



Non-destructive evaluation of residual stress using phased array ultrasonics

Brandon Mills

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Department of Electronic and Electrical Engineering

Faculty of Engineering

University of Strathclyde

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Signed: B. Mills

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Abstract

Residual stress (RS) affects the structural integrity and fatigue performance of welded and additively manufactured metallic components and can contribute to distortion, cracking, and premature failure. Established RS measurement techniques, including incremental hole drilling, neutron diffraction, and the contour method, provide valuable stress information but can be limited by localised sampling, lack of in-situ capability, or destructive material removal. Ultrasonic methods offer a non-destructive alternative, particularly through longitudinal critically refracted (LCR) waves, whose velocity is affected by material stress through the acoustoelastic effect. However, ultrasonic RS measurement relies on nanosecond-scale time-of-flight (ToF) changes, making it sensitive to external sources of ToF variation.

This thesis develops a phased-array, acoustoelasticity-based framework progressing from controlled stress measurement in bolts, to phased array ultrasonic residual stress measurement (PAURS), and finally to microstructure-sensitive interpretation (PAURS+). Full Matrix Capture (FMC) enables multiple ultrasonic paths to be assessed using ToF, amplitude, attenuation-related response, signal quality, and path-wise variance, providing a basis for determining measurement quality.

Bolted connections are used as the controlled-stress benchmark, with ultrasonic measurements compared against mechanical loading data and finite-element-derived average axial stress. Phased-array ultrasonics resolved preload-sensitive ToF changes and path-wise variation associated with asymmetric loading or disrupted acoustic paths.

PAURS was subsequently developed using a pitch-catch phased-array configuration to generate and receive LCR waves in available welded S275 steel samples, with further S275 steel acquired for complementary investigations. Simulation and experiments were used to verify LCR generation, assess penetration depth, calibrate the acoustoelastic response, and quantify couplant gel-thickness effects. Uncontrolled coupling variation produced practically significant apparent stress errors, while adjacent-receiver subtraction and multi-path processing reduced the compensated mean gel-induced ToF error to 0.27 ns, corresponding to an equivalent apparent stress error of 1.09 MPa using the approximation of $1 \text{ ns} \approx 4 \text{ MPa}$ present in steel. This value represents the mean across three steel plates. This is treated as a contributing source of error, and not an overall uncertainty.

PAURS was applied to a robotically welded S275 steel sample, selected as a representative weldable structural material for development of the residual-stress measurement methodology, and assessed against incremental hole-drilling measurements performed externally on the same specimen, and neutron-diffraction measurements obtained from a nominally identical welded specimen. Accounting for differences in measurement principle, gauge volume, and sampling depth, PAURS reproduced the principal residual stress trends observed by the independent techniques where suitable wedge–

specimen contact was achieved. Agreement was reduced near the weld centre, where weld geometry and poor wedge-specimen coupling affected the LCR response; measurements in these regions were therefore interpreted as semi-quantitative or qualitative. FMC reduced path-wise variability relative to matched linear paths and provided an internal measure of measurement consistency; this improvement is interpreted as increased precision rather than evidence of reduced absolute bias.

The final stage extends PAURS to microstructure-sensitive characterisation through PAURS+. Electron Backscatter Diffraction (EBSD), k-Wave simulation, frequency-dependent analysis, and robotic angular LCR measurements were used to investigate Al7075 produced by additive friction stir deposition. Amplitude and attenuation-related angular responses were used as the principal microstructure-sensitive observables. Angular attenuation signatures distinguished between equiaxed and columnar grain structures, indicating near-surface microstructural anisotropy and demonstrating that microstructure should be considered when interpreting ultrasonic RS measurements.

Overall, the thesis establishes an FMC-based phased-array methodology combining calibrated ToF stress calculation, multi-path processing, couplant-error control, signal-quality assessment, and comparison with independent RS measurements. The framework identifies when ultrasonic outputs support numerical stress calculation, trend-based interpretation, or rejection from quantitative assessment, and extends the same phased-array platform towards microstructure-sensitive indication through PAURS+.

Candidate contribution statement

The research presented in this thesis was conducted within collaborative research programmes at the Centre for Ultrasonic Engineering and associated partner institutions. The candidate was responsible for the thesis-level interpretation that links the bolt, PAURS, gel-thickness, and PAURS+ studies as connected stages of the same phased-array ultrasonic stress and microstructure measurement approach. The interpretation connects controlled-stress calibration and residual stress measurement with couplant-error control, FMC-based path analysis, and the PAURS+ microstructure-sensitive characterisation extension.

The candidate's primary contributions were in ultrasonic measurement design, phased-array data acquisition and processing, and interpretation of ToF and amplitude-based observables. The candidate also analysed repeatability and acoustic-path variability, compared the ultrasonic results with independent datasets, and prepared the lead-authored manuscripts that form the core of the thesis.

Elements of the finite element modelling, robotic welding, neutron diffraction, hole drilling, EBSD measurement, and experimental infrastructure were supported by supervisors, collaborators, technicians, or partner facilities, as stated in the relevant chapters. Where these methods were used as comparison or supporting evidence, the candidate's contribution was primarily in ultrasonic measurement design, data processing, interpretation, comparison, and integration of the results into the thesis.

Table of contents

Acknowledgements.....	3
Abstract.....	4
Candidate contribution statement.....	6
List of Figures	10
List of Tables.....	15
Terms and Abbreviations	16
Table of Notations.....	18
1. Introduction.....	20
1.1. Context of research.....	20
1.2. Research gap and thesis rationale	22
1.3. Research aims and objectives	23
1.4. Contribution to knowledge	24
1.4.1. Controlled-stress benchmark using bolts	25
1.4.2. Translation to welded RS measurement using PAURS	25
1.4.3. Couplant gel-thickness compensation and timing-error control	26
1.4.4. Microstructure-sensitive extension using PAURS+	26
1.4.5. Scope conditions, limitations, and quality-control requirements	27
1.5. Thesis structure.....	27
2. Research Background	29
2.1. Residual stress	29
2.1.1. Residual stress formation	29
2.1.2. Measurement of residual stress	30
2.2. Bolted connections as a controlled-stress benchmark	32
2.3. Acoustoelasticity and residual stress	33
2.4. Microstructure and PAURS+	35
2.5. Identified Research Gaps.....	37
3. Measurement theory and model.....	39
3.1. Measurement-model foundation and assumptions	39

3.2.	Residual stress quantities used in the measurement model	41
3.3.	Acoustoelasticity and PA-LCR stress calculation	44
3.4.	Microstructure and PAURS+	47
3.5.	Phased-array acquisition, FMC, and measurement quality	52
3.6.	Chapter Summary	53
4.	Experimental setup.....	54
4.1.	Controlled-stress benchmark using bolted connections	54
4.1.1.	Phased-array ultrasonic measurement procedure	55
4.1.2.	Finite element model for path-averaged axial stress	57
4.1.3.	Acoustoelastic calibration and sensitivity assessment	59
4.1.4.	High preload investigation	60
4.1.5.	Blind test on M42 bolt under representative access conditions	61
4.1.6.	Method elements carried forward by the controlled-stress benchmark.....	63
4.2.	Residual stress and PAURS	64
4.2.1.	Overview of methodology.....	64
4.2.2.	Sample manufacturing.....	66
4.2.3.	Independent RS comparison methods	69
4.2.4.	PA-LCR configuration verification	73
4.2.5.	Acoustoelastic constant calibration.....	78
4.2.6.	Couplant gel-thickness uncertainty: simulation and experimental assessment	79
4.2.7.	Ultrasonic inspection of welded plate	85
4.2.8.	Comparison and verification	87
4.2.9.	PAURS measurement basis and interpretation limits.....	90
4.3.	Microstructure and PAURS+	91
4.3.1.	Samples and EBSD	92
4.3.2.	Microstructure simulation	93
4.3.3.	Robotic PA-LCR experimental comparison.....	97
4.3.4.	PAURS+ measurement basis and interpretation limits	99
5.	Results and discussion	100

5.1.	Controlled-stress benchmark using bolted connections	100
5.1.1.	FEA-derived average axial stress	100
5.1.2.	Acoustoelastic calibration, sensitivity, and uncertainty	101
5.1.3.	High-preload response and calibrated-regime assessment	103
5.1.4.	Blind M42 transfer test.....	106
5.1.5.	Implications of the bolt benchmark for PAURS.....	107
5.2.	Residual stress and PAURS	108
5.2.1.	Acoustoelastic calibration	108
5.2.2.	Couplant gel-thickness uncertainty: simulation and experimental assessment	110
5.2.3.	Ultrasonic residual stress investigation	116
5.2.4.	Comparison and verification	124
5.2.5.	What PAURS establishes for welded residual stress measurement	129
5.3.	Microstructure and PAURS+	130
5.3.1.	Frequency sensitivity of the PAURS+ ToF and amplitude response.....	130
5.3.2.	5 MHz PAURS+ simulation and robotic validation	134
5.3.3.	What PAURS+ establishes for microstructure-sensitive characterisation.....	143
6.	Conclusions.....	144
	References.....	148
	Appendix A	157
	Argoshield Heavy Datasheet.....	164

List of Figures

Figure 1: Phased-array ultrasonic measurement framework developed in this thesis, showing PA-LCR/FMC acquisition, signal processing, measurement outputs and the main factors affecting their interpretation.	21
Figure 2: PA-LCR time-of-flight extraction and stress-calculation workflow. The input A-scan is windowed around the LCR arrival, a repeatable timing feature is selected, and the resulting ToF change is converted to a stress value using the calibrated acoustoelastic relationship. [5]	40
Figure 3: Schematic comparison of amplitude change in equiaxed and columnar microstructures using (a) pulse-echo and (b) LCR ultrasonics. The schematic illustrates how microstructure can affect ultrasonic amplitude, providing the basis for the PAURS+ observable selection.	49
Figure 4: Principle of directional LCR response in (a) randomly oriented or approximately isotropic microstructure and (b) approximately anisotropic microstructure.	51
Figure 5: Time-of-flight extraction used in the controlled-stress bolt benchmark. Top: full A-scan response. Middle: selected backwall region. Bottom: extracted backwall reflection, with the selected zero-crossing used as the repeatable timing feature. The time difference between successive echoes is used to reduce common coupling and interface-delay effects [1].	56
Figure 6: Finite element model of the controlled-stress bolt benchmark under 250 kN applied load. The model provides the average axial stress used as the mechanical comparator for the ultrasonic measurements [1].	58
Figure 7: Experimental setup for acoustoelastic calibration in the controlled-stress bolt benchmark. The bolt preload was monitored using a strain gauge, while phased-array ultrasonic measurements were acquired to determine the relationship between time-of-flight change and FEA-derived average axial stress [1].	59
Figure 8: High-preload controlled-stress M36 bolt benchmark after hydraulic tensioning. The inset identifies the PEAK Micropulse controller used for ultrasonic acquisition [1].	61
Figure 9: Blind M42 transfer test performed at the FASTBLADE facility. The test was used to assess whether the calibrated phased-array ultrasonic stress-measurement logic could transfer from the controlled M36 benchmark to a larger bolt under representative field-like access conditions [1].	62
Figure 10: PAURS RS methodology and sample allocation. Two nominally identical welded S275 specimens were manufactured using the same robotic welding procedure. Sample #1 was used for incremental hole drilling and subsequent PAURS inspection, while Sample #2 was used for neutron diffraction [5].	65
Figure 11: Schematic overview of the RS measurement locations for the welded S275 specimens. The schematic shows the PAURS, hole drilling, and neutron-diffraction measurement locations [5].	66
Figure 12: Weld layout used for the S275 RS specimens. The schematic defines the multi-pass weld geometry used to manufacture the robotically welded plates [5].	68

Figure 13: Robotic welding setup used to manufacture the S275 residual stress specimens. Robotic manufacture was used to improve repeatability of the weld path and process conditions between the nominally identical specimens used for PAURS, hole drilling, and neutron-diffraction comparison [5].	68
Figure 14: Incremental hole drilling setup used for the S275 residual stress specimen, showing (a) the bonded strain-gauge rosette before drilling and (b) the drilling operation at the first measurement position [5].	70
Figure 15: Neutron-diffraction setup used at the ANSTO KOWARI facility for the S275 welded specimen. Neutron diffraction was performed on Sample #2 to provide independent depth-resolved RS information. [5]	72
Figure 16: Experimental setup used for the PA-LCR penetration-depth assessment. Notches at known depths were introduced to assess the depth range over which the selected LCR response remained [5].	74
Figure 17: Representative A-scans from the PA-LCR penetration-depth assessment. The selected LCR arrival is highlighted for notch depths of 0.5, 1.25, 1.5, and 1.75 mm. The response demonstrates the approximate near-surface sensitivity of the selected PA-LCR configuration [5].	75
Figure 18: Finite element model used to assess LCR wave generation for the PAURS configuration. The model incorporates the phased-array probes, wedges and S275 steel sample used to verify the wedge angle for LCR generation [5].	77
Figure 19: Simulated progression of the LCR wave across the S275 specimen. The wavefield is shown at successive time steps, demonstrating near-surface propagation from the selected wedge configuration [5].	77
Figure 20: Experimental setup used for acoustoelastic constant calibration. A tensile load was applied to the S275 calibration specimen while LCR ToF measurements were acquired using the selected PA-LCR configuration [5].	78
Figure 21: K-Wave model used to simulate couplant gel-thickness effects in the PA-LCR configuration. The model represents the wedge, couplant layer and S275 specimen, with controlled changes in gel thickness introduced at the wedge-specimen interface [8].	81
Figure 22: A selection of gel thickness profiles at (a) iteration 1, (b) iteration 41, (c) iteration 101, and (d) iteration 141 [8].	82
Figure 23: Schematic arrangement for the experimental gel-thickness study. Shims were introduced between the wedge and specimen to vary the effective couplant layer thickness under controlled conditions [8].	83
Figure 24: Experimental setup for the shim-based gel-thickness study. The PA-LCR wedge and phased-array probe were positioned on the S275 specimen with controlled shim thicknesses used to alter the effective coupling layer. The measurements were used to compare uncompensated and compensated ToF variation [8].	84

Figure 25: PAURS inspection setup for the welded S275 specimen. The pitch–catch phased-array wedge arrangement was used to generate and receive LCR waves across the weld region, with measurements acquired at 21 scan locations arranged symmetrically about the weld centreline [5]...	86
Figure 26: RS comparison workflow. The workflow summarises how strain-relief, diffraction-based, and ultrasonic measurement routes were processed before final comparison. [5].....	89
Figure 27: Al7075 AFSD sample used for the PAURS+ microstructure study: (a) as-received AFSD sample, (b) EDM-cut sections extracted for EBSD, and (c) EBSD reference microstructures showing the equiaxed deposited AFSD region and the elongated grain substrate region.	93
Figure 28: Microstructure-informed simulation mesh for the AFSD region of the Al7075 sample: (a) full k-Wave simulation domain with the phased-array transducer arrangement and (b) zoomed EBSD-derived region used to construct the representative equiaxed microstructure.	95
Figure 29: Microstructure-informed simulation mesh for the substrate region of the Al7075 sample: (a) full k-Wave simulation domain with the phased-array transducer arrangement and (b) zoomed EBSD-derived region used to construct the representative elongated microstructure.	96
Figure 30: Robotic PA-LCR setup used for 5 MHz angular validation on the Al7075 sample: (a) inspection of the deposited AFSD region and (b) inspection of the substrate region.	98
Figure 31: Finite element stress distribution in the bolt up to 300 kN applied load. The dashed line indicates the average axial stress in the inspected region at an applied load of 250 kN, used as the ultrasonic comparator at that loading [1].	101
Figure 32: Acoustoelastic calibration for the controlled-stress bolt benchmark. The fitted relationship compares stress calculated from ultrasonic time-of-flight change with the FEA-derived average axial stress in the inspected bolt region [1].....	102
Figure 33: Ultrasonic stress estimate compared with FEA-derived average axial stress during high-preload bolt loading. The dashed line indicates the expected linear acoustoelastic response, while the measured response shows the point at which the calibrated relationship becomes less stable [1].	103
Figure 34: Time-of-flight distributions across the phased-array probe at increasing preload levels. The distributions provide a path-consistency measure for the controlled-stress benchmark [1].	105
Figure 35: Element-wise acoustoelastic calibration for the S275 PAURS configuration. The fitted responses show the relationship between applied tensile stress and LCR time-of-flight change for individual phased-array paths. T [5].	109
Figure 36: Averaged acoustoelastic calibration used for PAURS residual stress calculation. The averaged relationship combines the phased-array path responses to obtain the stress-conversion factor used in the welded-plate PAURS measurements. [5].....	110
Figure 37: Simulated effect of average couplant gel thickness on LCR time-of-flight error. The shaded or error-band region represents ± 1 standard deviation. [8].....	111

Figure 38: Equivalent apparent stress error associated with simulated gel-induced ToF variation. The stress error is calculated from the simulated ToF shift using the stress approximation of $1 \text{ ns} \approx 4 \text{ MPa}$. [8].....	112
Figure 39: Simulated compensated ToF difference after adjacent-receiver subtraction. The compensated ToF response is obtained by averaging adjacent receiver-pair differences across all transmitters. [8].....	113
Figure 40: Equivalent apparent stress error after simulated gel compensation. The compensated stress error is calculated from the adjacent-receiver-subtracted ToF response. [8]	113
Figure 41: Experimental ToF shift relative to the ideal matched coupling condition. [8]	114
Figure 42: Experimental compensated ToF error after adjacent-receiver subtraction. Across the three plates, the mean residual error is approximately -0.3 ns, with the largest observed residual error remaining below approximately -0.6 ns. [8]	115
Figure 43: Equivalent apparent stress error after experimental gel compensation. The residual ToF error after compensation is converted to an equivalent apparent stress error. The result shows that the mean compensated gel-induced error is reduced to approximately 1.1 MPa under the tested shim-controlled conditions. [8]	116
Figure 44: Individual PAURS stress estimates from selected acoustic paths along the top surface of the welded S275 specimen. [5]	117
Figure 45: Individual PAURS stress estimates from selected acoustic paths along the bottom surface of the welded S275 specimen. The results show the corresponding path-wise stress estimates for the bottom surface. [5]	118
Figure 46: Mean PAURS RS distribution across the top surface of the welded S275 specimen. [5] .	119
Figure 47: Mean PAURS RS distribution across the bottom surface of the welded S275 specimen. [5]	120
Figure 48: Standard deviation of PAURS stress estimates from matched transmit–receive paths on the top surface. Examples are shown at positions relative to the weld centre: (a) –195 mm, (b) –35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [5]	121
Figure 49: Standard deviation of PAURS stress estimates from matched transmit–receive paths on the bottom surface. Examples are shown at positions relative to the weld centre: (a) –195 mm, (b) –35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm [5].....	121
Figure 50: Standard deviation of PAURS stress estimates using the FMC acoustic-path set on the top surface. Examples are shown at positions relative to the weld centre: (a) –195 mm, (b) –35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [5]	122
Figure 51: Standard deviation of PAURS stress estimates using the FMC acoustic-path set on the bottom surface. Examples are shown at positions relative to the weld centre: (a) –195 mm, (b) –35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [5].....	123

Figure 52: Incremental hole drilling residual stress profile at the weld-centre region of Sample #1. This depth range provides the closest same-specimen near-surface comparison for the PAURS top-surface weld-centre result. [5].....	125
Figure 53: Neutron-diffraction residual stress results for the welded S275 replicate specimen. The results show the normal, longitudinal and transverse stress components measured within finite gauge volumes at selected depths. [5]	126
Figure 54: Comparison between PAURS, hole drilling, and neutron diffraction for the top surface of the welded S275 specimen. PAURS stresses are calculated from LCR ToF changes using the calibrated acoustoelastic relationship [5]	127
Figure 55: Comparison between PAURS and neutron diffraction for the bottom surface of the welded S275 specimen. [5].....	128
Figure 56: Simulated 10 MHz angular amplitude change in the elongated substrate (red) and equiaxed AFSD (blue) models.	131
Figure 57: Simulated 10 MHz ToF variation in the elongated substrate (red) and equiaxed AFSD (blue) models.	132
Figure 58: Simulated 32 MHz angular amplitude change in the elongated substrate (red) and equiaxed AFSD (blue) models.	133
Figure 59: Simulated 32 MHz ToF variation in the elongated substrate (red) and equiaxed AFSD (blue).	133
Figure 60: Comparison between the angular positions of the simulated amplitude-change features and the corresponding ToF response in the frequency-sensitivity study.....	134
Figure 61: Definition of the amplitude-change metric used in the 5 MHz PA-LCR analysis. The metric is extracted from the selected LCR arrival and used as an attenuation-related descriptor of how the received amplitude changes with propagation path and inspection angle.	135
Figure 62: Simulated 5 MHz angular amplitude-change response in the elongated substrate region. The directional features indicate the expected attenuation-related response as the LCR propagation direction changes relative to the EBSD-defined elongated grain morphology.	136
Figure 63: Simulated 5 MHz angular amplitude-change response in the equiaxed AFSD region. The weaker angular dependence provides the simulated reference case for comparison with the elongated substrate response above.	137
Figure 64: Experimental 5 MHz robotic PA-LCR angular amplitude-change response in the elongated substrate region. The measured response shows a directionally dependent attenuation-related signature consistent with the elongated substrate morphology.....	138
Figure 65: Experimental 5 MHz robotic PA-LCR angular amplitude-change response in the equiaxed AFSD region. The weaker angular dependence provides the experimental reference case for assessing whether the stronger substrate response is microstructure-sensitive or only system-driven.	139

Figure 66: Comparison between the 5 MHz simulated and experimental PA-LCR angular amplitude-change responses in the elongated substrate region. Agreement is assessed using the angular position and relative strength of the main attenuation-related features.	140
Figure 67: Comparison between the 5 MHz simulated and experimental PA-LCR angular amplitude-change responses in the equiaxed AFSD region. The weaker angular response supports the use of the AFSD region as the reference case for identifying the stronger directionally dependent response in the substrate.	141
Figure 68: Final synthesis of the phased-array ultrasonic measurement framework developed in this thesis. The framework progresses from the controlled-stress bolt benchmark, to welded residual-stress measurement using PAURS, and finally to PAURS+ microstructure-sensitive characterisation.	144

List of Tables

Table 1: Comparison basis for residual stress methods used in the PAURS assessment.	31
Table 2: Robotic TIG welding parameters used to manufacture the S275 RS specimens.	66
Table 3: Collation of longitudinal velocities and resultant wedge angles used in this thesis.....	80
Table 4: Blind M42 transfer-test comparison between mechanically derived stress and ultrasonic stress estimate.	106

Terms and Abbreviations

In this thesis, phased-array ultrasonic terminology is used according to the following hierarchy.

PAUT refers to the general inspection technology: phased-array ultrasonic testing. It includes beam steering, electronic focusing, B-scan and S-scan imaging, FMC acquisition, and post-processing methods such as TFM.

PA-LCR refers to the specific phased-array longitudinal critically refracted wave experimental setup used in this thesis. It describes the probe, wedge, and acquisition arrangement used to generate and receive LCR waves for near-surface stress- or microstructure-sensitive measurements.

PAURS refers to the residual stress implementation of PA-LCR. In PAURS, time-of-flight changes are the primary ultrasonic observables, and residual stress is calculated using acoustoelastic calibration, multi-path processing, and measurement-quality assessment. In this thesis, PA-LCR will refer to hardware setup, while PAURS refers to the use of PA-LCR to extract residual stress values.

PAURS+ refers to the microstructure-sensitive extension of the PA-LCR/PAURS approach. In PAURS+, amplitude, attenuation-related response, and angular variation are the primary observables. These features are interpreted through comparison with EBSD, simulation, and robotic angular measurements to assess near-surface microstructural anisotropy.

FMC refers to the acquisition strategy in which all available transmitter–receiver combinations are recorded. In this thesis, FMC increases the number of available acoustic paths, supports averaging and path selection, assists gel-error compensation, and provides internal evidence of measurement consistency. It improves precision and interpretability, but reliable stress calculation still depends on calibration, signal quality, and appropriate measurement conditions for accuracy.

Abbreviation/term	Definition
AFSD	Additive Friction Stir Deposition
ANSTO	Australian Nuclear Science and Technology Organisation
ASTM	American Society for Testing and Materials
AVC	Automatic Voltage Correction
DAAH	Detachable Active Array Head
EBSD	Electron Backscatter Diffraction
EDM	Electrical Discharge Machining
FEA	Finite Element Analysis
FMC	Full Matrix Capture
HAZ	Heat-Affected Zone
HD	Hole Drilling

k-Wave	MATLAB-based acoustic simulation toolbox used for time-domain ultrasonic wave propagation modelling
LCR	Longitudinal Critically Refracted wave
MATLAB	Numerical computing environment used for ultrasonic data processing and simulation workflows
MTEX	MATLAB toolbox used for crystallographic texture and EBSD data analysis
ND	Neutron Diffraction
PA	Phased Array
PA-LCR	Phased-array longitudinal critically refracted wave configuration
PAURS	Phased Array Ultrasonics for Residual Stress measurement
PAURS+	Microstructure-sensitive extension of PAURS based on phased-array LCR amplitude/attenuation/angular response
PAUT	Phased Array Ultrasonic Testing
Pogo	GPU-accelerated explicit finite element software for elastodynamic simulation
RS	Residual Stress
SEARCH	Sensor Enabled Automation, Robotics & Control Hub
SEURS	Single Element Ultrasonic Residual Stress measurement
SNR	Signal-to-Noise Ratio
TIG	Tungsten Inert Gas
TFM	Total Focusing Method
ToF	Time of Flight
WAAM	Wire + Arc Additive Manufacturing

Table of Notations

Symbol	Meaning	Unit / status
ε	Total strain	Dimensionless
ε^e	Elastic strain	Dimensionless
ε^p	Plastic strain	Dimensionless
ε^{th}	Thermal strain	Dimensionless
ε^{tr}	Metallurgical strain	Dimensionless
ε^{tp}	Transformation induced plastic strain	Dimensionless
σ_{ij}	Stress tensor	MPa
C_{ijkl}	4 th order elastic tensor	Pa
E	Young's Modulus	GPa
ν	Poisson's ratio	Dimensionless
δ_{ij}	Kronecker delta	Dimensionless
s_{ij}	Deviatoric stress tensor	MPa
σ_y	Yield stress	MPa
λ	Plastic multiplier	Dimensionless
α	Coefficient of thermal expansion	K ⁻¹
ΔT	Relative temperature change	K
σ_{RS}	Residual Stress	MPa
L	Acoustoelastic constant	Dimensionless
λ, μ	2 nd order Lamé constants	GPa
A, B, C	3 rd order Landau constants	GPa
l, m, n	3 rd order Murnaghan constants	GPa
v_w	Wedge velocity	ms ⁻¹
v_m	Material velocity	ms ⁻¹
θ_w	Wedge angle	Degrees
θ_c	Critical angle	Degrees
$\Delta\sigma$	Calculated Residual Stress	MPa
t_0	Reference, stress-free Time of Flight	μs or ns
dt	Difference between stressed and stress-free ToF	μs or ns
$dt_{i,j}$	ToF difference measured from the i th transmitter to the j th receiver	μs or ns
D	Penetration depth	mm
f	Frequency	MHz
A_n	Amplitude of n th backwall echo	Arbitrary

l	Specimen thickness	mm
$A_{T_i R_j}$	Amplitude of the LCR wave from the i^{th} transmitter to the j^{th} receiver	Arbitrary
x	Propagation distance between paths	mm
N_t, N_r	Number of transmitters/receivers	Dimensionless
p	Pitch of transducer	mm
A_0	Reference amplitude	Arbitrary
θ	Rotational angle	Degrees
t_{max}, t_{min}	Maximum and minimum gel thickness	mm
x_n	Current iteration	Dimensionless

1. Introduction

1.1. Context of research

Residual stress is a major factor in welded and additively manufactured components, affecting integrity, fatigue life, and defect propagation behaviour. These stresses are generated when incompatible elastic and inelastic strains remain within a material after manufacturing. In welded and additively manufactured structures, RS fields are often spatially heterogeneous, affected by local heat input and material history, and difficult to assess without altering the stress state of the component. Reliable RS assessment is therefore important for structural integrity management, process qualification, life prediction, and defect-tolerance assessment.

Established RS techniques remain essential for reference measurement and method comparison, but no single method provides a complete deployable solution for repeated, large-area inspection of welded or additively manufactured components. Incremental hole drilling provides near-surface RS information, but it is semi-destructive and requires local material removal. Neutron diffraction can provide depth-resolved lattice-strain measurements, but it requires access to specialist facilities and measures over a defined gauge volume. X-ray diffraction and the contour method provide further RS measurement capability, but their use is constrained by penetration depth and destructiveness respectively. These limitations motivate further development of non-destructive methods that can provide repeatable stress-sensitive measurements over larger or less accessible regions.

This research was conducted within the Centre for Ultrasonic Engineering at the University of Strathclyde and is concerned with phased-array ultrasonic methods for RS and microstructure analysis. The work is motivated particularly by welded and additively manufactured components, where conventional RS measurement can be difficult to apply repeatedly or over large areas. The wider research environment includes robotic inspection through the Sensor Enabled Automation, Robotics & Control Hub, where controlled probe positioning and repeatable scans support more consistent ultrasonic measurements.

Ultrasonic stress measurement exploits the acoustoelastic effect, where stress changes the velocity of an elastic wave. Longitudinal critically refracted (LCR) waves are particularly relevant for near-surface assessment because they propagate approximately parallel to the surface and are very sensitive to acoustoelastic velocity changes. In phased-array implementations, multiple transmitter–receiver paths can be acquired from a single probe position, allowing stable responses to be averaged and unreliable paths to be identified.

The starting point for all measurements in this thesis is the ultrasonic signal. The principal observables are time-of-flight (ToF), amplitude, attenuation-related response, and indicators of signal

quality. Figure 1 summarises how Phased Array – Longitudinal Critical Refracted wave (PA-LCR) acquisition and FMC-based processing are combined with calibrated ToF stress calculation and amplitude-based material response to support stress- or microstructure-sensitive outputs.

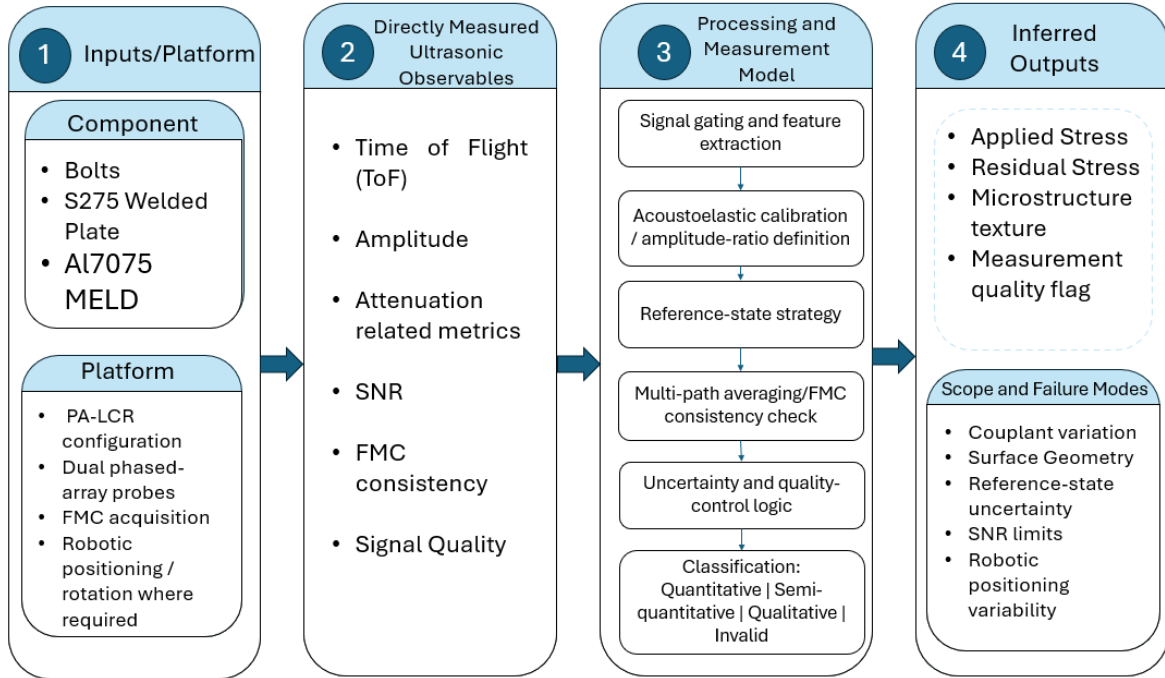


Figure 1: Phased-array ultrasonic measurement framework developed in this thesis, showing PA-LCR/FMC acquisition, signal processing, measurement outputs and the main factors affecting their interpretation.

The evaluation follows increasing measurement complexity. Bolted connections provide a controlled applied-stress case, welded S275 specimens introduce an unknown residual stress field and a more difficult comparison basis, and PAURS+ tests whether amplitude-based PA-LCR features can also provide microstructure-sensitive information from the same measurement platform.

This thesis investigates phased-array ultrasonics as a measurement method for interpreting stress- and microstructure-sensitive ultrasonic responses. Phased-array acquisition provides multiple acoustic paths, supporting averaging and path selection and exposing measurement variability that would be hidden in a single-path measurement. Path redundancy can therefore improve repeatability and identify disagreement between acoustic paths. Common effects acting across the measurement, including calibration error, coupling conditions, and material-state effects, may remain after multi-path processing. Reduced path-wise variation is consequently treated as evidence of improved internal measurement precision and consistency, and does not by itself establish absolute measurement accuracy.

1.2. Research gap and thesis rationale

The main gap addressed in this thesis is the limited internal evidence available in many ultrasonic residual stress measurements. LCR-based methods can detect stress-sensitive changes in time of flight, but these changes are small and comparable timing shifts can also arise from material condition or inspection interface effects, such as coupling variation and surface geometry.

Conventional single-element LCR approaches can estimate stress when the reference state and acoustoelastic calibration are well defined, and geometry is stable and smooth. Their key limitation is that each inspection provides only one transmitted acoustic path. This restricts how far the measurement can be averaged, compared, or checked for variability. The problem becomes more pronounced in welded or additively manufactured components, where local weld geometry, surface irregularity, and the resulting variable contact conditions can all influence the ultrasonic response.

Comparison with established residual stress methods introduces a further challenge, as hole drilling, neutron diffraction, and PAURS do not sample the same quantity in the same way. Hole drilling calculates stress from strain relief, neutron diffraction determines lattice strain over a defined gauge volume, and PAURS calculates stress from LCR time-of-flight changes along a near-surface ultrasonic propagation path. For this reason, calibration, verification, validation, and comparison are used as distinct terms in this thesis. Calibration determines the parameters required by the measurement model, such as the acoustoelastic constant. Verification checks that the ultrasonic configuration behaves as intended under controlled conditions. Validation assesses whether a calculated stress or microstructure quantity or feature is defensible within a stated scope, and comparison describes agreement or disagreement between methods with different measurement principles, sampling depths, or gauge volumes.

Incremental hole drilling and neutron diffraction were selected as the independent comparison methods available for the welded S275 study. Hole drilling provided a near-surface stress measurement on the same specimen subsequently inspected using PAURS, while neutron diffraction provided depth-resolved stress measurements from a nominally identical welded specimen. X-ray diffraction was not used as it is limited to micron scale penetration, which would provide no comparable data to the PAURS depth resolution.

Microstructure is another source of uncertainty in ultrasonic residual stress measurement. Grain morphology, crystallographic texture, and anisotropy can affect both ultrasonic velocity and amplitude response. If these effects are treated only as stress-induced time-of-flight change, they can bias the calculated stress. However, they can also provide useful material-state information when analysed. This thesis treats microstructure as a possible source of uncertainty in PAURS, and as the basis for the PAURS+ extension.

Robotic inspection provides a practical motivation for the work, particularly where repeatable positioning, controlled scan trajectories, and angular measurements are required. However, automation does not remove the underlying measurement problem. Contact force, wedge alignment, positioning tolerance, rotational control, and coupling stability remain sources of variability, though more controllable than in manual inspection. For this reason, robotic deployment is treated as part of the measurement chain, though not as a complete solution to measurement uncertainty.

The intended use of PAURS in this thesis is near-surface assessment of the stress component parallel to the LCR propagation direction. The method is evaluated as a non-destructive measurement and screening approach for identifying residual stress trends and estimating stress magnitude where the calibration, reference condition and measurement quality are sufficient. It is not proposed as a replacement for established reference methods at the present stage of development. The effective measurement depth and spatial resolution are determined by the LCR configuration and acoustic path and are quantified experimentally in Chapter 4. Measurement uncertainty is developed from the individual contributions identified throughout the thesis and consolidated in Chapter 5 and the conclusions. A maximum expanded uncertainty or allowable fraction of material yield stress was not specified before the experimental programme, as the scope of this methodology is intended for use as a residual stress measurement technique – any inspection acceptance criteria is identified as future work.

1.3. Research aims and objectives

The main aim of this PhD project is to develop and evaluate a phased-array ultrasonic measurement framework for the non-destructive assessment of residual stress and related microstructural effects in engineering components. The work progresses from controlled applied-stress measurement in bolted connections to residual stress assessment in welded steel and microstructure-sensitive characterisation using PAURS+.

The specific objectives of the thesis are:

- 1. To establish phased-array acoustoelastic measurement under controlled applied stress by comparing ultrasonic ToF measurements in bolted connections with mechanical loading data and finite element analysis.**
Addressed in Chapters 3–5.
- 2. To use the controlled bolt programme to establish calibration, repeatability, acoustic-path selection and measurement-quality procedures for subsequent stress measurement.**
Addressed in Chapters 4–5.
- 3. To develop and calibrate a pitch-catch PA-LCR configuration for near-surface residual stress measurement in welded steel, including wedge design, penetration-depth**

assessment, acoustoelastic calibration, ToF extraction and stress calculation.

Addressed in Chapters 3–5.

- 4. To quantify practical sources of ultrasonic timing error and measurement variability, with particular attention to couplant thickness, and evaluate multi-path methods for reducing their effect.**

Addressed in Chapters 4–5.

- 5. To evaluate PAURS on welded S275 steel through comparison with incremental hole-drilling and neutron-diffraction measurements, considering stress trend and approximate magnitude within the sampling and measurement constraints of each method.**

Addressed in Chapters 4–5.

- 6. To investigate microstructure-sensitive PA-LCR characterisation using EBSD-informed simulation, frequency-dependent analysis and robotic angular measurements based on amplitude- and attenuation-related response.**

Addressed in Chapters 3–5.

- 7. To establish the scope conditions, measurement-quality requirements, acceptance criteria, uncertainty sources and limitations associated with the developed methodology, using the evidence generated through Objectives 1–6.**

Developed across Chapters 3–5 and consolidated in Chapter 6.

Objective 7 is applied across the experimental programme and provides the link between the individual studies and the overall measurement framework. Evidence includes controlled mechanical loading, finite element analysis, simulation, repeat measurements, acoustic-path consistency and independent residual stress comparisons, as applicable to each study. These are used to define the conditions under which the ultrasonic measurements can support quantitative stress calculation, trend-based interpretation or require further measurement or investigation.

1.4. Contribution to knowledge

This thesis develops a phased-array ultrasonic framework for stress and microstructure measurement. The work begins with controlled loading of bolted connections, where the ultrasonic stress response can be calibrated against a known applied load. The method is then applied to residual stress measurement in welded steel through PAURS, with additional investigation of couplant-induced timing errors and their compensation. The final stage investigates the sensitivity of PA-LCR measurements to microstructure through PAURS+. Measurement quality, limitations and the conditions required for quantitative interpretation are considered throughout the work.

The research has produced a number of lead-author and collaborative publications, which are identified under the relevant contributions below. The candidate's role in the collaborative work is described in the Candidate Contribution Statement.

1.4.1. Controlled-stress benchmark using bolts

Bolted connections provide the controlled-stress benchmark used to develop the phased-array measurement procedure. This work establishes acoustoelastic calibration, stress-sensitive time-of-flight measurement, acoustic-path analysis and defect screening under controlled loading. High-preload measurements and blind testing are subsequently used to assess the behaviour of the method outside the initial calibration experiment.

The main publication associated with this work is:

[P1] B. Mills, Y. Javadi, F. Abad, and co-authors, “Inspection of wind turbine bolted connections using the ultrasonic phased array system,” *Heliyon*, vol. 10, no. 14, 2024. [1]

Related work on bolt inspection and preload measurement is reported in:

[P2] B. Mills, Y. Javadi, P. Leilabadi, and co-authors, “A novel procedure for the inspection of wind turbine bolts,” *Wind Energy Science Conference*, Glasgow, 2023. [2]

[P3] Y. Javadi, B. Mills, C. MacLeod, and co-authors, “Phased array ultrasonic method for robotic preload measurement in offshore wind turbine bolted connections,” *Sensors*, vol. 24, no. 1421, 2024. [3]

The experimental methods and results developed from this work are presented in Chapters 4 and 5.

1.4.2. Translation to welded RS measurement using PAURS

The controlled-stress work is extended to residual stress measurement in welded S275 steel through PAURS. A pitch-catch PA-LCR arrangement is combined with FMC acquisition and multi-path processing to measure stress-sensitive ToF changes. The method includes acoustoelastic calibration and measurement-quality assessment, followed by comparison with incremental hole drilling and neutron diffraction.

This work forms the basis of:

[P4] B. Mills, J. Walker, Y. Javadi, and co-authors, “Residual stress analysis in robotically welded plates using phased array ultrasonics with validation through neutron diffraction and hole drilling methods,” *International Journal of Pressure Vessels and Piping*, vol. 216, 2025 [4].

Two collaborative studies provide additional applications of phased-array ultrasonic residual stress measurement in additively manufactured material:

[P5] J. Walker, B. Mills, Y. Javadi, and co-authors, “Inter-pass peening for residual stress control in additive manufacturing: validation using ultrasonic, X-ray and contour method,” *Materials and Design*, vol. 260, 2025 [5].

[P6] J. Walker, B. Mills, Y. Javadi, and co-authors, “Study of residual stress using phased array ultrasonics in Ti-6Al-4V Wire-Arc additively manufactured components,” *Sensors*, vol. 24, no. 19, 2024 [6].

The welded S275 investigation is presented in Chapters 4 and 5.

1.4.3. Couplant gel-thickness compensation and timing-error control

Couplant thickness was investigated as a practical source of ToF variation in PA-LCR measurements. Numerical simulation and experiments were used to quantify the effect of changes in the coupling layer and the resulting apparent stress error. Adjacent-receiver subtraction and multi-path processing were then assessed as methods of reducing this timing error. This work contributes to the treatment of coupling effects within PAURS and defines one of the practical limits on nanosecond-scale ToF measurement.

The work is reported in:

[P7] B. Mills, Y. Javadi, and C. MacLeod, “Compensating Couplant Effects in Phased-Array Ultrasonic ToF Sensing for Residual Stress,” *Sensors*, special issue “Feature Papers in Physical Sensors”, 2026 [7].

[P8] B. Mills, Y. Javadi, and C. MacLeod, “Simulation of gel effects on the ultrasonic LCR wave for residual stress error quantification,” *BINDT*, 2025. [8]

The simulation and experimental studies are described in Chapters 4 and 5.

1.4.4. Microstructure-sensitive extension using PAURS+

PAURS+ investigates the response of PA-LCR measurements to changes in material microstructure. EBSD, numerical simulation, frequency-dependent analysis and robotic angular measurements are used to examine amplitude and attenuation-related responses from different grain morphologies. The work establishes microstructure-sensitive ultrasonic indicators and examines their relevance to the interpretation of PAURS measurements.

The main manuscript arising from this study is:

[P9] B. Mills, S. Serjeant, Y. Javadi, and co-authors, “Phased Array Longitudinal Critically Refracted Waves for Microstructure Characterisation: Towards In-Process Characterisation”, *Ultrasonics*, 2026, under peer review.

Related studies are:

[P10] Y. Javadi, B. Mills, J. Samuel, and co-authors, “Toward Isolation of Microstructural and Residual Stress Contributions in Phased-Array LCR Ultrasonics,” *International Journal of Pressure Vessels and Piping*, 2026, awaiting decision

The PAURS+ methodology and results are presented in Chapters 4 and 5. The measurements demonstrate sensitivity to microstructural condition; independent determination of crystallographic texture and orientation is outside the demonstrated scope of the method.

1.4.5. Scope conditions, limitations, and quality-control requirements

Measurement quality forms a common theme across the bolt, PAURS and PAURS+ investigations. Quantitative interpretation depends on the acoustoelastic calibration, reference condition, coupling, surface geometry, material state and consistency of the retained acoustic paths. These factors are used to determine whether a measurement is suitable for numerical stress calculation, provides a useful stress trend, or cannot support a quantitative interpretation.

FMC provides multiple acoustic paths from a single acquisition and allows the consistency of the measured response to be assessed. Path-wise variation is therefore used as an internal measure of measurement precision and as an indicator of inconsistent acoustic conditions. Standard deviation across the retained paths is used as the primary path-consistency statistic, supported by the path-wise ToF distribution and signal quality. Measurements with stable arrivals and consistent path behaviour can be retained for quantitative interpretation. Increased path-wise variation prompts reseating and repeat acquisition, with coupling, signal amplitude, arrival stability and probe alignment checked before further interpretation. Measurements that remain inconsistent after reseating are excluded from quantitative stress calculation. Persistent path asymmetry under repeatable coupling and signal conditions may indicate uneven seating or localised mechanical behaviour and requires further investigation. Numerical acceptance thresholds were not defined prospectively and are therefore retained as a requirement for future qualification. Absolute measurement performance also depends on calibration and the systematic effects considered in the measurement model. Independent residual stress measurements provide additional comparison for the welded S275 investigation. The resulting scope conditions and limitations are developed in Chapters 3–5 and summarised in the Conclusions.

1.5. Thesis structure

This thesis is organised into six chapters, covering the research background, measurement theory, experimental methodology, results, and conclusions.

Chapter 1 introduces the research context, identifies the research gap, states the aims and objectives, and defines the main contributions to knowledge.

Chapter 2 reviews the background literature on RS measurement, ultrasonic acoustoelasticity, phased-array ultrasonic testing, bolted-connection stress measurement, and ultrasonic microstructure characterisation. It identifies the limitations in existing methods that motivate the methodology developed in this thesis.

Chapter 3 presents the theoretical basis and measurement model used throughout the thesis, including RS formulation, acoustoelastic stress calculation, LCR wave generation, FMC-based multi-path processing, attenuation-related metrics, and the assumptions used when converting ultrasonic observables into calculated stress or microstructure-sensitive outputs.

Chapter 4 describes the experimental and simulation methods used for the bolt, PAURS, and PAURS+ studies, including the calibration, acquisition, comparison, and validation procedures. Additionally, it discusses which methodological elements are carried forward into the encompassing framework.

Chapter 5 presents and discusses the results. It follows the same order as Chapter 4 for continuity and discusses the controlled-stress, welded residual stress, and PAURS+ results. It also describes how each experimental stage adds to the measurement framework as a whole.

Chapter 6 presents the conclusions of this thesis. It summarises what has been demonstrated, the achieved measurement performance, the current deployment scope, the main uncertainty sources and failure modes, and the future work required before broader industrial qualification.

2. Research Background

This chapter positions the thesis within the literature on residual stress measurement, ultrasonic stress measurement, phased-array inspection, bolt preload assessment, coupling uncertainty, and microstructure-sensitive ultrasonics. It focuses on the measurement problems addressed by the methodology developed later in the thesis: how residual stress methods differ, how ultrasonic signal features are used in stress-sensitive measurement, and where comparison between techniques becomes uncertain.

Residual stress measurement in welded and additively manufactured components is difficult because the stress field is often spatially variable, process-dependent, and sensitive to local material history. Established methods provide important evidence, but they differ in sampling depth, gauge volume, destructiveness, and deployability. These differences matter here because comparison between methods can support an ultrasonic result only when the measurement basis of each technique is accounted for.

Single-element ultrasonic LCR methods provide a non-destructive route to near-surface stress assessment through stress-sensitive changes in time of flight. The measured ultrasonic response is also affected by coupling and surface condition. The literature motivates a measurement approach that considers the consistency of the ultrasonic data, the validity of the calibration, and basis for comparative validation alongside the measured timing change.

The chapter therefore follows the same measurement progression as the thesis: Section 2.1 reviews residual stress formation and measurement methods to establish the comparison basis for PAURS. Section 2.2 considers bolt preload assessment as a controlled applied-stress benchmark for acoustoelastic measurement, and Section 2.3 reviews LCR acoustoelastic measurement, phased-array acquisition, FMC-based path redundancy, and coupling uncertainty. Section 2.4 discusses microstructure as both a source of uncertainty in ultrasonic residual stress measurement and the basis for the PAURS+ extension.

2.1. Residual stress

2.1.1. Residual stress formation

Residual stresses are generated during manufacturing processes, thermal treatments, mechanical deformation, and phase transformations. These stresses affect material performance, including fatigue life, dimensional stability, and susceptibility to cracking and corrosion. [9] [10].

Residual stresses arise primarily due to non-uniform plastic deformation, thermal gradients, and phase changes within a material. Mechanical processes such as machining and rolling introduce plastic deformation gradients. When different regions of a material deform unevenly, internal stresses

develop to maintain equilibrium [11]. Residual stress can also be intentionally introduced through surface treatments to improve fatigue resistance [5]. Welding leads to significant RS development [4], which may reduce fatigue life and increase susceptibility to cracking or distortion [12]. Thermal gradients during manufacturing processes are a major source of residual stress. Rapid heating and cooling create differential expansion and contraction within the material. Regions that cool faster tend to contract more, leading to tensile stresses, while slower-cooling regions may develop compressive stresses [13].

Phase transformations, particularly in steels and alloys, can result in volumetric changes that generate residual stresses. For example, the transformation from austenite to martensite induces internal stress fields [14]. The interaction between thermal and transformation-induced strains further complicates stress distribution [15].

Residual stresses are typically categorised based on their scale [11]:

Type I (Macroscopic): Stresses that act over large distances, often across entire components.

Type II (Microstructural): Stresses between grains or phases within a material.

Type III (Microscopic): Stresses at the atomic or lattice scale, often associated with defects such as dislocations.

The scale of residual stress is important for measurement because different techniques respond to different physical quantities and sampling volumes. In welded and additively manufactured components, the stress field may vary with position, depth, and microstructural condition, so the sampled region must be defined when measurements are compared.

2.1.2. Measurement of residual stress

Residual stress can be measured using destructive, semi-destructive, and non-destructive techniques. Incremental hole drilling provides semi-destructive near-surface stress information [16], and the contour method provides a destructive route to section-based stress reconstruction [17]. X-ray diffraction and neutron diffraction determine lattice strain and convert it to stress using an appropriate stress-free reference [18] [19]. Ultrasonic methods use stress-sensitive changes in wave velocity or time of flight [20].

