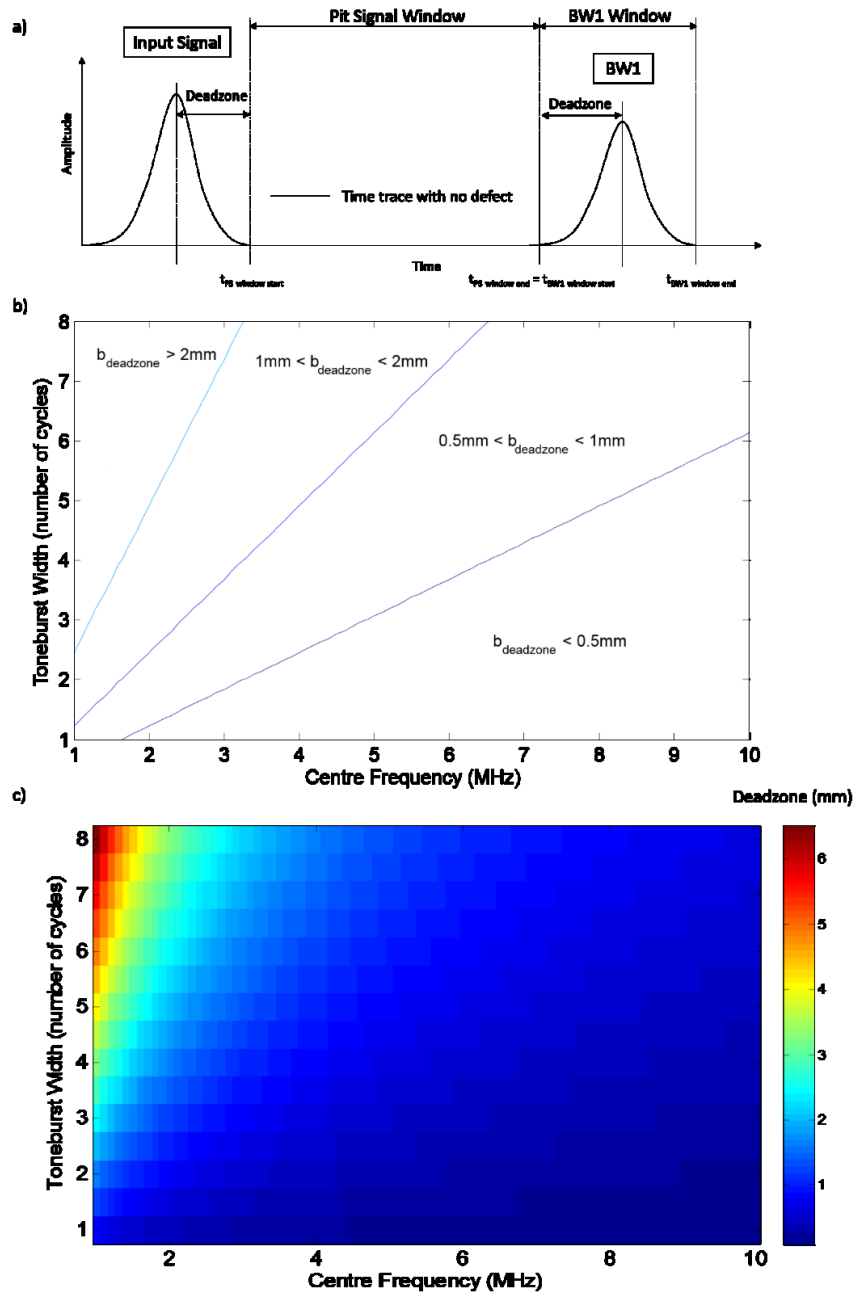


Figure 9.7 a) Schematic of the 'deadzone' which is represented as the thickness change required for peak of the pit signal to occur within the pit signal window b) shows broad areas of thickness deadzones for a range of centre frequencies and toneburst widths. (using a shear transducer $c_s = 3260\text{ms}^{-1}$), c) is the colour plot equivalent of b).

9.7 Derivation of First Backwall Reflection Amplitude Fields

To extract the backwall amplitude field $A_{n,m}$ the entire backwall of FE model ($N \times M$ grid) was monitored. The relative amplitude at each point was calculated using:

$$A_{n,m} = \frac{\max(|\hat{s}_{n,m}|)}{s_{max}} \quad (6.20)$$

where $s_{max} = \max(|\hat{s}|)$ and $|\hat{s}|$ denotes the Hilbert envelope of a signal, s .

9.8 Validation of the Longitudinal Finite Element Model

The longitudinal model used a 3 cycle Hann windowed toneburst with a 5MHz centre frequency. At $c_l = 5960\text{m/s}$ the centre wavelength of the pulse is 1.2mm, which is above the acceptable 10 nodes per wavelength limit, however, since the pulse has a wide bandwidth there are many frequency components below this threshold. Therefore, the capability and bounds of this model must be assessed. Furthermore, even at the centre frequency any mode converted shear wave signals will have a wavelength of 0.65mm.