Several residual stress measurement techniques are relevant to the wider literature, including hole drilling, contour measurement, X-ray diffraction, neutron diffraction, and ultrasonic methods. The comparison in this thesis focuses on HD and ND because these provide the independent datasets used to assess PAURS. *Error! Reference source not found.* summarises the measurement basis, strengths, and limitations of the methods used directly in the PAURS comparison.

Table 1: Comparison basis for residual stress methods used in the PAURS assessment.

Method	Measurement basis	Sampled region in this thesis	Reference and repeat basis	Main limitations for PAURS comparison/uncertainty	Role in this thesis
Incremental hole drilling	Strain relief during incremental material removal, converted to residual stress using standardised analysis	Up to 1.1 mm subsurface, on Sample #1. Longitudinal stress used for comparison with PAURS	Same-specimen comparison. Measurements performed at defined locations relative to the weld centre	Reported uncertainty approximately ± 60 MPa at $\leq 200 \mu\text{m}$, ± 11 MPa at $\sim 500 \mu\text{m}$, and ± 24 MPa at the final reported depth. Additional sensitivity to drilling, strain-gauge bonding and surface preparation	Provides the closest same-specimen near-surface comparison for PAURS
Neutron diffraction	Lattice-strain measurement within a defined gauge volume, converted to stress using a stress-free reference	2 x 2 x 2 mm ³ measurement volume at 2, 7, 10, and 13 mm on the nominally identical Sample #2. Longitudinal stress used for comparison with PAURS	Replicate-specimen comparison; α -Fe (211) reflection using a stress-free reference	Finite gauge-volume averaging, d_0 reference uncertainty and use of a nominally identical rather than the same specimen limit direct pointwise comparison	Provides independent depth-resolved comparison evidence from a replicate welded specimen
Ultrasonic LCR / PAURS	Stress-sensitive ultrasonic velocity or ToF change, converted to stress using acoustoelastic calibration and reference condition	Longitudinal stress parallel to the LCR propagation direction on Sample #1; near-surface path-weighted measurement at 1.2 mm depth	Stress-free reference ToF required for corresponding acoustic paths; FMC provides multiple Tx–Rx measurements for path comparison and averaging	Calibration and reference-ToF uncertainty; coupling/wedge contact; temperature; surface geometry; path selection; microstructure/material state. FMC path consistency indicates precision but does not remove common-mode bias	Main method developed in this thesis for near-surface welded RS assessment

The table is used here to discuss the comparison basis rather than to rank the techniques. HD, ND, and PAURS obtain residual stress information through different physical quantities and sampling regions, so agreement is interpreted in terms of trend, approximate magnitude, and consistency with the expected stress field.

Incremental hole drilling is widely used as a near-surface residual stress comparison method [21] [22] because it is standardised [23] and can be applied locally to engineering specimens. The method calculates stress from strain relief during controlled material removal, usually using a bonded strain-

gauge rosette. Its main limitations are that it is semi-destructive, sensitive to surface preparation and drilling procedure, and subject to higher uncertainty in the earliest near-surface increments.

Neutron diffraction provides an independent diffraction-based route to residual stress measurement by determining lattice strain within a defined gauge volume [24] [25] [26]. Its main advantages are penetration depth and depth-resolved measurement capability [27] [28]. However, ND requires specialist facility access, a suitable stress-free lattice reference, and interpretation of a finite gauge volume rather than a single point value [29]. It is highly valuable for method development and comparison, but less suitable for routine deployable inspection [30] [31].

For PAURS, this creates two practical requirements: independent comparison is needed, and agreement must be interpreted through the measurement basis of each technique. Here, HD and ND provide this independent comparison. HD gives the closest same-specimen near-surface comparison, while ND gives depth-resolved lattice-strain evidence from a replicate specimen.

2.2. Bolted connections as a controlled-stress benchmark

Bolted connections are widely used in offshore wind, tidal energy, and other fatigue-critical engineering structures where preload loss, embedded defects, thread damage, and uneven seating can reduce structural reliability [32] [33] [34]. In offshore wind foundations, bolted flange connections are particularly important because they transfer large cyclic loads between major structural sections and are subject to demanding inspection [35] [36] and maintenance requirements [37] [38].

In a tightened bolt, preload produces an axial stress state that can be assessed mechanically, numerically, or ultrasonically. Previous studies have demonstrated several ultrasonic routes for bolt-preload assessment, including guided waves [39], echo-based measurements [40], energy-ratio methods [41], and finite-element-supported interpretation [42]. These studies demonstrate that ultrasonic measurements can provide a measurable response to changes in bolt preload, although the measured quantity and calibration procedure vary between approaches. This provides the basis for using the bolt as a controlled-stress case in this thesis, where the emphasis is placed on ToF sensitivity, repeatability and the behaviour of individual phased-array acoustic paths. For this thesis, the important feature of a bolted connection is that the applied stress can be imposed and monitored more directly than in a welded residual stress field. This makes the bolted connection a useful, controlled case for assessing whether changes in ultrasonic time of flight are repeatable, stress-sensitive and consistent with an independently estimated loading condition.

Phased-array ultrasonic testing provides additional value in this context because it can combine stress-sensitive measurement with defect-aware inspection. Javadi et al. proposed a phased-array methodology for bolt inspection, showing that multiple acoustic paths can be used to assess the bolt volume and support stress evaluation, and related manual implementations have also been reported

[3], [2]. Related phased-array and ultrasonic inspection studies have also considered single-sided inspection access [43], material and interface effects [44], dissimilar or layered joints [45], defect characterisation [46], and reflected-wave velocity measurement [47]. These studies support the use of phased-array data for defect detection and for identifying acoustic paths suitable for stress-sensitive interpretation. Collectively, they show that phased-array acquisition can provide information from different regions of the inspected volume and that individual acoustic paths may respond differently to local inspection conditions. This is relevant to stress measurement because disagreement between paths can provide additional evidence of measurement quality before the responses are combined into a stress estimate, which is addressed through the path selection capabilities proposed here.

Certain phased-array capabilities, including two-dimensional arrays [48], advanced signal processing [49], Full Matrix Capture [50], Total Focussing Method [51], and phase-coherence methods [52], have improved inspection coverage, imaging performance, and signal interpretation [53]. Of these developments, FMC is particularly relevant to the measurement approach developed here because the individual transmitter–receiver signals remain available for subsequent analysis. The resulting path set can be used to compare responses across the aperture, identify inconsistent measurements and quantify path-wise variation in addition to calculating an averaged response.

Bolted connections provide a controlled loading condition in which preload-sensitive ToF measurements can be assessed against an independently monitored applied load and a model-assisted estimate of stress within the inspected region. Existing ultrasonic bolt-preload studies demonstrate stress sensitivity, and phased-array studies demonstrate improved inspection coverage and defect-aware path selection. Bolted connections have been less widely used as a transferable benchmark for evaluating how preload-sensitive ToF measurements are affected by calibration, repeatability, and disrupted acoustic paths. This makes the bolt study a useful benchmark before PAURS is applied to welded residual stress fields, where the stress state is less controlled. In the bolt benchmark developed in this thesis, the applied preload defines the controlled mechanical input. The corresponding axial stress is obtained from finite element analysis and averaged over the inspected region to provide the comparator for the path-averaged ultrasonic stress estimate. The resulting comparison therefore includes uncertainty associated with the mechanical loading measurement, FE representation and spatial averaging, alongside uncertainty within the ultrasonic measurement chain. The mechanical loading quantity, FE averaging procedure and associated uncertainties are defined in Chapter 4.

2.3. Acoustoelasticity and residual stress

Ultrasonic RS measurement is based on the acoustoelastic effect, where stress-induced changes in elastic wave velocity are detected through changes in time of flight. For near-surface stress assessment, the Longitudinal Critically Refracted (LCR) wave technique is widely used in Single Element Ultrasonic Residual Stress (SEURS) measurement [54], [55], because it propagates

approximately parallel to the surface [56] [57] [58] and is highly sensitive to stress-induced velocity change [59] [21] [6]. These methods depend on detecting variations in ultrasonic time of flight, which are related to stress-dependent changes in elastic wave velocity through the acoustoelastic effect [3] [60] [61]. Achieving high measurement precision is essential, particularly in applications involving fatigue-critical components, such as those found in the aerospace and nuclear industries [62]. The literature therefore establishes LCR ToF as a viable stress-sensitive observable, but its practical use depends on resolving small timing changes consistently. Variations in coupling, temperature, surface condition and material state can also alter the measured ultrasonic response, making measurement control and independent comparison important when ToF changes are converted to residual stress.

Although single-element LCR methods are well established, phased-array implementations remain less developed. Javadi et al. [63] showed that the use of multiple elements can improve the amount of stress-sensitive data available from a single scan, allowing results to be averaged across many element combinations rather than relying on a small number of conventional single-element paths.

Walker et al. [6] highlighted the importance of comparison with independent measurement techniques in ultrasonic RS measurement, due to the inherent strengths and limitations of each method. Prior phased-array residual stress studies have relied on established residual stress techniques, including contour measurement, HD, XRD, or ND, to assess whether ultrasonic stress trends are physically credible [64]. This demonstrates the benefit of increasing the number of stress-sensitive measurements available from a single inspection. The remaining question addressed in this thesis is how the additional acoustic paths can also be used to assess measurement consistency and identify conditions in which an averaged stress value may be unreliable.

A key limitation is that the stress-sensitive timing changes are small. Nanosecond-scale ToF shifts can correspond to stress changes of practical significance, so temperature variation, couplant thickness, and surface geometry can introduce stress-equivalent error if they are not controlled or accounted for [3]. Coupling and contact conditions are recognised sources of uncertainty in ultrasonic time-of-flight and amplitude measurement. Earlier analytical work established the theoretical basis for wave transmission across imperfect interfaces [65] and through couplant layers [66] [67], while experimental studies have shown that variation in couplant thickness can produce measurable changes in the received ultrasonic response [68]. These effects are important for LCR measurement because changes introduced at the inspection interface can affect the timing or amplitude of the received wave independently of the stress state.

Temperature represents a separate source of ToF variation from the coupling effects investigated experimentally in this thesis. A sufficiently resolved record of laboratory and specimen temperature was not retained during the PAURS experimental programme to establish a study-specific ToF–temperature sensitivity or apply a retrospective temperature correction. Temperature is therefore

retained as an unquantified contribution to the PAURS measurement uncertainty. The couplant investigation presented in Chapters 4 and 5 is interpreted specifically as an assessment of coupling-layer-induced timing variation under the tested laboratory conditions.

Ultrasonic wave simulation provides a route for assessing coupling-layer effects where interface geometry or local thickness variation is difficult to control experimentally. Time-domain modelling has been used to investigate ultrasonic propagation in complex media [69] [70]. K-Wave based approaches have also been applied to the simulation of ultrasonic wave propagation and interaction [71] [72]. These studies support the use of numerical modelling as part of the uncertainty assessment for PA-LCR measurement, while the specific gel-thickness model, parameter sweep and ToF-error analysis used in this thesis are presented in Chapter 4.

Numerical studies of layered interfaces have demonstrated changes in ultrasonic transmission associated with the properties of the intermediate layer [73] [74]. Surface contact and coupling conditions have also been shown to affect the resulting wave response [75] [76]. These effects become significant when small timing differences are used for stress-sensitive measurements. For PA-LCR residual stress measurement, an interface-induced timing shift may consequently be converted into apparent stress through the acoustoelastic calculation.

These effects make the interpretation of LCR timing changes as important as their detection. LCR ToF is stress-sensitive, but comparable timing changes can arise from the aforementioned sources of experimental error. This is a particular limitation for conventional single-element LCR measurements, where only a small number of paths are available to test whether the measured response is consistent across the inspection aperture.

A key gap addressed by this thesis is the limited internal measurement evidence currently available for deciding when an LCR timing change should support stress calculation and when it should be treated as uncertain or unsuitable. This motivates the FMC-based PA-LCR approach developed in this thesis, where multiple transmitter–receiver paths support measurement-quality assessment, compensation, and averaging during the RS extraction process.

2.4. Microstructure and PAURS+

The mechanical performance of engineering alloys is strongly affected by microstructure, including grain size, morphology, and crystallographic texture. Conventional characterisation methods, including optical microscopy, EBSD, and diffraction-based techniques, provide high-resolution microstructural or crystallographic information, but they are generally slow, localised, sample-preparation dependent, or difficult to integrate into large-area and process-adjacent inspection. This is relevant to additive and solid-state deposition processes such as WAAM and AFSD, where grain morphology, texture, and residual stress can vary spatially across deposited and substrate regions.

Ultrasonic methods provide a non-destructive route for assessing microstructure because wave propagation is affected by scattering and attenuation [77], as well as velocity, frequency content, and anisotropy [78]. Previous studies have linked attenuation to grain size [79] [80], while backscatter and other quantitative ultrasonic descriptors have been investigated as measures of microstructural condition [81] [82]. Grain morphology and crystallographic texture can also introduce directional dependence into the ultrasonic response. This has been observed through scattering and spectral behaviour [83] [84], and through velocity anisotropy and azimuthal time-of-flight measurements [85] [86]. Nonlinear ultrasonic methods have also been used to examine dislocation-related effects [87].

Together, this literature shows that microstructure can alter several ultrasonic observables that may otherwise be interpreted as stress- or measurement-related changes. In the PA-LCR context, this distinction matters because LCR ToF is primarily used for acoustoelastic stress assessment.

Attenuation and amplitude loss have separately been associated with microstructure-dependent scattering behaviour [88] [89], while backscatter and frequency-domain changes provide further microstructure-sensitive information [90] [91].

This observable-level separation is important for microstructure-aware RS measurement because it provides a way to interpret the same ultrasonic acquisition without treating all signal changes as stress-induced. In the work demonstrated in this thesis, PAURS+ uses amplitude- and attenuation-related PA-LCR responses as descriptors of near-surface microstructural condition. EBSD-informed simulation is used to establish the expected response to contrasting grain structures, and robotic angular measurements are used to assess whether the resulting directional response remains detectable experimentally.

The demonstrated scope of PAURS+ is therefore microstructure-sensitive characterisation. The longer-term objective is to combine complementary observables such that the ToF – based PAURS stress measurement can be interpreted alongside microstructural information based upon the amplitude – related information obtained during the same inspection. Quantitative separation of stress and texture, and recovery of crystallographic texture directly from PA-LCR measurements, remain future development requirements.

The underlying elements of the methodology are not all new individually. Acoustoelastic calibration, LCR-based stress measurement, phased-array acquisition, FMC, and comparison with established residual-stress techniques have all been reported previously in the literature and in earlier work from the research group. The contribution of this thesis is in how these elements are developed and combined into a staged PAURS measurement framework. The bolt study is used to establish the calibration procedure, stress-sensitive ToF extraction and path-wise quality assessment under a controlled loading condition before transfer to welded residual stress measurement. For PAURS, FMC is used not only to increase the number of available measurements, but to retain and compare

individual transmitter–receiver paths as an internal measurement-quality indicator before averaging. Couplant-induced timing error is then treated explicitly through simulation and controlled experiments, with adjacent-receiver ToF subtraction developed and evaluated as a compensation method for the PA-LCR configuration. Hole drilling and neutron diffraction are not introduced as new comparison techniques; their role here is to provide independent, measurement-specific evidence against which the limits of the PAURS result can be assessed. Finally, PAURS+ extends the same PA-LCR platform to angular amplitude- and attenuation-related measurements, supported by EBSD-informed simulation and robotic rotation, as a near-surface microstructure-sensitive characterisation method. Simultaneous quantitative separation of residual stress and crystallographic texture is not demonstrated and remains a future objective.

2.5. Identified Research Gaps

The literature reviewed in this chapter identifies several linked measurement gaps addressed by the experimental programme in this thesis. First, conventional single element LCR residual-stress measurements provide limited internal evidence for determining whether a measured ToF change is consistent across the inspection aperture. Phased-array acquisition provides additional acoustic paths, but their use as path-wise measurement-quality evidence, alongside averaging and stress calculation, requires further development for near-surface residual-stress measurement.

Second, the nanosecond-scale timing changes used for acoustoelastic stress calculation are sensitive to inspection-interface conditions. Couplant-layer variation can introduce ToF changes independently of material stress, and a practical basis is required for quantifying this contribution and assessing whether phased-array path information can reduce its effect.

Third, comparison of ultrasonic residual-stress measurements with established techniques requires explicit treatment of differences in measurement principle, sampling depth, gauge volume and reference state. A measurement framework is therefore required that uses independent methods as method-specific comparators and retains the limitations associated with each comparison.

Finally, the literature shows that grain morphology, crystallographic texture and associated elastic anisotropy can influence ultrasonic velocity, amplitude, attenuation and directional response. These effects create uncertainty when ultrasonic changes are interpreted solely through an acoustoelastic stress model. The corresponding PAURS+ knowledge gap considered in this thesis is whether angular amplitude- and attenuation-related PA-LCR measurements can provide a repeatable near-surface indicator of contrasting microstructural conditions using the same general phased-array platform used for residual-stress measurement. This is investigated using EBSD-defined microstructural regions, microstructure-informed simulation and robotic angular measurements. Quantitative separation of

residual stress and crystallographic texture is outside the demonstrated scope and remains a subsequent development requirement.

These gaps define the measurement theory developed in Chapter 3 and the staged experimental programme presented in Chapters 4 and 5.

3. Measurement theory and model

3.1. Measurement-model foundation and assumptions

This chapter defines the theoretical basis used for the stress and microstructure-sensitive investigations presented later in the thesis. The phased-array ultrasonic methods developed here are based on the measurement of repeatable signal features. Stress calculations use ToF change relative to a reference condition, while PAURS+ uses amplitude change, attenuation-related response and angular variation as microstructure-sensitive descriptors. These features are extracted from phased-array A-scans and are then used in the calculation or characterisation procedure appropriate to each part of the thesis.

In the bolt and PAURS studies, stress is calculated from ultrasonic time-of-flight change using the acoustoelastic relationship. This requires an experimentally determined acoustoelastic constant, a reference time of flight from a stress-free sample, an identified LCR or backwall arrival, and a defined set of acoustic paths. The calculated stress is dependent on both the underlying acoustoelastic response of the material and the stability of the measurement procedure used to obtain the time-of-flight value.

In PAURS+, the same PA-LCR measurement platform is used to derive amplitude and attenuation-related descriptors. These descriptors are used to characterise microstructure-sensitive ultrasonic behaviour, particularly differences associated with equiaxed and elongated grain structures and with angular variation in the LCR response. Within the scope of this thesis, PAURS+ is evaluated as a microstructure-sensitive indicator based on angular amplitude and attenuation-related response. The Al7075 investigation tests whether these observables differ between the EBSD-defined equiaxed deposited region and the elongated-grain substrate, and whether corresponding angular features are reproduced in simulation and robotic measurements. Quantitative separation of residual stress and crystallographic texture was not tested. PAURS+ is therefore interpreted as evidence of microstructure-sensitive angular behaviour and does not provide a quantitative texture measurement or a correction for microstructural contributions to PAURS stress calculations.

Overall, the measurement model follows the same general sequence: acquisition of an ultrasonic signal, extraction of a repeatable feature, processing across multiple acoustic paths, and use of this processed feature for stress calculation, measurement-quality assessment, or microstructure-sensitive characterisation.

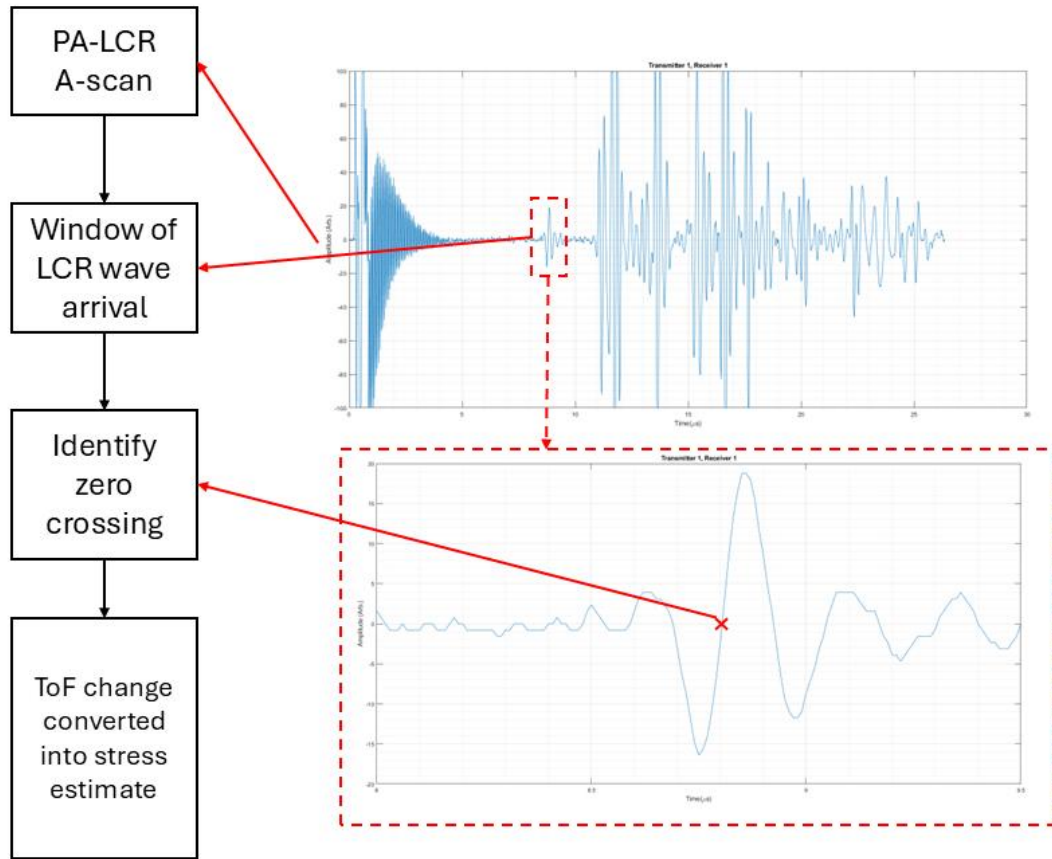


Figure 2: PA-LCR time-of-flight extraction and stress-calculation workflow. The input A-scan is windowed around the LCR arrival, a repeatable timing feature is selected, and the resulting ToF change is converted to a stress value using the calibrated acoustoelastic relationship. [4]

For the PAURS measurements, the second zero crossing within the identified LCR arrival was used consistently as the ToF timing feature for the calibration and welded-plate measurements. The retained experimental record does not contain a separate fixed-position repeat series or controlled lift-and-reseat series from which the repeatability of this timing feature can be quantified independently. A mean repeatability error, standard deviation, 95% interval and corresponding apparent-stress floor therefore cannot be reconstructed retrospectively. The standard deviation between FMC acoustic paths reported later in the thesis is a measure of path-wise consistency.

The LCR response was identified within a gated time region and a MATLAB algorithm applied the zero-crossing selection consistently across the compared measurements. Numerical gate limits were based upon the material and were applied as 8 μ s and 9 μ s in S275 Steel and 7 μ s and 8 μ s in AL7075. The interpolation procedure used between sampled points was the interp1 function in MATLAB. The explicit zero-crossing polarity was obtained using a Boolean function combined with a findpeaks function in MATLAB, counting the number of times a wave crossed the x axis significantly. These items, together with fixed-position and reseating repeatability, are therefore used as requirements for

measurement qualification. Stress conversion is based on the experimentally determined acoustoelastic calibration described in Sections 4.2.5 and 5.2.1.

The workflow in Figure 2 defines the measurement sequence used throughout the thesis. Path retention requires an identifiable and stable ultrasonic arrival, sufficient signal quality for consistent timing-feature extraction, and no clear evidence of disrupted coupling or physically inconsistent path behaviour. Standard deviation across the retained paths is subsequently used as the principal internal path-consistency statistic. Numerical acceptance thresholds for these quantities were not specified prospectively during the experimental programme, so the available path-selection procedure should be interpreted as a measurement-quality framework. Prespecified numerical thresholds, together with fixed-position and reseating repeatability limits, are required for subsequent qualification and transfer of the procedure.

For bolted connection measurements, the stress calculation is more directly constrained, because the applied load is controlled and can be compared with mechanical loading data and finite element analysis. For RS measurement using PAURS, the LCR wave is treated as a near-surface longitudinal wave whose velocity is stress-sensitive through the acoustoelastic effect. In the PAURS+ method, the extracted amplitude and attenuation-related descriptors are used to assess whether the PA-LCR response changes with microstructural condition and inspection angle.

Full Matrix Capture (FMC) is used to increase the number of available transmitter–receiver paths. For an array with n elements, FMC provides up to n^2 acoustic paths. In practice, these paths are used for averaging, path comparison, compensation, and measurement-quality assessment. Not every path is necessarily suitable for calculation, so path selection and rejection form part of the measurement procedure.

3.2. Residual stress quantities used in the measurement model

Residual stress is the stress that remains in a material after external loads have been removed. It is formed when non-elastic strains are introduced into a material and are prevented from relaxing freely. In welded and additively manufactured components, this commonly occurs through localised heating and cooling, plastic deformation, phase change, and mechanical constraint. Having reviewed these formation methods in Chapter 2, this section defines the stress and strain quantities required for the ultrasonic stress calculations used later in the thesis.

Residual stress may be described through the decomposition of total strain into elastic and non-elastic components. The total strain is expressed as shown in Equation 1 [14]:

$$\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^{th} + \varepsilon^{tr} + \varepsilon^{tp} \quad (1)$$

where ε is the total strain, ε^e is the elastic strain, ε^p the plastic strain, and ε^{th} the thermal strain. These are the main strains that are considered in this thesis. The remaining two (metallurgical (ε^{tr}) and transformation-induced plasticity (ε^{tp})) are caused by solid-state phase transformations (SSPTs) during welding. Each component here is considered as a second-order symmetric tensor ($\varepsilon_{ij} = \varepsilon_{ji}$). This provides a convenient framework wherein all non-elastic contributions may be treated as eigenstrains, which do not generate stress when they can develop freely and compatibly, but spatially incompatible or constrained eigenstrains require an elastic response and can therefore produce residual stress.

The elastic strain is related to the stress tensor σ through the generalised Hooke's law:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}^e \quad (2)$$

where C_{ijkl} is the fourth order elastic tensor, σ_{ij} the components of the stress tensor, and ε_{kl}^e the components of the elastic strain tensor. For isotropic materials, this reduces to

$$\varepsilon_{ij}^e = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\sigma_{kk}\delta_{ij} \quad (3)$$

where E is the Young's Modulus, ν the Poisson's Ratio, σ_{kk} denotes the trace of the stress tensor, such that $\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$, and δ_{ij} is the Kronecker delta.

Plastic deformation introduces permanent, path-dependent strain that can become incompatible when deformation is non-uniform or constrained. For isotropic metals, the von Mises yield criterion is typically used:

$$f(\sigma) = \sqrt{\frac{3}{2}s_{ij}s_{ij}} - \sigma_y \leq 0 \quad (4)$$

where s is the deviatoric stress tensor, $f(\sigma)$ is the Von Mises yield function, and σ_y the yield stress.

The associated flow rule gives

$$\varepsilon_{ij}^p = \dot{\Lambda} \frac{\partial f}{\partial \sigma_{ij}} \quad (5)$$

where $\dot{\Lambda}$ is a plastic multiplier determined from consistency conditions. Plastic strain is a primary source of residual stress, particularly in processes involving non-uniform deformation such as forming or welding.

Thermal strain arises from temperature variations and is governed by the coefficient of thermal expansion α_T . For isotropic materials:

$$\varepsilon_{ij}^{th} = \alpha_T \Delta T \delta_{ij} \quad (6)$$

where ΔT is the temperature change relative to a stress-free reference state and δ_{ij} is again the Kronecker delta. In an unconstrained body, thermal strain can occur without generating stress. Residual stress develops when spatial temperature gradients, material constraint, or incompatible deformation prevent free expansion and contraction.

In the materials and experiments considered, residual stress is treated as arising primarily from constrained plastic and thermal strains. The phase-transformation terms are retained in Equation 1 for completeness, but they are not treated as significant contributors in the experimental cases examined here, as the dominant contributions to the final residual stress values are assumed to be the elastic, plastic, and thermal components. This is considered a valid assumption as only overall residual stress is measured, but the individual contributing factors to these values cannot be decomposed using the measurement techniques discussed in this thesis. Equation 1 can then be approximated as:

$$\varepsilon = \varepsilon^e + \varepsilon^p + \varepsilon^{th} \quad (7)$$

Following this, the non-elastic strain terms may be grouped into an eigenstrain tensor, such that

$$\varepsilon^* = \varepsilon^p + \varepsilon^{th} \quad (8)$$

where ε^* is the non-elastic eigenstrain tensor and all strain quantities are dimensionless. The elastic strain is therefore $\varepsilon^e = \varepsilon - \varepsilon^*$, giving the residual-stress field as

$$\sigma_{rs} = C : \varepsilon^e = C : (\varepsilon - \varepsilon^*) \quad (9)$$

where σ_{rs} is the residual-stress tensor (MPa), C is the fourth-order elastic stiffness tensor (Pa), and $:$ denotes double tensor contraction.

For a continuous displacement field, the total small-strain field is compatible and satisfies $inc(\varepsilon) = 0$. Using $\varepsilon^e = \varepsilon - \varepsilon^*$, compatibility therefore requires

$$inc(\varepsilon^e) = -inc(\varepsilon^*) \quad (10)$$

Where the non-elastic eigenstrain is spatially incompatible, $inc(\varepsilon^*) \neq 0$, a corresponding elastic-strain field is required to maintain compatibility of the total deformation. Through Equation 9, this elastic strain produces residual stress. Here, $inc(\cdot)$ denotes the tensor incompatibility operator, defined for a second-order tensor A as $inc(A) \equiv \nabla \times (\nabla \times A^T)$ where (T) denotes tensor transpose.

After removal of external loading, and neglecting body forces, the residual-stress field must satisfy static equilibrium,

$$\nabla \cdot \sigma_{rs} = 0 \quad (11)$$

where $\nabla \cdot$ denotes the tensor divergence. Equations 8–11 therefore describe residual stress as the self-equilibrating elastic response to incompatible non-elastic strain.

3.3. Acoustoelasticity and PA-LCR stress calculation

Ultrasonic stress measurement is founded on the principle of acoustoelasticity, which states that the velocity of an elastic wave changes with the stress state of the material. The RS quantities defined in Section 3.2 provide the mechanical stress field of interest, while the acoustoelastic relationship provides the link between this stress field and the ultrasonic time-of-flight measurements used in PAURS.

A mathematical description of the acoustoelastic effect requires both second- and third-order elastic constants. The second-order constants describe the small-strain elastic response of the material, while the third-order constants describe the change in elastic stiffness with stress. An initial formulation is given by Abiza et al. [92]:

$$K_3 = -\frac{2\lambda(\lambda + 2\mu) + \lambda A + 2(\lambda - \mu)B - 2\mu C}{\lambda + \mu} \quad (12)$$

In this expression, K_3 the third-order elastic combination, with units of GPa, while λ and μ are the second-order Lamé constants, defined in Equations 13 and 14. The terms A , B , and C correspond to the third-order Landau constants, as introduced by Landau and Lifshitz [93].

$$\lambda = \frac{Ev}{(1 + \nu)(1 - 2\nu)} \quad (13)$$

$$\mu = \frac{E}{2(1 + \nu)} \quad (14)$$

A , B , and C are equivalent to the Murnaghan third-order elastic constants [94], such that

$$A = n, B = m - \frac{n}{2}, C = l - m - \frac{n}{2}$$

Where l , m , and n are the Murnaghan third-order elastic constants. This allows Equation 12 to be rewritten:

$$K_3 = -\frac{2\lambda(\lambda + 2\mu) + \lambda n + 2(\lambda - \mu)\left(m - \frac{n}{2}\right) - 2\mu\left(l - m - \frac{n}{2}\right)}{\lambda + \mu} \quad (15)$$

Equations 12 and 15 describe a theoretical combination of second- and third-order elastic constants and are included to establish the higher-order elastic basis of acoustoelasticity. This quantity is denoted K_3 here to distinguish it from the dimensionless acoustoelastic coefficient L used in the experimental stress calculation. The complete set of higher-order elastic constants required to determine K_3 was not measured for the specimens investigated in this thesis. Consequently, K_3 is not used directly in the PAURS stress calculation. Instead, the stress sensitivity of the selected ultrasonic configuration was obtained experimentally through calibration, following the approach outlined by

Mohammadi et al. [95]. The resulting acoustoelastic constant is specific to the inspected material, hence the separate bolt and welded plate calibrations.

PAURS uses longitudinal critically refracted waves because they provide a near-surface propagation mode with high sensitivity to stress-induced velocity change [59]. The LCR wave in the PAURS inspection process is generated using a specialised wedge following the methodology set out by Mills et al. [4]. The wedge ensures that the wave enters the sample under test at the critical angle, allowing propagation parallel to the surface. Using Snell's law:

$$\frac{v_w}{v_m} = \frac{\sin\theta_w}{\sin\theta_c} \quad (16)$$

where v_m and v_w are the sound velocities in the material under inspection and the wedge respectively, and θ_w and θ_c the angle in the wedge and the critical angle respectively. To induce LCR wave propagation, the critical angle is taken as 90° , allowing the required wedge angle to be determined:

$$\theta_w = \sin^{-1}\left(\frac{v_w}{v_m}\right) \quad (17)$$

The sound velocities used for wedge-angle calculation were nominal design values for the corresponding wedge and specimen materials and were not independently measured for each specimen or corrected using a specimen-specific temperature measurement. The calculated angles therefore define the nominal design condition for LCR generation. The wedges were machined with $\pm 0.1^\circ$ tolerance.

Using the wedge and material longitudinal wave velocities for the PAURS study of 2730 m s^{-1} and 5790 m s^{-1} respectively, the calculated wedge angle was 28.1° . For the gel-compensation experiments, the corresponding wedge and material velocities were 2360 m s^{-1} and 5790 m s^{-1} , giving a wedge angle of 24.1° . For the PAURS+ microstructure inspection, wedge and material velocities of 2360 m s^{-1} and 6280 m s^{-1} were used, giving a wedge angle of 22.1° . These values define the nominal wedge-angle conditions for LCR generation in the three PA-LCR configurations used in the thesis. The wedge design and LCR arrival are then checked through simulation and experiment to confirm that a usable, repeatable LCR response is obtained. For the experimental measurements, the wedge configuration was considered suitable when the expected near-surface LCR arrival could be identified consistently within the prescribed time gate and extracted using the same timing feature across the retained acoustic paths. This provides an experimental acceptance check on the nominal critical-angle design, although it does not constitute a direct measurement of the refracted angle.

The stress calculation used in PAURS relates a change in LCR time of flight to a change in stress through the calibrated acoustoelastic relationship:

$$\Delta\sigma = \frac{E \cdot \Delta t}{L \cdot t_0} \quad (18)$$

Here, $\Delta\sigma$ is the stress change from the reference case, E is the material's Young's modulus, L the acoustoelastic constant, t_0 the stress-free, reference ToF, and Δt the difference between the ToF in the stressed zone of the material and that of the stress-free zone. It is important to note the sign convention in the calculated stress output: negative values indicate compression, while positive values indicate tension. The uncertainty in this thesis was estimated through consideration of experimental factors, rather than a formal covariance propagation.

When FMC is used, the same relationship can be averaged across multiple transmitter–receiver paths:

$$\overline{\Delta\sigma} = \frac{\sum_{(i,j) \in N_{Retained}} \frac{E \cdot \Delta t}{L \cdot t_0}}{N_{Retained}} \quad (19)$$

where $\overline{\Delta\sigma}$ is the mean stress, $\Delta t_{i,j}$ is the ToF from transmitter element i to receiver element j , i and j identify the corresponding transmitter and receiver elements, and N is the number of elements. In this form, the time-of-flight differences are evaluated across every element pairing, with $N_{Retained}$ representing the total number of retained acoustic paths after signal-quality and path-consistency screening, thereby improving the robustness of the stress measurement.

Matched-index paths, $T_i R_i$, were included where they satisfied the same signal-quality and path-consistency requirements as the remaining transmitter–receiver combinations. Since transmission and reception were performed using separate arrays, these represent valid pitch-catch paths between corresponding elements rather than self-transmit–receive measurements on a single array.

The timing changes used for PAURS are small, typically on the order of nanoseconds. Javadi et al. reported that a 1 ns difference in time of flight can correspond to approximately 4 MPa of stress in steel specimens [3]. This relationship is used later to express timing errors as equivalent apparent stress errors where appropriate. Timing shifts of this magnitude can also be introduced by non-stress effects, including wedge alignment, surface condition, temperature, and couplant gel thickness. Of these contributions, couplant gel thickness is quantified experimentally in this thesis, while temperature remains an identified but unquantified source of systematic ToF variation for the PAURS measurements.

Time-of-flight differences between adjacent receiver paths are used to reduce common wedge-delay and coupling-layer error contributions. This approach does not remove all coupling effects, particularly where wedge contact, local gel distribution, or surface geometry varies across the aperture, but it does significantly reduce the resulting uncertainty. For this reason, couplant gel thickness is treated later in this thesis as a specific source of timing error requiring simulation, experimental assessment, and compensation.

The LCR wave samples an effective near-surface region whose depth depends on the ultrasonic frequency, material and inspection configuration. Javadi et al. [21] determined LCR penetration depth experimentally by progressively increasing the depth of a machined slot until the LCR amplitude approached the noise level. For the AISI 304L stainless-steel configuration investigated in that study, penetration depths of approximately 5, 2, 1.5 and 1 mm were measured at nominal frequencies of 1, 2, 4 and 5 MHz, respectively. Accordingly, penetration depth values are treated as configuration-specific effective sampling depths rather than predictions from a universal analytical relationship. For the 5 MHz PAURS configuration used in this thesis, the effective near-surface sampling range is assessed experimentally in Section 4.2.4 using the notch-depth investigation.

$$D = v_m \times f^{-0.96} \quad (20)$$

where D is the estimated penetration depth in mm, v_m is the material sound velocity in m s^{-1} , and f is the probe frequency in MHz. This depth estimate is important when PAURS is compared with hole drilling and neutron diffraction, as it determines the comparison basis between the three techniques.

The PA-LCR stress calculation used in this thesis is a calibrated time-of-flight based method. Its reliability depends on the acoustoelastic calibration, the stability of wedge coupling, the clarity of the selected LCR arrival, and the material condition being inspected. However, the same PA-LCR acquisition also contains amplitude and path-dependent signal information, which then provide the basis for the microstructure-sensitive extension developed in Section 3.4.

3.4. Microstructure and PAURS+

PAURS+ is used to describe the microstructure-sensitive extension of the PA-LCR measurement framework. In PAURS, the primary ultrasonic observable is LCR time-of-flight change, and residual stress is calculated using the calibrated acoustoelastic relationship. In PAURS+, the same PA-LCR acquisition is examined through additional observables: amplitude change and attenuation-related angular response, with frequency-dependent behaviour used to assess sensitivity. These features are treated as ultrasonic descriptors of microstructure-sensitive wave behaviour.

This extension is required because residual stress and microstructure can both alter ultrasonic propagation. Residual stress changes LCR velocity through the acoustoelastic effect, while microstructure affects attenuation, amplitude, and frequency content through grain morphology, texture, elastic anisotropy, and local heterogeneity. The measurement problem is to identify which ultrasonic features are most suitable for stress calculation and which are more suitable for microstructure-sensitive characterisation.

LCR ToF remains the stress-calculation observable used for PAURS, while PAURS+ focuses on amplitude change and attenuation-related angular behaviour. This division follows the observable-

level logic that different signal features have different dominant physical sensitivities, even when they are extracted from the same phased-array LCR acquisition.

Pulse-echo is not used as the primary PAURS+ measurement in this thesis; it is included here only to define attenuation in a familiar propagation geometry before adapting the same concept to near-surface LCR paths. The pulse-echo reference case is shown schematically in Figure 3a. In this configuration, an ultrasonic pulse travels through the specimen thickness, reflects from the back wall, and returns to the probe. Successive backwall echoes correspond to repeated propagation through the same material thickness. The reduction in echo amplitude can therefore be used as an attenuation-related measure, which for two successive backwall echoes can be written as:

$$a = \frac{20}{2l} \log_{10} \left(\frac{A_1}{A_2} \right) \quad (21)$$

where a is the attenuation coefficient in $dB\ mm^{-1}$, A_1 and A_2 are the amplitudes of two successive backwall echoes and l is the specimen thickness in mm. The factor $2l$ accounts for the additional round-trip propagation distance between successive echoes. Where multiple echoes are available, the attenuation estimate can be averaged across successive echo pairs to reduce sensitivity to local noise and peak-picking error. This expression attributes the change in echo amplitude primarily to propagation through the additional material thickness. Its interpretation as a material attenuation coefficient assumes that the compared echoes experience equivalent or appropriately accounted for reflection and transmission conditions, constant instrument gain and transducer response, and equivalent beam-spread effects.

This pulse-echo expression illustrates the basic attenuation principle: amplitude loss increases with propagation distance and may be influenced by scattering, absorption, grain morphology, texture, and elastic anisotropy. It is important to note that pulse-echo averages the response through the inspected thickness, whereas LCR propagates approximately parallel to the surface and samples a near-surface path. For this reason, pulse-echo attenuation is used here only to define the attenuation concept and provide comparison geometry. PAURS+ adapts this attenuation concept to directional LCR paths, where amplitude change is treated as an attenuation-related descriptor rather than an absolute attenuation coefficient.

Within the wider ultrasonic observable framework, microstructural effects are commonly expressed through amplitude change. This is illustrated in Figure 3, where pulse-echo (Figure 3a) and LCR (Figure 3b) configurations are compared for equiaxed and columnar microstructures. In both cases, equiaxed grains produce lower amplitude change compared with columnar grains, consistent with reports in the literature [96], [97], [98]. This highlights the need for calibration, comparison with reference techniques such as EBSD, and the development of hybrid approaches that integrate

modelling and experiment to achieve accurate quantification. For clarity, the schematic examples are shown using two representative transmitter–receiver paths.

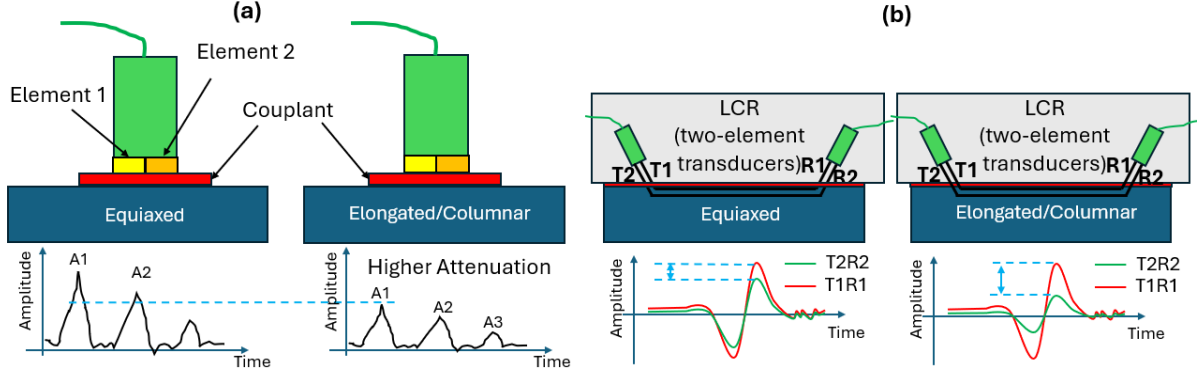


Figure 3: Schematic comparison of amplitude change in equiaxed and columnar microstructures using (a) pulse-echo and (b) LCR ultrasonics. The schematic illustrates how microstructure can affect ultrasonic amplitude, providing the basis for the PAURS+ observable selection.

For a single LCR path comparison, amplitude change can be defined between two transmitter–receiver pairs as:

$$\alpha = \frac{20 \log_{10} \left(\frac{A_{T_i R_j}}{A_{T_m R_n}} \right)}{x} \quad (22)$$

Where α is the two-path attenuation-related amplitude-change coefficient, $A_{T_i R_j}$ and $A_{T_m R_n}$ are the measured LCR amplitudes for the paths from transmitter T_i to receiver R_j and transmitter T_m to receiver R_n , respectively, and x is the difference in LCR propagation distance between the two paths. The subscripts i and m identify transmitter elements, while j and n identify receiver elements. For a phased-array acquisition, this amplitude-change descriptor may be generalised as:

$$\alpha_{PA,LCR} = \frac{1}{N_{Valid}} \sum_{(i,j) \in N_{Valid}} \frac{20}{p} \log_{10} \left(\frac{A_{T_i R_j}}{A_{T_i R_{j+1}}} \right) \quad (23)$$

where $\alpha_{PA,LCR}$ is the phased-array LCR attenuation-related amplitude-change descriptor, N_{Valid} is the number of retained adjacent-receiver comparisons, and p is the array pitch. A comparison is retained only where both amplitudes required for the adjacent-path ratio provide a usable LCR response. If all adjacent-receiver comparisons are retained, $N_{Valid} = N_t N_r - 1$. For the 8-element transmitter and receiver arrays used in the PA-LCR measurements, this gives a maximum of 56 adjacent-receiver comparisons.

Each logarithmic amplitude ratio is normalised by the additional pitch-length propagation distance.

When p is expressed in mm, $\alpha_{PA,LCR}$ is expressed in $dB \text{ mm}^{-1}$. The quantity is retained as an

attenuation-related amplitude-change descriptor because coupling, beam geometry, element response and other experimental factors may also contribute to the measured amplitude difference.

In the simplified two-path case shown in Figure 3b, amplitude change is obtained by comparing the representative T_1R_1 and T_2R_2 paths, giving the simplified expression:

$$\alpha_{2el,LCR} = \frac{20}{p} \log_{10} \left(\frac{A_{T_1R_1}}{A_{T_2R_2}} \right) \quad (24)$$

Where $\alpha_{2el,LCR}$ is the simplified two-path LCR amplitude-change descriptor, and $A_{T_1R_1}$ and $A_{T_2R_2}$ are the measured amplitudes of the two representative LCR paths shown in Figure 3b, which illustrates the expected increase in amplitude change for elongated or textured microstructures relative to more equiaxed microstructures. In this interpretation, the elongated or textured case produces a larger amplitude reduction between the two LCR paths because the wave interacts with a more directionally organised microstructure over the additional propagation distance. As only directly adjacent elements are considered, the LCR propagation distance only varies by one pitch value.

The principle of directional LCR is illustrated in Figure 4, which contrasts two representative microstructures: a weakly textured or isotropic polycrystal and a strongly textured or elongated microstructure. In the isotropic case, the LCR wave encounters a statistically similar distribution of grain orientations as the wedge is rotated. In the textured case, the grain alignment produces direction-dependent elastic and scattering behaviour. The surface-parallel LCR path is sensitive to the angle between the propagation direction and the dominant microstructural orientation.

For a transmitter–receiver pair T_iR_j rotated by an angle θ , the received amplitude can be expressed as:

$$A_{ij(\theta)} = A_0 \exp[-\beta(\theta)(j-i)p] \quad (25)$$

where $A_{ij(\theta)}$ is the received amplitude for the path from transmitter i to receiver j at rotation angle θ , A_0 is the reference amplitude, p is the array element pitch, and $\beta(\theta)$ is the effective exponential attenuation coefficient in direction θ .

The relevant PA-LCR observables can be separated by their main interpretation role. ToF is retained as the stress-calculation observable because it is directly linked to LCR velocity and the acoustoelastic relationship. Amplitude change and attenuation-related response are used as microstructure-sensitive observables because they are affected by scattering, grain morphology, and propagation direction. Frequency-domain behaviour provides an additional descriptor of microstructural interaction, since higher frequency components are preferentially attenuated when scattering and heterogeneity increase. These observables are used to assess angular microstructure-sensitive behaviour, not to calculate an absolute grain size or reconstruct full crystallographic texture.

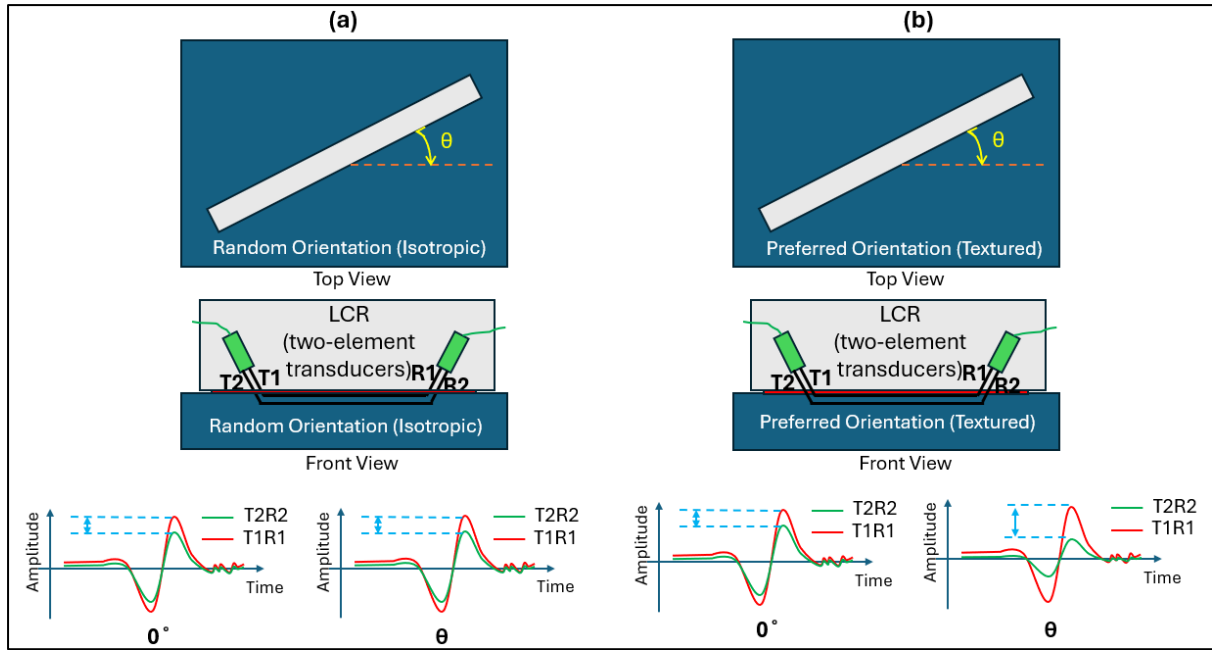


Figure 4: Principle of directional LCR response in (a) randomly oriented or approximately isotropic microstructure and (b) approximately anisotropic microstructure.

In an isotropic polycrystal, $\alpha(\theta)$ is nearly independent of inspection angle. Amplitude ratios such as that defined in Equation 22 will remain essentially constant as the wedge is rotated, producing similar attenuation trends at $\theta=0^\circ$ and rotated orientations (Figure 4a). In a textured material, $\alpha(\theta)$ varies significantly with propagation direction. The same amplitude ratios (Equation 25) then show pronounced angular dependence, with attenuation at $\theta=0^\circ$ differing strongly from that at a less preferred orientation (Figure 4b).

As shown in Figure 4, a directionally uniform microstructure is expected to produce comparatively small angular variation in the attenuation-related response. A directionally organised grain morphology may produce a stronger angular dependence as the LCR propagation direction changes relative to the microstructure. The angular response is therefore used in this thesis as a microstructure-sensitive descriptor.

The equiaxed AFSD region is used as the experimental reference condition because both the AFSD and elongated substrate regions were inspected using the same PA-LCR wedge, probe arrangement, amplitude-extraction procedure, and robotic rotation method, with fixed gain throughout. The stronger angular response measured in the elongated substrate, together with the corresponding angular features in the EBSD-informed simulation, provides evidence that the response is sensitive to the underlying microstructure.

The retained experimental programme did not include a separate isotropic calibration specimen or a dedicated repeated-rotation apparatus baseline. The AFSD-region measurement is consequently used as a comparative reference for the system response. Coupling variation, contact-force variation,

surface condition and robotic positioning remain additional contributors to the measured angular amplitude.

When directional LCR is integrated with robotic manipulation, the wedge can be rotated automatically at fine angular steps (e.g. every 1° or less) over a full 360° , generating a continuous polar map of attenuation sensitivity. When combined with frequency variation to adjust penetration depth - for example Javadi et al [21] demonstrated that 1, 2, 4, and 5 MHz waves probe approximately 5, 2, 1.5, and 1 mm depths in stainless steel, respectively. These values are configuration-specific and are used here only to illustrate the frequency dependence of the effective LCR sampling region. A future multi-frequency robotic PA-LCR implementation could potentially build a depth-indexed set of angular attenuation responses, providing a basis for microstructure-sensitive mapping over the effective LCR sampling region. The investigation presented here demonstrates the first stage of this concept through near-surface, EBSD-validated angular PA-LCR measurements.

The stress-sensitive and microstructure-sensitive interpretations described in Sections 3.3 and 3.4 both depend on the reliability of the underlying phased-array acquisition. The role of FMC, path selection, averaging, and measurement-quality assessment is considered next.

3.5. Phased-array acquisition, FMC, and measurement quality

The phased-array measurements used in this thesis are based on the acquisition and processing of multiple A-scans from a single probe position. In Full Matrix Capture, each array element is fired sequentially while the remaining elements record the received response, producing multiple transmitter–receiver paths for each inspection location. These paths both increase the number of measurements taken and provide a basis for path comparison, compensation, averaging, and measurement-quality assessment.

For stress calculation, ToF is extracted from the selected backwall or LCR arrival using a consistent timing feature. In the bolt measurements this is obtained from backwall reflections, while in PAURS it is extracted from the gated LCR response. The retained paths must give a repeatable arrival and a physically consistent ToF response before they are used in the calculated stress output.

The phased-array dataset therefore provides both a calculated value and a measure of confidence in that value. Paths with poor signal-to-noise ratio, inconsistent arrival behaviour or disrupted coupling can be excluded before averaging. The standard deviation across retained paths is used as a practical indicator of path-wise consistency: Low standard deviation indicates that the selected paths give similar timing or amplitude responses under the applied processing conditions, while high standard deviation indicates that the result may be affected by path- or inspection-dependent effects. This is particularly important in the bolt work, where asymmetric ToF distributions may indicate uneven

seating or local stress concentration, and in the welded-plate measurements, where weld-centre geometry can disrupt the LCR response.

FMC also supports compensation strategies. In the PAURS gel-thickness study, adjacent-receiver subtraction and multi-path averaging are used to significantly reduce timing errors associated with couplant-layer variation. For PAURS+, the same multi-path principle is applied to amplitude change and attenuation-related descriptors, allowing angular microstructure-sensitive behaviour to be assessed across different propagation paths.

The main value of FMC in this thesis is therefore not simply that more A-scans are acquired. It is that individual acoustic paths can be compared before an averaged output is accepted, providing the basis for compensation and measurement-quality assessment. FMC cannot remove systematic error by itself; and wedge-specimen interface effects, surface geometry, and reference-state assumptions can still bias the result. Where calibration is valid, the selected arrival is stable, and the paths are consistent, the result is assigned higher confidence, while if these conditions are only partly satisfied, the result is interpreted with lower confidence. If the LCR arrival is unreliable or the reference feature condition is physically inappropriate, the measurement is rejected or repeated.

3.6. Chapter Summary

The chapter establishes the mechanical and ultrasonic basis for interpreting the later measurements: residual stress is treated as the elastic response to constrained non-elastic strain, while phased array stress calculation relies on calibrated ToF change from the stable arrival of a consistent ultrasonic feature. This calculation requires a stress-free reference time of flight, known material properties, and an experimentally determined acoustoelastic constant. The bolt study uses a single phased-array probe in pulse-echo configuration to obtain a stress value from a repeated backwall echo, while the LCR configuration provides the near-surface propagation mode used for the PAURS stress calculation.

The PAURS+ section discusses the microstructure-sensitive extension of the same PA-LCR basis. Amplitude change and attenuation-related angular response were identified as the main descriptors used to compare equiaxed and elongated grain structures, with frequency-dependent behaviour used to assess sensitivity. These descriptors are interpreted with support from EBSD, simulation, and robotic angular measurement.

Phased-array acquisition and FMC provide the practical basis for the multi-path measurements used throughout the thesis. FMC increases the number of available acoustic paths and supports path selection, measurement-quality checks, averaging, and compensation. These principles provide the theoretical and processing basis for the experimental methods in Chapter 4 and the results discussed in Chapter 5.

4. Experimental setup

The experimental programme is organised as a staged development of the phased-array measurement framework. Section 4.1 establishes the controlled-stress benchmark, Section 4.2 translates the calibrated measurement logic to welded residual stress measurement using PAURS, and Section 4.3 extends the same platform to microstructure-sensitive angular characterisation through PAURS+.

4.1. Controlled-stress benchmark using bolted connections

Bolted connections are used in this thesis as the controlled-stress benchmark for the PAURS measurement procedure. The application is relevant to wind turbine and offshore energy structures, where large bolted connections are safety-critical, and loss of preload can lead to reduced fatigue life, joint separation, or progressive structural damage. The wider role of the bolt study here is to provide a known applied-stress case in which the phased-array ultrasonic measurement chain can be evaluated before being translated to welded RS measurement.

The bolt benchmark provides a more controlled measurement problem than the welded RS case considered later in the thesis. In this section, the applied loading condition is known or mechanically monitored, the stress field can be estimated using finite element analysis, and the ultrasonic response can be compared against a defined mechanical comparator. This allows the relationship between time-of-flight change and applied axial stress to be examined under conditions where the stress state is more constrained than in a welded plate.

Four experimental stages were conducted. The first utilised finite element analysis (FEA) to estimate the expected average axial stress within the inspected bolt region. This was required because the ultrasonic measurement samples an acoustic path through the bolt instead of the local peak stress at a thread root or contact edge. The second stage was an acoustoelastic calibration experiment, where ultrasonic measurements were obtained from a bolt subjected to controlled tightening and compared with mechanical loading data. The third stage investigated a defect-free M36 bolt under higher preload using a hydraulic tensioner, representing loading conditions closer to those encountered in operational wind-farm applications. Finally, a blind transfer test was performed on an M42 bolt at the FASTBLADE facility [99] to assess whether the calibrated measurement procedure could be applied to a larger bolt in a representative field-like setting.

All ultrasonic inspections were conducted using a Sonatest Detachable Active Array Head (DAAH) phased-array probe with 20 elements, a pitch of 1.2 mm, and a centre frequency of 2.25 MHz. The datasheet for this probe can be found in Appendix A. This frequency was selected to provide sufficient penetration through the bolt section while maintaining a usable backwall response for time-of-flight extraction. The phased-array configuration allows multiple acoustic paths to be obtained from a single probe position, giving a larger dataset than a single-element measurement. This is important because

the average ToF response can be used for stress calculation, while the distribution of ToF values across the array provides information about path consistency.

In this benchmark, the primary ultrasonic quantity measured is the time of flight extracted from selected backwall responses. Applied axial stress is then calculated using the acoustoelastic relationship defined in Chapter 3 and compared with mechanical loading data and FEA-derived average axial stress. Paths affected by poor coupling, unclear backwall response, or inconsistent timing can be excluded from the stress calculation. This gives the bolt benchmark a dual function: it tests whether phased-array ultrasonics can detect preload-related ToF changes, and it establishes how path-wise information can be used to judge whether a calculated stress value is reliable.

4.1.1. Phased-array ultrasonic measurement procedure

The inspection procedure followed the phased-array methodology developed in the associated bolt-inspection work [2]. The procedure combined defect-aware inspection with stress-sensitive time-of-flight extraction, which is significant because the extracted stress value is only meaningful if the acoustic paths used for calculation are not significantly disrupted by defects, poor probe-specimen interface, or weak backwall response.

A sector scan was first performed to screen the bolt volume and threaded region for potential defects. The sector scan allowed the beam to be steered through a range of angles, improving coverage of the bolt section and enabling indications from internal flaws or thread-region discontinuities to be identified. Detected indications were assessed against an acceptance criterion of 10% of the bolt diameter, corresponding to 3.6 mm for the M36 bolt, obtained through discussions with industry. This criterion was used also on the later M42 investigation. Any indication exceeding this criterion would result in the bolt being classified as defective and unsuitable for stress measurement or use.

Where required, a more focused B-scan was then acquired to refine defect position and sizing. The B-scan was used to assess the through-thickness response and to identify regions where a clear backwall reflection could be obtained. FMC and TFM processing were used where appropriate to support defect characterisation and to identify acoustic paths that should not be included in the stress calculation. This step is important because even an acceptably sized defect can interrupt or distort a backwall reflection, causing an apparent time-of-flight change that is unrelated to applied stress.

Once the bolt had passed the defect-screening stage, the probe was positioned to obtain the clearest available backwall response, and an FMC dataset was then acquired for stress measurement. The backwall reflection was used because it provided a repeatable response through the inspected bolt section and allowed the ToF to be extracted from a consistent signal feature. The selected zero crossing on the backwall response was used as the timing point, as shown in Figure 5.

To reduce sensitivity to coupling gel thickness and fixed interface delay, the time difference between successive backwall echoes was used to avoid relying only on the absolute arrival time of a single echo. In this approach, timing contributions associated with the probe, couplant layer, and near-surface interface are common to both echoes and are reduced when the echo-to-echo difference is taken. This does not remove all coupling effects, but it reduces one of the main sources of timing error in practical ultrasonic stress measurement and is a key starting point for later PAURS gel compensation methods.

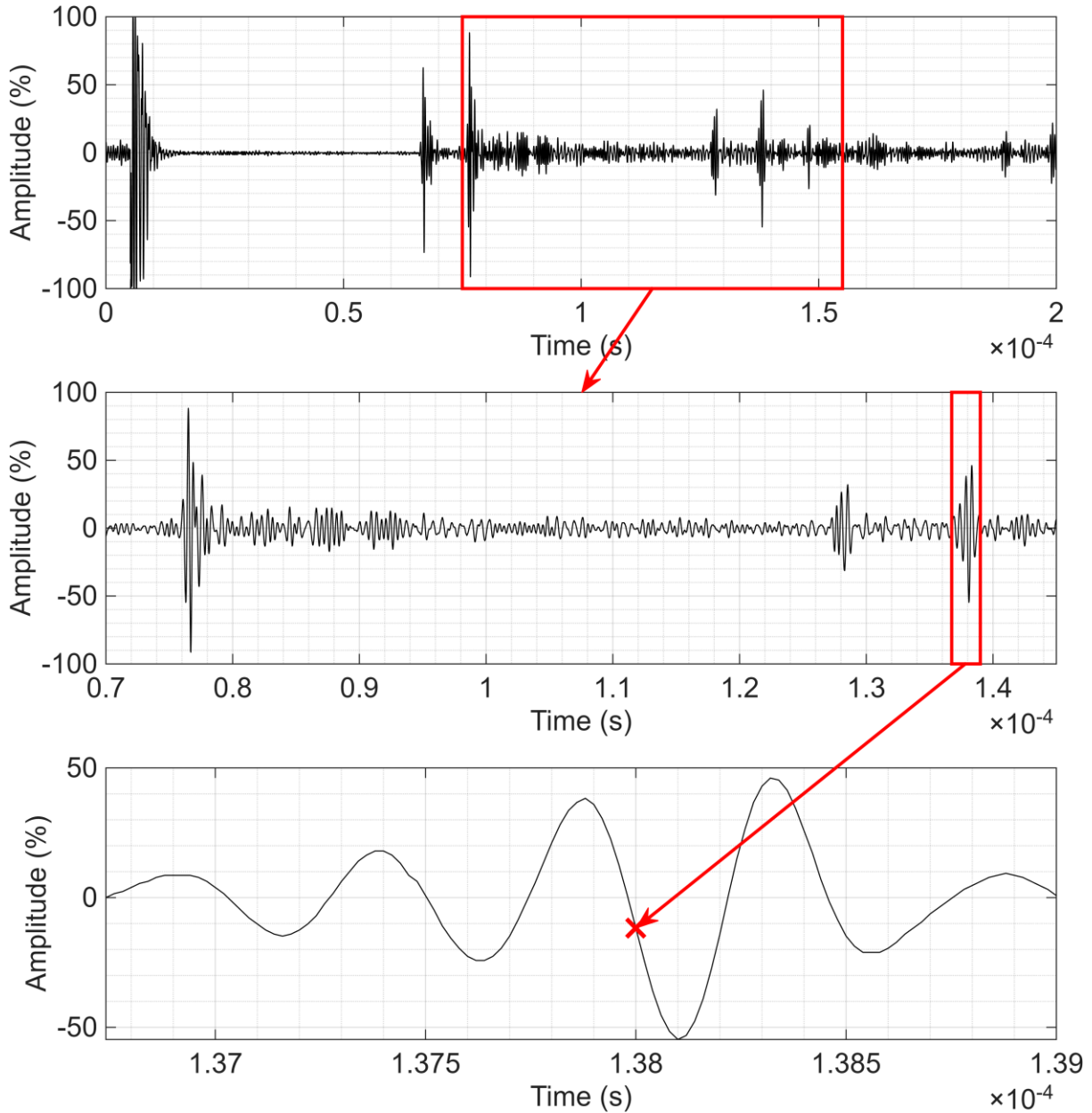


Figure 5: Time-of-flight extraction used in the controlled-stress bolt benchmark. Top: full A-scan response. Middle: selected backwall region. Bottom: extracted backwall reflection, with the selected zero-crossing used as the repeatable timing feature. [1].

The extracted time-of-flight values were converted to stress using the acoustoelastic relationship defined in Equation 18. Since the phased-array probe provides multiple paths through the bolt, the calculated stress can be averaged across selected paths. The individual path distribution was also retained because it provides information about path-wise consistency: a narrow and symmetric distribution indicates that the selected paths are responding consistently, while a broad or asymmetric distribution may indicate uneven loading, poor coupling, or departure from the assumed measurement condition.

4.1.2. Finite element model for path-averaged axial stress

Finite element analysis was performed in ABAQUS to provide the mechanical stress comparator used. Finite element analysis was used to provide a mechanical stress comparator for the ultrasonic bolt measurements. The FE model was developed as part of the collaborative bolt-inspection study by a researcher within NAOME, with the resulting stress data supplied for comparison with the ultrasonic measurements. The candidate's contribution in this part of the study was the processing and interpretation of the phased-array ultrasonic measurements and their comparison with the supplied mechanical and FE data. This is consistent with the collaborative contribution described in the Candidate Contribution Statement.

The model was developed in ABAQUS using three-dimensional representations of the bolt and nut. C3D8R elements and sweep meshing were used, with the geometry partitioned to support the mesh distribution. Detailed thread geometry was omitted to reduce local geometric complexity and focus the analysis on the axial stress distribution through the central bolt region. The resulting model therefore provided a representation of the broader axial stress field used for ultrasonic comparison, with local thread-root and contact-edge stress concentrations outside the intended comparison basis.

Boundary conditions were defined to represent the experimental bolt-loading arrangement, with the applied load matched to the mechanical loading data obtained during testing. The supplied FE results provided the average axial stress within the central inspected region at the investigated preload levels. This average stress was selected as the mechanical comparator because the ultrasonic backwall measurement samples the stress-sensitive response over a finite propagation region through the bolt. Figure 6 shows the model for the 250 kN loading condition.

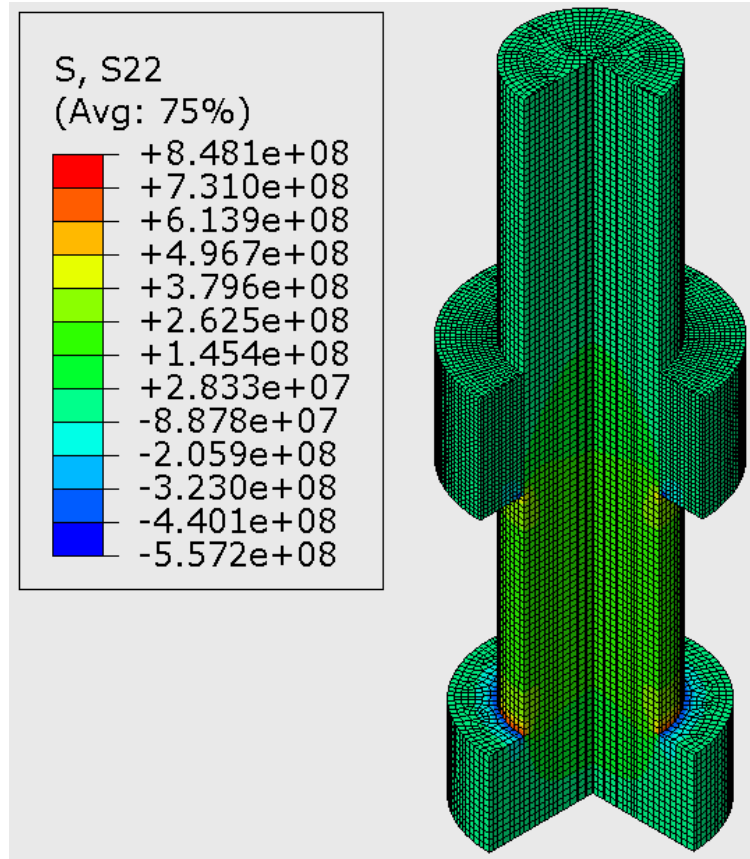


Figure 6: Finite element model of the controlled-stress bolt benchmark under 250 kN applied load. The model provides the average axial stress used as the mechanical comparator for the ultrasonic measurements [1].

The FE model and associated output data were generated within the collaborative study and were not independently re-developed as part of this thesis. The available dataset consisted of the supplied axial stress results required for comparison with the ultrasonic measurements. Consequently, additional model-specific studies of mesh convergence, contact sensitivity and spatial averaging uncertainty were outside the scope of the present work. The FE-derived values are therefore treated as model-assisted comparator stresses with uncertainty associated with the underlying loading and modelling assumptions. This limitation is carried through to the interpretation of agreement between the ultrasonic and FE-derived stress values.

For the calibration experiment, the applied preload was monitored mechanically using the Boltsafe strain-gauge system described in Section 4.1.3. The known experimental quantity is therefore the applied loading condition, while the corresponding average axial stress used for calibration is obtained from the supplied FE analysis. The combined calibration uncertainty reported in Section 5.1.2 includes the contribution assigned to the mechanical loading and FE comparator alongside ToF repeatability, acoustic-path variation and equipment-related effects.

4.1.3. Acoustoelastic calibration and sensitivity assessment

This stage tests whether the phased-array ultrasonic setup can operate as a stress-sensitive measurement system under controlled loading. It also defines the conditions under which the later high-preload and blind-transfer tests should be interpreted.

The experimental setup for acoustoelastic calibration is shown in Figure 7. Preload was monitored mechanically using a Boltsafe strain gauge, while ultrasonic measurements were acquired using the 20-element PAUT probe described above. Ultrasonic data acquisition was performed using a PEAK Micropulse Controller system (MP6 HDR) [100]. The strain gauge has a reported accuracy of within 1% from BoltSafe [101]. The bolt was secured in a vice and tightened using an adjustable wrench, allowing a controlled increase in preload while ultrasonic data was collected.

The full inspection workflow was followed during calibration, even though no defects were expected. This same procedure was used for defect screening, time-of-flight extraction, and stress calculation as in the later high-preload and blind-test experiments. Maintaining the same workflow was important because changes in timing feature identification or path selection would alter the measured ToF response and therefore affect the calculated stress, as well as ensuring that any unexpected defects could be identified.

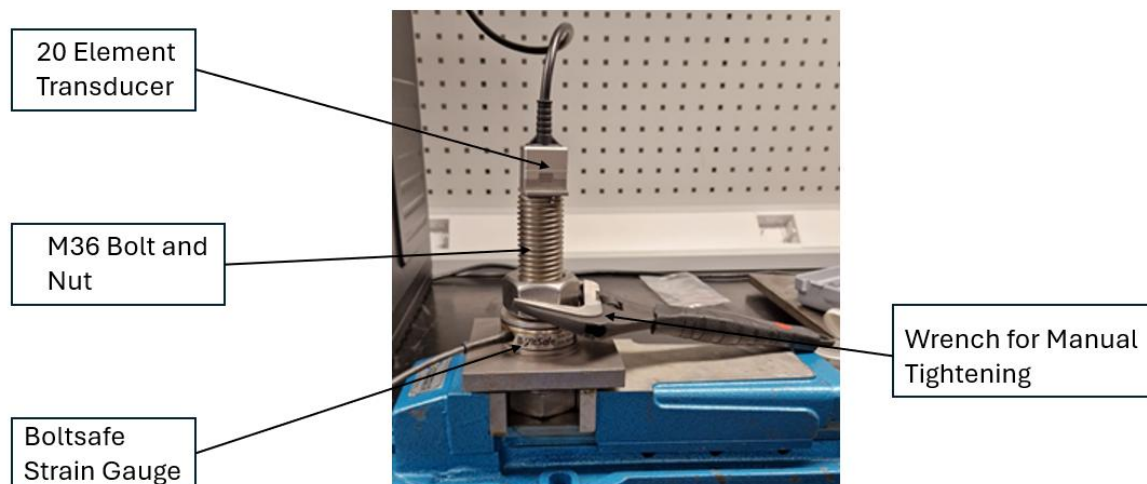


Figure 7: Experimental setup for acoustoelastic calibration in the controlled-stress bolt benchmark. The bolt preload was monitored using a strain gauge, while phased-array ultrasonic measurements were acquired to determine the relationship between time-of-flight change and FEA-derived average axial stress [1].

The calibration procedure established the relationship between measured ToF change and applied axial stress for the selected bolt material, probe configuration, acoustic paths, and loading range. The FEA-derived average axial stress was used as the stress comparator, while the ultrasonic data provided the corresponding ToF change. The fitted relationship produced the acoustoelastic constant

used for subsequent stress calculations in the bolt benchmark. The uncertainty associated with the calibrated coefficient was assessed as a combination of experimental, data processing, and equipment factors. These contributions are reported with the calibration result in Section 5.1.2.

Here and in the later M36 and M42 preload investigations, a 100V driving voltage was used, with a gain of 45dB and a linear pulse echo scan with an aperture of 1 element. The probe was placed on the end of the bolt with no wedge at an angle of 0°.

This calibration stage is essential because the acoustoelastic coefficient is not treated as a universal value independent of inspection conditions, as it can vary depending on the material, or even within a run of samples. For this reason, calibration is performed as part of the measurement chain and not reused from existing literature values. The calibration also provides a sensitivity assessment: it established whether the selected phased-array configuration can resolve preload-related changes in ToF with sufficient repeatability to support stress calculation.

4.1.4. High preload investigation

This experiment extends the calibration stage by testing the measurement chain under more demanding loading conditions. The key result is an assessment of when the averaged ultrasonic stress value remains reliable and when the path-wise distribution begins to indicate reduced confidence.

The high-preload investigation was conducted using an M36 bolt. A hydraulic tensioner was employed to apply higher preload levels, while the remaining equipment and data-extraction procedure were kept consistent with the calibration experiment. This allowed the calibrated measurement chain to be assessed at higher loads, closer to those expected in larger bolted connections used in offshore and wind-energy structures.

The post-tensioning inspection setup is shown in Figure 8. Ultrasonic data acquisition was performed using the same PEAK Micropulse Controller system as above, selected here for its flexibility and high dynamic range. The datasheet for the MP6 HDR controller can be found in Appendix A. The bolt was tightened using the tensioner in 50 kN steps, from 0kN up to 300 kN, providing seven loading states across the investigated high-preload range. This loading sequence allowed the evolution of the ultrasonic ToF response and path-wise distribution to be assessed progressively as preload increased, and is the procedure described in discussions with industry members during this investigation.

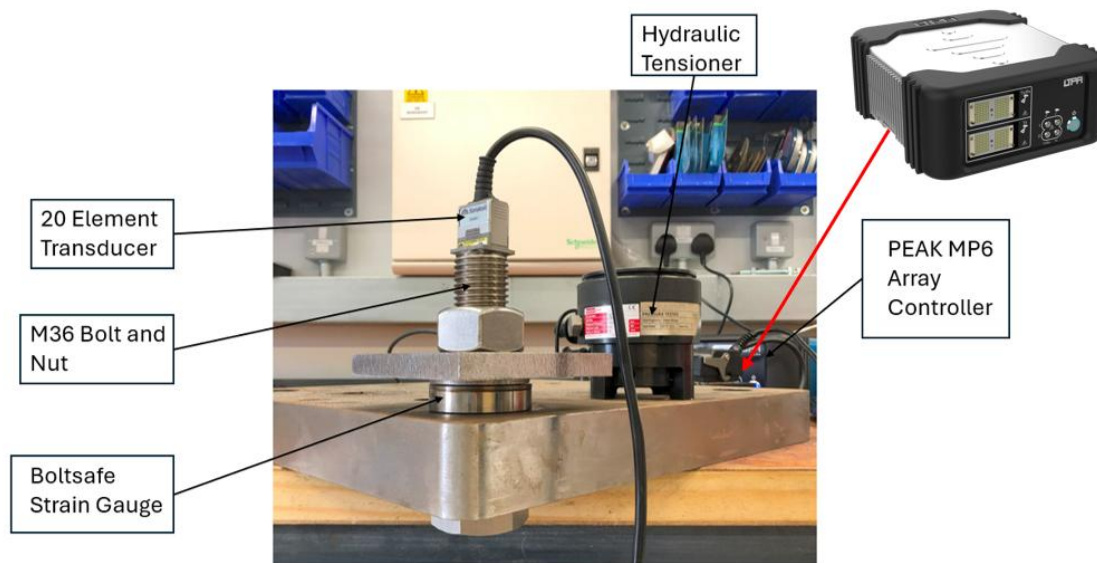


Figure 8: High-preload controlled-stress M36 bolt benchmark after hydraulic tensioning. The inset identifies the PEAK Micropulse controller used for ultrasonic acquisition [1].

A defect-free bolt was intentionally selected for this experiment because the bolt was subjected to loads up to 300 kN, so any pre-existing defect could create a safety risk during hydraulic loading; but also since the aim of the experiment was to evaluate the stress measurement response under high-preload conditions without the additional uncertainty introduced by known internal defects. By removing defect-related acoustic disruption, the test focused on the relationship between preload, ToF change, calculated stress, and path-wise consistency.

The high-preload experiment assessed the stress extraction methodology as the preload increased towards in-situ levels. It also provided a means of identifying the point at which the ToF response became less consistent, potentially due to nonlinear loading behaviour or seating effects. The phased-array dataset was particularly useful in this context because the distribution of ToF values across the array could be examined alongside the average calculated stress.

4.1.5. Blind test on M42 bolt under representative access conditions

The blind test was designed to assess whether the calibrated phased-array ultrasonic stress measurement procedure could be transferred to a larger bolt under representative field-like access conditions. The test was conducted on an M42 bolt installed in a turbine blade undergoing fatigue testing at the FASTBLADE facility, as shown in Figure 9.

The FASTBLADE facility provided a useful test environment because the installed bolts were larger than those used in the controlled M36 experiments and were part of a real mechanical test structure rather than a laboratory calibration fixture. The bolts were installed using procedures comparable to

those used in large offshore and wind-energy applications, utilising hydraulic tensioning. A loose or incorrectly tensioned bolt in this context could affect the fatigue test, making preload assessment practically relevant to the operation of the facility.

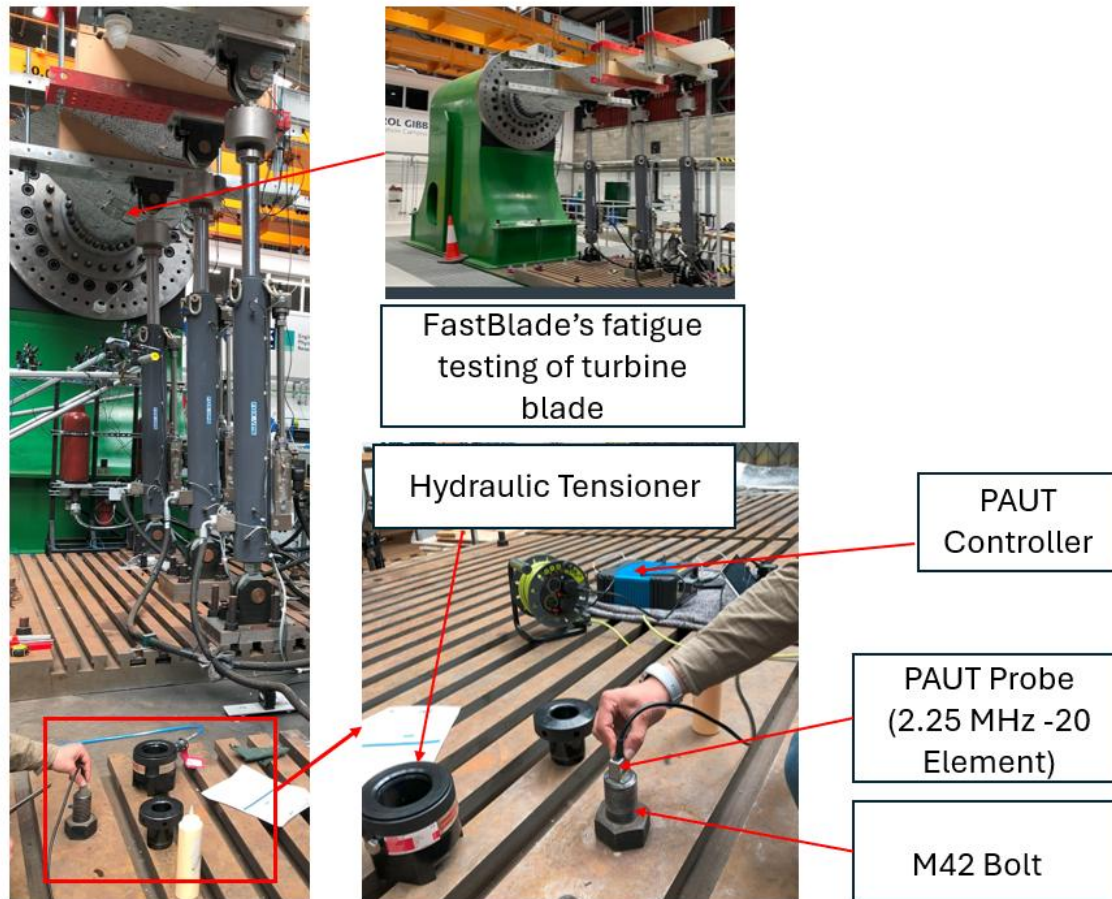


Figure 9: Blind M42 transfer test performed at the FASTBLADE facility. The test was used to assess whether the calibrated phased-array ultrasonic stress-measurement logic could transfer from the controlled M36 benchmark to a larger bolt under representative field-like access conditions [1].

The tested M42 bolt was longer than the M36 bolts used in the previous experiments and presented different access and geometry conditions. It was the same grade of steel as the M36 bolts tested previously, and was inspected using the same firing voltage, gain, and focal settings as the M36 bolt. Although the acoustoelastic constant wasn't measured, the value obtained for the M36 bolts was used with the understanding that this was an approximation and so higher uncertainty was assigned to the result. It was inspected under both loaded and unloaded states, allowing changes in ultrasonic ToF to be assessed relative to the loading condition. The same general ultrasonic procedure was followed: the bolt was inspected for usable acoustic response, the clearest backwall paths were selected, ToF was extracted from repeatable signal features, and stress was calculated using the calibrated relationship.

During processing the bolt geometry, previously obtained acoustoelastic constant, and approximate temperature were known. The applied preload was withheld and only considered after the ultrasonic stress calculation had been performed. Relative to the original calibration condition, the bolt diameter and length were larger.

The test was treated as a blind transfer assessment because the ultrasonic procedure was applied to a bolt geometry and inspection setting that differed from the original controlled calibration arrangement. Although this single blind test does not fully qualify the method for industrial deployment across all bolt sizes or access conditions, it does provide evidence that the phased-array measurement procedure can be transferred beyond the initial calibration fixture and is an important step towards possible future scaled deployment.

The blind M42 test acts as an intermediate step between controlled laboratory calibration and practical deployment. It assesses whether the stress calculation remains plausible under less controlled conditions and whether the phased-array dataset still provides useful path-wise information for judging measurement quality.

4.1.6. Method elements carried forward by the controlled-stress benchmark

The bolt methodology establishes the controlled evidence needed before PAURS is applied to welded residual stress. Under known applied loading, it tests whether the selected ToF feature responds systematically to stress, whether usable acoustic paths can be selected, and whether path-wise consistency provides a useful confidence indicator.

Under controlled loading, ultrasonic ToF is related to applied axial stress using loading data and FEA-derived average axial stress to provide the stress comparator. The phased-array probe provides multiple acoustic paths for averaging and comparison, which allows the stress-sensitive timing feature to be assessed alongside the distribution of path-wise responses.

The bolt study establishes the quality-control logic used later in PAURS. Defect screening is performed before stress calculation, and those acoustic paths that are affected by defects, poor coupling, or weak signal quality can be excluded. Where the path-wise ToF distribution is narrow and repeatable, the averaged stress estimate is used with higher confidence. Where the distribution broadens, becomes asymmetric, or shows unstable timing extraction, the result requires reduced confidence and further checking. These principles are applied to the welded RS study in Section 4.2, where the stress field is entirely unknown and the comparison basis more complex. While this is not an exact transfer, as PAURS uses a pitch-catch setup instead of pulse-echo and there is no defect detection stage, the overall concepts and advantages of the application of phased array transducers (such as the acoustoelastic constant calibration methodology, the sensitivity of the stress to the ultrasonic ToF, and the path-averaging and quality indicator capabilities) are carried forward.

4.2. Residual stress and PAURS

This section applies the phased array procedure established in Section 4.1 to a welded S275 specimen, with two probes in a pitch-catch PA-LCR configuration. Unlike the bolt case, the welded specimen contains an unknown residual stress field, and the LCR response may be affected by weld geometry, coupling condition, stress gradients, and microstructure. The PAURS methodology combines welded specimen manufacture, independent RS comparison methodologies, PA-LCR configuration verification, acoustoelastic calibration, couplant gel-thickness assessment, and ultrasonic inspection of the welded plate. Hole drilling and neutron diffraction are used as the aforementioned independent comparison methods to assess whether PAURS reproduces the main residual stress trends and approximate magnitudes within the relevant depth and gauge-volume limits.

4.2.1. Overview of methodology

The overall methodology is summarised in Figure 10, also available in a larger size in Appendix B. The workflow separates specimen manufacture, external RS measurements, PAURS acquisition, and final comparison so that each dataset retains its own measurement basis.

A) Two nominally identical samples were robotically manufactured at the University of Strathclyde (Glasgow, UK). One sample was retained in the UK, while the other was shipped to Australia for neutron diffraction (ND) measurements at ANSTO (Lucas Heights, Australia).

B) Sample #1 was initially sent to Stresscraft (Loughborough, UK) for incremental hole drilling (iCHD). Although this process is semi-destructive and required machining of the weld cap to enable drilling, the sample remained suitable for ultrasonic testing. The machining process also improved contact between the ultrasonic wedge and the sample surface.

C) Sample #1 was then returned to the University of Strathclyde for residual stress measurements using the phased array ultrasonic method.

C1) Prior to wedge manufacture, ultrasonic simulations were conducted to optimise the angle required to generate LCR waves. Following fabrication, the penetration depth of the LCR wave was both calculated and experimentally validated.

C2) The acoustoelastic constant was determined through tensile testing. Couplant gel-thickness effects were also investigated using k-Wave simulation and controlled shim experiments, as variation in the coupling layer can introduce time-of-flight shifts comparable with stress-induced changes.

C3) LCR ToF measurements were then acquired on Sample #1 to calculate the PAURS residual stress distribution.

D) Sample #2 was sent to the ANSTO KOWARI facility for neutron diffraction. Neutron diffraction provided an independent depth-resolved RS comparison dataset, with stresses calculated from lattice-spacing measurements over a finite gauge volume. Since neutron diffraction was performed on a nominally identical replicate specimen and not on Sample #1, the PAURS/ND comparison is interpreted as a comparison of RS trends and approximate magnitudes generated by the same robotic welding procedure.

E) After completion of the external and ultrasonic measurements, the PAURS, hole drilling, and neutron-diffraction datasets were compiled for comparison. PAURS/HD provides the closest near-surface comparison because both measurements were performed on Sample #1. PAURS/ND provides a replicate-specimen, depth-dependent comparison because ND was performed on Sample #2 over a defined gauge volume at several depths.

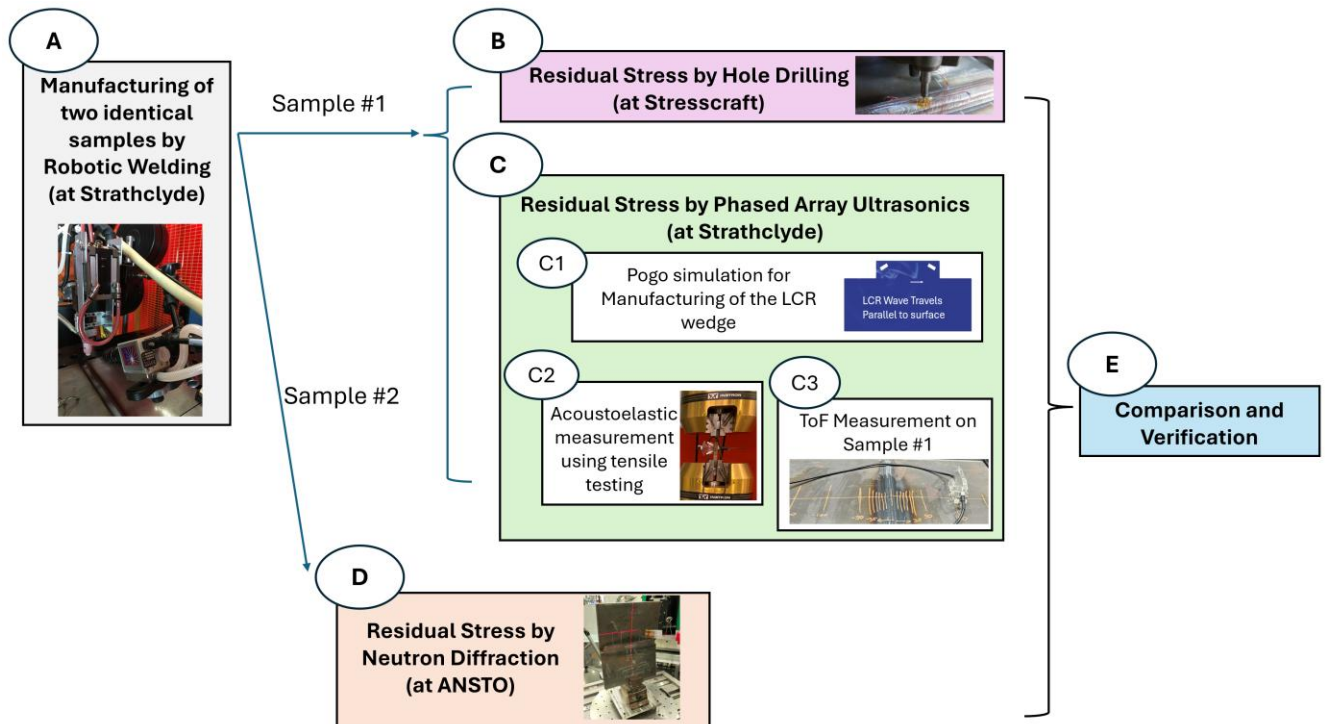


Figure 10: PAURS RS methodology and sample allocation. Two nominally identical welded S275 specimens were manufactured using the same robotic welding procedure. Sample #1 was used for incremental hole drilling and subsequent PAURS inspection, while Sample #2 was used for neutron diffraction [4].

Hole drilling and neutron diffraction were performed by specialist external facilities as part of the collaborative comparison programme, with results returned for inter-methodology comparisons.

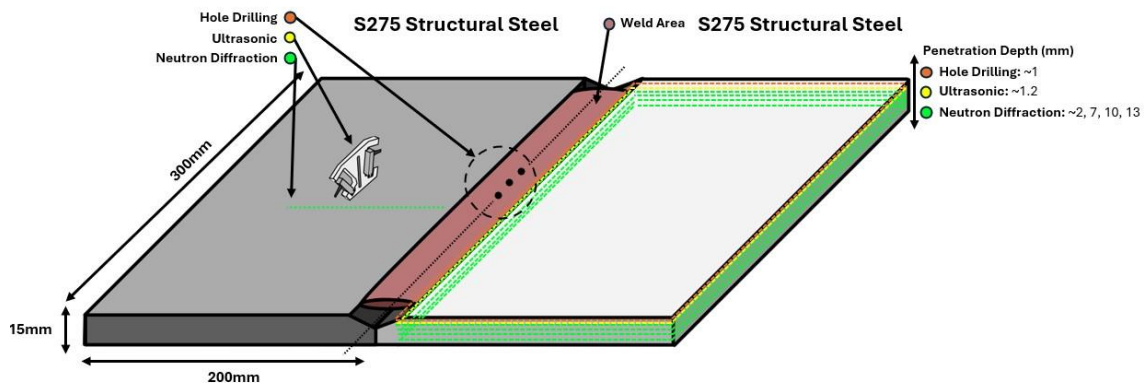


Figure 11: Schematic overview of the RS measurement locations for the welded S275 specimens. The schematic shows the PAURS, hole drilling, and neutron-diffraction measurement locations [4].

Figure 11 summarises the measurement locations and depth basis used for the RS comparison. PAURS is interpreted as a near-surface ultrasonic measurement, hole drilling as a near-surface strain-relief method, and neutron diffraction as a depth-resolved lattice-strain method. The comparison is strongest where the sampling depth and physical measurement basis are compatible, hence why the deepest hole drilling values and the 2 and 13 mm neutron diffraction values are used to compare with the 1.2 mm PAURS values.

4.2.2. Sample manufacturing

The RS specimens were manufactured from S275 structural steel using robotic Tungsten Inert Gas welding. Robotic welding was used to improve repeatability of the weld path and process conditions compared with manual welding, and to provide a controlled basis for comparing PAURS with independent RS measurements. The weld was deposited in 21 passes within a 90° V-groove. The welding parameters used for the root pass, hot pass, filling passes and capping passes are given in Table 2.

Table 2: Robotic TIG welding parameters used to manufacture the S275 RS specimens.

	AVC Set Voltage (V)	Current (A)	Travel Speed (mm/min)	Weaving Amplitude (mm)	Weaving Frequency (Hz)	Inter-Pass Temperature (°C)
Pass 1 (root pass)	12	120	50	2	0.3	80-100
Pass 2 (hot pass)	13.5	220	100	4	0.6	80-100
Passes 3-16 (filling passes)	13.5	210	120	3	0.55	80-100
Pass 17-21 (capping passes)	13.5	240	100	4	0.6	80-100

The inter-pass temperature was maintained between 80 and 100 °C for all pass groups. The specimen was rigidly clamped during welding to restrict deformation, thereby contributing to the development of residual stresses. The supplied material properties included a Young's modulus of 205 GPa and a Poisson's ratio of 0.295, which were used in the subsequent RS calculations and comparison with independent datasets.

The weld layout and pass sequence is shown in Figure 12. This geometry is important because the regions close to the weld centre may exhibit stronger stress gradients, greater surface-geometry variation and increased microstructural heterogeneity, all of which can influence the ultrasonic response. The shielding gas used was Argoshield Heavy, an Argon based shielding gas. The datasheet can be found in Appendix A.

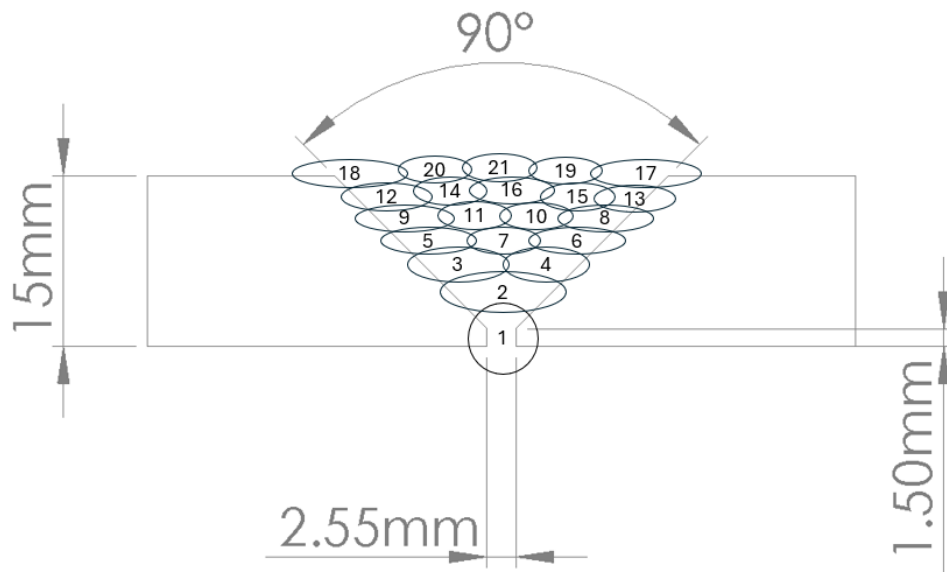


Figure 12: Weld layout used for the S275 RS specimens. The schematic defines the multi-pass weld geometry used to manufacture the robotically welded plates [4].

The robotic welding arrangement is shown in Figure 13. The use of robotic manufacture reduced operator-dependent variation in torch path and process control, supporting the use of nominally identical replicate specimens for the RS comparison programme. Local differences in heat input and clamping response can produce differences in the RS field, particularly when comparing PAURS on Sample #1 with neutron diffraction on Sample #2.

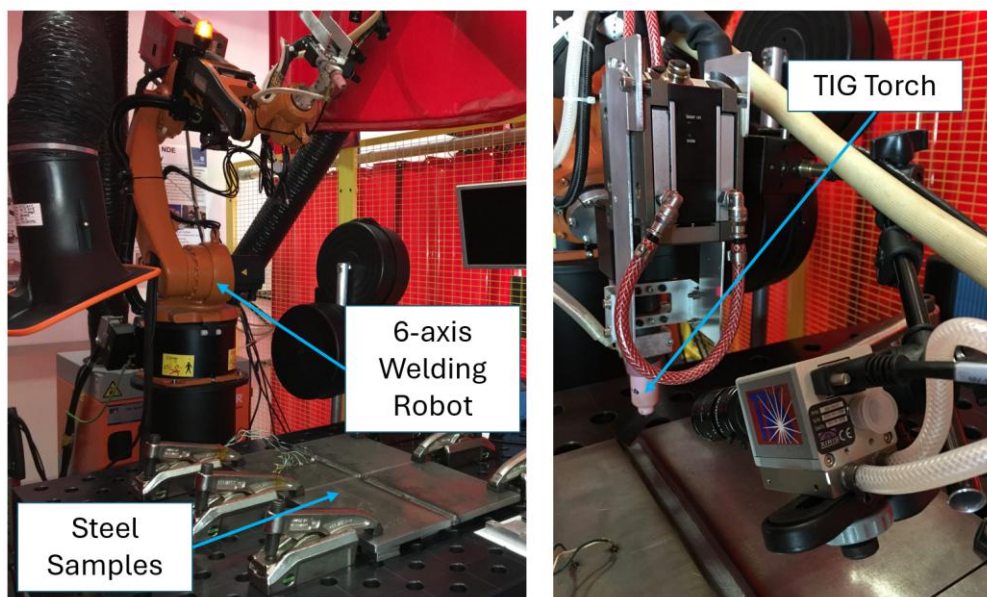


Figure 13: Robotic welding setup used to manufacture the S275 residual stress specimens. Robotic manufacture was used to improve repeatability of the weld path and process conditions between the nominally identical specimens used for PAURS, hole drilling, and neutron-diffraction comparison [4].

Sample #1 was used for hole drilling and PAURS inspection. Hole drilling required local machining and surface preparation around the measurement region to enable strain-gauge placement and drilling. This preparation also improved local contact for subsequent ultrasonic wedge placement, but it means that the PAURS measurement was performed on a prepared surface, not a fully as-welded weld-cap surface.

Sample #2 was used for neutron diffraction. Since this was a nominally identical replicate, the neutron diffraction dataset is used as an independent depth-resolved comparison of the RS field generated by the same welding procedure. Although ND and PAURS/HD were performed on different samples, it is believed that the nominally identical nature of the sample manufacture has contributed towards broadly similar RS trends, if not values. The limitations introduced by this sample allocation are considered in the comparison and interpretation section.

4.2.3. Independent RS comparison methods

Incremental hole drilling and neutron diffraction were used as independent comparison methods for assessing the PAURS RS measurements. They are grouped here because both provide RS evidence external to the ultrasonic measurement chain, while differing from PAURS in measurement principle, sampling depth, and gauge volume.

Hole drilling provides the closest near-surface comparator because it was performed on Sample #1, which was later inspected using PAURS. Neutron diffraction provides depth-resolved diffraction data from Sample #2. Together, the two methods allow PAURS to be assessed against both near-surface and depth-resolved RS information.

4.2.3.1. Incremental hole drilling

Incremental hole drilling was performed externally by Stresscraft Ltd. on Sample #1 to provide a same-specimen near-surface residual-stress comparison for PAURS. The method used a bonded strain-gauge rosette centred on the drilled location, with relieved strain recorded following successive material-removal increments. Residual stress was determined from the measured strain-relief response using the standard incremental hole-drilling procedure. The methodology is consistent with the incremental hole-drilling approach described in ASTM E837, which is used in this thesis as the reference basis for the technique.

Drilling was performed in 16 increments comprising four 32 μm increments, four 64 μm increments and eight 128 μm increments. The programmed cumulative increment depth was therefore 1.408 mm. The three holes were drilled in the centre of the weld cap, which was machined for this purpose. In this thesis, the centre point of the middle hole was defined as the origin, and all other positions measured relative to this. The remaining two holes were offset by ± 20 mm vertically.