Validation of this model was performed on 4mm and 5mm radius pits, which were machined into a 10mm thick steel plate. The 25.4mm (1 inch) thick plate in Figure 6.8b as initially tried however, the increased propagation distance (50.8mm against 20mm for first backwall reflection) significantly increased numerical dispersion within the FE model, especially at second backwall reflection and after. The experimental setup used a 5MHz 0.5" V109 Panametrics Ltd longitudinal probe (Olympus, Japan) and a custom made amplifier (Imperial College London, UK), controlled by a HandyScope HS5 (TiePie, NL) and MATLAB (MathWorks, USA). The probe was placed directly above the pits. The switching and subsequent ring down time between input and output signals on the HandyScope meant that the first backwall signal was masked. The second, third and fourth backwall signal were therefore used. The amplitudes of the simulated (Hilbert enveloped) signals were normalised to the amplitude of the second backwall signals from the experiment. The probe was modelled as a circular node set on the top surface of the model with a 12mm diameter.

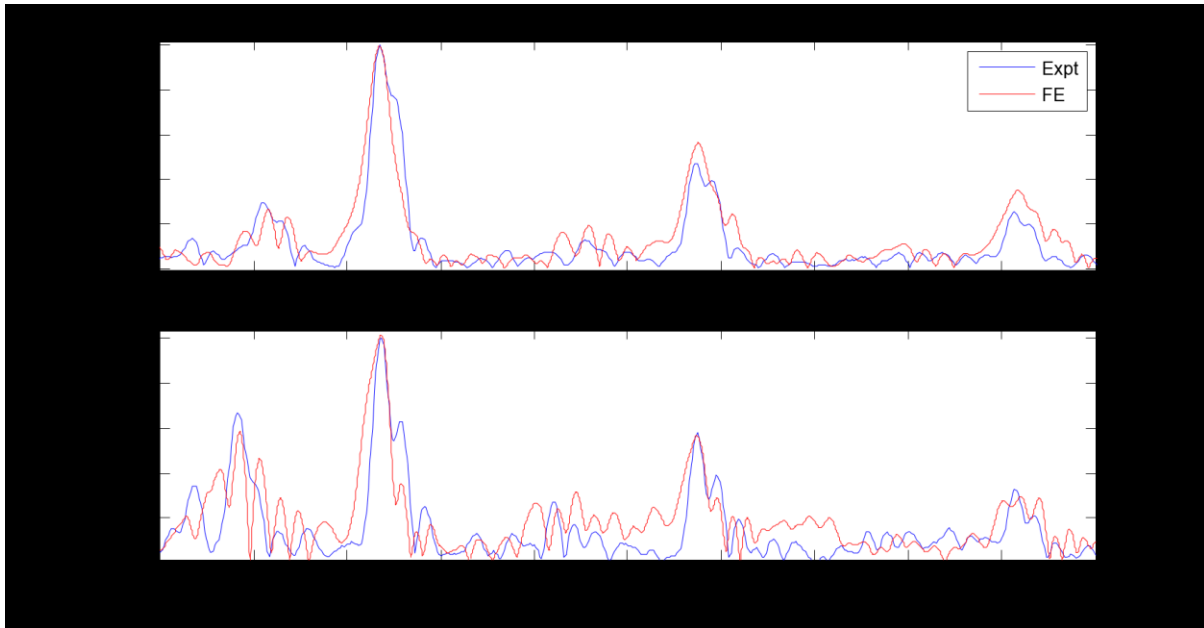


Figure 9.8 The Hilbert enveloped time traces of a longitudinal pulse reflecting off either a a) 4mm and b) 5mm radius pit. The experimental (blue) and simulated (red) second, third and fourth backwall reflections are shown. (5MHz 3 cycle Hann windowed toneburst, 10mm thick steel plate)

Figure 9.8 shows a good approximate relationship between the amplitude of the experimental and simulated signals. The backwall amplitude decay is more precise in the 5mm case (see Table 9.4). The double reflection off the BW and pit is clearly visible in each case and there is approximately 10% amplitude difference between the model and experiment. The effects of numerical dispersion are obvious in the model, with the pulses broadening and the jagged nature of the reflections from the pits. The author concedes that this FE setup is limited in scope. However, in this study the reflection amplitudes are the sole area of interest, which behave similarly in both experimental and simulated cases, whereas inferences cannot be made regarding the phase or pulse width.

	4mm Pit	5mm Pit
Feature	% change in amplitude between experimental and finite element signals	
BW3	16.15	2.92
BW4	27.97	9.77
BW-pit	11.05	12.7
BW-BW-pit	31.45	10.67

Table 9.4 The percentage change in amplitude between the simulated and experimental signals from various features in the 4mm and 5mm time traces in Figure 9.8

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