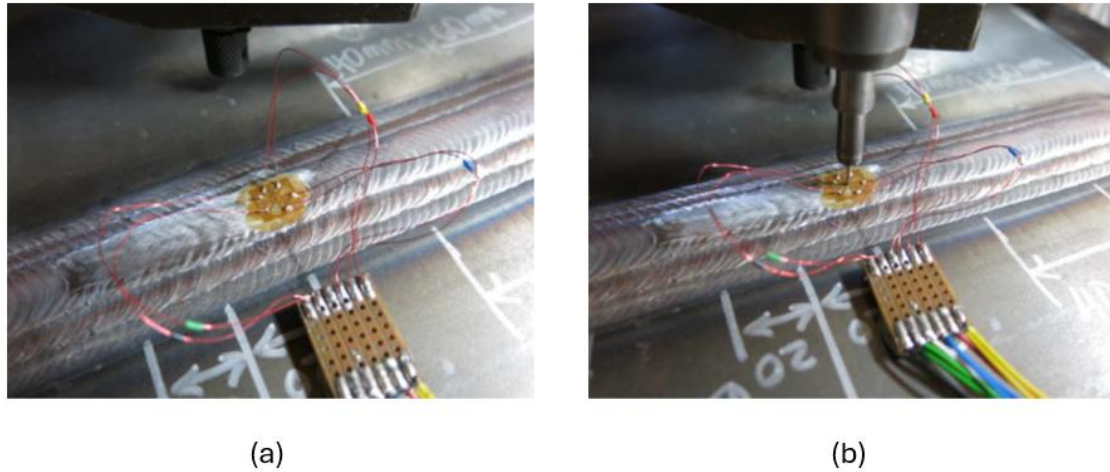


Figure 14: Incremental hole drilling setup used for the S275 residual stress specimen, showing (a) the bonded strain-gauge rosette before drilling and (b) the drilling operation at the first measurement position [4].

The longitudinal residual-stress component was used for comparison with PAURS because this corresponds most closely to the stress component parallel to the LCR propagation direction used in the ultrasonic measurement. The reported hole-drilling uncertainty varied strongly with depth, reaching approximately ± 60 MPa within the first 200 μm , reducing to approximately ± 11 MPa around 500 μm and increasing to approximately ± 24 MPa near the final comparison depth. The earliest increments were therefore not used as the principal quantitative comparator because their uncertainty was substantially greater than that of the deeper measurements.

Hole drilling and PAURS do not sample the same physical volume. Hole drilling provides a local strain-relief measurement centred on the drilled position, whereas PAURS provides a path-weighted near-surface ultrasonic measurement with an effective depth of approximately 1.2 mm. The hole-drilling data are therefore used as a same-specimen near-surface magnitude comparison. Strong stress gradients through the drilled depth can further limit direct comparison because the incremental reduction procedure assumes that the relieved-strain response can be related consistently to the underlying depth-dependent stress field. For direct comparison, only the stress value at depths of around 1.1 mm were considered, as it is the closest available to the PAURS penetration depth.

Detailed external metadata describing the strain-gauge rosette model, gauge-circle diameter, final hole diameter, drilling alignment apparatus and calibration coefficients were not retained within the dataset supplied for this thesis and cannot be reconstructed retrospectively. These quantities are consequently identified as limitations of the external comparison dataset.

4.2.3.2. Neutron diffraction

Neutron diffraction measurements were performed at the ANSTO KOWARI facility on Sample #2 to provide an independent depth-resolved residual-stress dataset. The diffraction measurements were

performed using the α -Fe (211) reflection and a monochromatic neutron beam. Residual stress was calculated from the measured elastic lattice strain using a stress-free lattice-spacing reference, d_0 .

Measurements were obtained at nominal depths of 2, 7, 10 and 13 mm using a $2 \times 2 \times 2$ mm³ gauge volume. Each reported stress value therefore represents an average lattice-strain response over an 8 mm³ material volume and should not be interpreted as a point measurement at the nominal depth. The longitudinal stress component was used as the principal comparator for PAURS because this corresponds most closely to the stress direction assessed by the LCR propagation path. The transverse and normal components are retained as supporting information on the through-thickness residual-stress state.

The 2 mm measurement provides the closest depth-resolved ND comparison with the approximately 1.2 mm PAURS sampling region from the top surface. The deeper measurements at 7 and 10 mm are used to describe through-thickness variation rather than as direct PAURS comparators. Where the 13 mm measurement represents the near-surface region approached from the opposite plate surface, its comparison with the bottom-surface PAURS measurement must still account for the finite $2 \times 2 \times 2$ mm³ ND gauge volume and the path-weighted nature of the ultrasonic measurement. The ND and PAURS sampling regions therefore overlap only approximately in depth and do not represent identical measurement volumes.

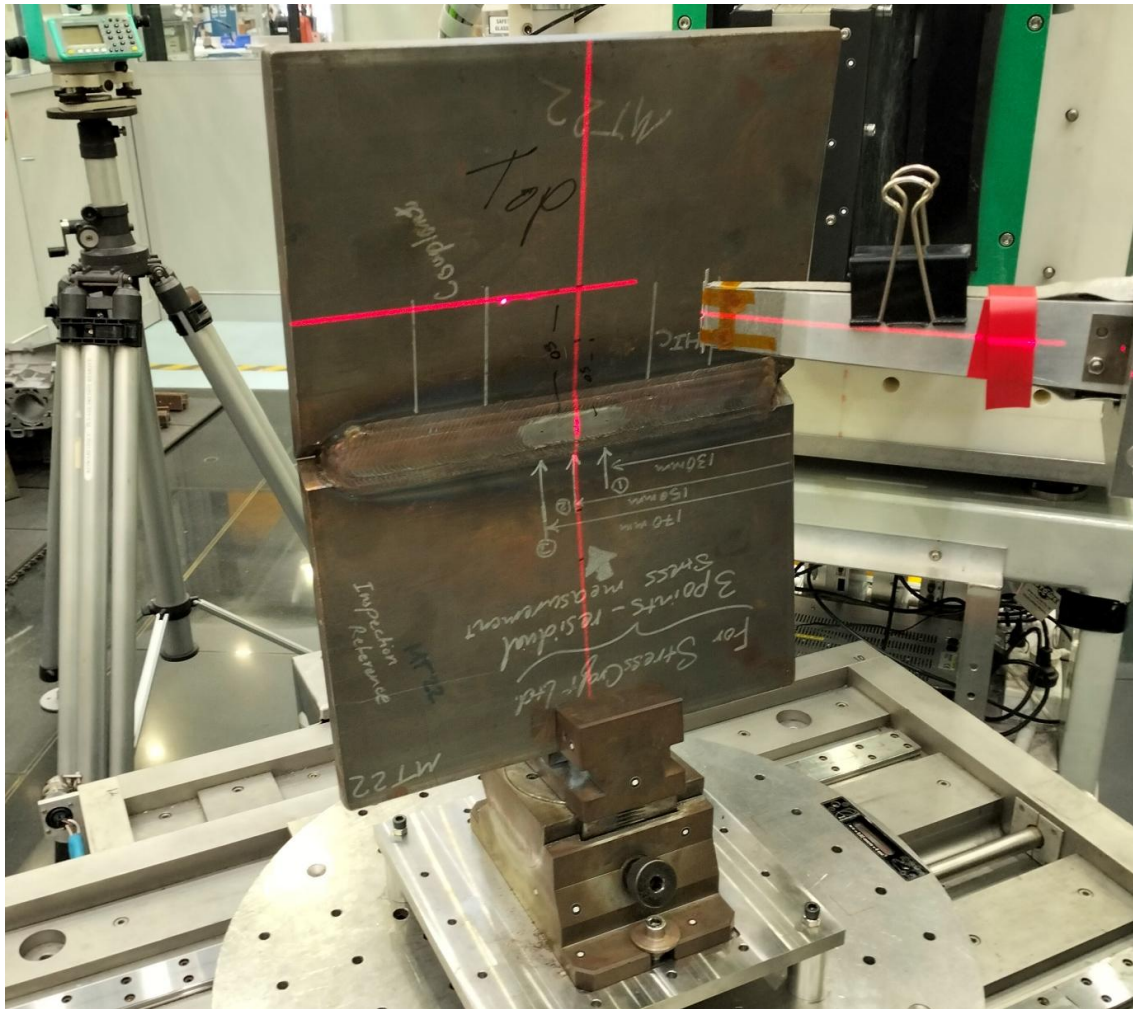


Figure 15: Neutron-diffraction setup used at the ANSTO KOWARI facility for the S275 welded specimen. Neutron diffraction was performed on Sample #2 to provide independent depth-resolved RS information. [4]

A stress-free reference specimen was used to establish the reference lattice spacing required for the ND stress calculation. The dataset available for this thesis did not retain sufficient facility metadata to reconstruct the individual count times, count-time uncertainties, complete scattering geometry, exact measurement-coordinate registration, or the diffraction elastic constants used in the original stress reduction. This limits reconstruction of the complete ND uncertainty budget and is one reason the ND dataset is used as an independent depth-resolved trend and approximate-magnitude comparison rather than as a pointwise validation of PAURS.

Because ND was performed on the nominally identical Sample #2, whereas PAURS was performed on Sample #1, differences between the two datasets can also include specimen-to-specimen variation arising from welding and restraint. The ND comparison is therefore interpreted in terms of residual-stress trend and approximate magnitude within the limits imposed by gauge volume, depth, reference state and specimen allocation.

4.2.4. PA-LCR configuration verification

Before PAURS was applied to the welded RS specimen, the PA-LCR configuration was assessed to verify that the selected probe, wedge, and processing approach produced a usable LCR response. This stage was required because the subsequent stress calculation depends on extracting a repeatable LCR arrival from a defined near-surface propagation condition.

The configuration verification consisted of two linked stages. First, an experimental penetration-depth study was performed to estimate the effective near-surface region sampled by the selected LCR configuration. Second, finite element wave-propagation simulation was used to assess the wedge angle and propagation behaviour associated with LCR generation in the S275 specimen. Together, these studies define the wave mode and approximate sampling region used in the later PAURS inspection.

4.2.4.1. Penetration depth study

The penetration-depth study was performed to estimate the effective depth range over which the selected PA-LCR configuration remained sensitive to near-surface features. LCR waves propagate approximately parallel to the surface, but their sensitivity is not confined to an infinitesimally thin plane. Instead, the response is distributed over a finite near-surface region that depends on the material velocity, frequency, aperture, wedge geometry, and coupling condition. Establishing this effective region is necessary before comparing PAURS with hole drilling and neutron diffraction, due to the depth basis mentioned above.

The experimental setup used for the penetration-depth assessment is shown in Figure 16. A series of notches were introduced at known depths below the surface, and the corresponding A-scans were examined to determine whether the subsurface interruption produced a detectable change in the selected LCR signal.

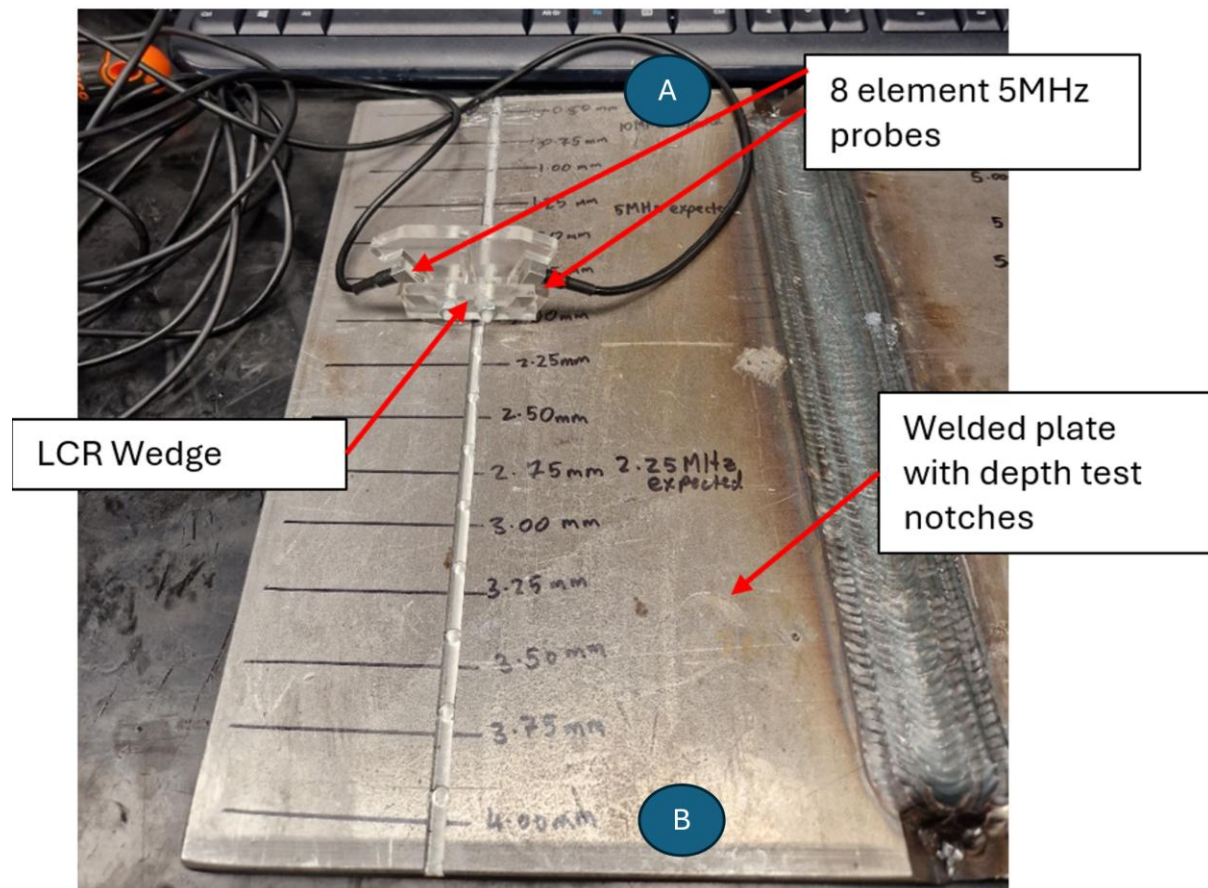


Figure 16: Experimental setup used for the PA-LCR penetration-depth assessment. Notches at known depths were introduced to assess the depth range over which the selected LCR response remained [4].

Four of the total representative A-scans are shown in Figure 17. The LCR arrival is highlighted for each tested depth. Changes in the identified LCR response indicate that the selected configuration remains sensitive to features within the near-surface region, while features beyond this region produce a reduced or negligible influence on the selected arrival. This provides an experimental basis for treating PAURS as a near-surface RS calculation method.

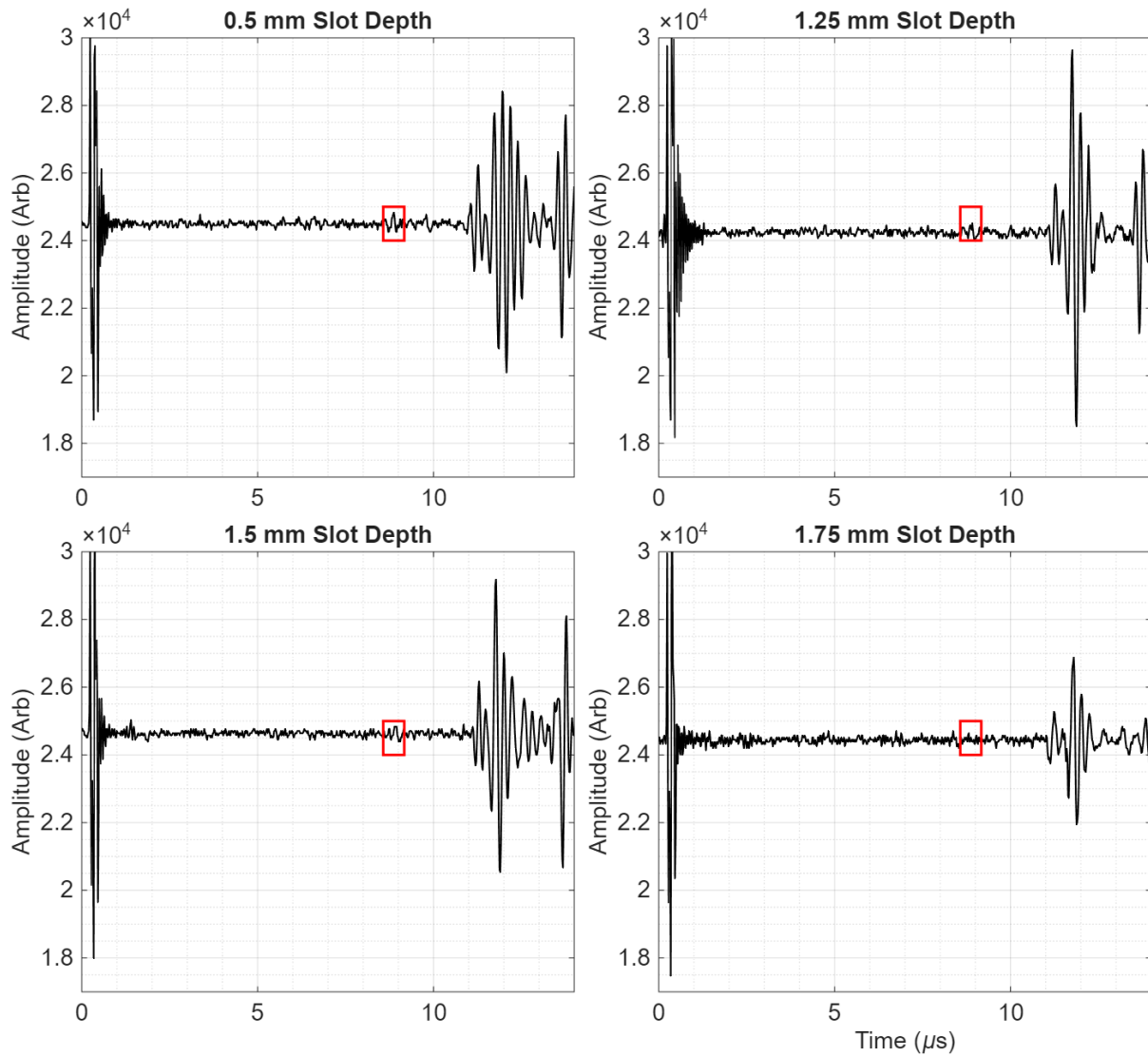


Figure 17: Representative A-scans from the PA-LCR penetration-depth assessment. The selected LCR arrival is highlighted for notch depths of 0.5, 1.25, 1.5, and 1.75 mm. The response demonstrates the approximate near-surface sensitivity of the selected PA-LCR configuration [4].

The calculated LCR sampling depth for the selected 5 MHz configuration was approximately 1.2 mm. The notch validation gave a consistent effective working range of approximately 1.25 ± 0.25 mm, with the response becoming unreliable beyond approximately 1.5 mm. This depth range provides the basis for comparison with the hole drilling result and with the shallowest neutron-diffraction measurement. The ± 0.25 mm uncertainty arises from the LCR wave becoming illegible between the 1.25 mm and the 1.5 mm case. As the notches were milled in 0.25 mm increments, it is possible the LCR is able to propagate up to a point within the 0.25 mm between 1.25 mm and 1.5 mm, but this is unknowable without the use of finer notch depth increments.

Although the LCR sensitivity region estimated here is shallower than the nominal 2 mm neutron-diffraction depth, the 2 mm ND measurement remains the closest available depth-resolved comparator. Because the ND gauge volume was $2 \times 2 \times 2$ mm³, this measurement represents an

average over a finite near-surface volume instead of a point measurement at exactly 2 mm depth. It is treated as a depth-adjacent comparison, while the deeper ND measurements are used to interpret through-thickness stress variation.

4.2.4.2. Pogo simulation of LCR wave generation

Pogo is a software package developed for explicit time-domain finite element simulation of elastodynamic problems, designed to run on GPUs using NVIDIA's CUDA architecture [102]. It has been applied to a range of ultrasonic simulation problems including guided-wave propagation, backscattering and Rayleigh-wave attenuation [102] [103] [104]. In this study, Pogo was accessed through an in-house simulation application developed within the research group. The application provided the interface used to define the ultrasonic inspection geometry and execute the simulation, while mesh generation, time stepping and the associated solver configuration were performed automatically within the application backend.

Consequently, the retained simulation record does not contain the complete solver-level information required to reconstruct the model independently, including the generated mesh, time-step stability assessment, boundary implementation, source-pulse definition, element excitation delays or receiver metric. These quantities cannot therefore be reported retrospectively without reconstructing a simulation that may differ from that originally used. No separate angular-tolerance, mode-purity or mesh-sensitivity study was retained for this model.

A finite element model incorporating the phased-array probes, wedges and S275 steel sample was developed, as shown in Figure 18. The wedge angle was selected using the critical-angle relationship described in Chapter 3, based on the properties of the wedge material and steel specimen. The simulation was then used to assess whether the selected configuration generated the intended LCR wave and to visualise its propagation across the sample. This provided a modelling basis for confirming that the selected inspection geometry could generate a near-surface longitudinal wave suitable for ToF extraction in the later PAURS measurements.

The Pogo result is therefore used as qualitative support for the selected wedge geometry and is not treated as a quantitatively converged verification of LCR angle, mode purity or penetration depth. Experimental evidence for the effective near-surface sampling region was obtained independently from the notch-depth study described immediately above. In that experiment, changes in the LCR response were observed as notch depth increased, providing the experimental basis for the effective PA-LCR sampling depth used later in the thesis. A quantitative comparison between simulated and measured arrival time or penetration depth cannot be reconstructed from the retained Pogo output and is therefore not claimed.

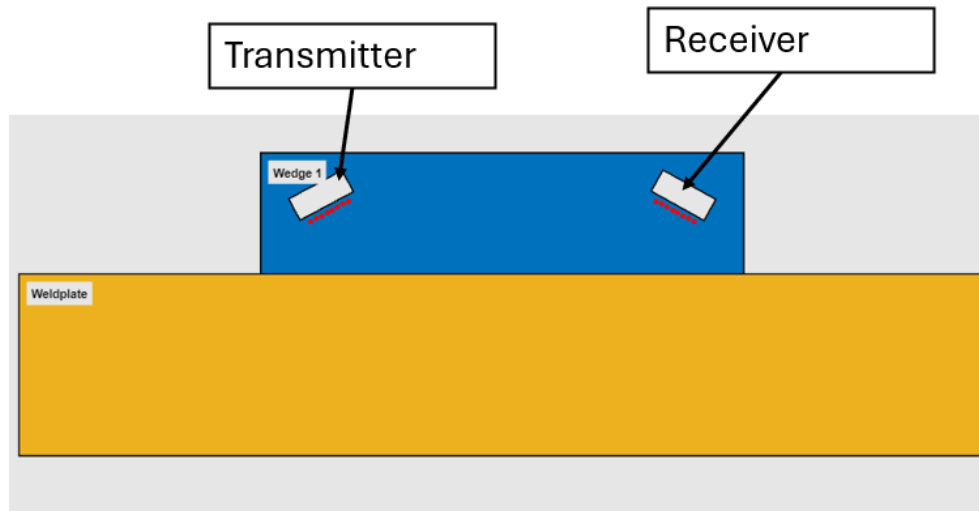


Figure 18: Finite element model used to assess LCR wave generation for the PAURS configuration. The model incorporates the phased-array probes, wedges and S275 steel sample used to verify the wedge angle for LCR generation [4].

The simulated wavefield is shown in Figure 19. The sequence shows formation and propagation of a near-surface longitudinal wave along the inspection direction, supporting the use of the selected wedge and phased-array arrangement for LCR ToF extraction. The simulation verifies the intended wave-mode behaviour under the modelled conditions, while the stress sensitivity of the measured ToF response is established separately through acoustoelastic calibration.

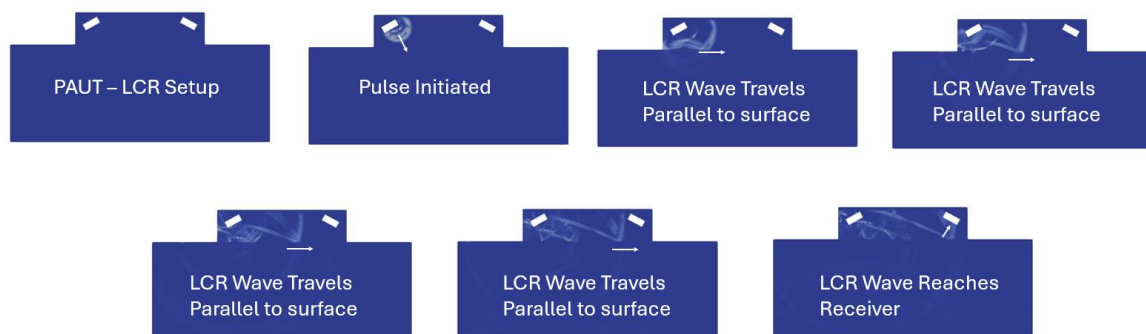


Figure 19: Simulated progression of the LCR wave across the S275 specimen. The wavefield is shown at successive time steps, demonstrating near-surface propagation from the selected wedge configuration [4].

This simulation stage assesses the intended measurement geometry before stress calculation is attempted. Together with the penetration-depth study, it defines the intended wave mode and approximate near-surface region associated with the selected PA-LCR configuration. The model also supports interpretation of the transmit–receive path structure used for subsequent ToF analysis. The next stage is to determine the acoustoelastic calibration for converting measured LCR ToF changes into calculated stress.

4.2.5. Acoustoelastic constant calibration

A representative dumbbell-shaped S275 specimen measuring 36×36 mm at its thinnest point was used to determine the acoustoelastic constant for the selected PA-LCR configuration, as shown in Figure 20. The LCR wedge assembly was attached to the specimen, and ultrasonic ToF measurements were recorded at multiple load levels during tensile testing. The applied load generated a known tensile stress state in the calibration region, while the corresponding ToF change was extracted from the acquired ultrasonic signals. Equation 18 was then rearranged so that the acoustoelastic constant could be obtained from the slope of the fitted ToF–stress relationship. Two experiments were performed: an initial test of the methodology from 0 to 48 kN and back in 3 kN steps, and the full test from 0 to 57 kN and back in 1 kN steps. These maximum values were chosen to avoid reaching the plastic region with the sample, as the additional deformation would have significantly affected the resulting acoustoelastic constant value, as well as the potential damage that could be caused to the ultrasonic equipment in the case of unexpected failure.

The resulting dataset contained 9,472 path-level observations. These observations should not be interpreted as 9,472 independent stress calibrations. The dataset has a hierarchical structure consisting of two loading tests, 148 load-state acquisitions and 64 acoustic paths within each acquisition. Paths recorded at the same load state share the same applied load, specimen condition, temperature, coupling arrangement and acquisition system and are therefore correlated observations. The large path count provides information on path-to-path variability and supports averaging and internal consistency assessment, while the experimental replication is defined principally by the loading sequence and repeated load states..

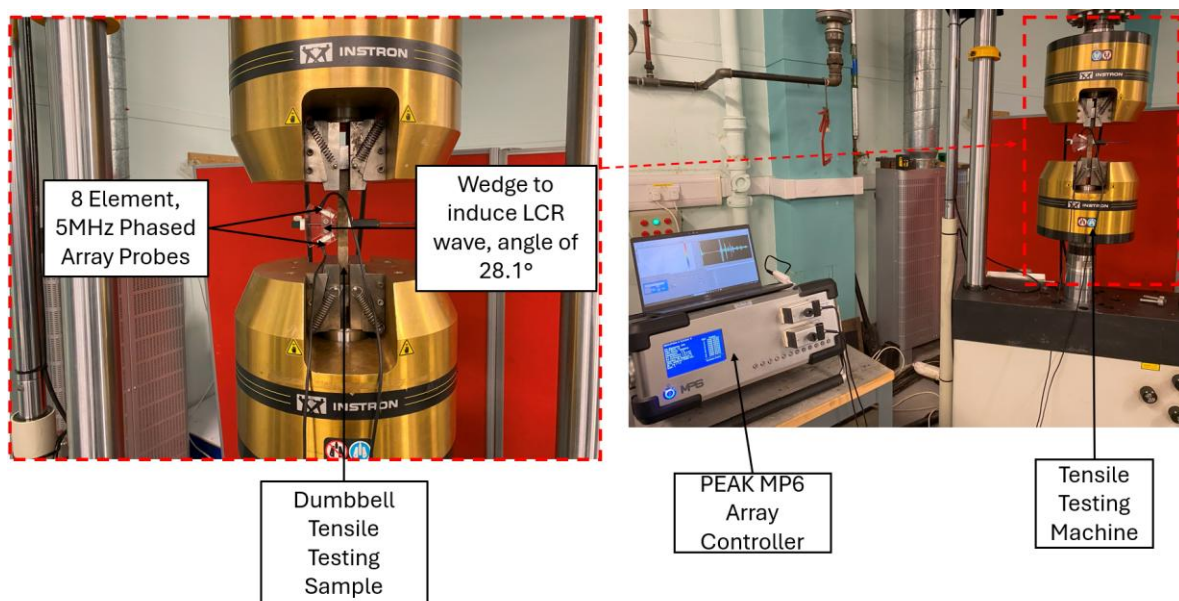


Figure 20: Experimental setup used for acoustoelastic constant calibration. A tensile load was applied to the S275 calibration specimen while LCR ToF measurements were acquired using the selected PA-LCR configuration [4].

The acoustoelastic coefficient was obtained from the fitted relationship between applied tensile stress and measured LCR ToF change. Element-wise fits were used to assess variation between individual acoustic paths, while the averaged phased-array response provided the coefficient subsequently used for welded-plate stress calculation. Loading and unloading data were retained so that any systematic separation between the two branches could be identified. Fit statistics, coefficient uncertainty and the treatment of the regression intercept are reported with the calibration results in Section 5.2.1.

Loading and unloading measurements were retained in the calibration dataset so that branch-dependent behaviour remained visible. A separate numerical hysteresis uncertainty was not defined prospectively, and the observed loading/unloading variation is therefore included within the experimental calibration scatter rather than assigned an independent uncertainty term.

The calibration uncertainty is treated hierarchically. Path-level scatter represents variability between transmitter–receiver measurements within the same acquisition. Variation between repeated load states and between the two loading tests provides experimental repeatability information, while common contributions including applied-load uncertainty, specimen geometry, reference ToF, coupling condition and temperature act across multiple paths and cannot be reduced simply by increasing the number of FMC observations.

Detailed records of the tensile-machine load-cell calibration, independent strain/alignment verification and specimen temperature history were not retained at sufficient resolution to reconstruct separate uncertainty terms for these quantities.

4.2.6. Couplant gel-thickness uncertainty: simulation and experimental assessment

The effect of couplant gel thickness was investigated since changes in the wedge–specimen interface can introduce ToF shifts comparable with stress-induced acoustoelastic changes. This is particularly important for PAURS because the stress calculation is based on nanosecond-scale variations in LCR arrival time. If coupling-related timing changes are not quantified, they may be misinterpreted as RS variation.

The couplant study combined simulation and experiment: the MATLAB k-Wave toolbox was used to examine the influence of controlled gel-thickness variation on LCR ToF, while the experimental shim study assessed whether these effects could be observed and compensated under laboratory conditions. K-Wave was selected here over Pogo because the model geometry and material-property maps could be easily modified between iterations, allowing known changes in couplant thickness to be introduced efficiently across a large number of simulated cases. The purpose of this work was to quantify this major timing-error source and determine whether phased-array path redundancy could reduce its influence on the calculated stress.

The k-Wave coupling model used a two-dimensional 128×128 computational grid with a uniform spatial discretisation of 0.2 mm, giving a nominal model domain of 25.6×25.6 mm. The medium contained acrylic, steel, acoustic couplant and air. The values specified in the retained simulation script were 2788 m s^{-1} and 1180 kg m^{-3} for acrylic, 5920 m s^{-1} and 7850 kg m^{-3} for steel, 1500 m s^{-1} and 1000 kg m^{-3} for the couplant, and 343 m s^{-1} and 1.21 kg m^{-3} for air.

The steel region began at approximately one quarter of the model height, corresponding to grid row 32. An air region was represented over x-indices 70–74 and y-indices 1–31. The couplant layer was introduced immediately above the wedge–steel boundary and its thickness was discretised to the 0.2 mm spatial grid. Consequently, imposed couplant thicknesses were rounded to integer numbers of grid cells.

Two eight-element phased-array transducers were represented with a nominal element width of 0.4 mm, element length of 6 mm and pitch of 0.5 mm. The source frequency was 5 MHz and the source pressure amplitude was 1×10^6 in the numerical pressure units used by k-Wave. The excitation was defined as a sinusoidal pressure waveform, $p(t) = 10^6 \sin(2\pi \times 5 \times 10^6 t)$, with the temporal array generated automatically using the k-Wave makeTime function.

Table 3 below collates all experimental velocities and wedge angles.

Table 3: Collation of longitudinal velocities and resultant wedge angles used in this thesis

Sample Material	Wedge Material	Sample Velocity	Wedge Velocity	Wedge Angle
S275 Steel (Weld)	Acrylic	5790 m s^{-1}	2788 m s^{-1}	28.1°
S275 Steel (Gel thickness)	Rexolite	5790 m s^{-1}	2360 m s^{-1}	24.1°
Al7075 (Microstructure)	Rexolite	6280 m s^{-1}	2360 m s^{-1}	22.1°

The k-Wave simulation represented the couplant as a homogeneous acoustic fluid with a longitudinal sound velocity of 1500 m s^{-1} . This value was used as the nominal acoustic property of the modelled coupling layer.

At 5 MHz, the corresponding wavelengths are approximately 0.558 mm in the wedge, 0.300 mm in the couplant, 1.158 mm in steel and 0.0686 mm in air. The 0.2 mm spatial discretisation therefore gives approximately 2.79, 1.50, 5.79 and 0.34 grid points per wavelength in these regions, respectively. The steel region is resolved more finely than the couplant and air regions, while the latter are represented at comparatively coarse spatial resolution.

A dedicated spatial- and temporal-refinement study was not retained for the original simulation programme. The model is therefore not presented as a formally converged prediction of the absolute LCR timing or detailed pressure field. Its purpose is restricted to examining the relative change in the extracted LCR timing response as the imposed wedge–specimen coupling condition is varied while the remaining numerical configuration is held constant.

The coarse representation of the couplant and air regions introduces an additional modelling limitation, particularly where the imposed separation approaches the scale of the numerical grid. The simulated ToF shifts are consequently interpreted as a numerical sensitivity study supporting the experimentally observed influence of wedge–specimen separation. The experimental shim measurements provide the primary evidence that coupling variation produces timing shifts of practical significance in the PAURS measurement.

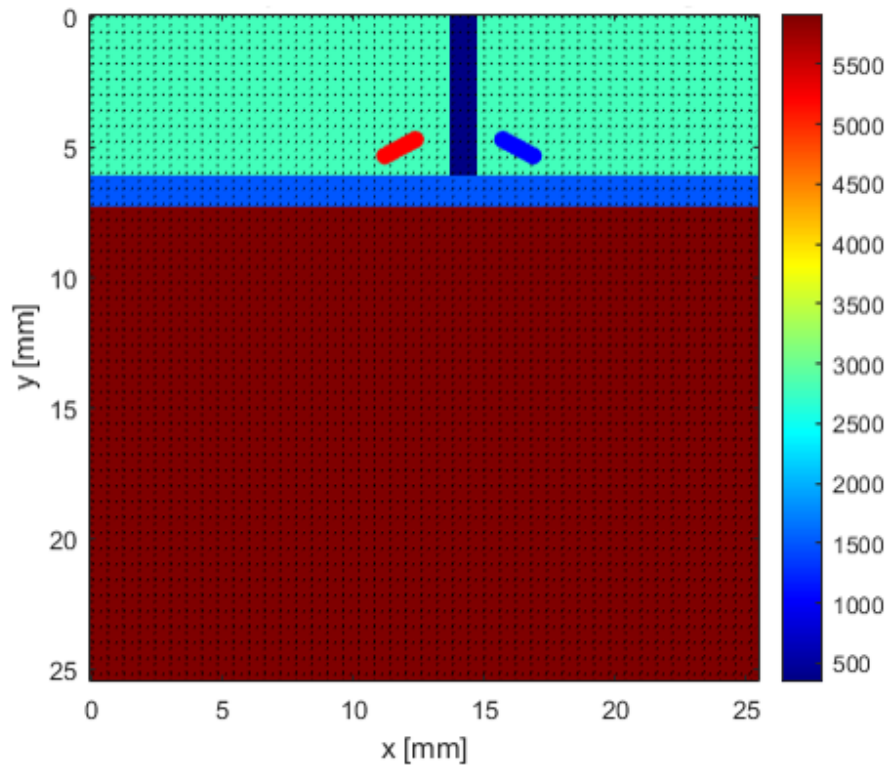


Figure 21: K-Wave model used to simulate couplant gel-thickness effects in the PA-LCR configuration. The model represents the wedge, couplant layer and S275 specimen, with controlled changes in gel thickness introduced at the wedge–specimen interface [7].

Two ultrasonic transducers were simulated, each with 8 elements, a frequency of 5 MHz, and a pitch of 0.5 mm to match those used for experimental validation. These were set up in a pitch-catch configuration, with an angle of 28.1° to induce an LCR wave.

The gel-thickness profile was varied across the interface to represent non-uniform coupling conditions caused by local surface roughness and corresponding couplant variation [105]. Example simulated profiles are shown in Figure 22. For each simulated condition, the LCR arrival was extracted using the same timing logic as the experimental measurements. The resulting ToF change was then interpreted as a coupling-induced timing error as opposed to a stress-induced material response.

The gel profile was generated as a one-dimensional variation along the wedge–specimen interface. A dimensionless random sequence was first generated over the 128 interface nodes, smoothed by convolution to avoid abrupt cell-to-cell changes, and normalised to give a dimensionless spatial weighting between 0 and 1. For each simulation iteration, this weighting was scaled between the prescribed minimum and maximum gel thicknesses, while the mean gel thickness was increased progressively between iterations. The physical gel-thickness profile was then converted into grid cells by dividing by the 0.2 mm mesh spacing. This process was seeded using the rngSeed function in MATLAB, with the results reported here using seed 741.

This approach produced a coupling layer that increased in average thickness while retaining local spatial variation along the wedge–specimen interface. The model therefore represents the practical case in which the wedge is nominally in contact with the specimen, but the couplant layer varies locally because the surface and contact condition are not perfectly uniform. No topography data was recorded of the experimental specimen for comparison here, which is identified as a limitation.

$$\text{Thickness Profile} = t_{min} + (t_{max} - t_{min}) * (x_n/n) * \text{Noise Profile} \quad (26)$$

where t_{max} and t_{min} are the maximum and minimum thicknesses, n the number of iterations, and x_n the iteration of note. The term x_n/n increases the mean gel thickness approximately linearly between iterations, while the noise profile imposes local variation along the interface.

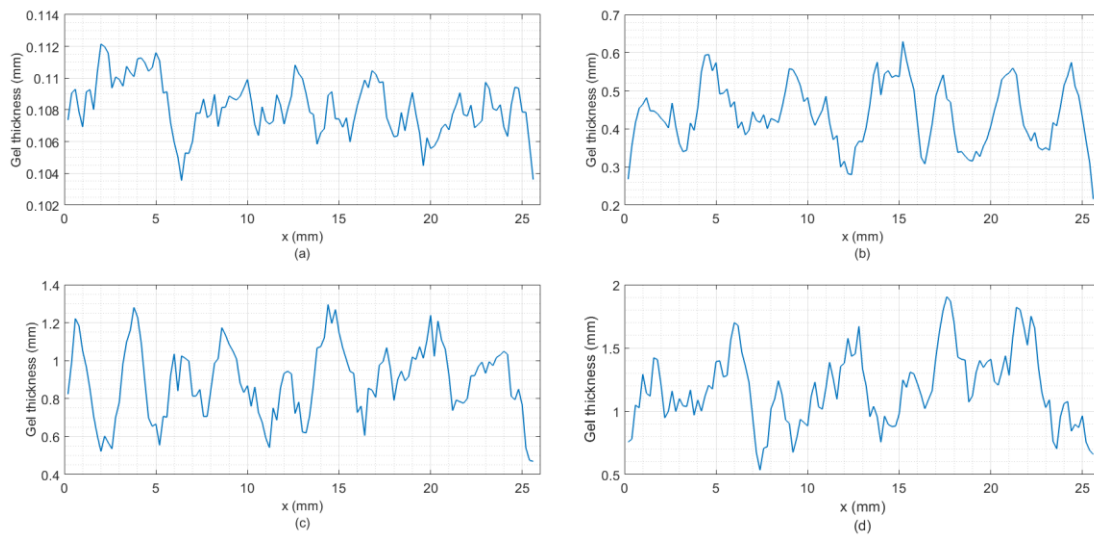


Figure 22: A selection of gel thickness profiles at (a) iteration 1, (b) iteration 41, (c) iteration 101, and (d) iteration 141 [7].

For each transmitter–receiver path, the simulated ToF under a perturbed gel condition was compared with the baseline ToF. The coupling-induced timing error was therefore calculated as the difference between the perturbed and reference arrival times.

Gel-thickness compensation was performed using the additional path information available from the phased-array acquisition. For each iteration, the LCR ToF was extracted for each usable transmitter–receiver path using the same zero-crossing timing feature applied in the PAURS measurements. The uncompensated timing error was calculated by comparing the ToF at each imposed gel thickness with the baseline ToF obtained under the minimum gel-thickness condition. The compensated timing quantity was then calculated from the difference in ToF between adjacent receivers at the same gel thickness, referenced to the equivalent adjacent-path difference under the baseline condition.

The compensated ToF error represents the residual timing change after subtracting the common coupling contribution between neighbouring paths. This correction does not remove all coupling effects, but it reduces timing shifts that affect adjacent paths in a similar way.

The simulated timing errors were converted into equivalent stress errors using the $1 \text{ ns} \approx 4 \text{ MPa}$ approximation, to express the coupling-induced ToF error in stress-equivalent units and allow for the practical significance of gel-thickness variation to be assessed relative to the RS measurement objective.

The same compensation approach was then tested experimentally using the shim arrangement shown in Figure 23, introducing controlled wedge–specimen separation to be imposed before applying adjacent-receiver subtraction to the measured ToF values.

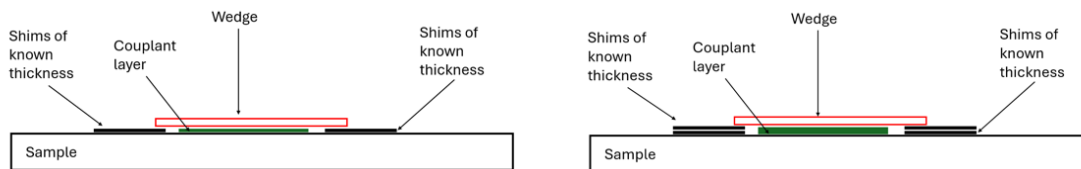


Figure 23: Schematic arrangement for the experimental gel-thickness study. Shims were introduced between the wedge and specimen to vary the effective couplant layer thickness under controlled conditions [7].

The experimental setup is shown in Figure 24. Three rolled S275 structural-steel samples were used, for which low and relatively consistent residual stress values were expected. A Sonatest Sonagel ultrasonic coupling gel was used between the Rexolite wedge and the steel specimen throughout the experimental study. The same couplant type was used for each shim-controlled measurement to avoid introducing variation associated with changing couplant material. A PEAK MP6 controller was used to drive two 5 MHz, 8 element, 0.5 mm pitch Olympus transducers, mounted in a custom Rexolite wedge with a 24.1° probe angle for LCR wave induction. This differs from the acrylic-wedge configuration because Rexolite and acrylic have different sound velocities and therefore require

different wedge angles to generate the LCR wave. To further reduce the possibility of biasing the result by detecting unexpected RS, the wedge position was kept constant at the centre of each sample across all 3 plates and every gel-thickness level.

Based on the LCR penetration depth relationship given in Equation 20, as the couplant thickness approaches approximately 0.8 mm, the LCR wave energy is increasingly confined within the couplant layer and less useful energy reaches the steel specimen. Under this condition, a valid ToF corresponding to propagation within the sample would not be expected. The experimental gel thickness was therefore limited to 0.7 mm.

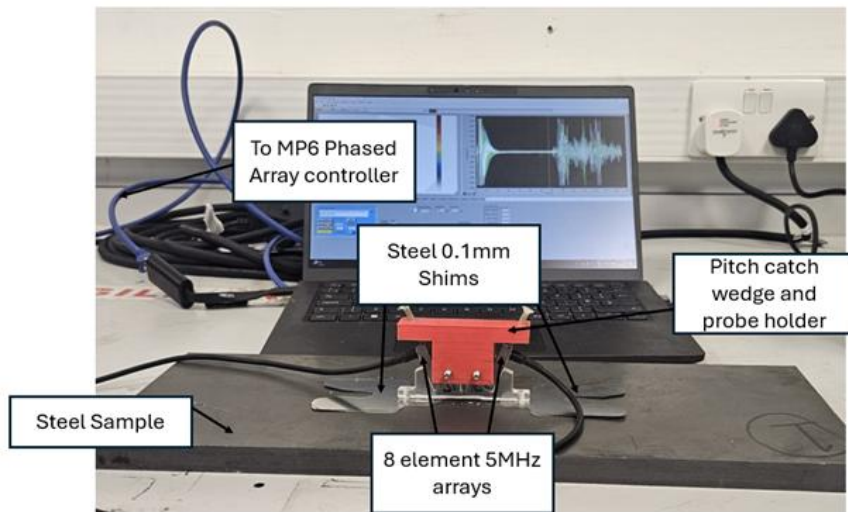


Figure 24: Experimental setup for the shim-based gel-thickness study. The PA-LCR wedge and phased-array probe were positioned on the S275 specimen with controlled shim thicknesses used to alter the effective coupling layer. The measurements were used to compare uncompensated and compensated ToF variation [7].

Steel shims with a thickness of 0.1 mm were placed on the specimen surface so that the couplant layer was compressed to a defined value, as shown in Figure 23. A shim increment of 0.1 mm was selected because it provided a repeatable and physically measurable change in wedge–specimen separation, while remaining small enough to investigate the transition from stable coupling to degraded LCR transmission. The experimental range of 0 to 0.7 mm was chosen on all three samples used to assess gel-induced timing error before the measurement condition became dominated by loss of valid LCR propagation in the sample. The plates were rolled steel and so were assumed to have minimal residual stress, but to mitigate any potential residual stress data contaminating the results, the wedge was kept in a constant position in the centre of each plate to perform the scan at each shim height, to avoid the ToF differences resulting from scanning the wedge along the sample – however minimally.

Temperature was not varied as an experimental parameter during the shim-based coupling study. A continuous laboratory- or specimen-temperature record was not retained at sufficient resolution to

establish the temperature range experienced during the measurements, quantify equilibration between the specimen and laboratory environment, or determine a study-specific ToF–temperature coefficient. No temperature correction has therefore been applied retrospectively to these data. The experiment isolates the effect of controlled wedge–specimen separation by referencing each coupling condition to the matched-contact measurement acquired within the same experimental series. The resulting timing differences are consequently interpreted as coupling-specific quantities, with temperature retained separately as an unquantified contribution to the wider PAURS uncertainty. As the nominal spacer thickness does not necessarily correlate exactly to gel thickness, this is treated as a controlled separation study.

The same adjacent-receiver compensation logic used in the simulated study was then applied to the experimental ToF values. The uncompensated and compensated ToF errors were then converted into stress-equivalent values using the $1 \text{ ns} \approx 4 \text{ MPa}$ approximation. This allowed the remaining coupling-induced timing error to be expressed in MPa and compared directly with the expected scale of PAURS RS measurements in Chapter 5 as one source of experimental error.

4.2.7. Ultrasonic inspection of welded plate

The PAURS inspection of Sample #1 was performed after completion of the incremental hole-drilling measurements and return of the specimen to the University of Strathclyde. The ultrasonic inspection comprised 21 nominal scan locations distributed symmetrically about the weld centreline. The outer reference positions were located at -195 mm and $+195 \text{ mm}$ relative to the weld centre. A coarser positional spacing was used in the parent material, reducing to 5 mm in the HAZ and weld region to provide greater spatial resolution where stronger residual-stress gradients were expected (Figure 25).

Incremental hole drilling had already required local material removal and surface preparation before the subsequent PAURS inspection. The surface condition encountered during PAURS therefore represents the post-hole-drilling specimen condition. Improved ultrasonic contact following this preparation describes the measurement condition during the later ultrasonic inspection and does not demonstrate that the original residual-stress field remained unchanged locally following machining and drilling. As mentioned in Section 4.2.4.1, the centre HD hole was defined as the origin, and the other two holes at $[0, 20] \text{ mm}$ and $[0, -20] \text{ mm}$ respectively. All holes were 2 mm diameter. The centreline of the wedge was positioned on the 0 of the y axis, in line with the centre hole. The scan positions were therefore 195, 150, 100, 50, 35, 25, 20, 15, 10, 5, 0, and the same mirrored on the negative x axis. The overall wedge footprint was 8 mm by 60 mm . The plate was scanned from left to right ($[-195, 0]$ to $[195, 0]$) five times and an average taken. These scans were performed completely before being repeated, as opposed to lifting and reseating the probes every repeat.

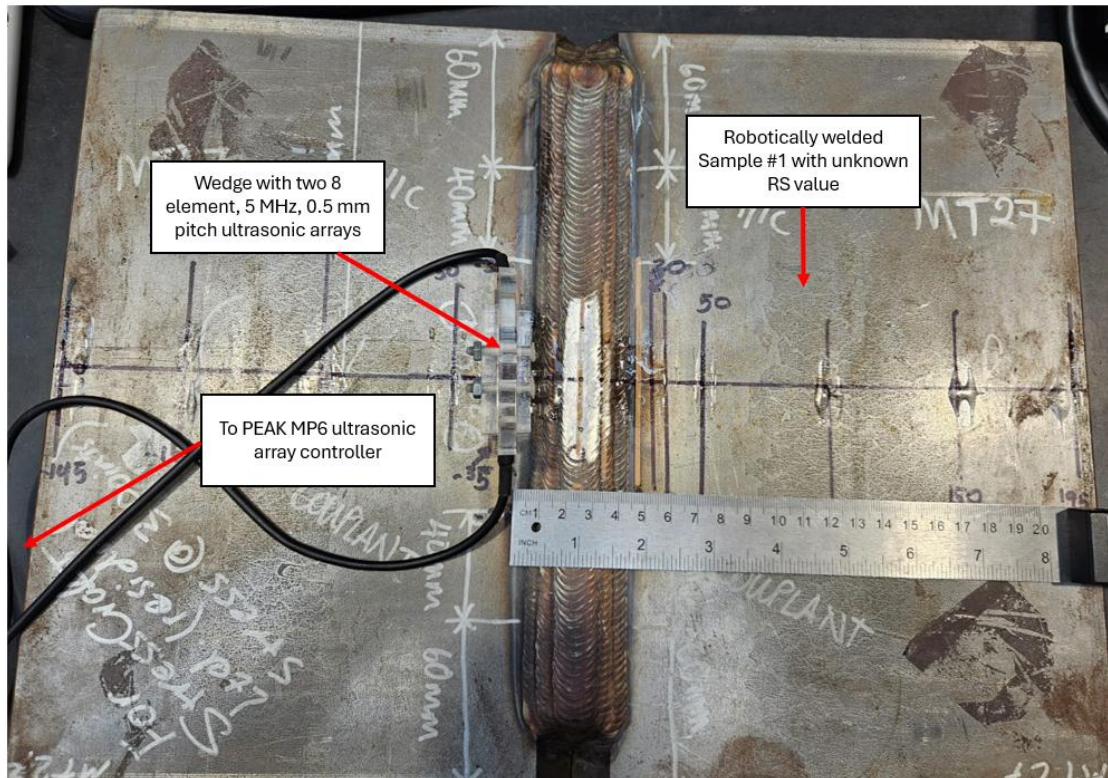


Figure 25: PAURS inspection setup for the welded S275 specimen. The pitch-catch phased-array wedge arrangement was used to generate and receive LCR waves across the weld region, with measurements acquired at 21 scan locations arranged symmetrically about the weld centreline [4].

Full Matrix Capture was used to acquire multiple transmitter–receiver combinations at each scan location. The resulting dataset allowed the LCR arrivals to be assessed for path consistency, signal quality, and repeatability, and gel thickness to be compensated for. Challenges were encountered due to the weld surface geometry, as certain areas lacked sufficient smoothness to ensure consistent coupling between the ultrasonic wedge and the sample. These areas were not further machined, as doing so would relieve the existing residual stress and compromise the validity of comparisons between measurement techniques. Consequently, results obtained in these regions—indicated by a grey boundary in the PAURS results in Chapter 5— were retained as reduced-confidence rather than treated at the methodology stage as fully reliable stress magnitude values.

The acquired A-scans were processed using the time-of-flight extraction procedure described in Chapter 3. For each path, the LCR arrival was identified within a defined time window, and the second zero crossing of the LCR wave was used as the timing point for the stress calculation. This timing feature was selected to provide a repeatable ToF marker within the identified LCR arrival, while reducing sensitivity to amplitude variation compared with peak-picking alone.

The change in time of flight was calculated relative to the scan positions furthest from the weld centre at -195 mm and 195 mm, considered to have minimal or baseline residual stress relative to the HAZ

and the weld itself, and so treated as the reference position, and the corresponding residual stress in the HAZ and the weld region was calculated using the calibrated acoustoelastic constant. The stress calculation therefore depends on the suitability and the consistency of the extracted LCR arrival.

For each scan location, the retained paths were assessed before the stress value was interpreted. The main quality criteria were the clarity of the LCR arrival, consistency between adjacent and neighbouring paths, and standard deviation across selected paths. Paths with weak, distorted, or ambiguous LCR arrivals were excluded from the averaged result, and the retained paths showing good consistency used to obtain an averaged ToF, which itself was used to calculate residual stress after gel compensation was applied. Clarity of the LCR wave was assessed through comparison to an ideal example, which was preset at the beginning of the data processing algorithm. The gate, as mentioned before, was specific to the material under inspection, and in this case was between 8 μs and 9 μs . Amplitude, path agreement, and allowable standard deviation were also assessed in comparison to this idealised wave. The full 64 path data is not published here for brevity.

This path-based assessment is particularly important in the welded region. Near the weld centreline, the surface profile and local material condition can disrupt the wedge–specimen interface and alter the received LCR response. In addition, stress gradients and microstructural variation across the weld and heat-affected zone may produce local changes in ultrasonic velocity that are not solely caused by residual stress. These effects are therefore included in the confidence assigned to each PAURS result.

The PAURS inspection produced both a calculated RS distribution and a measurement-quality basis for interpreting that distribution. The stress values were subsequently compared with the hole drilling and neutron-diffraction datasets, while the associated signal quality and path consistency were used to identify regions where the ultrasonic result should be assigned higher or lower confidence.

Continuous contact-force measurement, specimen-temperature logging and a documented randomised visiting order were not retained for the 21-position scan. The original acquisition order was not designed to separate position-dependent residual-stress variation from possible long-term drift. These quantities are identified as requirements for subsequent PAURS measurement qualification.

4.2.8. Comparison and verification

The PAURS results were compared with the hole drilling and neutron-diffraction datasets to assess whether the ultrasonic method reproduced the main RS trends and approximate magnitudes generated by the welded specimens. The comparison was interpreted using the measurement basis defined in Sections 4.2.3 and 4.2.4, including sampling depth, gauge volume and specimen allocation.

Figure 26 illustrates the overall comparison workflow, outlining the sequence from HD, ND and PAURS data acquisition through to MATLAB-based processing and final comparative analysis. This

representation shows how the three measurement routes were brought together for final comparison, while retaining the separate processing and measurement basis of each method.

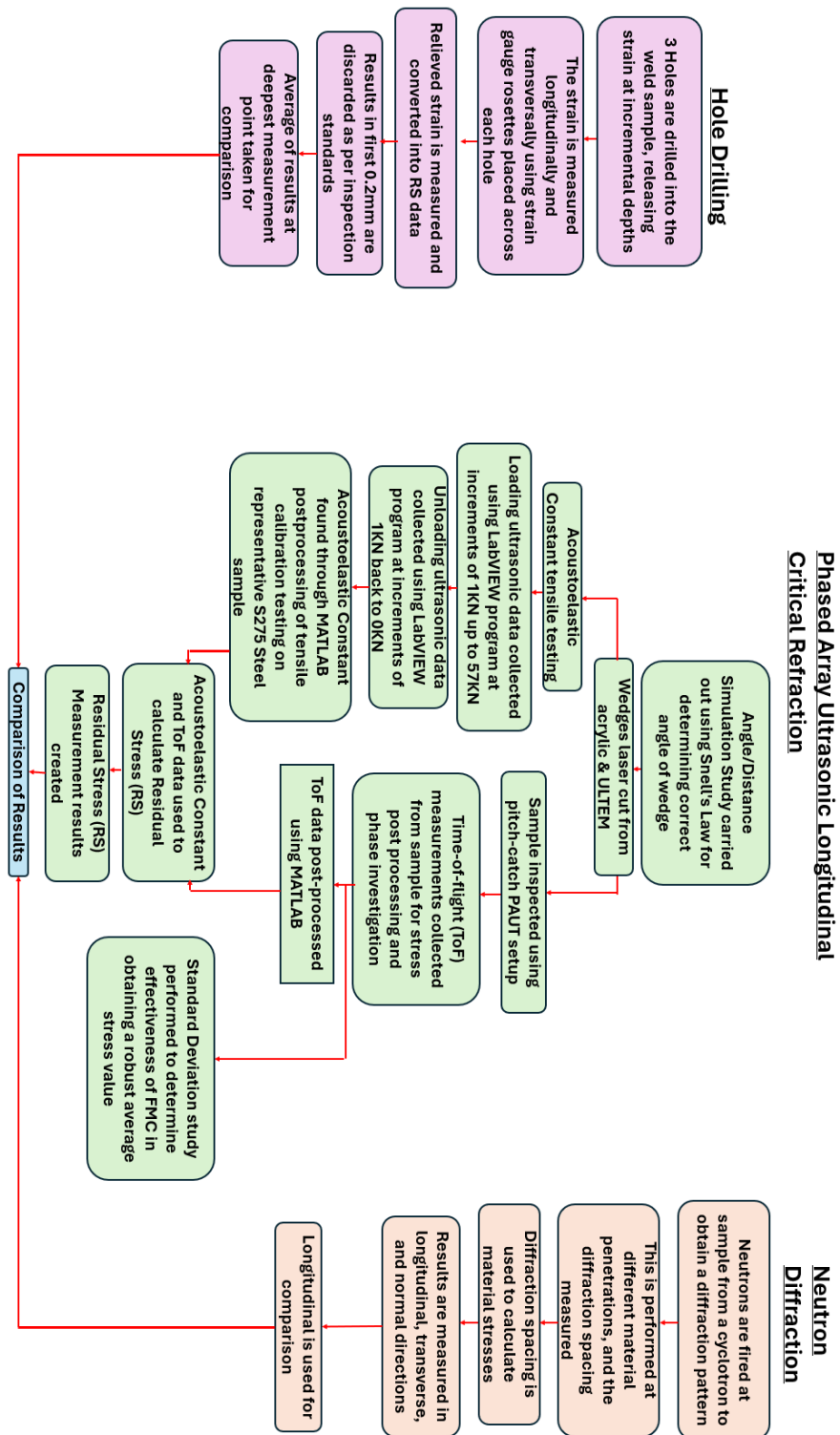


Figure 26: RS comparison workflow. The workflow summarises how strain-relief, diffraction-based, and ultrasonic measurement routes were processed before final comparison. [4].

In addition to comparing mean stress values, the PAURS data were assessed using the standard deviation across retained acoustic paths. This allowed the averaged stress estimate to be interpreted alongside an internal measure of ultrasonic consistency.

Hole drilling provides the closest same-specimen near-surface comparator because both measurements were performed on Sample #1. The methods still have different measurement bases: hole drilling provides a local strain-relief measurement, while PAURS calculates stress from a path-weighted LCR response over the near-surface propagation region, but overall the average HD result gives a good comparative base for approximate RS magnitude.

Neutron diffraction provides independent depth-resolved evidence from Sample #2. ND measures lattice strain within a finite gauge volume and requires a stress-free lattice-spacing reference. This is interpreted in terms of RS trends produced by the same robotic welding procedure, within the limits imposed by specimen allocation.

The PAURS results were assessed using both the calculated stress values and the associated measurement-quality indicators. A scan position was considered suitable for higher-confidence numerical interpretation where the LCR arrival was identifiable across the retained paths, the SNR supported stable zero-crossing extraction, and no visible coupling loss or wedge separation was present. Positions not meeting these criteria were treated as reduced-confidence or qualitative trend indicators, or excluded from numerical assessment where the measurement basis was not reliable. An additional and essential measurement quality indicator at this stage of the methodology development is comparison with established methodology. Through this validation method, the level of agreement between PAURS and HD or ND is treated as a major factor in determining the confidence of the RS measurement.

This quality classification is used in Chapter 5 to interpret agreement and mismatch between PAURS, hole drilling, and neutron diffraction. It is particularly important near the weld centreline, where reduced agreement may arise from local PAURS measurement difficulty as well as genuine differences in sampled stress state.

4.2.9. PAURS measurement basis and interpretation limits

PAURS retains calibrated ToF extraction, path selection, and independent comparison evidence from the controlled bolt benchmark, but applies them to an unknown welded residual stress field. Interpretation of the calculated stress field depends on these conditions being defined before comparison with HD and ND.

The wedge-angle simulation and penetration-depth assessment define the LCR wave, how it propagates, and its approximate near-surface sampling region. The S275 acoustoelastic calibration then gives the stress-conversion basis for the measured LCR ToF changes. A PAURS output is treated

as a calculated near-surface stress value only when coupling stability and retained-path consistency are acceptable.

The gel-thickness simulation and shim study quantify one practical source of coupling-related timing error, while FMC acquisition provides additional paths for averaging, comparison, and rejection.

These methods reduce part of the measurement uncertainty under controlled conditions, but they do not remove the need to assess the wedge–specimen interface at each scan position. HD and ND offer independent RS evidence for assessing PAURS, with interpretation limited by measurement principle, sampling depth, gauge volume, and specimen allocation.

PAURS measurement confidence was assessed from the ultrasonic acquisition before comparison with the independent residual-stress datasets. Internal indicators included LCR arrival stability, retained-path behaviour, path-wise standard deviation, coupling condition, and validity of the acoustoelastic calibration and reference condition. HD and ND agreement was subsequently used as external comparison evidence and was not used to determine whether an individual PAURS measurement was accepted.

Chapter 5 uses these criteria to separate higher-confidence numerical RS results from trend-based or limited-confidence regions.

4.3. Microstructure and PAURS+

The preceding PAURS methodology uses measured LCR time-of-flight changes, acoustoelastic calibration, and measurement-quality checks to calculate near-surface residual stress and assess the reliability of the resulting stress distribution. Here, PAURS+ uses the same PA-LCR measurement platform to examine additional ultrasonic observables associated with microstructure-sensitive wave behaviour.

Residual stress and microstructure both influence ultrasonic propagation; residual stress changes LCR velocity through the acoustoelastic effect, while microstructure affects attenuation, amplitude, frequency content, and directional response. This is directly relevant to residual stress measurement because microstructure can affect the ultrasonic signal used for stress calculation. It also provides a measurement opportunity, since the PA-LCR response contains information beyond ToF.

Although microstructure-sensitive ultrasonics can include attenuation, backscatter, and frequency-domain response, the implementation used here focuses on angular PA-LCR amplitude and attenuation-related change because it can be measured with the same wedge and probe arrangement used for PAURS on a sufficiently sized sample, with the addition of robotic rotation for angular resolution.

EBSD provides the reference microstructural contrast between the equiaxed AFSD region and elongated substrate. The simulation stage uses this data to test whether that contrast is expected to produce an angular PA-LCR amplitude or attenuation-related signature, while the 5 MHz robotic measurements test whether the signature remains measurable under practical coupling and positioning conditions.

4.3.1. Samples and EBSD

The PAURS+ study used an Al7075 AFSD sample produced by additive friction stir deposition. The sample was selected because it contained two distinct microstructural regions within the same material system: the deposited AFSD region and the rolled substrate region. This provided a suitable test case for assessing whether PA-LCR amplitude and attenuation-related response could distinguish between a more equiaxed microstructure and a directionally elongated microstructure.

The sample is shown in Figure 27a. It was sectioned using EDM and two specimens, labelled 6-13 and 9-13, were extracted for EBSD, as shown in Figure 27b. The EBSD analysis was used to establish the reference microstructural condition for the later simulation and robotic PA-LCR measurements. This provided the microstructural basis for defining the equiaxed and elongated cases used throughout the PAURS+ study.

The EBSD results, shown in Figure 27c, show a fine, equiaxed grain structure in the deposited AFSD region and a more elongated, columnar grain structure in the substrate. Therefore in the following experiments, the AFSD region is treated as the comparatively isotropic reference case, and the substrate as the relative directionally anisotropic case. This distinction is important because angular dependence in the PA-LCR amplitude or attenuation-related response is expected to be weaker in the equiaxed region and stronger in the elongated substrate, when the ultrasonic propagation direction changes relative to the dominant grain morphology during rotation.

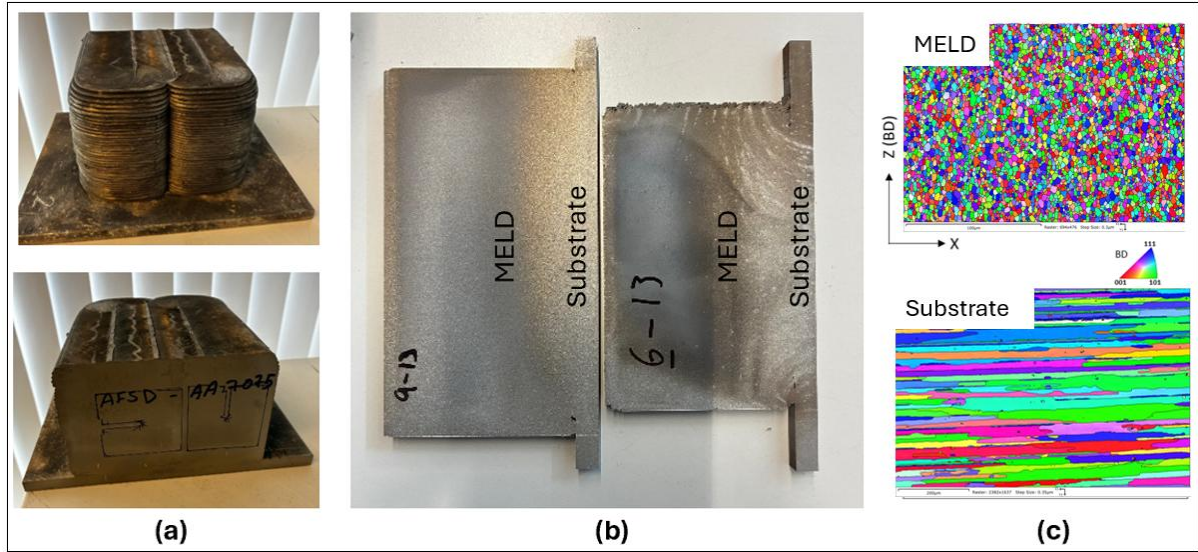


Figure 27: Al7075 AFSD sample used for the PAURS+ microstructure study: (a) as-received AFSD sample, (b) EDM-cut sections extracted for EBSD, and (c) EBSD reference microstructures showing the equiaxed deposited AFSD region and the elongated grain substrate region.

These EBSD-defined regions provide the basis for the simulation study in Section 4.3.2, which then tests whether this equiaxed-to-elongated contrast produces a repeatable angular amplitude or attenuation-related PA-LCR signature.

4.3.2. Microstructure simulation

The EBSD data were used to define the spatial grain morphology and grain-boundary topology of the numerical models. Indexed EBSD points were segmented into grains using a 10° misorientation criterion and the resulting grain-ID field was mapped onto the k-Wave domain by nearest-neighbour interpolation. Each reconstructed grain was then assigned a single scalar property value g , randomly distributed between -1 and $+1$. Local acoustic properties were defined as $c = 6320 + 150g \text{ m s}^{-1}$ and $\rho = 2810 + 100g \text{ kg m}^{-3}$. Consequently, adjacent grains could have different sound speeds and densities, producing acoustic-impedance discontinuities at the EBSD-defined grain boundaries.

The EBSD crystallographic orientations were reconstructed during preprocessing, but they were not used to rotate an elastic stiffness tensor or otherwise assign direction-dependent elastic constants. No explicit grain-dependent attenuation coefficient was prescribed. Changes in received amplitude therefore arise from propagation through the heterogeneous scalar sound-speed and density field, including scattering and refraction at the morphology-defined impedance interfaces. The model represents the influence of EBSD-defined grain morphology and heterogeneous acoustic properties; it does not reproduce crystallographic elastic anisotropy or provide a direct simulation of texture-dependent attenuation.

Angular differences between the equiaxed and elongated models are therefore interpreted as morphology-sensitive numerical responses. In the elongated model, rotation changes the number and orientation of heterogeneous grain interfaces encountered along the propagation direction, whereas the equiaxed morphology provides a less directionally organised reference. The simulation is used to test whether these contrasting morphologies can produce distinguishable angular ultrasonic responses under the imposed acoustic-property model. Attribution of the measured response specifically to crystallographic texture or orientation-dependent elastic scattering is outside the scope of this model.

Two representative microstructure meshes were generated using the MATLAB k-Wave toolbox, with the microstructural geometry informed by EBSD data using the MTEX toolbox. One mesh represented the equiaxed AFSD region, and the second represented the elongated substrate region. In each case, two 8-element phased-array transducers with 0.5 mm pitch were positioned at the top and bottom of the mesh to represent the PA-LCR propagation geometry used in the experimental validation. For simplicity, only the time window during which the acoustic wave propagated within the material was considered during analysis. The microstructure mesh was rotated about the centre by 360° in 1° increments, keeping the probe positions constant. The wave ToF was extracted, and the amplitude change across adjacent receivers calculated to give an angular response trend.

The resulting AFSD and substrate meshes are shown in Figure 28 and Figure 29, respectively. These models provide the link between the EBSD-defined reference microstructures and the robotic angular PA-LCR measurements described in Section 4.3.3.

The EBSD data represented a much smaller area than the simulation mesh, and so was used as a tile to create the full mesh. Additionally, transformations were performed to induce variability: the tiles were flipped horizontally and cropped in the relatively anisotropic case, and rotated, cropped, and flipped horizontally and vertically in the comparatively isotropic case. This was again performed randomly seeded per simulation, and the seed in this case was 777. The 20×20 mm domain contained 25 transformed repetitions of the same EBSD-derived 4×4 mm tile. Random horizontal mirroring and translation were introduced to reduce periodic repetition at tile boundaries while preserving the primary grain morphology. These transformed tiles should not be interpreted as statistically independent EBSD realisations.

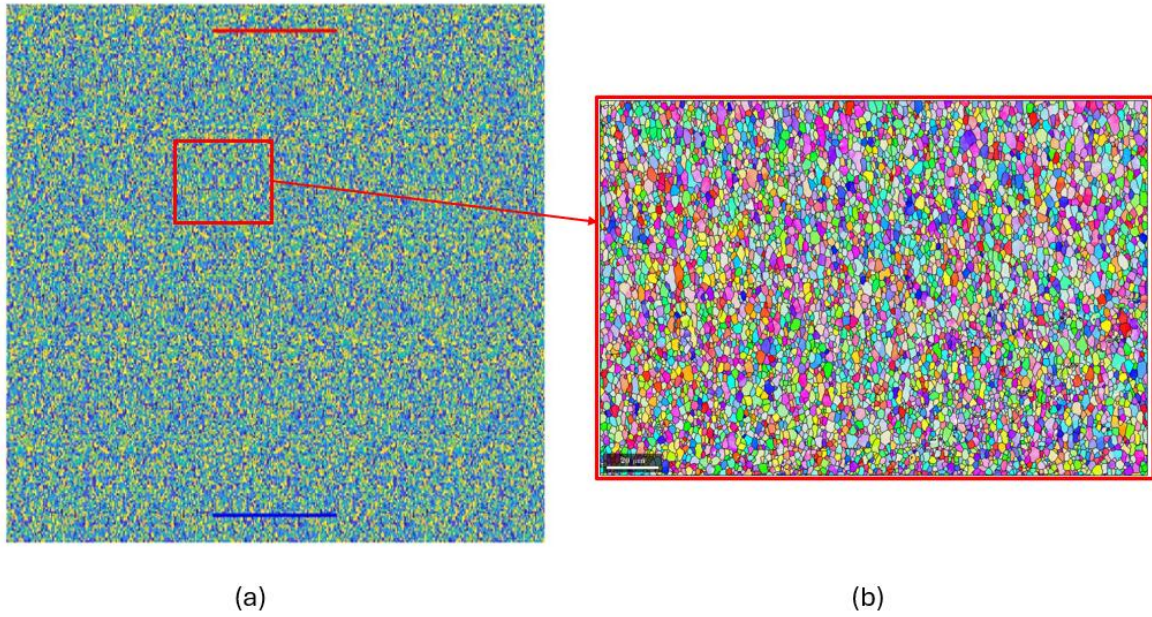


Figure 28: Microstructure-informed simulation mesh for the AFSD region of the Al7075 sample: (a) full k-Wave simulation domain with the phased-array transducer arrangement and (b) zoomed EBSD-derived region used to construct the representative equiaxed microstructure.

The EBSD data was used to preserve the dominant microstructural morphology observed in each region. For the AFSD model, the mesh retained the equiaxed grain structure. For the substrate model, the mesh retained the elongated grain morphology and its dominant orientation. Because the EBSD scan area was smaller than the simulation domain, tiling was required to populate the full model. The EBSD data was transformed using operations such as flipping along the axis of elongation and selecting smaller sampled regions. This reduced artificial repetition in the tiled model while retaining the main morphology and orientation features required for the PAURS+ sensitivity study.

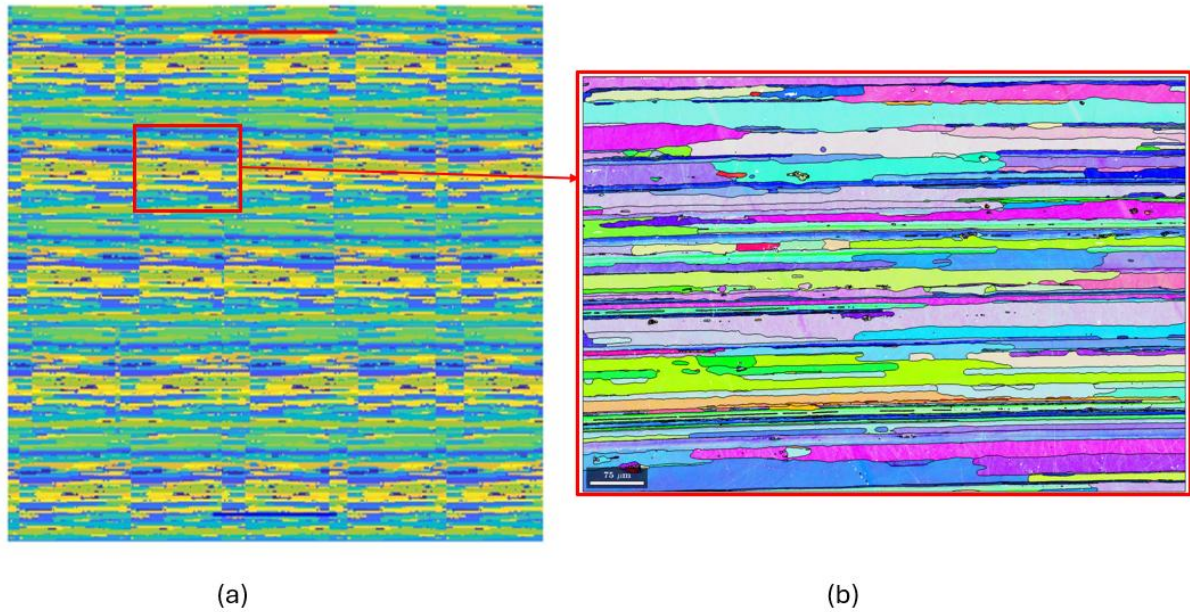


Figure 29: Microstructure-informed simulation mesh for the substrate region of the Al7075 sample: (a) full k-Wave simulation domain with the phased-array transducer arrangement and (b) zoomed EBSD-derived region used to construct the representative elongated microstructure.

The simulation is interpreted as a representative microstructure model, appropriate for the aim of this section of testing whether PA-LCR contains an angular ultrasonic signal feature associated with microstructural morphology. The expected output is an amplitude or attenuation-related rotational trend that distinguishes the elongated substrate from the equiaxed AFSD region.

Following the theory presented in Section 3.4, the columnar grain structure is expected to produce a direction-dependent response when the LCR propagation direction coincides with the relative grain elongation direction. As the wave propagation direction aligns closer to the elongation direction, fewer grain boundaries are crossed per unit propagation distance, so a reduced attenuation-related response and a corresponding change in ToF are expected to occur. In the simulation, this is assessed by plotting attenuation-related amplitude change and ToF against microstructure-probe orientation. Features are interpreted as microstructure-sensitive where they are stronger than the equiaxed reference response and show the expected approximate 180° periodicity.

Two simulation routes were used: initial 10 MHz and 32 MHz simulations were performed as frequency-sensitivity studies to examine how the PA-LCR amplitude and ToF response changed as the ultrasonic wavelength approached the characteristic microstructural length scale. Following this, a 5 MHz simulation was performed to match the firing frequency of the probes used in the robotic PA-LCR validation. This provided the direct comparison case between simulation and experiment. These cases support the 5 MHz validation by establishing the expected wavelength-dependent sensitivity before testing whether a similar angular signature remains detectable under practical experimental conditions.

The same nominal Al7075 longitudinal sound velocity of 6320 m s^{-1} was used throughout the frequency-sensitivity simulations. This gives nominal wavelengths of approximately 1.264 mm at 5 MHz, 0.632 mm at 10 MHz and 0.198 mm at 32 MHz. The numerical domain was $20 \times 20 \text{ mm}$ with a uniform grid spacing of 0.05 mm, corresponding to a 400×400 -node computational grid.

At this spatial resolution, the 5, 10 and 32 MHz cases correspond to approximately 25.3, 12.6 and 4.0 grid points per wavelength, respectively. The substantially lower spatial resolution of the 32 MHz case is therefore recognised when interpreting the frequency-sensitivity results.

The temporal grid was generated automatically using the k-Wave `makeTime` function. An independent time step or CFL value was not prescribed separately in the retained simulation script. The absorbing layer was positioned outside the stated $20 \times 20 \text{ mm}$ simulation domain using the `PMLInside = false` setting. The numerical excitation consisted of a sinusoidal pressure source at the specified nominal frequency. The 10 and 32 MHz implementations used this same numerical arrangement, with the source frequency changed between simulations.

A separate spatial-refinement study was not retained for the 32 MHz simulation. The absolute peak amplitude and exact angular position of the 32 MHz response are therefore not treated as numerically converged quantities. The 32 MHz result is retained as a wavelength-sensitivity study showing the effect of reducing wavelength relative to the represented microstructural scale. The 5 MHz case provides the principal simulation-to-experiment comparison because it matches the available experimental probe frequency and provides substantially greater spatial resolution within the numerical model.

4.3.3. Robotic PA-LCR experimental comparison

The robotic PA-LCR validation was used to test whether the angular amplitude and attenuation-related signatures identified in simulation could be measured under practical inspection conditions. The measurements were performed at 5 MHz, matching the frequency used in the feasible simulation case and the available phased-array LCR hardware. This frequency was selected because it provided a stable LCR response while maintaining compatibility with the PAURS wedge and probe configuration developed earlier in the thesis.

The experimental arrangement is shown in Figure 30. LCR waves were generated and received using two 5 MHz, 8-element, 0.5 mm pitch phased-array probes mounted in the PA-LCR wedge configuration. The wedge angle was 22.1° , selected to generate the longitudinal critically refracted wave in the Al7075 sample. The same general PAURS configuration used for residual stress measurement was retained, but the analysis focused on the angular variation in amplitude and attenuation-related response.

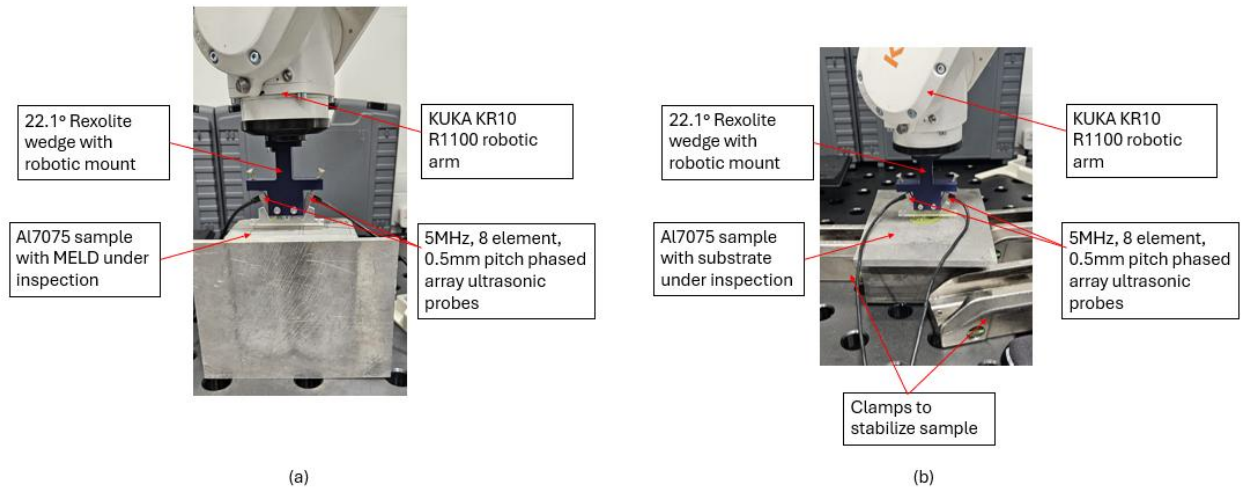


Figure 30: Robotic PA-LCR setup used for 5 MHz angular validation on the Al7075 sample: (a) inspection of the deposited AFSD region and (b) inspection of the substrate region.

The robotic PA-LCR experiment used two 5 MHz, 8-element phased-array probes with a 0.5 mm pitch, mounted using the 22.1° wedge configuration developed for the Al7075 measurements. Measurements were acquired through a nominal 360° rotation in 1° increments for both the deposited AFSD region and the elongated substrate region, in a clockwise direction for both.

The LCR response was identified within the 7–8 μ s Al7075 time gate defined in Chapter 3. Amplitude change was extracted from the selected LCR arrival using the same processing procedure for both microstructural regions. The same probe, wedge, angular acquisition procedure and signal-processing method were retained for the AFSD and substrate measurements so that their angular responses could be compared on a consistent basis.

The robotic experiment was intended as an initial comparison between two EBSD-characterised microstructural regions. Independent measurements of robot rotational accuracy, backlash and run-out were not retained for this experiment, and contact force was not continuously measured. The retained experimental record also does not contain dedicated clockwise and counter-clockwise repeat scans, a randomised angular acquisition sequence or an independent drift-monitoring series. These effects therefore cannot be assigned a retrospective numerical uncertainty.

The AFSD and substrate measurements are instead used as a comparative control because both regions were inspected using the same experimental procedure. The stronger angular response observed in the elongated substrate relative to the comparatively equiaxed AFSD region provides evidence that the measured response is sensitive to the differing microstructural morphology. Contributions from coupling variation, contact-force variation, robot positioning and rotational run-out cannot be separated quantitatively from the retained dataset.

Agreement between simulation and experiment was assessed using the presence and angular position of the main amplitude or attenuation-related features, together with the contrast between the AFSD and substrate responses. The AFSD/substrate comparison also provided a control against purely system-driven angular variation: if the measured angular response were dominated by wedge rotation eccentricity, coupling discrepancies, or robot angular error, similar angular trends would be expected in both regions under the same inspection procedure. A stronger and more repeatable angular signature in the elongated substrate, aligned with the EBSD-defined morphology, supports a microstructure-sensitive interpretation. The remaining influence of coupling, contact force, surface condition, and robotic repeatability is considered in the results discussion.

4.3.4. PAURS+ measurement basis and interpretation limits

PAURS+ retains the PA-LCR wedge, probe, and robotic platform used for PAURS, but changes the output from stress-calibrated ToF to amplitude change, attenuation-related angular response, and signal consistency. EBSD defines the reference microstructural contrast, k-Wave simulations assess whether that contrast should produce an angular PA-LCR response, and the robotic 5 MHz measurements test whether the response remains detectable under practical coupling and positioning conditions.

The k-Wave simulations test whether this EBSD-defined microstructural contrast produces a measurable angular PA-LCR response. The 10 MHz and 32 MHz simulations assess wavelength sensitivity, while the 5 MHz simulation provides the direct comparison condition for robotic validation.

The robotic 5 MHz measurements tested whether the simulated angular response remains detectable with the available hardware and practical coupling conditions. The AFSD/substrate comparison also provides a control against system-driven angular effects, because both regions are inspected using the same rotation procedure.

The PAURS+ output is defined as an amplitude- and attenuation-related angular descriptor of near-surface microstructural anisotropy. Section 5.3 then assesses whether this descriptor is repeatable and where coupling, signal quality or robotic positioning limit interpretation.

5. Results and discussion

The results are presented in the same staged order as the methodology. The bolt benchmark first evaluates the calibrated stress-measurement chain under known loading; the PAURS results then test that chain against welded residual stress using HD and ND comparison data; and the PAURS+ results assess whether additional PA-LCR observables can provide microstructure-sensitive information from the same platform.

5.1. Controlled-stress benchmark using bolted connections

The bolt results assess the phased-array ultrasonic stress measurement under controlled applied loading. Mechanical loading data and FEA-derived average axial stress provide the comparator for evaluating ToF response, acoustoelastic calibration, and path-wise consistency, before the transfer to a larger bolt geometry is investigated.

The measured ultrasonic quantity in this section is time of flight extracted from selected acoustic paths. Applied axial stress is then calculated from this measured ToF change using the calibrated acoustoelastic relationship and compared with mechanical loading data and FEA-derived average axial stress. The analysis therefore considers both the averaged stress value and the distribution of the individual path responses.

5.1.1. FEA-derived average axial stress

Finite element analysis was used to provide the expected average axial stress for comparison with the ultrasonic measurements. The model was solved at applied loads from 50 kN to 300 kN, and the average axial stress was calculated across the central inspection path of the bolt. This average value was used because the ultrasonic measurement samples the acoustic response over a finite region through the bolt.

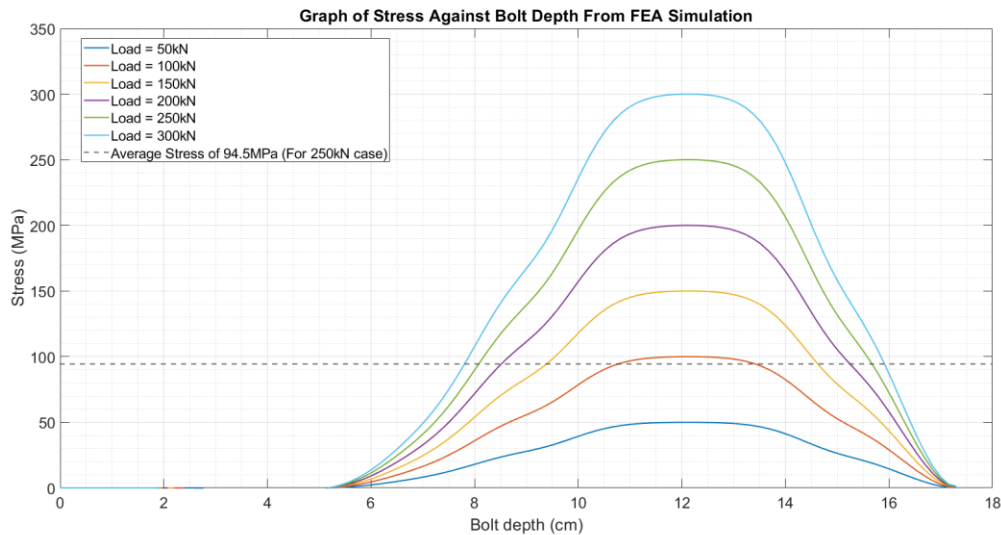


Figure 31: Finite element stress distribution in the bolt up to 300 kN applied load. The dashed line indicates the average axial stress in the inspected region at an applied load of 250 kN, used as the ultrasonic comparator at that loading [1].

Figure 31 shows the stress distribution for up to the 300 kN loading case. The 250 kN case is considered here, with a peak stress of 250 MPa and an average stress in the inspected region of 94.5 MPa. This difference is important because the ultrasonic measurement does not sample the local peak stress, but the average stress across the inspection volume. The ToF response is influenced by the stress distribution along the acoustic path, so the FEA-derived average stress across this region was used as the comparator for both acoustoelastic calibration and ultrasonic inspection.

The FEA result establishes an interpretation limit for the benchmark: the calculated ultrasonic stress should be compared with the stress averaged over the inspected acoustic region, not with the maximum local stress in the bolt assembly.

5.1.2. Acoustoelastic calibration, sensitivity, and uncertainty

The acoustoelastic constant was determined by comparing measured time-of-flight changes with the FEA-derived average axial stress. This calibration establishes the sensitivity of the selected phased-array ultrasonic configuration to applied axial stress in the bolt material.

Figure 32 shows the calibration relationship obtained from the controlled loading data. The approximately linear trend confirms that the selected ToF feature is sensitive to applied axial stress over the calibration range. Under controlled loading, the phased-array ultrasonic measurement chain resolved preload-related timing changes and converted them into a calculated stress value using the fitted acoustoelastic coefficient.

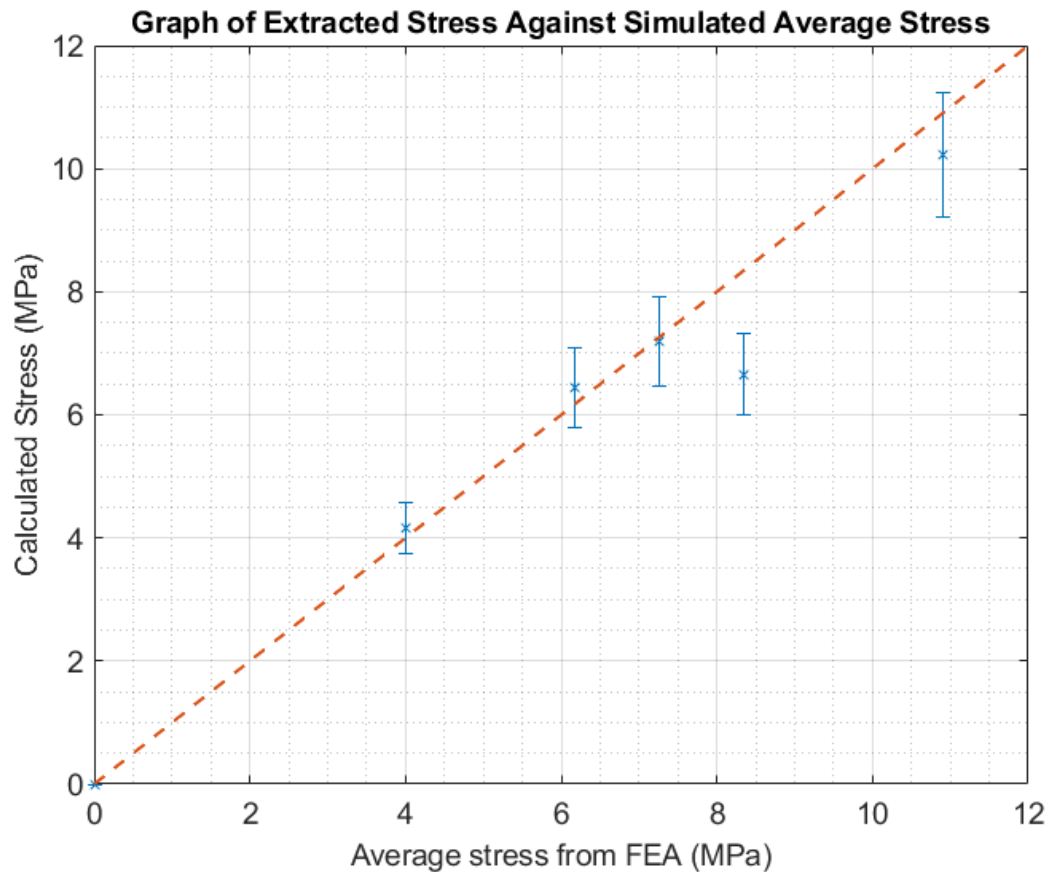


Figure 32: Acoustoelastic calibration for the controlled-stress bolt benchmark. The fitted relationship compares stress calculated from ultrasonic time-of-flight change with the FEA-derived average axial stress in the inspected bolt region [1].

To obtain the acoustoelastic constant, the measured ToF changes were converted into stress using and compared with the FEA-derived average axial stress. The value of the acoustoelastic constant was set such that the plotted relationship between the average ultrasonic volume stress and the average FEA-defined stress was linear. In this representation, a unit gradient indicates agreement between the calibrated ultrasonic stress estimate and the mechanical comparator over the controlled loading range. The unit-gradient comparison uses the benchmark conditions to obtain a validated acoustoelastic constant value for use in later bolt stress investigations.

The calibrated acoustoelastic coefficient obtained from this fit was $L = 7.9 \times 10^6$, with an estimated combined uncertainty of approximately 10% from measurement and calibration contributions. This uncertainty combines the repeatability of ToF extraction, variation between retained acoustic paths, uncertainty in the mechanical loading/FEA stress comparator, equipment measurement uncertainty, and scatter around the fitted calibration relationship. The fitted coefficient is therefore treated as specific to the material, bolt geometry, and probe configuration used in this benchmark.

One calibration point at approximately 8.3 MPa deviated from the fitted trend and was excluded from the fitted relationship. This point is attributed to a likely experimental measurement issue, such as

local coupling variation, insufficient couplant coverage, or unstable probe contact. The outlier is retained in the discussion because it illustrates why individual path behaviour and measurement quality must be checked before accepting an averaged ultrasonic stress estimate, and is retained towards future uncertainty values.

5.1.3. High-preload response and calibrated-regime assessment

Figure 33 presents results obtained from a bolt subjected to operational preload levels. The ultrasonic measurements are compared with the average stress predicted by finite element modelling, and the stress calculated using the previously determined acoustoelastic constant together with the measured time-of-flight data. In the corresponding graph, the FEA-derived average stress is plotted along the horizontal axis, while the stress calculated from ultrasonic measurements is shown on the vertical axis. The ultrasonic stress estimate follows the expected, approximately linear trend at lower load levels, up to approximately 75 MPa. Beyond this range, the ultrasonic stress estimate increases far more rapidly than the FEA-derived average stress, indicating that the measurement has moved outside the most stable part of the calibrated response.

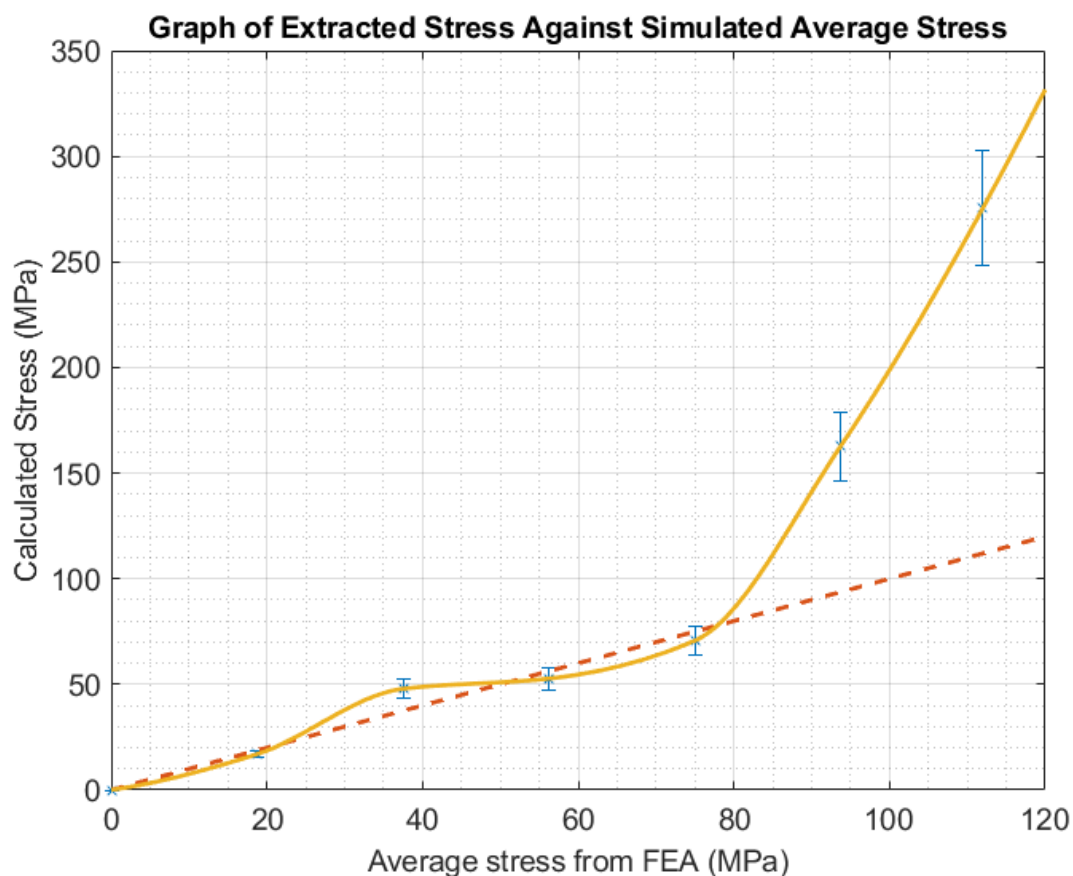


Figure 33: Ultrasonic stress estimate compared with FEA-derived average axial stress during high-preload bolt loading. The dashed line indicates the expected linear acoustoelastic response, while the measured response shows the point at which the calibrated relationship becomes less stable [1].

This high-preload behaviour is interpreted as a reduction in confidence in the single averaged stress calculation. Several effects could contribute to the deviation, including uneven seating, alignment error, localised yielding, or plastic deformation effects. A mechanical interpretation of this error is that the ToF change due to the acoustoelastic relationship is less than that caused by the change in length of the bolt under high tensile stress. The important result is that the phased-array data reveal this change in measurement behaviour rather than hiding it within the output stress value.

The high-preload result therefore establishes a practical boundary for the controlled-stress benchmark. Within the lower, approximately linear range, the ultrasonic stress estimate can be treated as quantitative within the calibration uncertainty. At higher load, the result remains stress-sensitive, but its interpretation depends more strongly on path consistency and measurement quality.

To investigate further, the path-wise time-of-flight distributions were used in order to interpret this behaviour. Instead of relying only on the averaged stress estimate, the phased-array data allows the individual acoustic paths to be examined across the loading range. This is demonstrated in Figure 34.

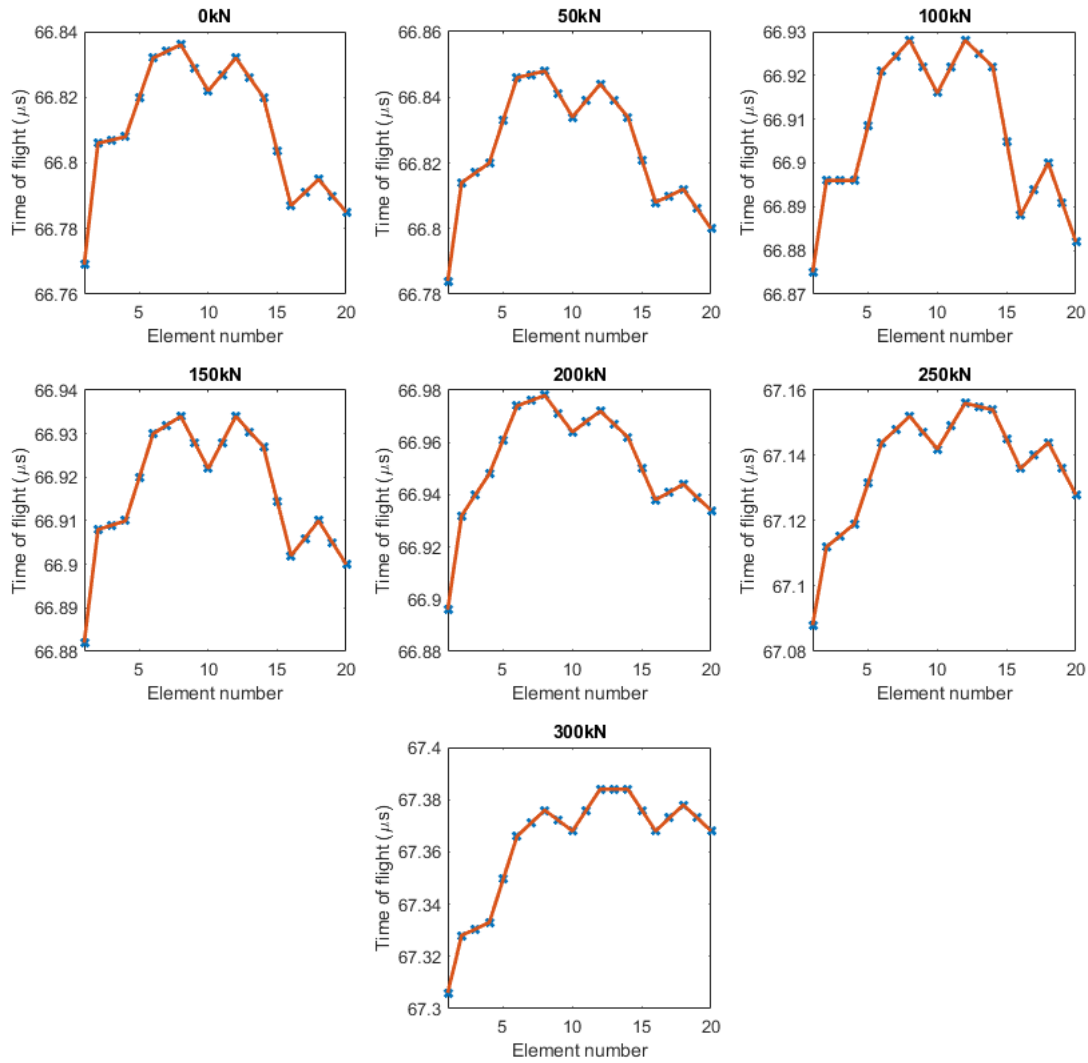


Figure 34: Time-of-flight distributions across the phased-array probe at increasing preload levels. The distributions provide a path-consistency measure for the controlled-stress benchmark [1].

A key observation is the loss of symmetry in the time-of-flight distribution at higher loads. Up to a preload of 150 kN, the distribution remains approximately symmetric about the central element (Element 10). This symmetry begins to deteriorate at 200 kN and becomes increasingly pronounced at higher loads. This asymmetry provides useful evidence that the averaged stress estimate is no longer fully representative of a symmetric loading condition. Possible contributors include uneven nut seating, high loading, axial elongation, and local acoustic-path changes. This is a significant advantage of phased-array stress testing, as it can identify asymmetrical stress concentrations due to the multiple acoustic paths in use.

The observed non-linearity in Figure 33 is consistent with asymmetric loading conditions, particularly when using hydraulic tensioners. In practice, perfect symmetry in bolt tightening is difficult to achieve due to variations in seating conditions and alignment. As a result, localised regions may experience stresses exceeding the design limits, increasing the likelihood of plastic deformation.

The ability of the PAUT system to detect such asymmetries represents high practical value for inspections, enabling early identification of potentially critical stress concentrations. In an operational context, bolts exhibiting such behaviour would likely flag for additional inspection and possible repair or replacement. Careful monitoring of bolted connections over their in-situ lifespans using these capabilities can be analysed and allow for future predictive maintenance procedures.

These results show why the averaged ToF value should be interpreted alongside the path-wise distribution. The spread and symmetry of the response provide internal evidence of measurement consistency, which is later used in PAURS to identify reduced-confidence regions affected by poor coupling or complex geometry.

5.1.4. Blind M42 transfer test

The blind M42 test assessed whether the calibrated measurement procedure retained stress sensitivity when transferred to a larger bolt under representative access and loading conditions. Two loading states were investigated: an unloaded reference condition and an operational preload condition. During ultrasonic processing, the bolt geometry, previously calibrated acoustoelastic coefficient and approximate inspection temperature were known. The applied preload was withheld until the ultrasonic stress estimate had been completed.

The M42 bolt was subjected to an applied preload of 440 kN, corresponding to a derived average axial stress of approximately 317.6 MPa under the mechanical calculation used for the FASTBLADE test. This value was obtained through an additional FEA investigation, performed again by colleagues in NAOME. The applied preload represents the independently established mechanical quantity, with the derived stress value used as the comparator for the ultrasonic estimate.

The longer propagation path in the M42 bolt produced a larger absolute ToF than in the M36 experiments. The unloaded and loaded measurements gave ToF values of 153.21 μ s and 155.29 μ s respectively. Table 4 summarises the resulting comparison.

Table 4: Blind M42 transfer-test comparison between mechanically derived stress and ultrasonic stress estimate.

Time of Flight (μ s)	Expected Stress from calculation (MPa)	Stress from Ultrasonic Measurement (MPa)
153.21	0	0
155.29	317.5881	352.2922

The path-averaged ultrasonic estimate for the loaded condition was 352.29 MPa, compared with the mechanically derived comparator of 317.59 MPa. The absolute difference was 34.70 MPa, equivalent to approximately 10.9% of the comparator value. This percentage is reported as the relative deviation

between the two stress estimates. Its interpretation accounts for uncertainty in the ultrasonic calibration and measurement chain, together with uncertainty associated with establishing the mechanical comparator.

The preload was introduced to the comparison only after completion of the ultrasonic calculation, preserving the blind nature of the transfer test. The M42 bolt also differed from the original M36 calibration specimen in diameter, length and inspection conditions. Geometry, contact condition, coupling and material variability may therefore contribute to the observed difference between the two stress estimates.

The available mechanical and modelling data for this transfer test were obtained through the wider collaborative bolt-inspection programme. A complete uncertainty budget for the mechanically derived M42 comparator was not available for independent reconstruction within this thesis. The 10.9% difference is consequently used as an indication of agreement under the specific FASTBLADE test condition. Wider validation would require repeated measurements across additional bolts and preload levels, together with independently traceable mechanical loading measurements and a fully defined comparator uncertainty.

5.1.5. Implications of the bolt benchmark for PAURS

The bolt results define how ToF changes should be interpreted before the same measurement approach is applied to welded RS. Under controlled loading, the stress state is known well enough to test calibration, path averaging, and confidence indicators directly.

The calibration results show that the selected phased-array ultrasonic timing feature responds systematically to applied axial stress when the loading condition is known. By comparing this response with the FEA-derived average axial stress in the inspected region, the benchmark also defines the type of mechanical comparator that is appropriate for ultrasonic stress calculation. The ultrasonic measurement is path-influenced and is best compared with a mechanically compatible average stress.

The high-preload results show that the averaged stress estimate is only one part of the phased-array measurement. The distribution of individual acoustic paths provides additional evidence about whether the averaged value should be treated with high confidence. Where the path-wise response remains stable, the averaged value is more defensible. Where the response broadens or becomes asymmetric, the result remains stress-sensitive but requires reduced confidence and further checking. This links path consistency and signal quality to the confidence assigned to each calculated stress value, which is the same principle used later in PAURS. Additionally, this path-wise variation can highlight areas of stress concentration within a sample that would not be easily discernible from an equivalent single-element transducer scan.

The blind M42 result shows that the calibrated procedure can transfer evidence beyond the original M36 calibration specimen, with an error of approximately 10.9% under the tested facility condition. This result does not remove the need for geometry-specific calibration or uncertainty reporting, but it demonstrates that the calibrated phased-array procedure retained practically useful agreement when applied to a larger and longer bolt.

These results define the controlled reference point for the PAURS measurements in Section 5.2. In the welded specimens, the stress field is unknown, the reference condition is less direct, and the ultrasonic response may be affected by coupling, geometry, stress gradients, and microstructure. The bolt benchmark therefore establishes the measurement feature, calibration and calculation route, and path-consistency logic used to interpret the later PAURS results.

5.2. Residual stress and PAURS

The welded S275 study applies the PA-LCR approach established in the bolt benchmark to residual stress measurement, where the stress field is unknown and the reference condition is less direct. This section assesses both the calculated PAURS residual stress values and the measurement conditions that determine their confidence.

Phased-array path redundancy is central to this result. In this study, FMC provides a larger set of transmitter–receiver paths which support averaging, path comparison, and internal consistency assessment. A key result of this section is that FMC reduces the standard deviation of calculated PAURS stress values by approximately 5–10× relative to the matched-path subset. This improves measurement precision and internal consistency, while systematic uncertainty from calibration, coupling condition, and comparison basis must still be considered separately.

5.2.1. Acoustoelastic calibration

The acoustoelastic calibration provided the conversion factor required to calculate residual stress from the measured LCR time-of-flight changes. Known tensile loads were applied to the S275 calibration specimen, while PA-LCR measurements were acquired using the same probe, wedge, and acquisition configuration used for the welded-plate inspection. The applied stress was calculated from the known tensile loading condition and specimen cross-sectional area, and the corresponding ToF change was extracted from the selected LCR arrival for each acoustic path. The results were plotted using the rearranged form of Equation 18:

$$\frac{Edt}{t_0} = L\Delta\sigma \quad (27)$$

such that the gradient of the resulting best-fit line could be extracted as the acoustoelastic constant.

Figure 35 shows the element-wise calibration results. The individual paths show the expected relationship between applied stress and ToF change, but with measurable variation between paths. This spread is consistent with the practical behaviour of a contact phased-array LCR measurement, where each transmitter–receiver pair has slightly different wedge transit, coupling, signal amplitude, and path quality. The calibration therefore provides both the stress-conversion basis and an indication of the path-wise variability that must be considered when interpreting later welded-plate measurements.

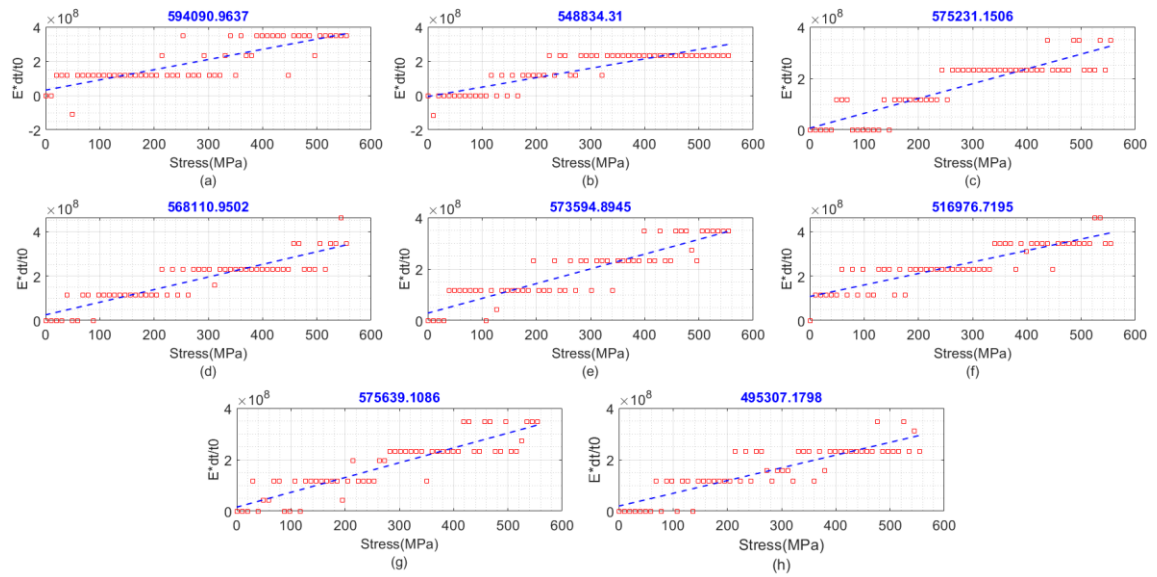


Figure 35: Element-wise acoustoelastic calibration for the S275 PAURS configuration. The fitted responses show the relationship between applied tensile stress and LCR time-of-flight change for individual phased-array paths. $T [4]$.

Figure 36 shows the averaged acoustoelastic calibration obtained from the full phased-array dataset. This averaged value was used for the subsequent residual stress calculation because it represents the full phased-array response rather than a single acoustic path. Across the calibration programme, loading and unloading data were collected over repeated tests, giving a large path-wise dataset for fitting the stress–ToF relationship. Averaging across this dataset reduces the influence of individual path variability and gives a more stable calibration value for application to the welded-plate inspection.

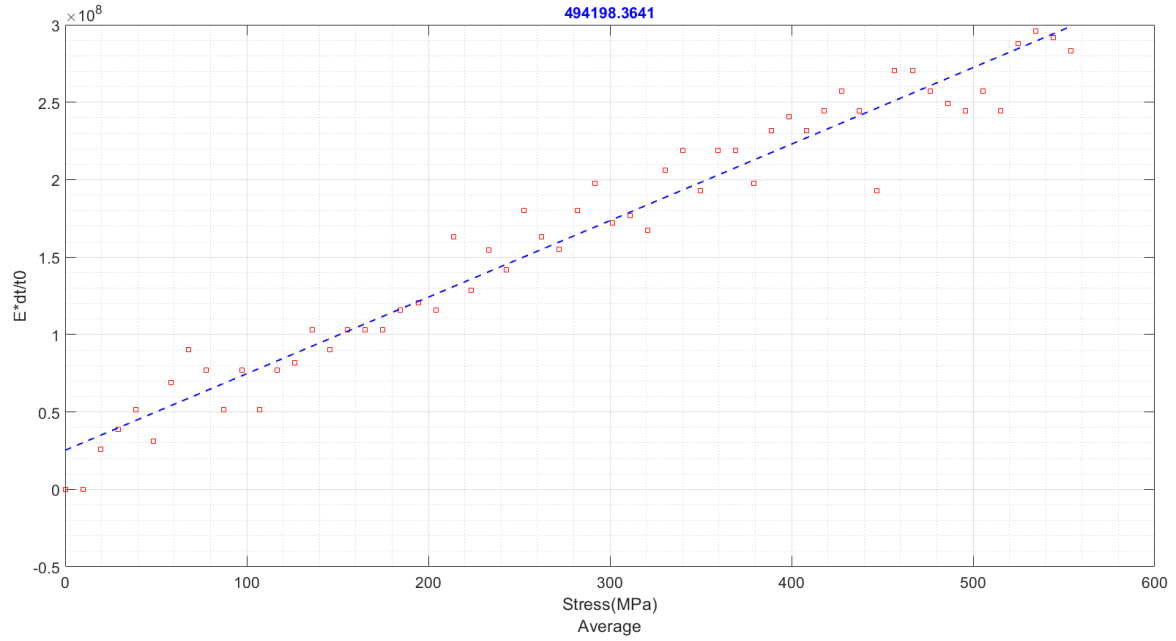


Figure 36: Averaged acoustoelastic calibration used for PAURS residual stress calculation. The averaged relationship combines the phased-array path responses to obtain the stress-conversion factor used in the welded-plate PAURS measurements. [4]

The gradient of the averaged fit was used as the acoustoelastic constant for the welded-plate investigation. This value was determined to be 4.94×10^5 , and is dimensionless as the x and y axis both have units of MPa. The path-wise variation observed in Figure 35 is therefore retained as calibration variability and is carried forward into the final uncertainty value, while Figure 36 provides the stress-conversion factor used for the residual stress calculations.

5.2.2. Couplant gel-thickness uncertainty: simulation and experimental assessment

The gel-thickness study quantifies the timing error that can be introduced by non-uniform coupling in the PA-LCR measurement. In the simulation, increasing average gel thickness produced a systematic increase in LCR ToF relative to the minimum-thickness baseline, which is interpreted as a coupling-induced error since the material stress state is unchanged in the model. When converted using the $1 \text{ ns} \approx 4 \text{ MPa}$ approximation, the result shows that uncontrolled coupling variation can produce apparent stress errors large enough to affect residual stress interpretation.

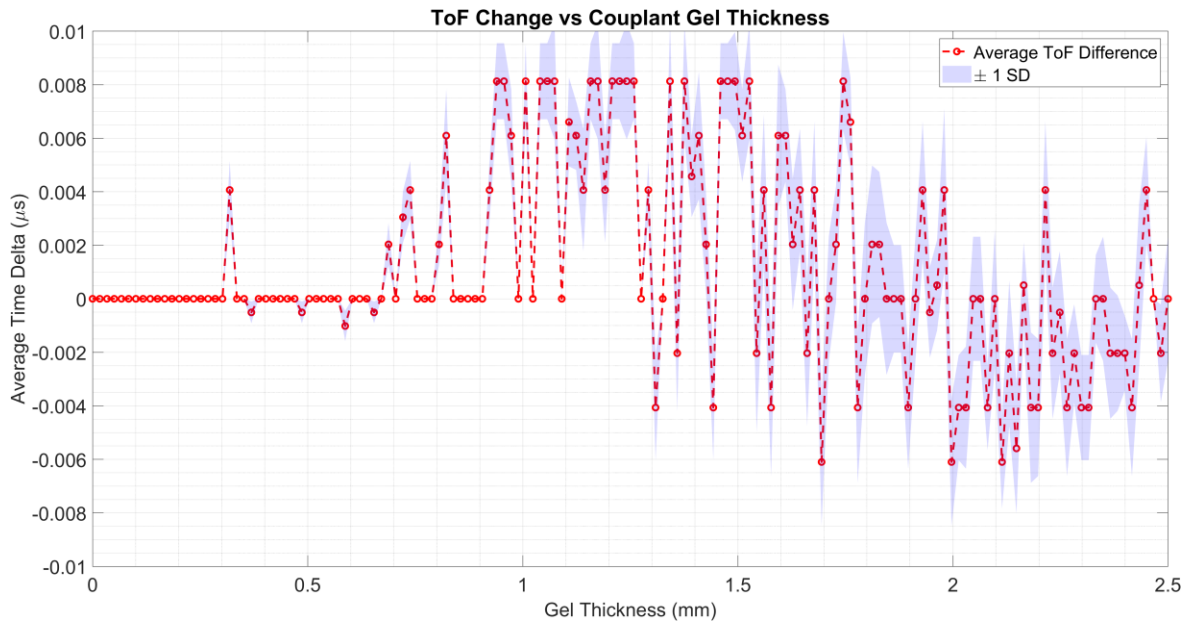


Figure 37: Simulated effect of average couplant gel thickness on LCR time-of-flight error. The shaded or error-band region represents ± 1 standard deviation. [7]

As described in Section 4.2.6, the estimated LCR sampling depth in steel is approximately 1.2 mm, while the corresponding limiting depth in the couplant is approximately 0.8 mm. As the couplant layer approaches this thickness, an increasing proportion of the wave energy remains within the couplant rather than forming a stable LCR wave in the steel. This explains the low ToF variation at smaller gel thicknesses and the rapid increase in variability once the couplant layer approaches the limiting thickness.

The standard deviation in Figure 37 also increases as the ToF response becomes unstable. At smaller gel thicknesses, the path-wise spread remains limited, but once the coupling layer approaches the limiting thickness, the variation across the transducer elements increases sharply. This indicates that excessive gel thickness affects not only the mean ToF but also the consistency of the retained acoustic paths.

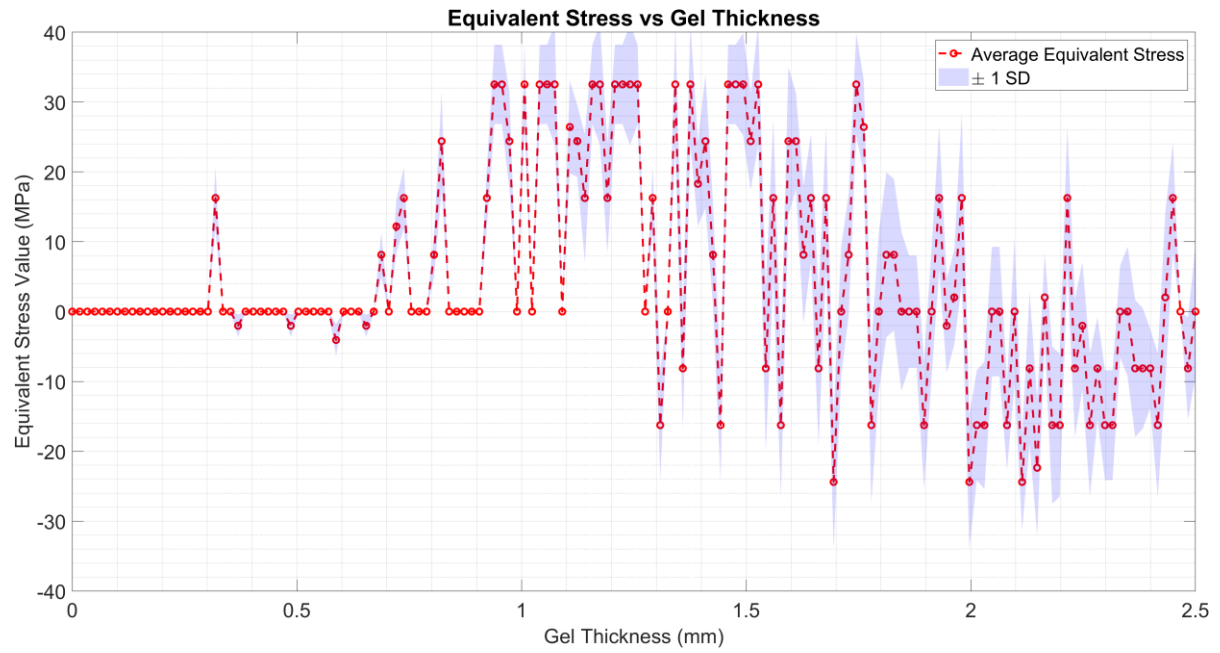


Figure 38: Equivalent apparent stress error associated with simulated gel-induced ToF variation. The stress error is calculated from the simulated ToF shift using the stress approximation of $1 \text{ ns} \approx 4 \text{ MPa}$. [7]

Though the absolute value is below the yield stress, it is important to note that this sample is considered to have minimal RS, and the scans have occurred in the same position upon the sample. Therefore, this 32 MPa value, if left uncompensated, is considered to be a potential uncertainty present in a standard inspection. This error is 13% of the yield strength of the sample and, in a real-world residual stress inspection, could result in a significant under- or over-reporting of the present residual stress and lead to early failure due to fatigue or overloading, or erroneous part replacement respectively.

Adjacent-receiver subtraction was then applied to reduce the common timing contribution associated with the couplant layer. In the 8-element transducers used here, adjacent receiver subtraction provides seven differential ToF values per transmitter, giving 56 differential values across the full acquisition. These values were averaged to obtain the compensated ToF response, as described in Equation 28.

$$\Delta t = \frac{1}{n(n-1)} \sum_{i=1}^n \sum_{j=1}^{n-1} t_{i,j+1} - t_{i,j} \quad (28)$$

When all 56 subtractions are averaged, the compensated mean ToF remains close to 0 ns over the stable coupling range. Although the response still becomes erratic once the gel layer is sufficiently thick, the onset of this behaviour is shifted from approximately 0.8 mm to approximately 1.1 mm. Values in this higher-thickness region should not be treated as valid inspection ToF values, because

the LCR pulse is no longer reliably propagating in the steel.

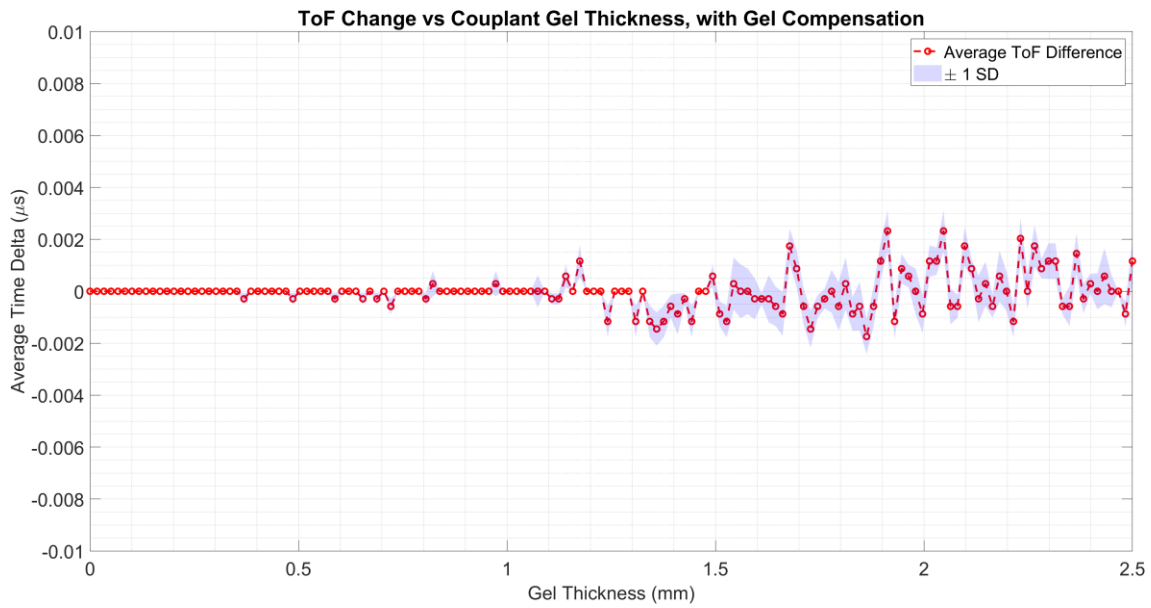


Figure 39: Simulated compensated ToF difference after adjacent-receiver subtraction. The compensated ToF response is obtained by averaging adjacent receiver-pair differences across all transmitters. [7]

The equivalent stress error after compensation is shown in Figure 40. Compared with the uncompensated case, the compensated response shows lower and more consistent apparent stress error over the stable coupling range.

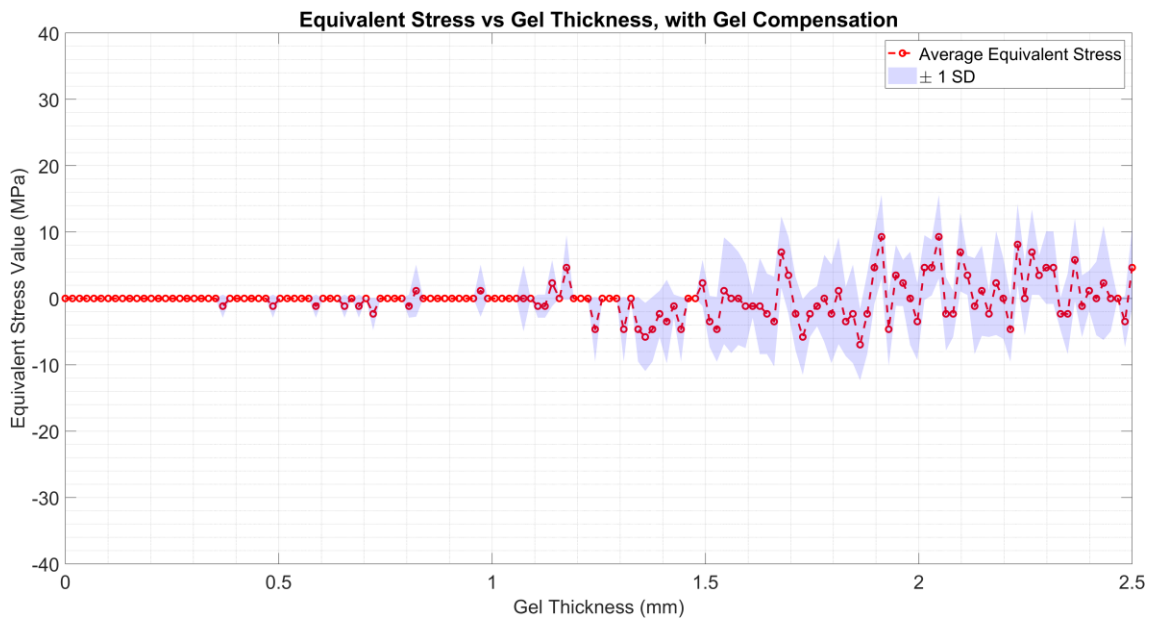


Figure 40: Equivalent apparent stress error after simulated gel compensation. The compensated stress error is calculated from the adjacent-receiver-subtracted ToF response. [7]

After compensation, the peak ToF variation is just approximately 2.5 ns, corresponding to approximately 10 MPa of equivalent stress error. This represents a significant reduction compared with the uncompensated case. However, the higher-error region begins after approximately 1.1 mm of

gel thickness, which corresponds to a separation between the wedge and the sample that would be visible during inspection. Such a condition should not be treated as a normal compensable coupling state, but as a quality-control failure or rejected measurement condition. The sudden erratic behaviour in this region is consistent with the ultrasonic pulse propagating substantially through the couplant rather than forming a stable LCR wave in the steel, resulting in inconsistent arrival times at the receiving elements.

The simulation results are supported by the experimental validation presented below. To ensure that the experiment remained within a realistic coupling regime, and that the LCR wave remained detectable in the sample, gel thicknesses up to a maximum of 0.7 mm were considered. Experimental validation followed similar trends to the simulation. Initial analysis showed that the ToF shift relative to the matched-contact baseline increased approximately linearly over the stable coupling range, as shown in Figure 41.

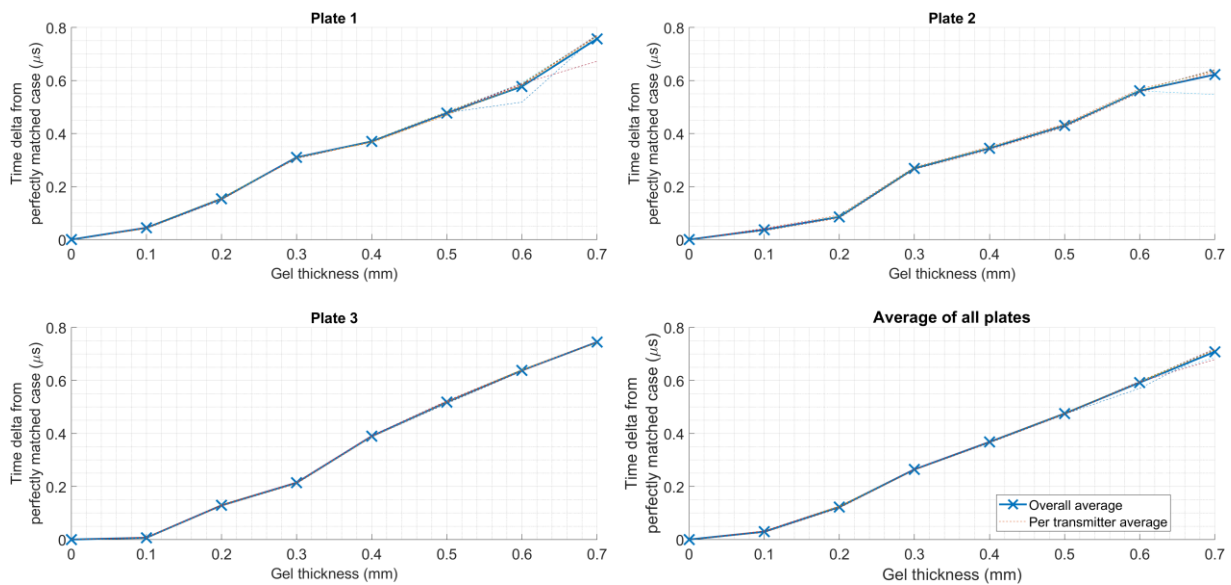


Figure 41: Experimental ToF shift relative to the ideal matched coupling condition. [7]

At low gel thicknesses, the deviation between the mean ToF shift and the path-wise ToF shift is comparatively small, even as the mean ToF changes relative to the matched case. The subtraction methodology was then applied to the experimental data to compensate for the gel-thickness effect. This step is necessary because even small timing shifts can correspond to substantial apparent stress errors when converted through the acoustoelastic relationship.

After compensation, the average residual ToF error was reduced to approximately 0.3 ns across all three plates, with a maximum mean value of approximately -0.57 ns and a minimum mean value of approximately -0.03 ns, as shown in Figure 42. Because the results are expressed as ToF or stress-equivalent differences from the matched-contact case, the negative signs indicate that the

compensated mean ToF values are below the matched-contact ToF. Under the stress approximation, this would underestimate rather than overestimate the apparent stress.

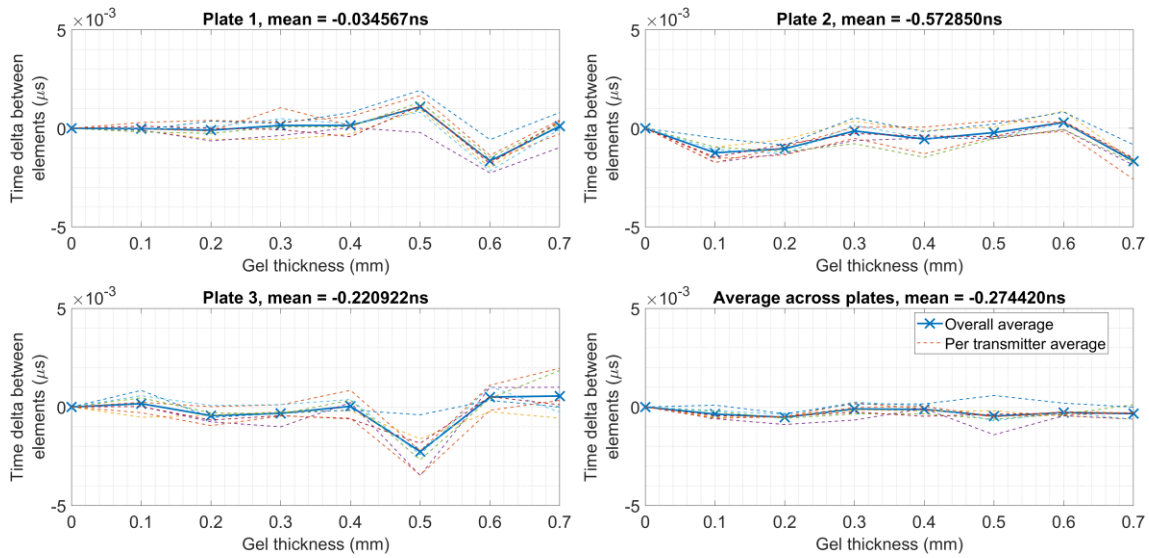


Figure 42: Experimental compensated ToF error after adjacent-receiver subtraction. Across the three plates, the mean residual error is approximately -0.3 ns, with the largest observed residual error remaining below approximately -0.6 ns. [7]

Adjacent-receiver subtraction substantially reduced the timing variation associated with controlled changes in acoustic couplant thickness under the tested conditions. Across the three plates, the mean residual gel-induced ToF difference was approximately -0.27 ns. Using the $1 \text{ ns} \approx 4 \text{ MPa}$ approximation, this corresponds to approximately -1.1 MPa in stress-equivalent terms, as shown in Figure 43. These values describe the residual coupling-related contribution following compensation. They do not represent the uncertainty of the complete PAURS measurement chain, which also includes acoustoelastic calibration, reference ToF, temperature, surface geometry, path selection and material-state effects.

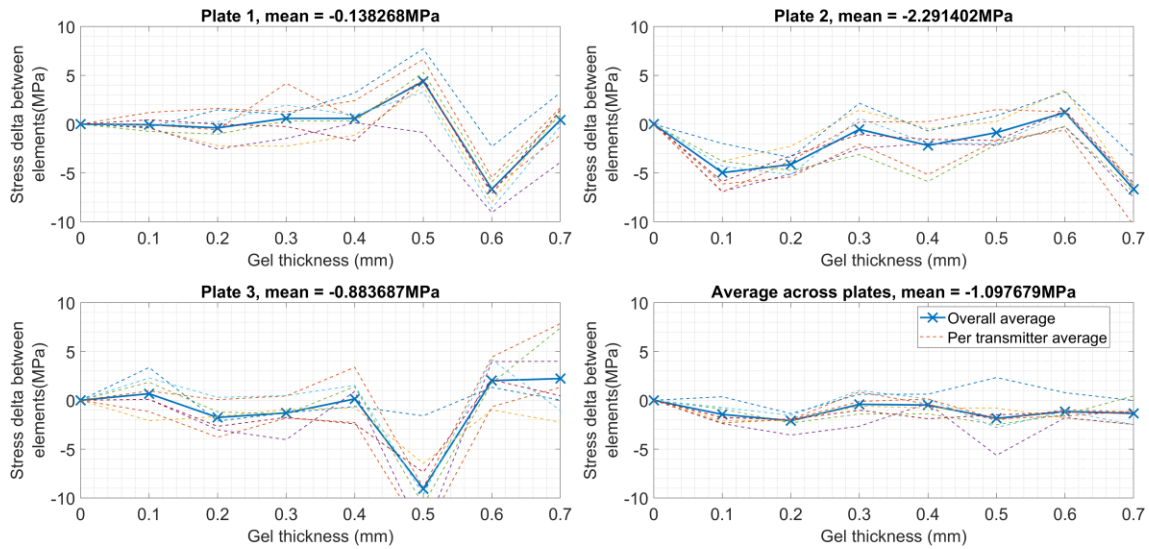


Figure 43: Equivalent apparent stress error after experimental gel compensation. The residual ToF error after compensation is converted to an equivalent apparent stress error. The result shows that the mean compensated gel-induced error is reduced to approximately 1.1 MPa under the tested shim-controlled conditions. [7]

These results show that, where a stable LCR wave can be detected across a sufficient number of adjacent-receiver paths, gel-induced timing error can be reduced to a level that is small relative to the residual stress magnitudes investigated later in this chapter. The compensation should not be interpreted as complete elimination of couplant effects. It is valid only under conditions where the wedge remains in effective acoustic contact with the sample, the LCR arrival is detectable, the adjacent receiver paths are consistent, and the coupling layer remains within the tested range. However, visible wedge separation, poor signal-to-noise ratio, unstable LCR arrival, or excessive path-wise scatter should instead be treated as quality-control failures.

The difference between the experimental and simulated cases is expected, as the experiment includes real-world factors that were simplified in the model. These include material microstructure, small changes in gel viscosity, and contact pressure. The agreement in trend between simulation and experiment nevertheless supports the use of the compensation method as part of the PAURS uncertainty-control procedure.

5.2.3. Ultrasonic residual stress investigation

The ultrasonic inspection followed the LCR acoustoelastic measurement principle used in conventional single-element RS procedures, but was implemented here using two phased-array probes in a pitch-catch PA-LCR configuration. During scanning, the second zero crossing of the LCR wave was recorded for each selected acoustic path and scan position on both the top and bottom surfaces of the specimen. This timing feature was selected because it provided a stable and repeatable reference for detecting the small changes in wave travel time associated with stress-induced velocity change.

The measured time-of-flight data were processed using the acoustoelastic calibration reported in Section 5.2.1, and the gel compensation methodology described in Section 4.2.6. Substituting the calibrated acoustoelastic constant into Equation 18 enabled residual stress to be calculated at each measurement location. The PAURS results represent the effective near-surface LCR sampling region, approximately 1.2 mm beneath the inspected surface, not a sharply defined point measurement at a single depth. Selected individual acoustic-path results from the top and bottom surfaces are shown in Figure 44 and Figure 45.

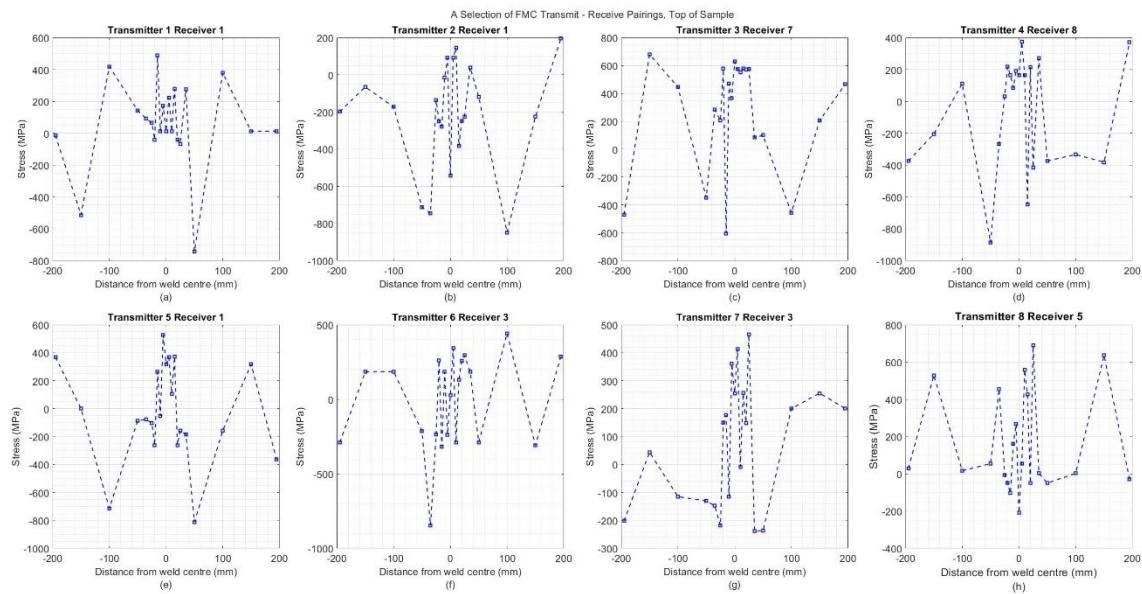


Figure 44: Individual PAURS stress estimates from selected acoustic paths along the top surface of the welded S275 specimen. [4]

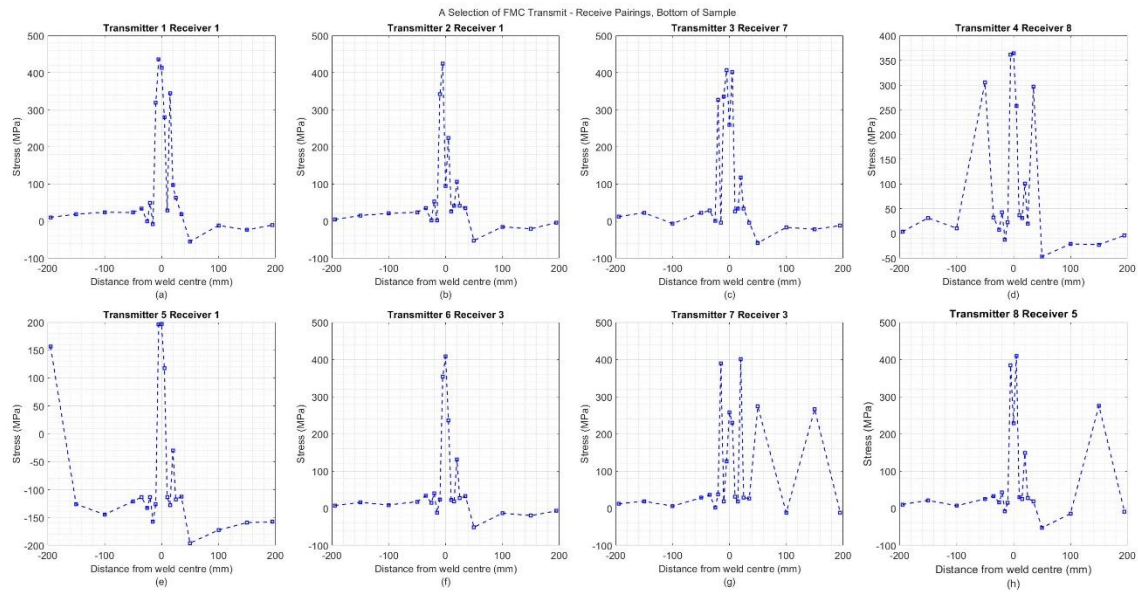


Figure 45: Individual PAURS stress estimates from selected acoustic paths along the bottom surface of the welded S275 specimen. The results show the corresponding path-wise stress estimates for the bottom surface. [4]

Averaging the retained acoustic paths produced the residual stress distributions shown in Figure 46 and Figure 47. Both surfaces show high calculated near-surface residual stress, with peak values of approximately 290 MPa. This is the main PAURS result from the welded-plate inspection: the calibrated LCR measurements identify the high-stress region generated by the welding process and produce stress distributions suitable for comparison with the independent HD and ND datasets.



Figure 46: Mean PAURS RS distribution across the top surface of the welded S275 specimen.

[4]

The central weld region is the least favourable region for PAURS because the weld profile reduces the consistency of wedge contact and can disturb the LCR path. These positions are therefore retained as useful stress-trend information, but with lower confidence in the absolute calculated value.

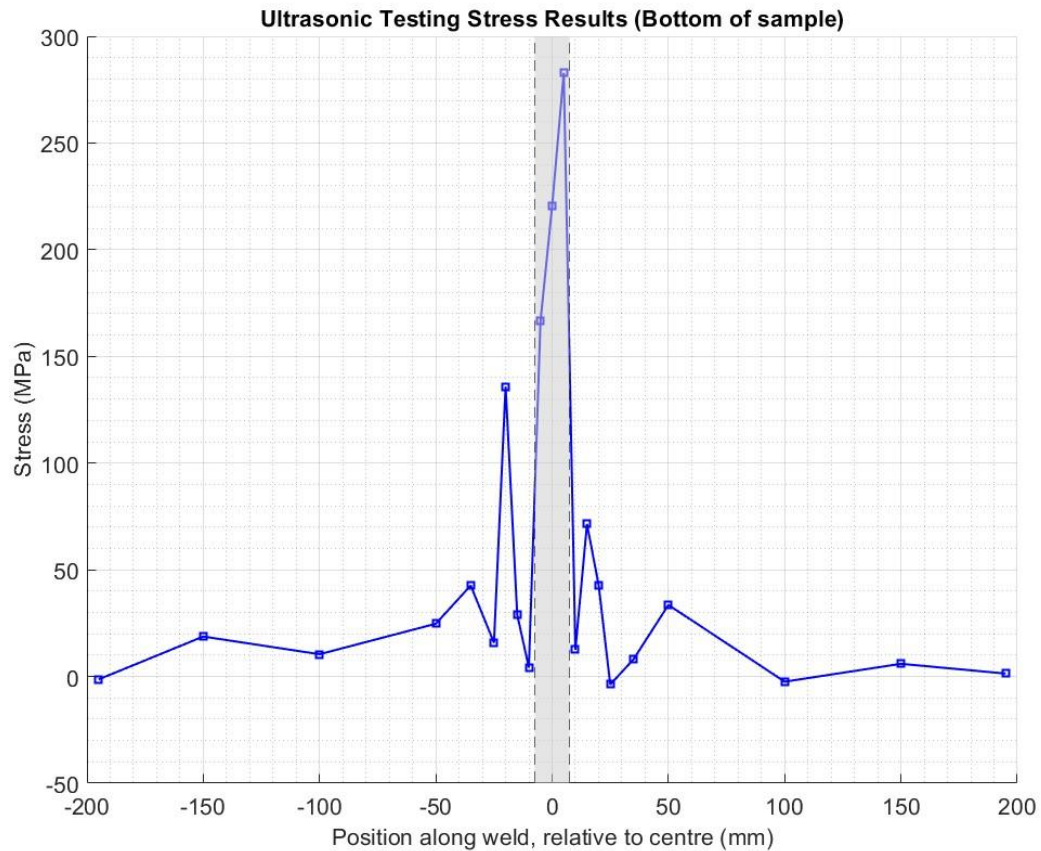


Figure 47: Mean PAURS RS distribution across the bottom surface of the welded S275 specimen. [4]

To evaluate measurement consistency, the standard deviation of residual stress along individual acoustic paths was analysed. Considering only matched transmit–receive pairs (linear paths) resulted in relatively high standard deviation values (Figure 48 and Figure 49), suggesting that reliance on linear paths alone may increase sensitivity to local path-dependent variation.

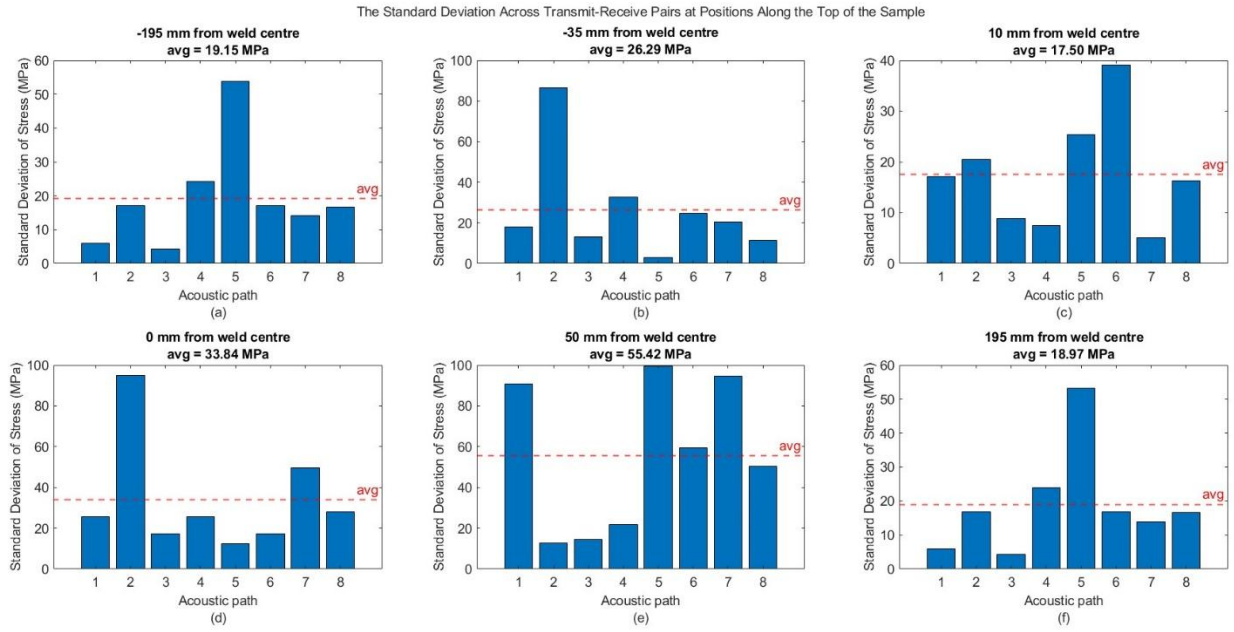


Figure 48: Standard deviation of PAURS stress estimates from matched transmit-receive paths on the top surface. Examples are shown at positions relative to the weld centre: (a) -195 mm, (b) -35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [4]

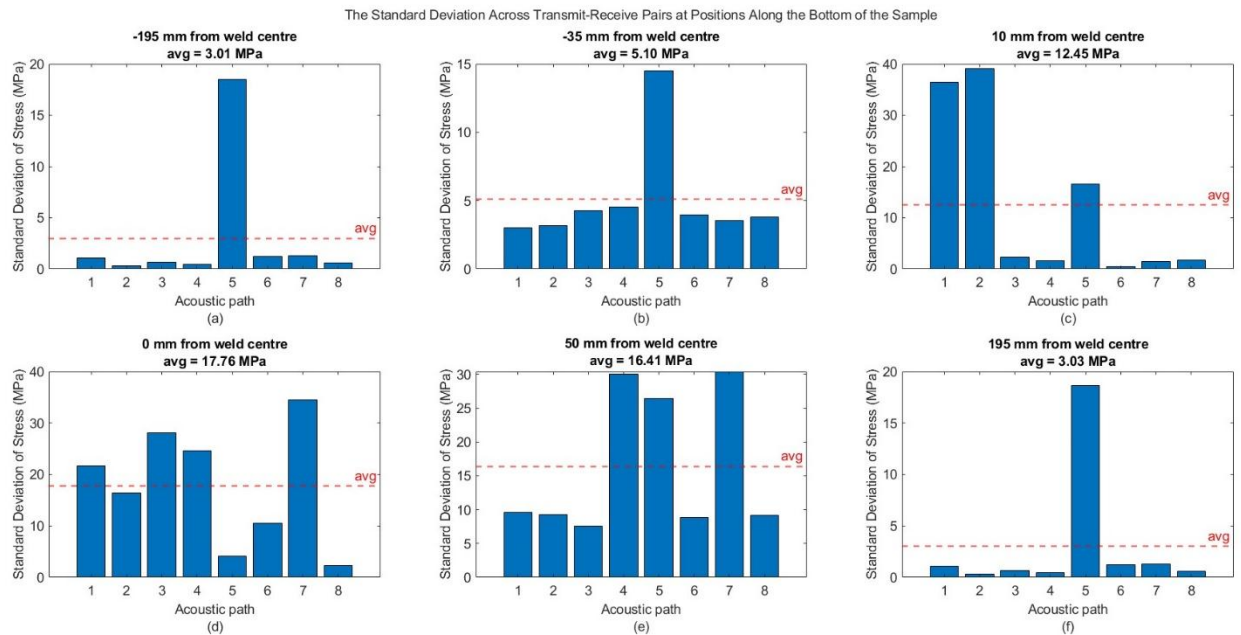


Figure 49: Standard deviation of PAURS stress estimates from matched transmit-receive paths on the bottom surface. Examples are shown at positions relative to the weld centre: (a) -195 mm, (b) -35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm [4]

These results indicate that linear-path analysis alone may introduce localised inaccuracies, particularly in heterogeneous regions such as welds. When the full FMC acoustic-path set was included, the standard deviation was reduced by a factor of approximately 5–10, as shown in Figure 50 and Figure 51. This reduction is one of the clearest advantages of the phased-array implementation: the result is

averaged over a larger path set, and the remaining variability provides an internal consistency indicator.

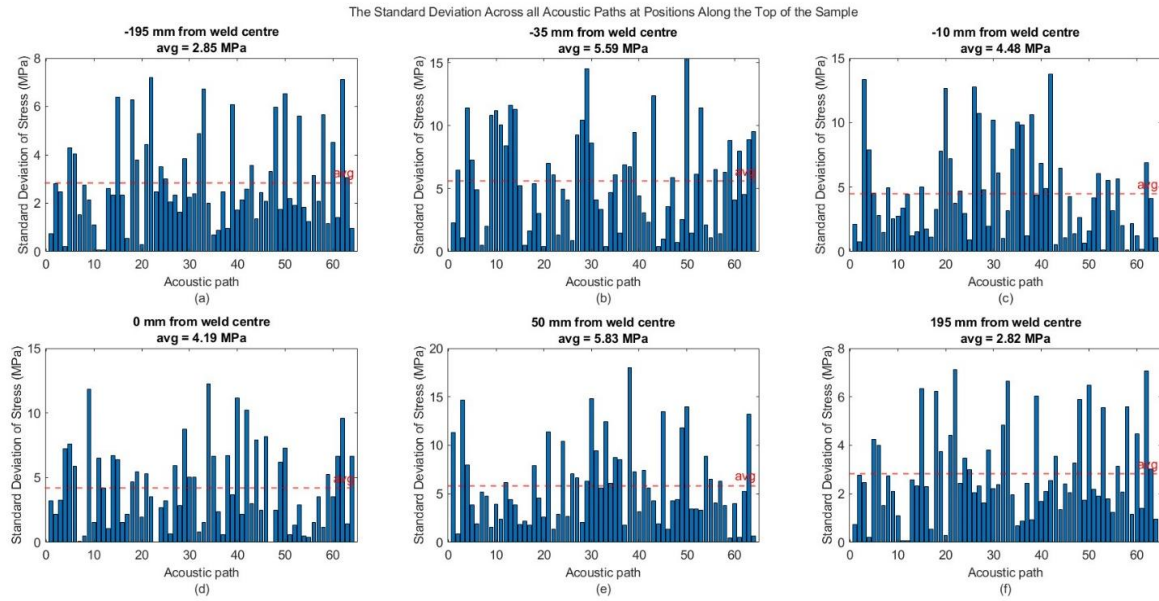


Figure 50: Standard deviation of PAURS stress estimates using the FMC acoustic-path set on the top surface. Examples are shown at positions relative to the weld centre: (a) -195 mm, (b) -35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [4]

The selected positions represent the parent material, HAZ, and weld regions. Lower variability was generally observed in the parent material than in the HAZ and weld zones, consistent with the more uniform geometry and material condition away from the weld. The bottom surface also exhibited lower variance than the top surface. This may reflect more stable wedge contact on the flatter underside of the plate, as well as differences in local thermal history, clamping condition, and weld geometry. The lower bottom-surface variance should therefore be interpreted as improved measurement consistency. At each scan position, the reported mean and standard deviation were calculated from N_{retained} acoustic paths remaining after the signal-quality/path-selection procedure.

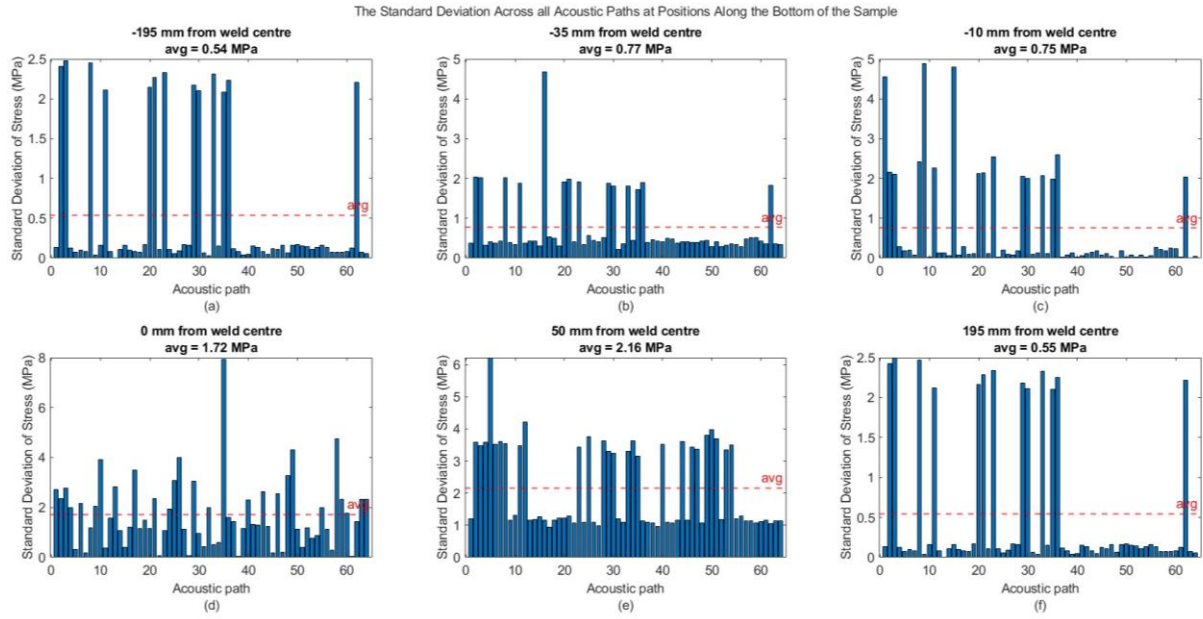


Figure 51: Standard deviation of PAURS stress estimates using the FMC acoustic-path set on the bottom surface. Examples are shown at positions relative to the weld centre: (a) –195 mm, (b) –35 mm, (c) 10 mm, (d) 0 mm, (e) 50 mm, and (f) 195 mm. [4]

The reduction in path-wise standard deviation obtained using FMC demonstrates the additional internal measurement evidence provided by phased-array acquisition for PAURS. FMC increases the number and diversity of acoustic paths available for comparison and averaging; however, the FMC and matched-path cases contain different acoustic-path populations, so the observed reduction in standard deviation cannot be attributed solely to the increased number of measurements. The reported 5–10× reduction refers specifically to reduced dispersion across the retained acoustic-path population and is interpreted as improved internal path consistency, not an equivalent reduction in absolute measurement uncertainty.

The mean PAURS stress maps are consequently interpreted alongside the standard deviation of the retained path-level stress estimates. This standard deviation describes variability between acoustic paths at a given scan position. Systematic contributions associated with calibration, coupling, weld-cap geometry, reference condition and material state remain common to multiple paths and are considered separately.

Lower path-wise variability provides stronger internal evidence that the calculated mean is representative of the retained path population, whereas increased scatter indicates reduced measurement consistency. Numerical standard-deviation thresholds for acceptance or rejection were not defined prospectively during this experimental programme. The resulting quantitative, semi-quantitative and qualitative classifications therefore use path-wise variability together with LCR arrival quality, coupling condition and validity of the calibration and reference state. Establishing pre-specified numerical thresholds forms part of the proposed future qualification procedure.

5.2.4. Comparison and verification

The PAURS results were assessed against incremental hole drilling and neutron diffraction to assess whether the ultrasonic stress calculations reproduced the main residual stress trends and approximate magnitudes measured using independent techniques. In the PAURS measurements, the directly measured quantity is the LCR time-of-flight, from which RS is calculated using the calibrated acoustoelastic relationship. The HD and ND data are therefore used to evaluate the calculated PAURS stress distribution against independent residual stress measurements and to identify regions where the ultrasonic interpretation becomes less certain.

The interpretation must account for the different measurement basis of each technique. PAURS provides a near-surface stress calculation from LCR time-of-flight changes, with an effective propagation depth of approximately 1.2 mm beneath the inspected surface. HD determines near-surface residual stress from strain relief during incremental drilling, with the final comparison taken from the depth range closest to the PAURS sampling region. Although the PAURS LCR sensitivity region is shallower than the nominal 2 mm neutron-diffraction depth, the 2 mm ND measurement remains the closest available depth-resolved comparator.

The ND gauge volume was $2 \times 2 \times 2 \text{ mm}^3$, so the nominal 2 mm measurement represents an average over a finite near-surface volume. It is therefore not identical to the PAURS sampling region, but it is physically closer to the approximately 1–1.5 mm LCR response than the deeper ND measurements at 7, 10, and 13 mm. For this reason, the 2 mm ND result is used as a depth-adjacent comparison, while the deeper ND measurements are used to interpret through-thickness stress variation. The 2 mm ND results used here therefore represent a finite gauge volume overlapping a deeper region than PAURS.

The HD results are shown in Figure 52. HD was applied at the weld-centre region of Sample #1 and therefore provides the closest same-specimen near-surface comparison for the PAURS top-surface weld-centre result. The first 200 μm of the HD profile were excluded from the comparison because this region exhibited relatively high uncertainty, reaching approximately $\pm 60 \text{ MPa}$. This higher uncertainty is expected because the earliest drilling increments are more sensitive to surface preparation, strain-gauge bonding, drilling alignment, and local near-surface disturbance. The uncertainty reduced to approximately $\pm 11 \text{ MPa}$ at around 500 μm depth, before increasing again to approximately $\pm 24 \text{ MPa}$ near the final depth of approximately 1 mm.

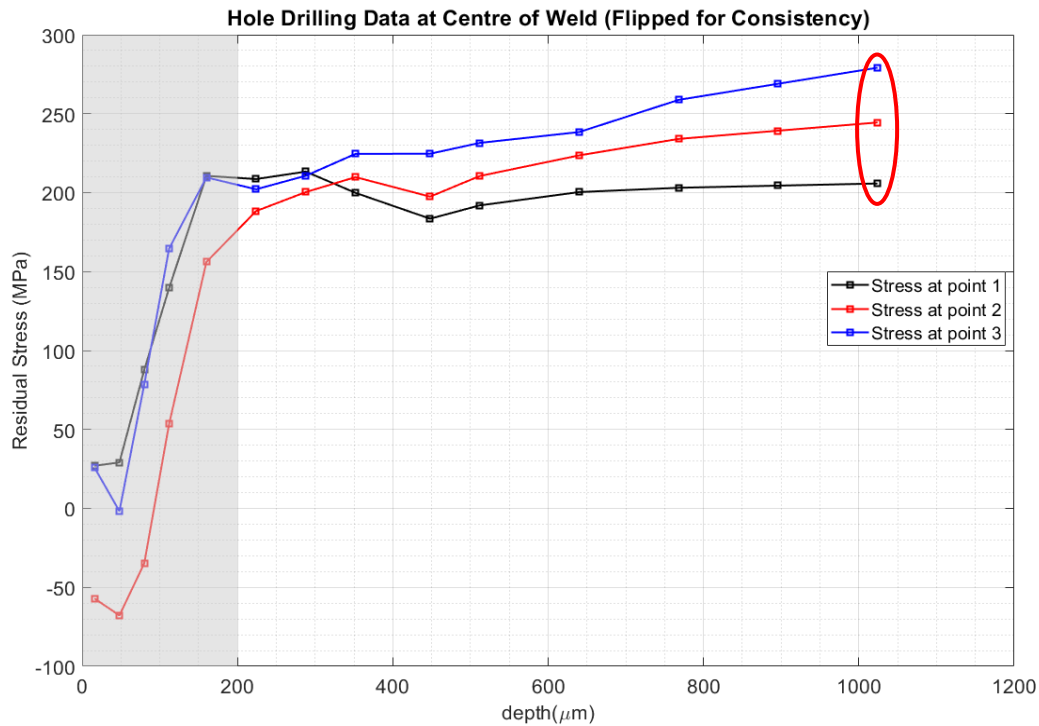


Figure 52: Incremental hole drilling residual stress profile at the weld-centre region of Sample #1. This depth range provides the closest same-specimen near-surface comparison for the PAURS top-surface weld-centre result. [4]

For comparison with PAURS, the HD value at approximately 1 mm depth was used because it is closest to the effective LCR sampling region of the PAURS configuration. The average HD stress at this depth was approximately 243 ± 24 MPa. This value is broadly consistent with the peak calculated PAURS stresses, which reached approximately 290 MPa in the weld cap centre region. The difference between these values is not unexpected because HD provides a local strain-relief measurement beneath the drilled hole, while PAURS provides a path-averaged ultrasonic response over the near-surface LCR propagation region. The comparison therefore supports the approximate magnitude of the PAURS weld-centre stress result.

The HD dataset also has two important limitations for this comparison. First, HD was concentrated at the weld-centre region and was not repeated along the full length of the weld plate. It therefore supports the centre-point comparison, but does not provide independent evidence for every PAURS scan position. Second, HD was not performed on the bottom surface of the specimen. The bottom-surface PAURS results therefore cannot be assessed using HD and must instead be interpreted through comparison with the ND dataset.

Figure 53 presents the longitudinal, transverse, and normal stress components obtained from neutron diffraction. The longitudinal component is the primary comparator for PAURS because it is aligned with the weld direction and is expected to dominate the welding-induced stress field. The transverse

and normal components provide additional information on the internal stress state, but they are used mainly to support interpretation of the welded specimen.

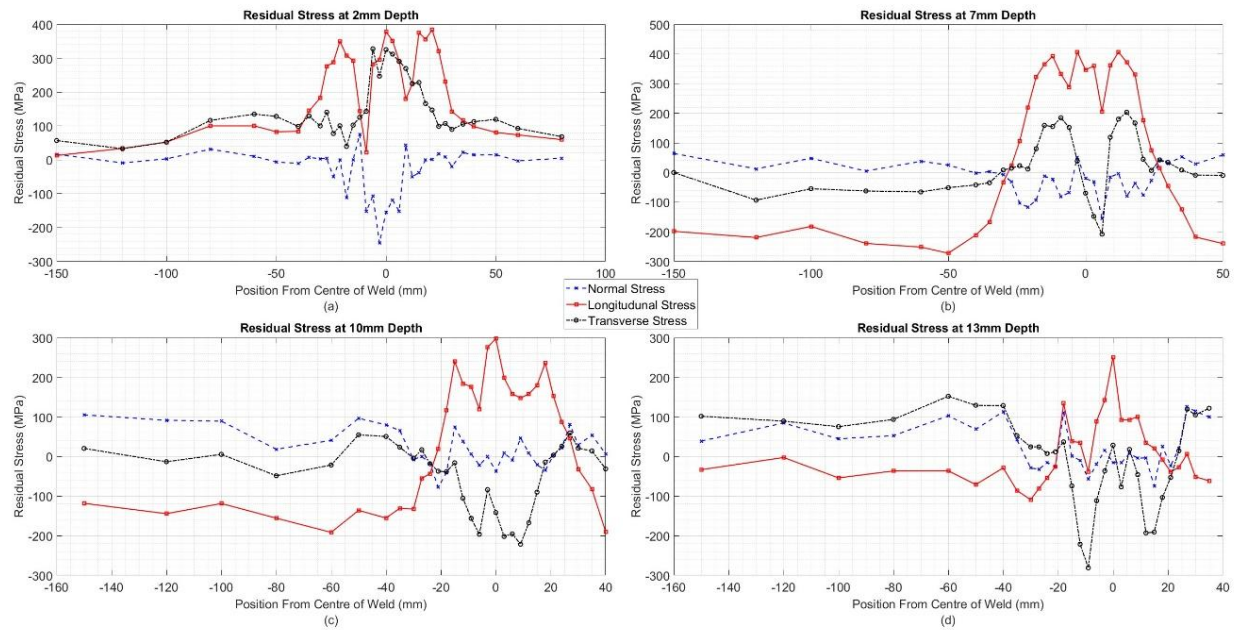


Figure 53: Neutron-diffraction residual stress results for the welded S275 replicate specimen. The results show the normal, longitudinal and transverse stress components measured within finite gauge volumes at selected depths. [4]

The ND results provide an important comparison as they extend through the thickness and therefore give information that cannot be obtained from the near-surface PAURS measurement alone. However, ND and PAURS should not be expected to match exactly at every position. ND averages lattice strain over a finite gauge volume at specified depths, while PAURS extracts stress from a near-surface LCR wave travelling parallel to the inspected surface. Differences between the two methods are therefore expected where strong stress gradients exist through the thickness or where the ultrasonic measurement is affected by surface condition or coupling.

The top-surface comparison between PAURS, HD, and ND is shown in Figure 54. Considering first the weld centre, only qualitative trend agreement can be observed between PAURS and ND, though the HD average value does share an approximate magnitude with the centre of the PAURS scan, indicating quantitative agreement. The centre of the PAURS scan shows an RS value of approximately 220 MPa, within the uncertainty range of the HD value.

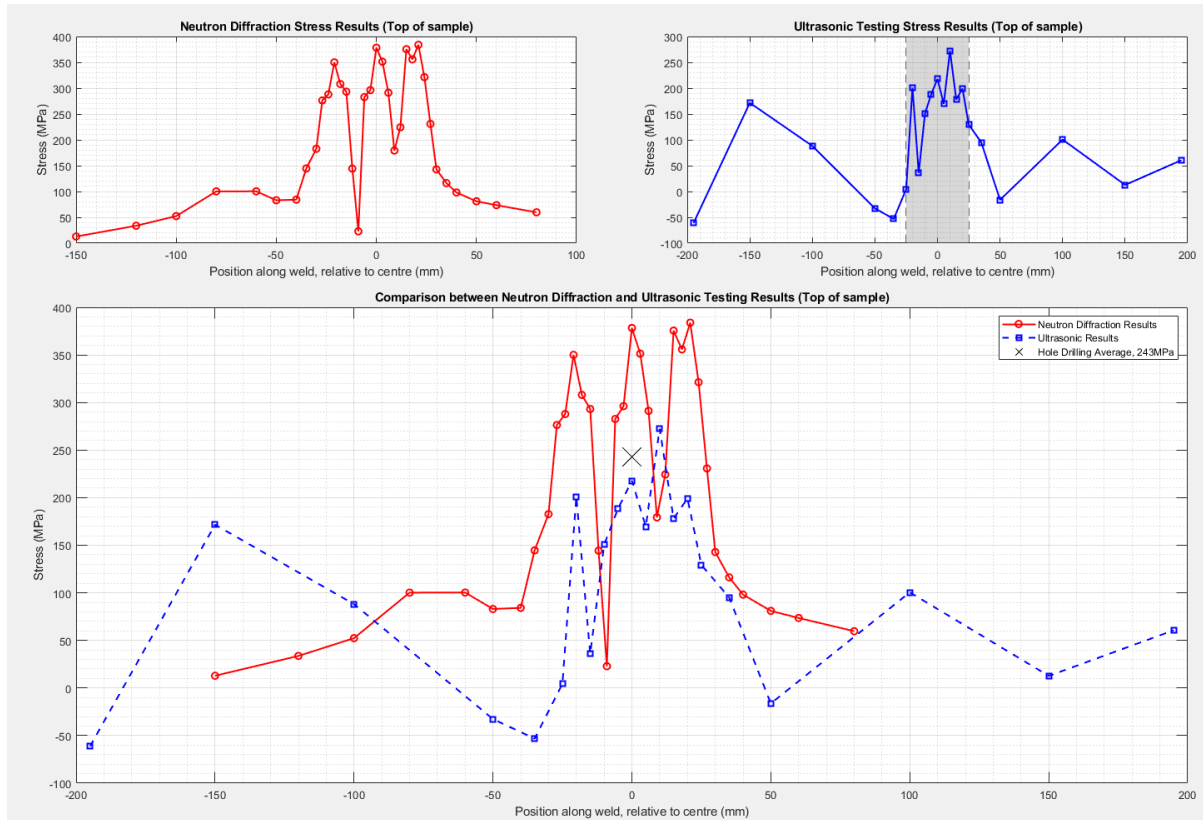


Figure 54: Comparison between PAURS, hole drilling, and neutron diffraction for the top surface of the welded S275 specimen. PAURS stresses are calculated from LCR ToF changes using the calibrated acoustoelastic relationship [4]

Agreement is weaker in the central weld region, as this is the most difficult region for PAURS due to several uncertainty sources coinciding. The weld cap and local surface geometry can reduce wedge contact stability, which affects coupling and LCR arrival consistency. The RS gradient is also likely to be steep close to the weld centre, meaning that small differences in depth, gauge volume or lateral position can produce different measured stress values. In addition, the weld and HAZ may contain microstructural variation and texture that can influence ultrasonic velocity, attenuation and scattering. These effects can bias the PAURS ToF response if they are not fully separated from stress-induced velocity change.

The higher ND value relative to the PAURS top-surface result at the weld centre can be explained by three interacting factors. First, ND and PAURS average different physical quantities over different sampling regions. Second, local weld-cap geometry and microstructure can destabilise wedge coupling and LCR arrival consistency. Third, absolute ND stress levels depend on the stress-free lattice reference and were measured on a nominally identical replicate specimen rather than Sample #1.

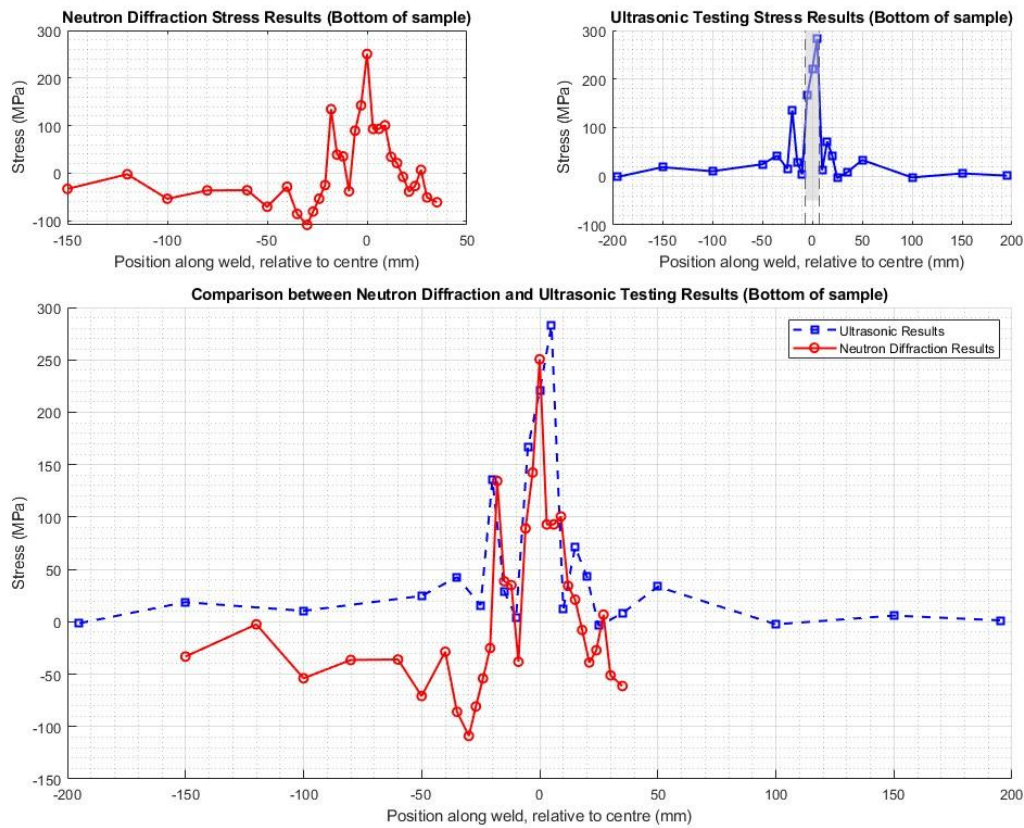


Figure 55: Comparison between PAURS and neutron diffraction for the bottom surface of the welded S275 specimen. [4]

The bottom-surface comparison between PAURS and ND is shown in Figure 55. Because no bottom-surface HD measurement was performed, this comparison relies on PAURS internal consistency and the ND replicate-specimen dataset. The bottom-surface PAURS measurements showed lower path-wise variance than the top surface, as discussed in Section 5.2.3. This provides stronger internal evidence for measurement consistency on the bottom surface, likely because the underside of the plate provided more stable wedge contact and less severe local weld-cap geometry. Per the quality flagging criteria discussed in this thesis, the agreement in the HAZ at the bottom of the welded plate can be described as quantitative.

Overall, the RS measurement methodology is presented as quantitative through validation in ideal cases, such as on the bottom of the weld sample where the geometry is simple, allowing for a consistent, stable wedge-sample interface across the inspected path. In less ideal cases, such as on the top of the specimen as the scan path encounters the complex geometry of the weld cap, the results are presented as only a qualitative recreation of the stress trend, here due to poor mating between the wedge and the sample, resulting in low SNR LCR waves where the repeatable timing reference point was indistinct. The numerical acceptance thresholds for these categories were not defined prospectively during the experimental programme. The classifications used here therefore summarise

the evidence available from calibration validity, signal quality, path consistency, coupling condition and comparator compatibility. Establishing pre-qualified numerical thresholds is included in the future qualification programme.

An additional potential confounder is the nominal replicate status of the sample sent for ND. Although the overall trend of the RS is broadly similar, the overall magnitudes differ. This is treated as a magnitude difference and not a PAURS or ND measurement error as the HD stress magnitude on Sample #1 is within uncertainty of the PAURS weld centre stress value, within very similar depths (1 mm vs 1.2 mm respectively).

5.2.5. What PAURS establishes for welded residual stress measurement

The welded-plate results test whether the calibrated PA-LCR approach developed in the controlled bolt benchmark can be applied to an unknown residual stress field. The S275 acoustoelastic calibration provided the stress-conversion basis for the selected PA-LCR configuration, while the welded-plate results show that the calculated stress values must also be interpreted alongside coupling condition, signal quality, path consistency, and independent residual stress evidence.

The gel-thickness study identifies couplant variation as a practical timing-error source in PAURS. Simulation and shim-based testing showed that coupling variation can generate stress-equivalent ToF shifts if left uncompensated. Adjacent-receiver subtraction reduced the gel-caused experimental residual timing error to approximately 0.3 ns on average, corresponding to an equivalent stress error of approximately 1.1 MPa under the calibration used in this thesis. This provides a practical uncertainty-control step before PAURS is applied to the welded specimen.

In the welded-plate measurements, FMC reduced the standard deviation of the calculated stress values by approximately 5–10× compared with the matched-path subset. This supports path averaging and internal consistency assessment, while also identifying regions where the averaged stress value should be treated with reduced confidence. This materially improves stress-map precision by reducing path-wise standard deviation while preserving a quality indicator for identifying lower-confidence weld-centre regions.

The comparison with HD and ND supports the main PAURS stress trends and approximate magnitudes where measurement conditions are favourable. The bottom surface provides the strongest PAURS/ND agreement, consistent with more stable wedge contact and lower path-wise variability. The weaker agreement near the top weld centre is also informative, because it identifies the current limit of quantitative interpretation where weld geometry, coupling stability, stress gradients, and comparator gauge-volume differences coincide.

These results show that PAURS can provide defensible near-surface residual stress information in welded S275 steel under the laboratory conditions tested here. The method is strongest where the

LCR arrival is stable, standard deviation across retained paths is low, acoustoelastic calibration is valid, and the comparison basis is physically meaningful. It is not yet a qualified industrial inspection procedure for arbitrary weld geometries, rough surfaces, elevated temperature or uncharacterised microstructures, but it does establish the main requirements for further PAURS development: acoustoelastic calibration, couplant-error control, FMC-based path redundancy, quality classification, and comparison with independent residual stress measurements.

5.3. Microstructure and PAURS+

The 10 MHz and 32 MHz simulations first compare the sensitivity of amplitude change and ToF to the equiaxed–elongated microstructure contrast, showing how the ultrasonic response changes as wavelength decreases. The 5 MHz simulation and robotic measurements then test whether the same angular attenuation-related response remains detectable using the available PA-LCR hardware.

The measured features in this section are ToF, amplitude change, attenuation-related angular response, and signal consistency. In PAURS+, the output is interpreted as an angular descriptor of near-surface microstructural anisotropy. LCR ToF is retained mainly as a stability feature, while amplitude- and attenuation-based LCR observables provide the stronger microstructural contrast under the conditions considered here.

Simulation and experiment are compared using the angular position of the main amplitude or attenuation-related features, together with the contrast between the more equiaxed AFSD region and the elongated substrate.

5.3.1. Frequency sensitivity of the PAURS+ ToF and amplitude response

The frequency study was used to assess which PA-LCR observables were most sensitive to the simulated microstructural difference between the equiaxed AFSD region and the elongated grain substrate region. Two quantities were examined: the amplitude change between selected LCR peaks and the ToF of the selected LCR arrival. The comparison was performed at 10 MHz and 32 MHz to examine how the response changed as the ultrasonic wavelength approached the characteristic microstructural length scale, and to identify the most useful microstructure-sensitive observable before assessing whether the response could be reproduced using the practical 5 MHz robotic application of PAURS+.

The 10 MHz and 32 MHz simulations were used as frequency-sensitivity studies. These frequencies were selected to increase the interaction between wavelength and grain morphology in the numerical model. Using the approximate longitudinal wave velocity in Al7075, the corresponding half-wavelengths are approximately 300 μm at 10 MHz and 100 μm at 32 MHz. These length scales are closer to the characteristic dimensions of the elongated substrate morphology than the 5 MHz case,

making them useful for testing whether the PAURS+ response is sensitive to microstructural directionality.

Figure 56 and Figure 57 show the simulated 10 MHz amplitude-change and ToF responses, respectively, for the equiaxed AFSD and elongated substrate models. Figure 56 shows that the elongated substrate produces a stronger angular amplitude variation than the equiaxed AFSD region. The main difference occurs around the angular regions associated with grain alignment, where the amplitude-change response departs most clearly between the two models. This behaviour is consistent with the EBSD-defined morphology: the equiaxed region presents a more directionally uniform propagation environment, while the elongated substrate changes the LCR response as the propagation direction rotates relative to the dominant grain elongation direction. Outside the angular regions close to 90° and 270° , the amplitude-change responses of the equiaxed AFSD and elongated substrate models are more comparable.

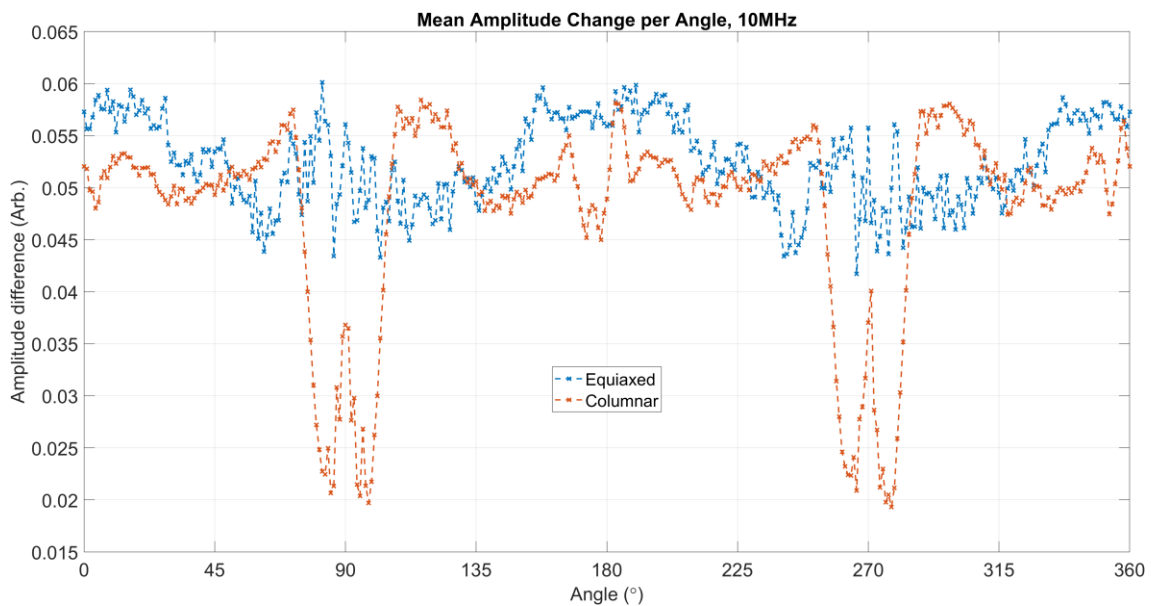


Figure 56: Simulated 10 MHz angular amplitude change in the elongated substrate (red) and equiaxed AFSD (blue) models..

Figure 57 shows the corresponding 10 MHz ToF response. The equiaxed AFSD model remains comparatively stable, while the elongated substrate shows a larger angular variation - with the main features again occurring around the alignment-sensitive regions where the acoustic paths travel approximately parallel to the dominant grain elongation direction. This confirms that ToF can also respond to microstructure, although it only changes significantly when considering rotational LCR within the substrate. Within the equiaxed grain region, even when rotated, ToF remained broadly consistent.

This result is relevant to PAURS because it indicates that microstructure-related ToF variation is most pronounced when the propagation direction changes relative to the elongated grain morphology, as under a fixed inspection orientation both regions show limited ToF variation. For the elongated substrate, the simulation indicates that angular misalignment can contribute to ToF variation and so probe orientation should be treated as a possible uncertainty source when inspecting textured or elongated microstructures.

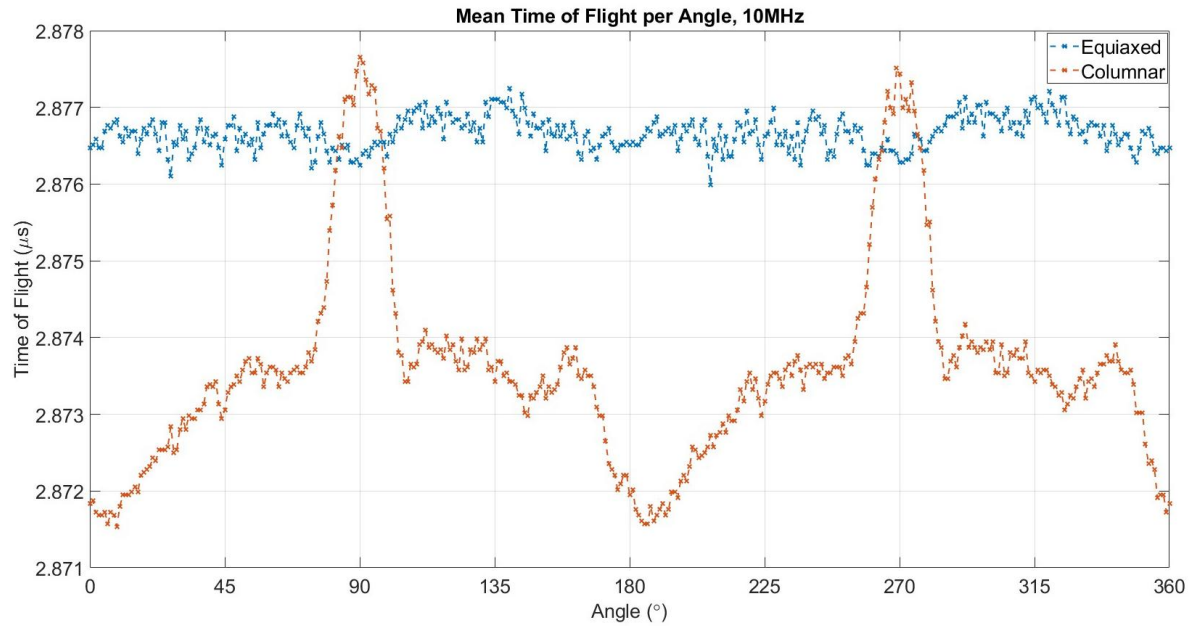


Figure 57: Simulated 10 MHz ToF variation in the elongated substrate (red) and equiaxed AFSD (blue) models.

The same trend is stronger in the 32 MHz simulations shown in Figure 58 and Figure 59. At this frequency, the shorter wavelength is closer to the characteristic scale of the elongated grain morphology, increasing the simulated sensitivity to propagation direction. The 32 MHz case is not treated as a practical deployment frequency for the PA-LCR configuration used in this thesis. Not only is the firing frequency impractically high, but the penetration depth is calculated as approximately 400 microns. Although the shorter wavelength increases the simulated sensitivity to microstructural morphology, higher-frequency inspection results in a lower penetration depth and higher couplant sensitive error. This simulation is used to confirm the wavelength-sensitivity trend under controlled numerical conditions, while the experimental validation is performed at 5 MHz.

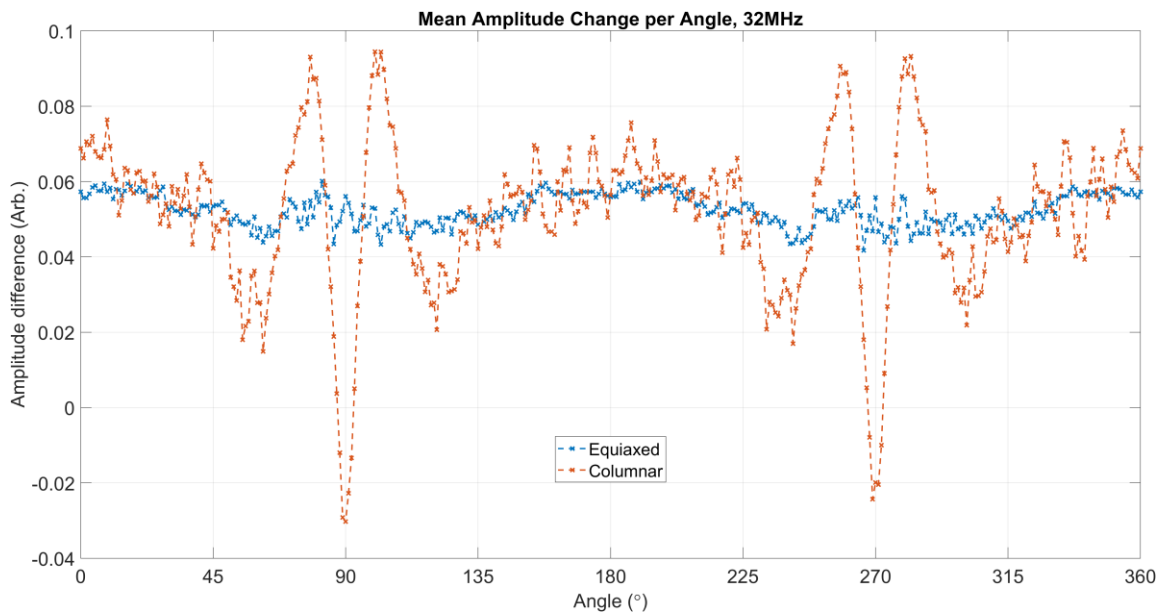


Figure 58: Simulated 32 MHz angular amplitude change in the elongated substrate (red) and equiaxed AFSD (blue) models.

In Figure 58 the elongated substrate shows a stronger and broader angular amplitude-change response than in the 10 MHz case. The divergence between the substrate and AFSD responses extends over a wider angular range, supporting the interpretation that amplitude change is sensitive to wavelength-scale interaction with the elongated microstructure.

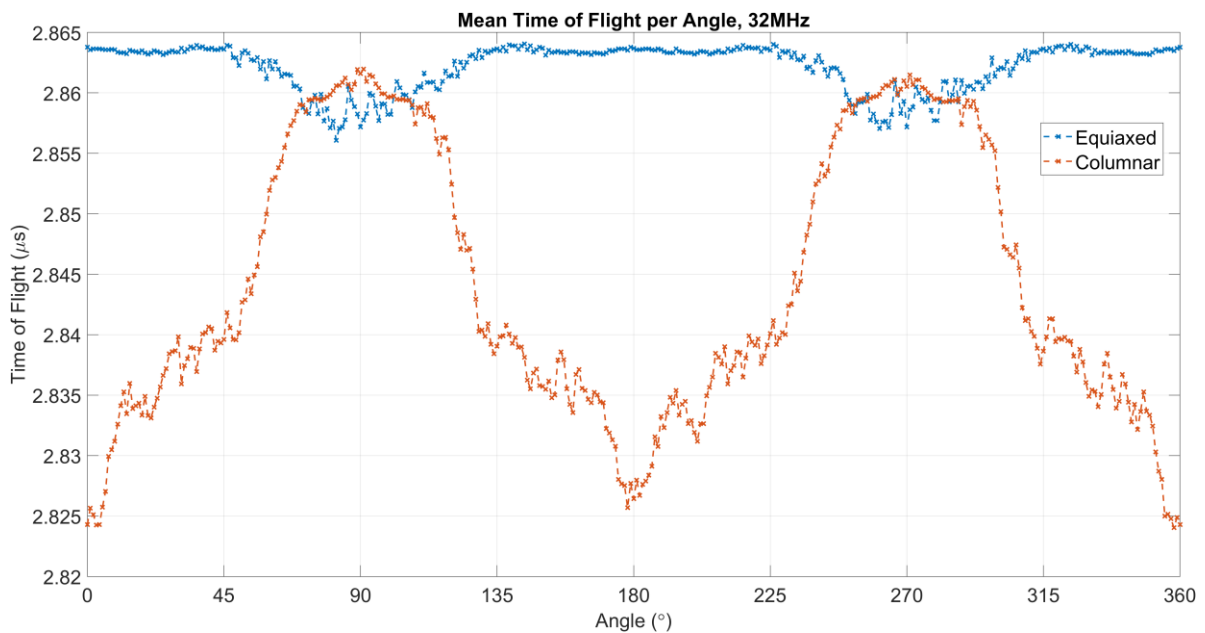


Figure 59: Simulated 32 MHz ToF variation in the elongated substrate (red) and equiaxed AFSD (blue).

Figure 59 shows a wider angular interaction region in the 32 MHz ToF response compared with the 10 MHz case. The largest variation occurs between 45° and 135° and around the equivalent region near 270°, where the LCR propagation direction changes relative to the elongated substrate morphology. The ToF variation is also larger than in the 10 MHz simulation, increasing from

approximately 6 ns to approximately 40 ns across the main interaction region. This is consistent with the shorter wavelength increasing sensitivity to local variations in effective wave speed caused by the representative grain morphology.

The ToF response in the elongated substrate also reaches a plateau around 2.86 μs across part of the interaction region. As shown in Figure 60, this plateau overlaps with the main peak–trough–peak pattern in the amplitude-change response. This supports the use of amplitude change as the clearer PAURS+ descriptor, because the strongest attenuation-related features occur in an angular region where the ToF response is less discriminating.

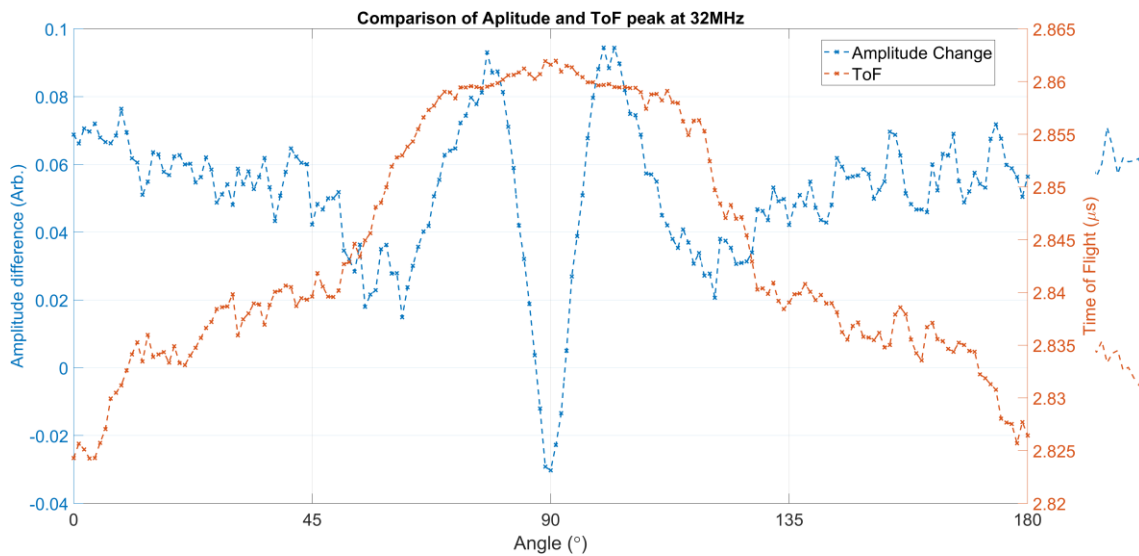


Figure 60: Comparison between the angular positions of the simulated amplitude-change features and the corresponding ToF response in the frequency-sensitivity study.

The 10 MHz and 32 MHz simulations show that PA-LCR amplitude response is more suitable than ToF for microstructure-sensitive angular characterisation. The elongated substrate produces stronger and more directionally dependent amplitude variation than the equiaxed AFSD region, and the effect becomes more pronounced as the wavelength decreases. These results motivate the 5 MHz simulation and robotic validation in Section 5.3.2, where the aim is to determine whether the same angular attenuation-related signature remains measurable under experimentally feasible PA-LCR conditions.

5.3.2. 5 MHz PAURS+ simulation and robotic validation

The 5 MHz simulation and experimental results test whether the angular attenuation-related response identified in the higher-frequency simulations remains measurable using the available robotic PA-LCR hardware. The 10 MHz and 32 MHz simulations in Section 5.3.1 were used to assess frequency sensitivity and identified amplitude change as the clearer microstructure-sensitive response. The 5 MHz simulation is used as the comparison case for the robotic measurements because it matches the probes used for the robotic validation.

The analysis focuses on amplitude change, attenuation-related angular response, and signal consistency. ToF is retained only as a supporting feature for assessing LCR arrival stability; it is not used here to calculate stress or define the PAURS+ output.

Figure 61 shows representative LCR signals used to define the amplitude-change measurement. The selected LCR arrival is visible across the phased-array paths, and the received amplitude changes with propagation distance and microstructural region. The amplitude-change metric is extracted from the selected LCR response and used as an attenuation-related descriptor of how the signal varies with both path and inspection angle. The same extraction approach is applied to the simulated and experimental 5 MHz data so that the angular trends can be compared on a consistent basis.

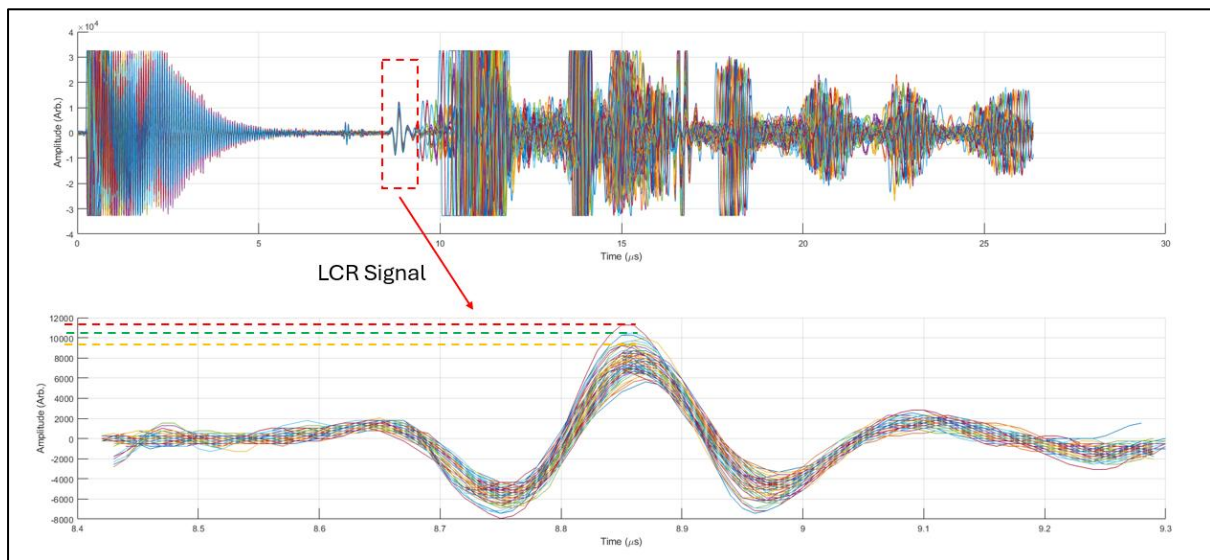


Figure 61: Definition of the amplitude-change metric used in the 5 MHz PA-LCR analysis. The metric is extracted from the selected LCR arrival and used as an attenuation-related descriptor of how the received amplitude changes with propagation path and inspection angle.

Figure 62 and Figure 63 show the 5 MHz simulated angular amplitude-change response for the elongated substrate and equiaxed AFSD regions. These simulations define the angular response expected under the same frequency used for the robotic measurements. The comparison then assesses whether the predicted substrate/AFSD contrast is reproduced in the measured PA-LCR data.

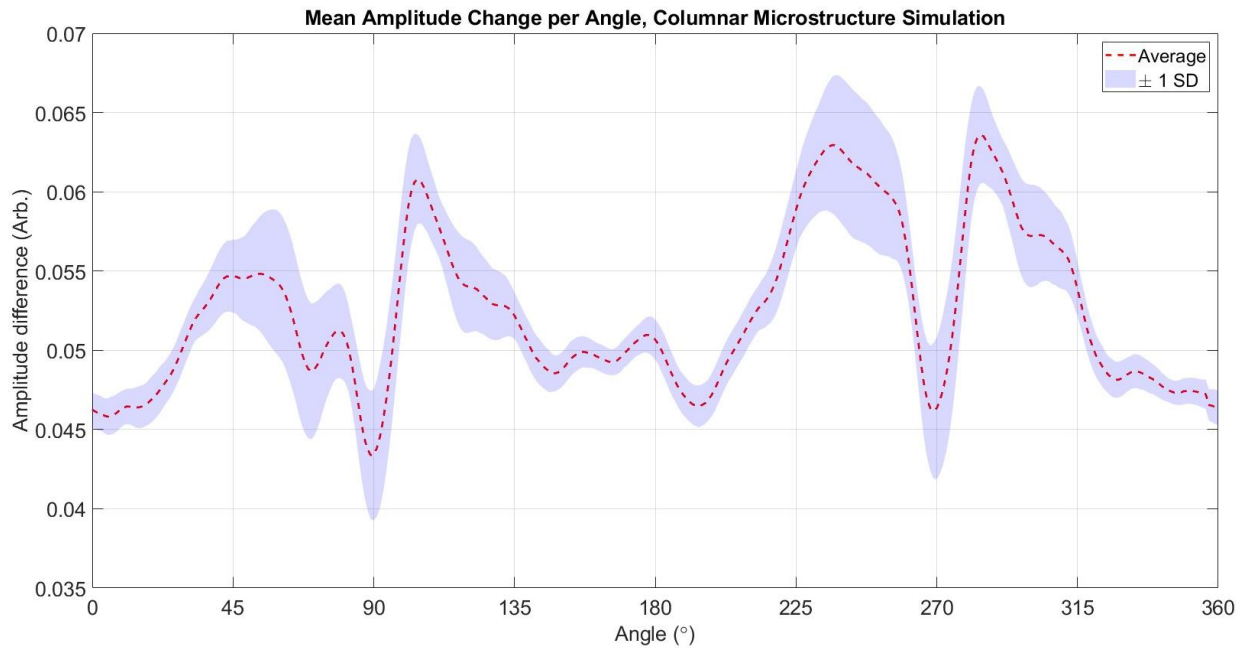


Figure 62: Simulated 5 MHz angular amplitude-change response in the elongated substrate region. The directional features indicate the expected attenuation-related response as the LCR propagation direction changes relative to the EBSD-defined elongated grain morphology.

Figure 62 shows the simulated response for the elongated substrate. The amplitude-change response varies with inspection angle, with the strongest features occurring around the angular positions where the LCR propagation direction aligns relative to the elongated grain morphology. This agrees with the EBSD-defined substrate condition and with the frequency-sensitivity results in Section 5.3.1, where the elongated region produced the stronger direction-dependent response.

The magnitude of the 5 MHz variation is lower than in the 10 MHz and 32 MHz cases, which is expected because the longer wavelength interacts less strongly with the representative grain morphology. However, the persistence of an angular trend at 5 MHz is an important result ahead of the robotic experimental validation.

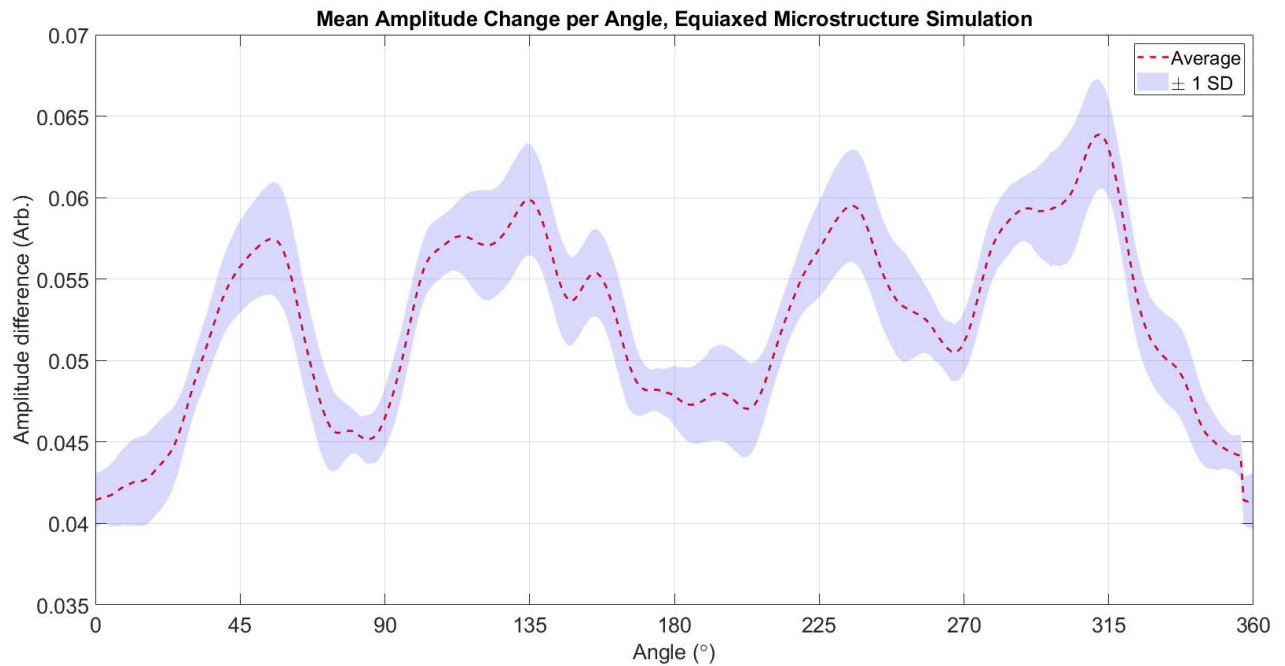


Figure 63: Simulated 5 MHz angular amplitude-change response in the equiaxed AFSD region. The weaker angular dependence provides the simulated reference case for comparison with the elongated substrate response above.

Figure 63 shows the simulated response for the equiaxed AFSD region. The angular variation is smaller than in the substrate simulation, consistent with the more directionally uniform grain morphology observed in EBSD. This provides the simulated reference case for PAURS+: the AFSD region is expected to show a weaker angular attenuation-related response than the elongated substrate.

Figure 64 and Figure 65 show the corresponding experimental measurements acquired using the robotic PA-LCR setup. The same amplitude-change calculation was applied to the experimental data as to the 5 MHz simulation results, so that the angular response could be compared using the same observable. The experimental measurements also include contact, coupling and robotic positioning effects that are not fully represented in the simulation.

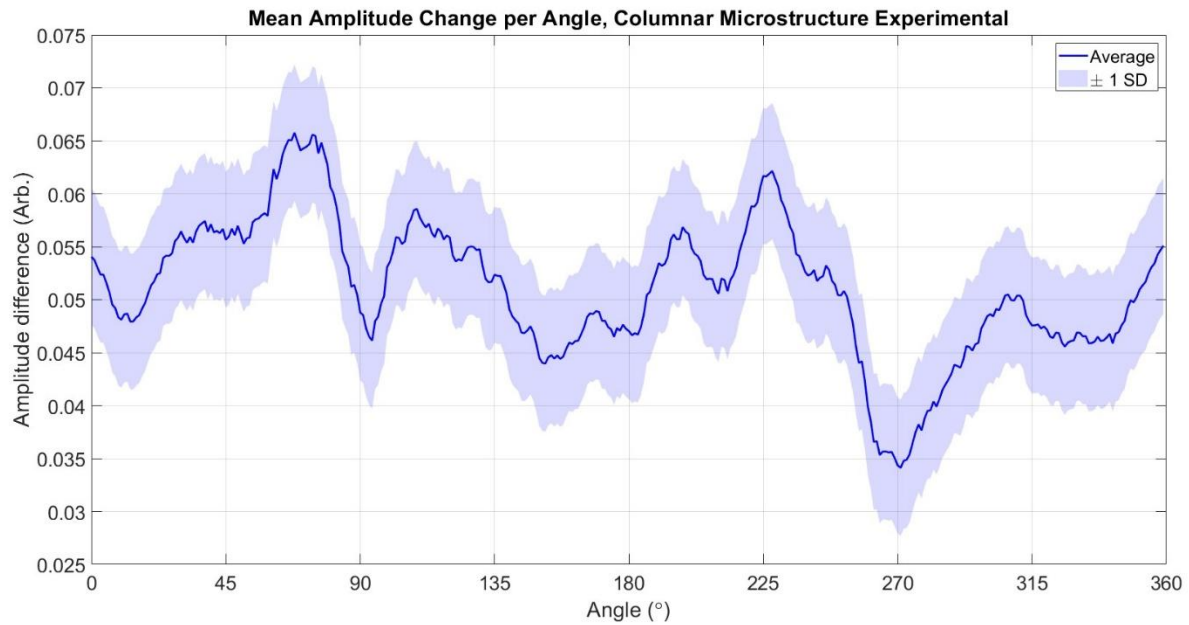


Figure 64: Experimental 5 MHz robotic PA-LCR angular amplitude-change response in the elongated substrate region. The measured response shows a directionally dependent attenuation-related signature consistent with the elongated substrate morphology.

Figure 64 shows the experimental response from the elongated substrate region. A clear angular dependence is again observed here, with the main amplitude-change features occurring at similar angular positions to those predicted by the 5 MHz simulation. The measured response is not expected to match the simulation in absolute amplitude, because the simulation uses a representative EBSD-informed morphology and idealised boundary conditions. The substrate retains a repeatable angular attenuation-related response under the practical 5 MHz PA-LCR inspection condition.

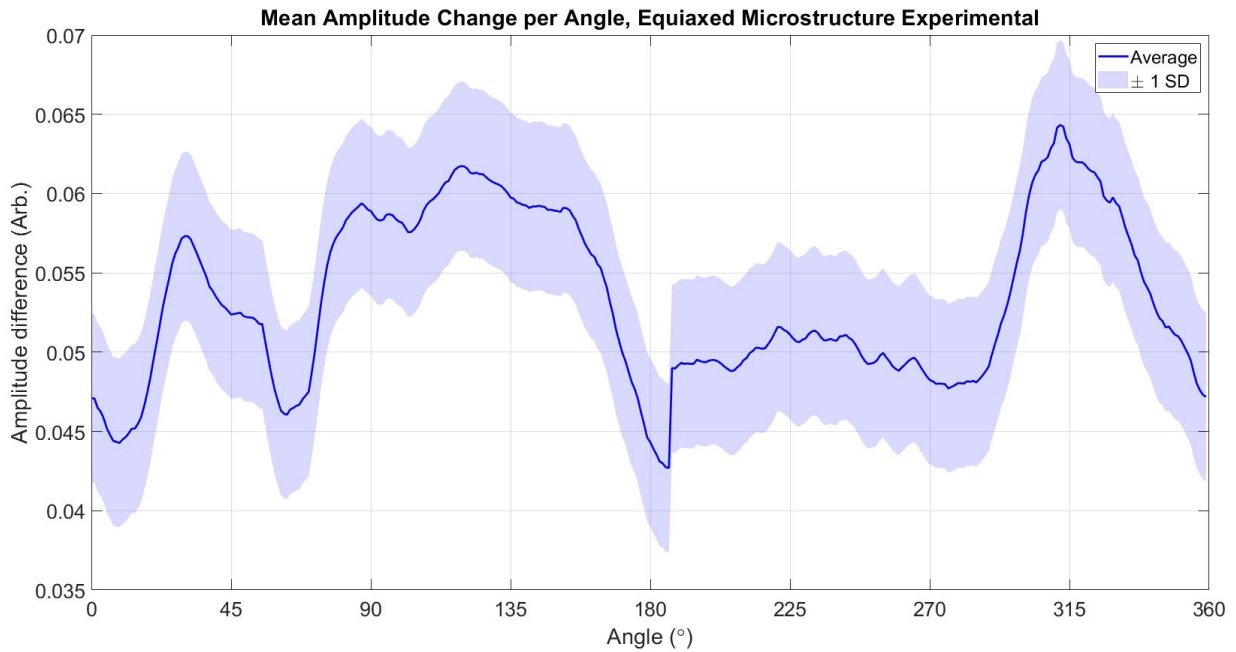


Figure 65: Experimental 5 MHz robotic PA-LCR angular amplitude-change response in the equiaxed AFSD region. The weaker angular dependence provides the experimental reference case for assessing whether the stronger substrate response is microstructure-sensitive or only system-driven.

Figure 65 shows the experimental response from the equiaxed AFSD region. The angular variation is weaker than in the substrate measurement, which is consistent with the simulated AFSD response and the comparatively equiaxed grain morphology observed in EBSD. This comparison is important because the AFSD region was inspected using the same PA-LCR wedge, probes, amplitude-extraction procedure and robotic rotation method as the substrate. The weaker AFSD response therefore provides a reference case against which the stronger substrate response can be interpreted.

Taken together, the experimental results reproduce the main contrast predicted by the 5 MHz simulations: the elongated substrate gives the stronger angular attenuation-related response, while the equiaxed AFSD region remains more stable over the same rotation range. This supports the interpretation that the measured angular response is linked to the EBSD-defined microstructure and not caused by errors arising from the experimental setup. However, this comparison does not remove all experimental uncertainty. Coupling variation, contact-force changes, surface condition, and robot angular positioning error can still influence the measured amplitude response.

Figure 66 and Figure 67 compare the 5 MHz simulated and experimental responses for the elongated substrate and equiaxed AFSD regions. The comparison is based on the relative angular attenuation trend and common features between simulated and experimental results, which is appropriate as the simulation represents the EBSD-informed microstructure under controlled numerical conditions while the experiment includes additional variation as mentioned above.

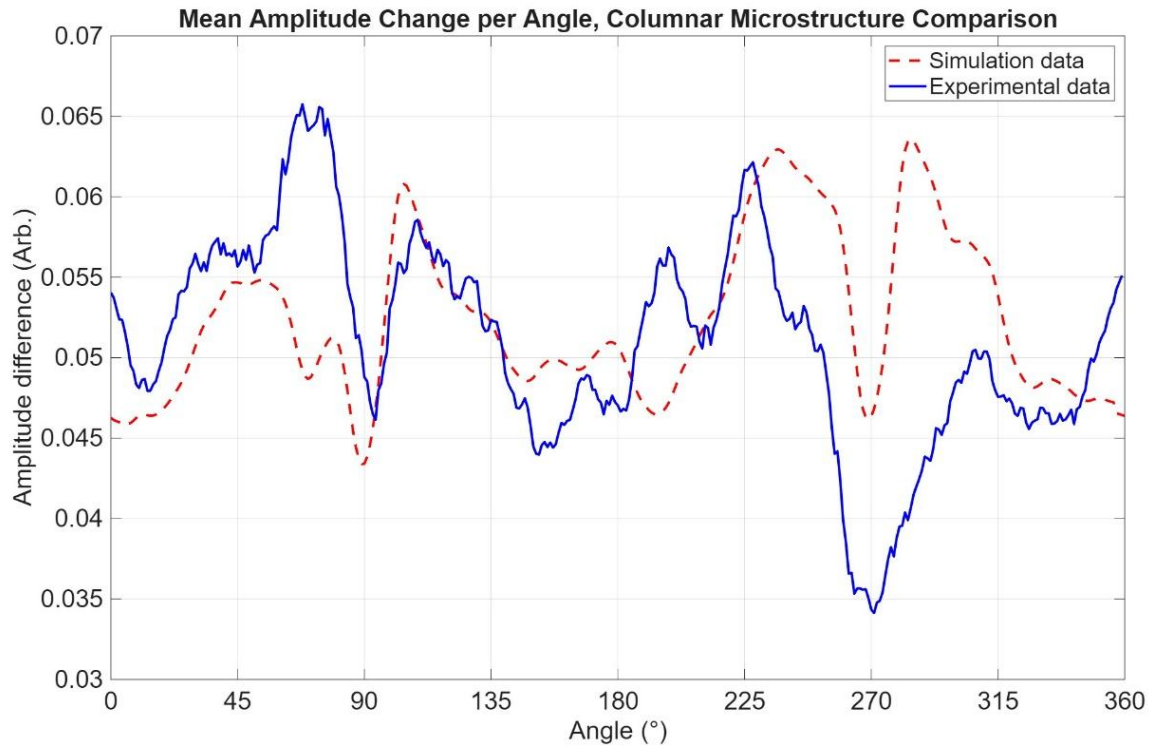


Figure 66: Comparison between the 5 MHz simulated and experimental PA-LCR angular amplitude-change responses in the elongated substrate region. Agreement is assessed using the angular position and relative strength of the main attenuation-related features.

Figure 66 shows that the main simulated and experimental substrate features occur over similar angular regions. The strongest changes are associated with the orientations where the LCR propagation direction aligns relative to the elongated substrate morphology. This agreement supports the interpretation that the measured angular response is linked to the EBSD-defined grain morphology. The match is not exact, particularly in amplitude magnitude, but this is expected because the simulation uses only a representative microstructure and does not fully reproduce the experimental coupling, surface and contact conditions.

The substrate response also shows an approximate 180° periodicity across both simulated and experimental results. This behaviour is consistent with an elongated microstructure, where propagation parallel and antiparallel to the dominant grain direction gives a similar attenuation-related response. In future implementations, this symmetry may allow the angular scan range to be reduced where the initial probe orientation and dominant material direction are already known.

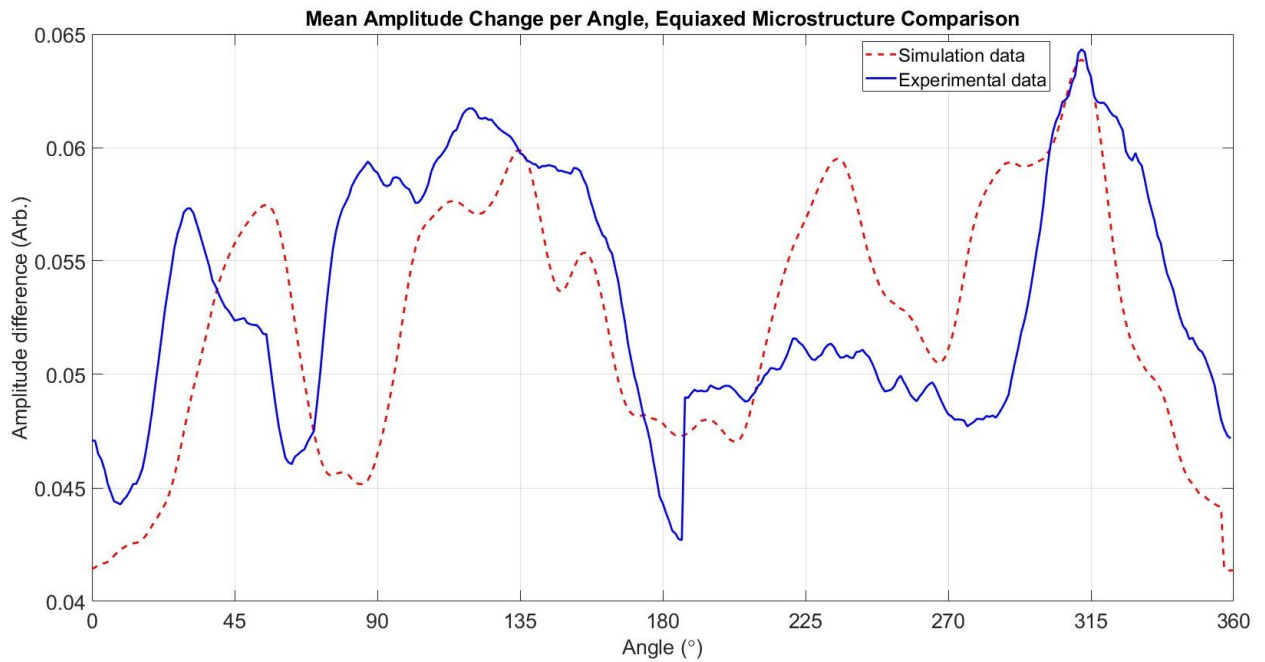


Figure 67: Comparison between the 5 MHz simulated and experimental PA-LCR angular amplitude-change responses in the equiaxed AFSD region. The weaker angular response supports the use of the AFSD region as the reference case for identifying the stronger directionally dependent response in the substrate.

Figure 67 shows that both the simulated and experimental AFSD responses have weaker angular dependence than the substrate response. This is consistent with the comparatively equiaxed EBSD morphology and supports the use of the AFSD region as the reference case. The AFSD result is important because it reduces the likelihood that the stronger substrate response is caused solely by the measurement setup. If wedge rotation, coupling anisotropy, or robot angular error dominated the result, a similar angular pattern would be expected in both regions.

The 5 MHz simulated and experimental amplitude-change responses were compared using the same 1° angular sampling over one complete rotation. For statistical comparison, the 360° point was treated as a duplicate of 0° and excluded, giving 360 unique angular observations between 0° and 359° .

Absolute amplitude was not compared directly because the numerical model does not reproduce the complete experimental transfer function, including probe response, coupling, surface condition and contact force. Each simulated and experimental angular response was therefore normalised independently by subtracting its angular mean and dividing by its angular standard deviation. This retains the relative angular response while removing differences in absolute amplitude scale.

The principal feature angle was defined before comparison as the angle corresponding to the largest absolute deviation of the normalised response from its angular mean. Simulation–experiment angular agreement was then assessed from the signed difference between the experimental and simulated principal-feature angles. The signed angular difference was wrapped to the range -180° to $+180^\circ$,

with positive values indicating that the experimental feature occurred at a greater angular position than the corresponding simulated feature.

Agreement across the complete angular response was assessed using correlation between the normalised simulated and experimental curves. Circular cross-correlation was also used to determine the angular shift giving the greatest correspondence between the two responses. This provides a whole-curve comparison independent of the selection of an individual peak.

The substrate and AFSD results are interpreted separately. The elongated substrate is expected to show a stronger angular response and greater 180° periodicity, while the comparatively equiaxed AFSD region provides a lower-anisotropy material comparison. The AFSD measurement was acquired using the same wedge, probes, rotation procedure and processing method as the substrate and therefore provides useful evidence against a purely apparatus-driven angular response. It does not constitute an independent apparatus baseline because it remains a material measurement with its own microstructural response.

A dedicated isotropic calibration specimen or apparatus-only rotational baseline was not acquired during the original experiment. The experiment was completed twice per microstructure geometry and an average taken. The experiment was only performed clockwise. Repeat-scan uncertainty and apparatus-baseline angular variation therefore cannot be quantified retrospectively. The numerical comparisons reported here quantify agreement between the retained simulated and experimental angular responses; they do not establish the repeatability or absolute angular accuracy of the robotic measurement. Dedicated repeat rotations and an isotropic apparatus baseline are required for subsequent quantitative PAURS+ qualification.

Several non-microstructural effects may still contribute to the measured amplitude response. These include coupling variation during rotation, contact-force changes, local surface roughness, and robot angular positioning error. The present comparison reduces the likelihood that these effects dominate the interpretation by comparing two EBSD-defined regions using the same inspection procedure and by considering agreement in terms of angular trend and relative contrast. For this reason, the PAURS+ output is treated as a descriptor of near-surface microstructural anisotropy, with basic orientation of elongated grains identifiable with further processing.

The 5 MHz simulation and robotic measurements show that the attenuation-related angular signature identified in simulation remains measurable under practical PA-LCR conditions. The elongated substrate gives a stronger and more repeatable angular response than the equiaxed AFSD region, and the main angular features are consistent with the EBSD-defined grain morphology. Together with the frequency-sensitivity study, this supports PAURS+ as a microstructure-sensitive extension of PAURS.

5.3.3. What PAURS+ establishes for microstructure-sensitive characterisation

PAURS+ extends the PA-LCR approach from stress-calibrated ToF measurement to microstructure-sensitive characterisation. Here, amplitude change and attenuation-related angular response are used as descriptors of near-surface microstructural anisotropy.

The main outcome is that amplitude change provides the clearer PAURS+ descriptor in this study. The 10 MHz and 32 MHz simulations show stronger angular amplitude variation in the elongated substrate than in the comparatively equiaxed AFSD region, with the contrast becoming more pronounced as wavelength decreases. ToF also varies in the simulations, particularly at higher frequency, but it provides a less direct microstructure-sensitive descriptor than the amplitude response and is treated as a supporting feature for LCR arrival stability and signal consistency.

The 5 MHz simulation and robotic measurements show that an attenuation-related angular response remains measurable under the practical PA-LCR condition used experimentally. The elongated substrate produces the stronger and more repeatable angular response, while the AFSD region shows weaker angular dependence. Because both regions were inspected using the same wedge, probe configuration, and robotic rotation procedure, this contrast supports the interpretation that the measured angular response is linked to the EBSD-defined grain morphology.

The present PAURS+ output should be treated as a qualitative to semi-quantitative indicator of near-surface microstructural anisotropy. Agreement between simulation and experiment is judged from angular trend, feature position, relative response, and substrate/AFSD contrast. This scope is appropriate because the simulation uses representative EBSD-informed microstructures, while the experimental measurements include contact, coupling, bandwidth, SNR, and robotic positioning effects.

These results define PAURS+ as a bounded use of the same PA-LCR platform developed for residual stress measurement to perform microstructure-sensitive angular characterisation. Quantitative grain-size measurement, full texture reconstruction, and closed-loop in-process deployment remain future work, but the present results establish the measurement basis for developing PAURS+ beyond the initial validation stage.

6. Conclusions

This thesis establishes an FMC-based PA-LCR methodological framework for residual stress measurement, and related microstructure characterisation. The residual stress implementation, termed PAURS, combines calibrated ToF stress calculation, multi-path FMC processing, couplant-error control, signal-quality assessment, and comparison with independent residual stress measurement methodologies to determine when ultrasonic outputs support numerical stress calculation or trend-based stress interpretation. PAURS+ extends the same platform towards microstructure-sensitive indication by using amplitude- and attenuation-related angular responses as additional descriptors. Figure 68 summarises the overall doctoral contribution of this thesis.

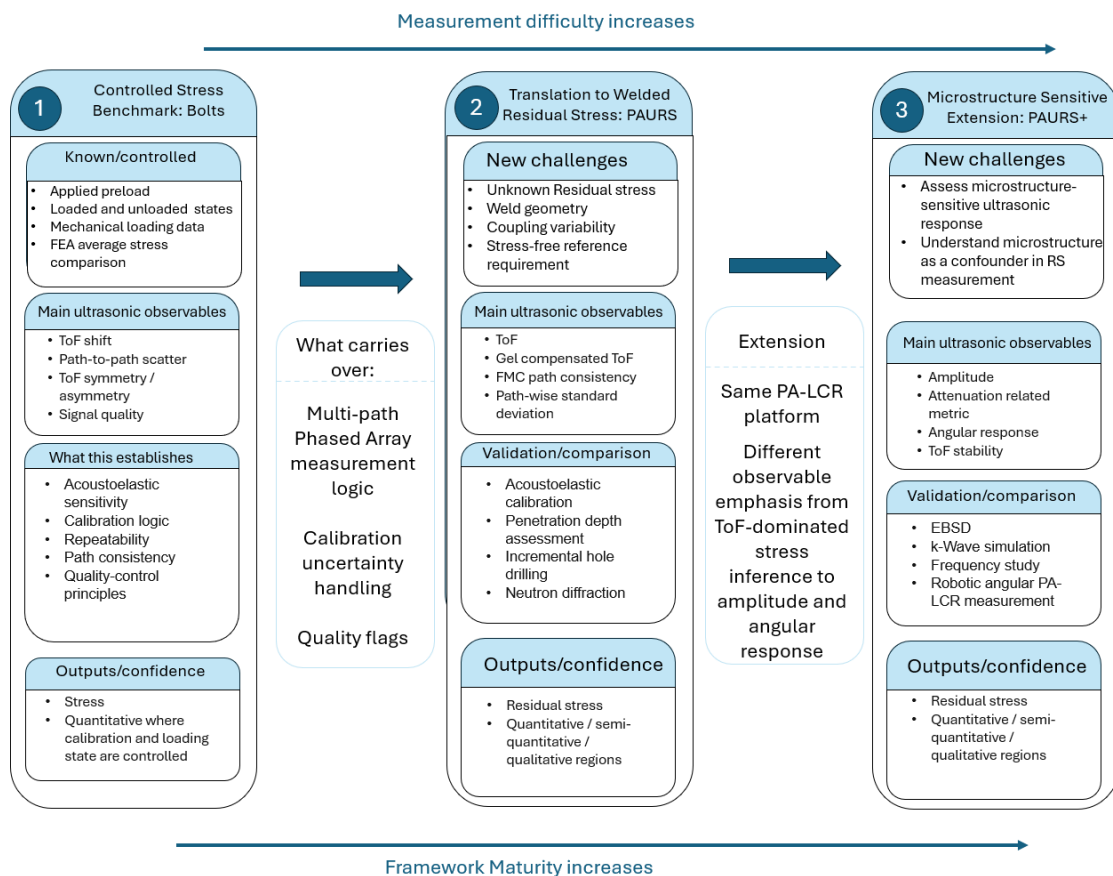


Figure 68: Final synthesis of the phased-array ultrasonic measurement framework developed in this thesis. The framework progresses from the controlled-stress bolt benchmark, to welded residual-stress measurement using PAURS, and finally to PAURS+ microstructure-sensitive characterisation.

The contributions to knowledge established through this thesis are revisited here in relation to the evidence developed across the three experimental stages. The method becomes more complex at each stage: the bolt benchmark uses a controlled applied load, the welded PAURS study introduces unknown residual stress, weld geometry, coupling variability and non-identical comparison volumes, and PAURS+ introduces microstructural anisotropy as both a measurable material-state feature and a potential confounding influence in ultrasonic RS measurement. Across these stages, the common

contribution is the combined use of phased-array LCR waves with FMC-based path redundancy to support averaging, compensation, path selection, and confidence assessment.

The controlled bolt study demonstrated that phased-array ultrasonic inspection can resolve preload-sensitive ToF changes while also retaining path-wise information for defect-aware inspection and measurement-quality assessment. Comparison with FEA-derived average axial stress provided a mechanically compatible calibration route, and the high-preload tests showed that broadening or asymmetry in the path-wise ToF distribution marks reduced confidence in a single averaged stress estimate. In the blind M42 transfer test, the ultrasonic stress estimate was within approximately 10.9% of the mathematically derived comparator stress, providing evidence of the transferability of the calibrated procedure to a larger representative bolt under restricted access conditions.

The couplant and timing-error study quantified one of the main practical uncertainty sources in PAURS. Because PAURS calculates residual stress from nanosecond-scale time-of-flight changes, variation at the wedge–specimen interface can produce apparent stress changes that are unrelated to the material stress state. The simulation and shim-based experimental results showed that couplant gel thickness can introduce significant timing errors. The adjacent-receiver compensation approach reduced the mean residual gel-induced ToF difference to approximately 0.3 ns across the controlled shim experiments, corresponding to approximately 1.1 MPa in stress-equivalent terms. This result quantifies the remaining coupling-related contribution under the tested conditions and demonstrates the use of phased-array path redundancy for targeted timing-error compensation. Temperature and other systematic contributions remain separate from this coupling-specific result and require further quantification before a complete PAURS uncertainty budget can be established.

PAURS uncertainty arises from the combined effects of acoustoelastic calibration, reference-state selection, couplant variation, temperature, acoustic-path selection, probe positioning and material state. Of these, couplant variation was quantified experimentally: adjacent-receiver compensation reduced the mean residual ToF error to approximately -0.27 ns, corresponding to approximately -1.1 MPa under the calibration used here, with the largest plate-mean residual approximately -0.57 ns (-2.3 MPa). These values represent coupling-specific residual bias, not total PAURS uncertainty. Temperature, reference-state bias, positioning/reseating effects and microstructural contributions were not independently quantified in the retained dataset and remain systematic limitations. FMC path-wise variation provides an internal measure of precision but does not remove common-mode bias. An overall uncertainty of ± 30 MPa is estimated based on experimental factors, comparison to HD measurements on the same sample, and general confidence based upon uneven weld cap/root geometry in key inspection zones.

The PAURS study demonstrated calibrated near-surface residual stress calculation in welded S275 steel using phased-array transducers in a pitch–catch PA-LCR configuration. The method gave its

strongest quantitative evidence where the measurement conditions were most favourable, particularly on the bottom surface of the welded specimen where the simpler geometry supported a more stable wedge–specimen interface and stronger agreement with the ND trend in the HAZ and weld-root region. On the top surface where the scan path crossed the weld cap, the result is more appropriately treated as a qualitative reproduction of the near-surface tensile stress trend. In this region, irregular cap geometry degraded wedge contact and reduced LCR signal quality, thus making the repeatable timing reference less distinct. The difference between the top-surface PAURS and ND magnitudes is therefore interpreted within the comparison limits of the experiment: ND was performed on a nominally identical replicate specimen and sampled a finite gauge volume, while the same-specimen HD result at a comparable near-surface depth supported the approximate PAURS weld-centre magnitude. FMC was central to this interpretation, reducing the standard deviation across acoustic paths by approximately 5–10× compared with matched linear paths and providing an internal consistency measure for each calculated stress value. These results support PAURS as a laboratory-stage near-surface residual stress measurement procedure under defined quality conditions and comparison between established methodologies.

PAURS+ showed that the same PA-LCR configuration can also provide microstructure-sensitive angular information when amplitude and attenuation-related response are analysed alongside EBSD and simulation. The 10 MHz and 32 MHz simulations showed that amplitude change was more sensitive than ToF to the contrast between the equiaxed AFSD region and the elongated-grain substrate. The 5 MHz simulations and robotic measurements then showed that the attenuation-related angular signature remained measurable using the available experimental hardware: the elongated-grain substrate produced the stronger and more direction-dependent response, while the equiaxed AFSD region produced a weaker and more stable response. PAURS+ should therefore be treated as a descriptor of near-surface microstructural anisotropy with basic orientation characterisation capabilities, rather than as direct grain-size, texture, or morphology reconstruction.

Within the conditions investigated, the most mature outputs are the phased-array bolt inspection workflow, the gel-compensation for PA-LCR, and the PAURS near-surface residual stress calculation procedure for laboratory welded specimens. These are usable as controlled measurement procedures where surface and coupling condition, calibration, and signal-quality requirements are managed. The work does not yet represent a qualified industrial residual stress inspection method across arbitrary materials, geometries, or service environments, with key limits of coupling stability, weld geometry, and positioning variability defining whether a calculated stress value or extracted microstructure-sensitive descriptor should be treated as numerical, semi-quantitative, or qualitative.

Future qualification should use repeated measurements across a minimum of five specimens for each material and geometry, with at least three independent lift-and-reseat measurements at each validation

position. Temperature compensation should be established before stress conversion, with same-specimen residual-stress measurements used as the primary external comparator. PAURS+ qualification should additionally include an approximately isotropic reference specimen to establish the rotational apparatus baseline. Proposed exit criteria are an LCR SNR of at least 12 dB, retention of at least 75% of candidate FMC paths, path-wise stress standard deviation below 10 MPa, reference-ToF drift below 0.5 ns, and a combined expanded stress uncertainty below 20 MPa under the qualified inspection condition. For increased repeatability, robotic measurement should be used where possible.

Longer-term work should extend PAURS+ through systematic comparison with EBSD, diffraction, or metallography across multiple alloys and grain structures, with the aim of separating grain morphology, texture, porosity, and residual stress contributions to PA-LCR observables. In-process and closed-loop robotic monitoring should follow this qualification work rather than precede it. Such a validation programme would also generate the dataset required for longer-term machine-learning-assisted quality classification or automated RS monitoring.

Overall, the thesis shows that phased-array ultrasonics can strengthen residual stress measurement by replacing reliance on a single ToF value with calibrated PA-LCR observables, FMC-based multi-path analysis, uncertainty control, and measurement-quality evidence. The principal contribution is a staged FMC-based phased-array measurement route established through a controlled bolt benchmark, translated to welded S275 residual stress measurement, and extended through PAURS+ for near-surface microstructure-sensitive angular characterisation. Broader industrial use now depends on qualification across larger validation datasets, more varied geometries and materials, and automated quality-control thresholds.

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Appendix A

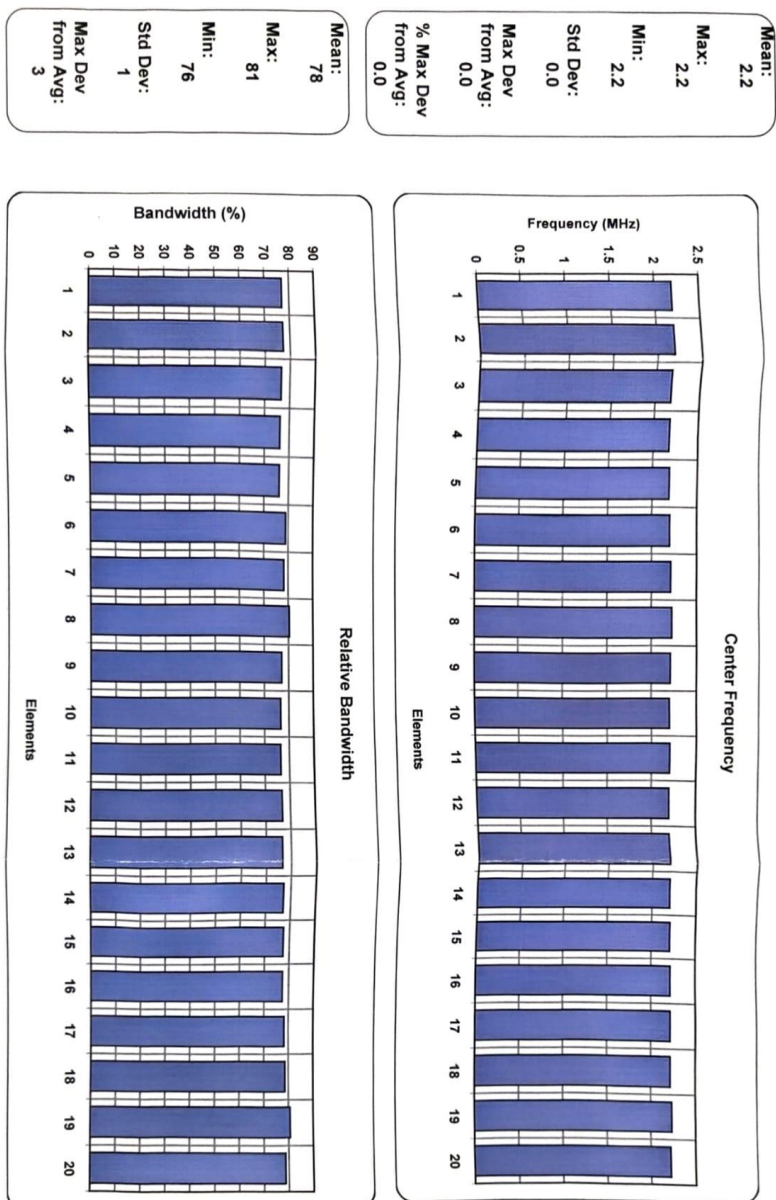
Sonatest 20 Element 2.25 MHz Transducer Datasheet

Detachable Active Array Head (DAAH) Test Report



Probe Model: D1B-2.25M20E-1.2x12 (D1B-001)
 File Name: 41498.txt
 Test Date/Time: 12/5/22 5:23 AM
 Operator: 1111

Number of Elements: 20
 Probe Type: AT29037-1122-6924
 Serial Number: 0162
 Last System Calibration: Dec-21



Detachable Active Array Head (DAAH) Test Report



Probe Model: D1B-2.25M20E-1.2x12 (D1B-001)
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 Probe Type: AT29037-1122-6924
 Serial Number: 0162
 Last System Calibration: Dec-21

PASS

	Lower Limit	Upper Limit	Value	Pass/Fail
Center Frequency Average (MHz)	2	2.5	2.2	PASS
Center Frequency Minimum (MHz)	2	--	2.2	REF ONLY
Center Frequency Maximum (MHz)	--	2.5	2.2	REF ONLY
Bandwidth Average (%)	70	--	76	PASS
Bandwidth Minimum (%)	70	--	76	PASS
-20dB Ringdown Average (µs)	--	0.650	0.552	PASS
-20dB Ringdown Maximum (µs)	--	0.650	0.568	PASS
Sensitivity Average (dB)	-39.00	--	-36.88	PASS
Sens. Dev. From Avg. (dB)	--	3	1.49	PASS

Imasonic 8 Element 5 MHz Transducers Datasheet



CERTIFICATE of CONFORMANCE

REFERENCE DOCUMENT	CdC 06041-8
PROJECT #	06041
SERIAL #	1001

Checking of Acoustical Performance

	Unit	Acceptance criteria	Value	Conformity
Central Frequency (-6dB)	(MHz)	[4.5;5.5]	5.0	YES
Bandwidth (-6dB)	(%)	≥ 60	66	YES
Pulse Duration (-20dB)	(ns)	≤ 600	454	YES
Sensitivity	(mV)	/	166	/
Sensitivity Homogeneity	(dB)	6	1.3	YES

Checking of Elements Wiring

Element wiring order	YES
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OVERALL CONFORMITY YES

**QUALITY CONTROL
APPROVED BY**

Amaud SPITZ

17/06/2021

PHASED ARRAY PROBE SPECIFICATIONS

Piezocomposite technology



CUSTOMER reference:

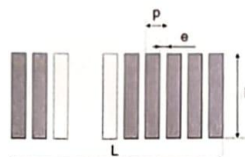
IMASONIC reference:

CDC6041-8

ACOUSTICAL CHARACTERISTICS ACCEPTANCE LEVEL

Array type: linear array
Number of channels: 8

Mechanical focusing: none, flat active area
Elementary pitch (p): 0.5 mm
Inter element spacing (e): 0.1 mm
Width of the element (h): 4 mm
Total active length (L): 3.9 mm



Acoustic design ☒ Versatile ☐ Dynamic ☐ Accuracy ☐ Hard face ☐ Custom

Centre frequency (-6dB): 5 MHz $\pm$ 10% ⁽¹⁾ ⁽²⁾

Matching layer Front face with improved resistance for use in direct contact

Pulse Duration (-20dB) : < 600 ns ⁽¹⁾ ⁽²⁾

Bandwidth (-6dB): $\geq$ 60 % ⁽¹⁾ ⁽²⁾

⁽¹⁾ Measurement conditions described in performances measurement and test paragraph

⁽²⁾ Average value calculated on all the elements

MECHANICAL CHARACTERISTICS

Housing: Stainless steel
Geometry: According to drawing 6041D 01 000 02
Interface for wedge attachment: None
Cable output: On the side near the element 1, close to the top of the probe

INTERCONNECTIONS:

Cable: 50 Ω Multi-coaxial with overall shielding
Protective jacket: none
Length: 3.0 m $\pm$ 0.1 m
Connectors: Item 6041XCR01 : Ipex Latch
Item 6041XCR02 : Hypertronics
Pinout diagram: standard

Other specification according to "Linear phased array probes standard specifications-revision 6" attached

MicroPulse 6PA Phased Array Channels

Parameter		Range	Step Size
Configurations		32/64, 64/128, 128/256 and 256/512	
Pulser	Pulser Type	Negative square wave	-
	Pulser Voltage	50 to 200Volts	50Volt
	Pulser Rise Time	<5ns	-
	Pulser Width	20nsec to 500nsec	2nsec
	Pulser Output Impedance	<10Ω	-
	Pulser Damping	100Ω	-
	Pulse Repetition Frequency	1Hz to 55kHz**	1Hz
	Parallel Firing	Yes	-
	Phased Array Pulser Delay	0 to 25000nsec	1nsec
	Number of Tx Focal Laws	Up to 2048	-
Receiver	Gain	70dB	0.25dB
	Gain Linearity	Better than 0.25dB	-
	Input Impedance	100Ω	-
	Bandwidth	0.75MHz to 20MHz (-3dB)	-
	Analogue Filters	0.75MHz to 5MHz (-3dB) Bandpass 5MHz to 10MHz (-3dB) Bandpass 2MHz to 10MHz (-3dB) Bandpass	Discrete selection
	Digital Filters	Programmable high and low pass	User definable
	Phased Array Receiver Delay	0 to 25000nsec	1nsec
	Number of Rx Focal Laws	Up to 2048	-
	Dynamic Depth Focusing	At 100MHz realtime	-
	Channel Crosstalk	>60dB between channels at 2MHz	-
Distance Amplitude Correction	DAC Dynamic Range	0 to 60dB*	0.25dB
	DAC Trigger	Transmit pulse or material interface echo	Selectable
	No of DAC curves	2048 utilising up to 64kbytes	N/A
	DAC update	40dB/μsec	N/A
Digitiser and Digital Processing	DAC Clock	0.78125MHz, 1.5625MHz, 3.125MHz, 6.25MHz, 12.5MHz and 25MHz selectable	6 settings (selectable)
	ADC Resolution	12 bits	N/A
	Amplitude Resolution	16 bits	N/A
	Sample Rate	10, 25, 50 and 100MHz	Selectable
	Number of ADC's	One per 2 channels (128 in a 256 system)	N/A
	Element Summing	Up to 512 channels	N/A
	Acquisition Gate Delay	64k sample points from trigger or I/F echo	1 sample point
	Acquisition Gate	Up 32K sample points (Conventional PA) In FMC up to 8K samples points	1 sample point
	Rectification	No Rectification Fullwave +ve halfwave -ve halfwave	Selectable
	Smoothing	None and 10 selectable settings	N/A
	Hardware Gates	4 gates utilising up to 32K samples each (Conventional PA)	N/A
	Interface Echo	Hardware interface trigger for gate and DAC	N/A
	Hardware Peak Processing	For each gate up to 80 peaks (N + largest), first peak, largest peak, threshold crossing (N/A for FMC)	N/A
	Output Options	Peak processed data and/or full digitised waveform	N/A
	Threshold	10 to 4095	1
	Averaging	2 to 256 realtime; 2 to 8 realtime for FMC	N/A
	Gain Reduced Firing	Selectable to be triggered on saturation with programmable adjustment level	N/A

MicroPulse 6PA Conventional Channels

Parameter		Range	Step Size
Configurations		12, 24 channels	
Pulser	Pulser Type	Negative square wave	-
	Pulser Voltage	50 to 300Volts	50Volt
	Pulser Rise Time	<5ns	-
	Pulser Width	16nsec to 1010nsec	2nsec
	Pulser Output Impedance	<10Ω	-
	Pulser Damping	50Ω too 660Ω in 8 steps	-
	Pulse Repetition Frequency	1Hz to 55kHz*	1Hz
	Parallel Firing	Yes	
Receiver	Gain	70dB*	0.25dB
	Gain Linearity	Better than 0.25dB	N/A
	Input Impedance	660Ω	N/A
	Bandwidth	0.75MHz to 25MHz (-3dB)	N/A
	Analogue Filters	0.75MHz to 12MHz (-3dB) Bandpass	Discrete selection
		2.5MHz to 18MHz (-3dB) Bandpass	
		3MHz to 22MHz (-3dB) Bandpass	
		3MHz to 25MHz (-3dB) Bandpass	
		0.5MHz Bandpass Filter	
		1MHz Bandpass Filter	
		2MHz Bandpass Filter	
		4MHz Bandpass Filter	
		5MHz Bandpass Filter	
		10MHz Bandpass Filter	
		5MHz 2nd order TOFD Bandpass Filter	
		10MHz 2nd order TOFD Bandpass Filter	
	Digital Filters	Programmable high and low pass	User definable
	Channel Crosstalk	Better than 60dB between channels at 2MHz	
Distance Amplitude Correction	DAC Dynamic Range	0 to 60dB*	0.25dB
	DAC Trigger	Transmit pulse or material interface echo	User selectable
	No of DAC curves	256 utilising up to 64kbytes	N/A
	DAC update	40dB/μsec	N/A
	DAC Clock rate	0.78125MHz, 1.5625MHz, 3.125MHz, 6.25MHz, 12.5MHz and 25MHz selectable	
Digitiser and Digital Processing	ADC Resolution	12 bits	N/A
	Amplitude Resolution	Up to 12 bits	
	ADC Rate	10, 25, 50 and 100MHz	N/A
	Number of ADC's	One per 6 channels	
	Acquisition Gate Delay	64k sample points from trigger or interface echo	1 sample point
	Acquisition Gate	Up 32K sample points	1 sample point
	Rectification	No Rectification	Discrete selection
		Fullwave	
		+ve halfwave	
		-ve halfwave	
	Post Rectification Filter (Ascan smoothing)	None and 10 selectable settings	User selectable
	Hardware Gates	4 gates utilising up to 32K samples each	
	Interface Echo	Hardware interface trigger for gate and DAC	Selectable
	Hardware Peak Processing	For each gate up to 80 peaks (N + largest), first peak, largest peak, threshold crossing	

Parameter	Range	Step Size
Peak Threshold	10 to 4095	1
Averaging	2 to 256 realtime	
Gain Reduced Firing	Selectable to be triggered on saturation with programmable adjustment level	

General Specifications

Interfaces	Communication Interface	Gigabit Ethernet capable of up to 120MB/s
	Digital Encoders	4 axes of differential 32-bit encoder inputs accepting 5Volt encoders at rate of up to 700kHz
	Digital I/O	16 TTL inputs and 16 TTL outputs
	Analogue Outputs	Trigger, Gate, A-scan
Connectors	Phased Array Connectors	Two 160-pin female connectors. Hypertronics™ HLMYJPAPF1600
	Conventional UT Connector	12 Coaxial Lemo 00
	Ethernet Connector	Industrial RJ45 / 9-pin D-type
	LVDS Master/Slave	1 x high speed EQDP connector
	Encoder Connector	Lemo Lemo 4B.330
	I/O Connector	2 x Lemo 4B.324
	Power Connector	Switched IEC Inlet
	Analogue O/P Connectors	3 x 50Ω BNC
	Trigger I/P Connectors	1 x 50Ω BNC
Physical	Case Size (D x W X H)	380x450x180mm
	Power Supply	100-240V, 50-60Hz
	Power Consumption	300W Max
	Weight	14kg
Environmental	Operating / Storage Conditions	Operating Temperature: 0 to 45°C Storage Temperature: -10 to 55°C Relative Humidity: less than 85% non-condensing
	EMC	EN61326
	Safety	EN61010

Argoshield Heavy Datasheet

25-W		25-E50		25-WW		25-WZ	
Cylinder Size	Large	Large		15-cylinder pack		15-cylinder pack	
Contents Volume (m³)	11.84	16.8		177.6		252	
Water Capacity (litres)	46.6	50		15 x 46.6L		15 x 50L	
Gross Weight Full (kg)	86	96		1500		1500	
Dimensions HxD (mm)	1460 x 230	1760 x 230		1810 (L) x 840 (W) x 1290 (H)		2058 (L) x 870 (W) x 1230 (H)	
Pressure at 15°C (bar)	230	300		230		300	
Valve Type	Standard	Lever		Standard		Standard	
Valve Outlet Connection	BS 341 No.3	BS 341 No.30		BS 341 No.3		BS 341 No.30	
Valve Outlet Specification	5/8" BSP female right hand cone recessed at 230 bar	1/4" NPT male		5/8" BSP female right hand cone recessed at 230 bar		1/4" NPT male	
Gas Composition	78% Ar, 20% CO ₂ , 2% O ₂	78% Ar, 20% CO ₂ , 2% O ₂		78% Ar, 20% CO ₂ , 2% O ₂		78% Ar, 20% CO ₂ , 2% O ₂	