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BINDT THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

University of Strathclyde Glasgow

Gap Bridging Between Simulated and Experimental Ultrasonic Guided Waves Signals For Liquid Flow Front Estimation

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UKRI Engineering and Physical Sciences Research Council

NMIS National Manufacturing Institute Scotland

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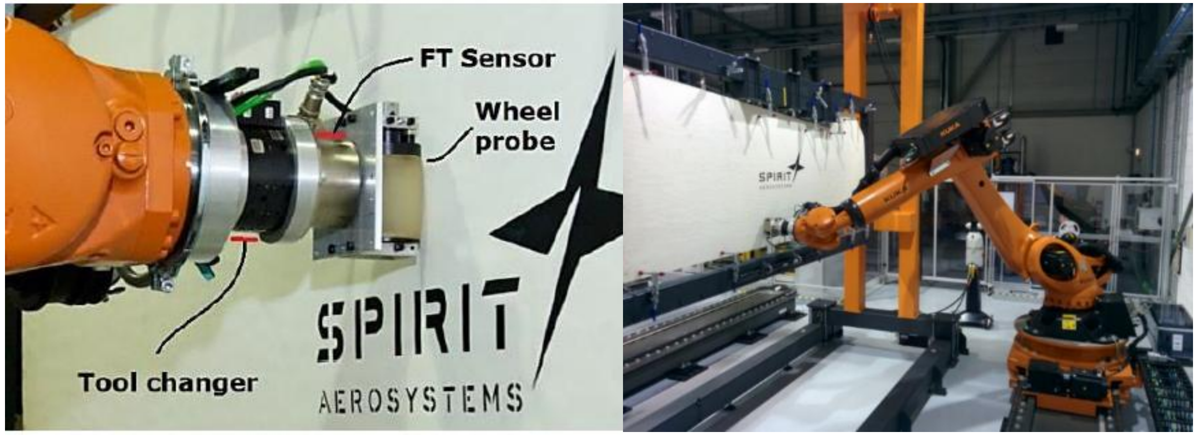
SEARCH Sensor Enabled Automation Robotics & Control Hub

Introduction to SEARCH

- More demand from robotic systems to perform in-loop adaptive behaviour.
- Industry 4.0 requires data driven approaches for manufacturing and asset management.



Flexible robotics inspection for ***composites*** *at AFRC with high speed ultrasonic NDT – up to 40 m^2 / hour rate*

Fully automated robotic ***welding*** *with integrated NDT for complex multipass welds in high integrity materials*

- Multiple types of sensors required for robot feedback and control.
- New approach required to integrate robotics and sensing (encoding the human perception of "*sense and response*" into measurement processes).

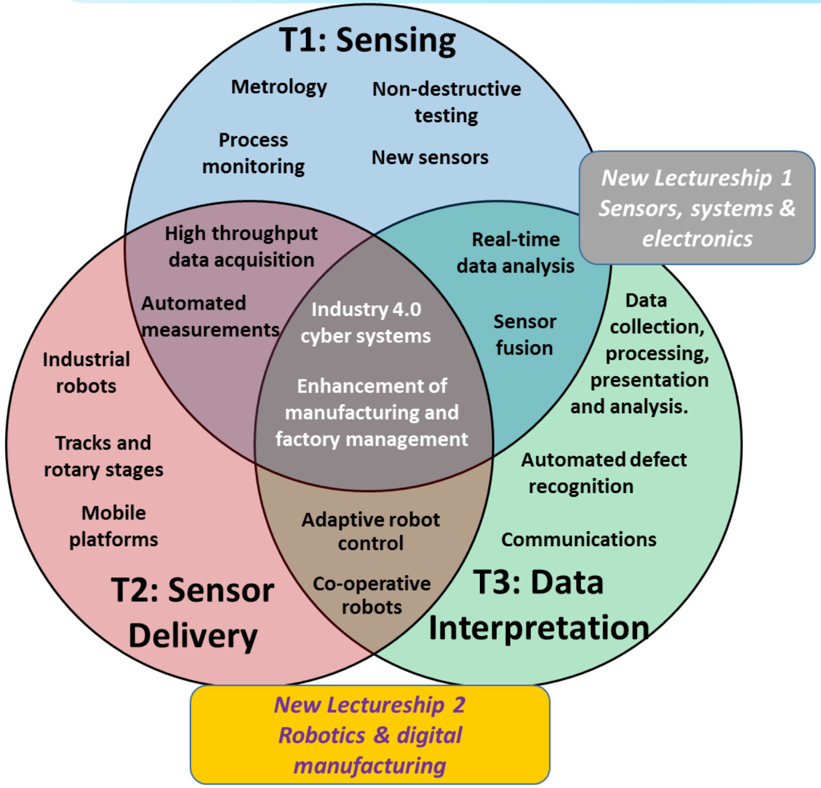
SEARCH

Sensor Enabled Automation Robotics & Control Hub

Our Team & Research Focus

Centre for Ultrasonic Engineering (CUE):

- >30 years of knowledge and history in the field.
- 13 academics and more than 100 staff.
- Founding member of Research Centre in Non-Destructive Evaluation (RCNDE UK)



Research themes:

- ***Sensing***: Advanced NDE sensor development.
- ***Sensor Delivery***: Leveraging state of the art robotics.
- ***Data Interpretation***: Automating data analysis workflows.

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Towards Out-of-Autoclave

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Current method:

- Preformed prepregs
- Curing in **autoclaves**
- Controlled resin and fibre content

- Complex infrastructure
- Energy-consuming
- Limited part complexity

[1]

[2]

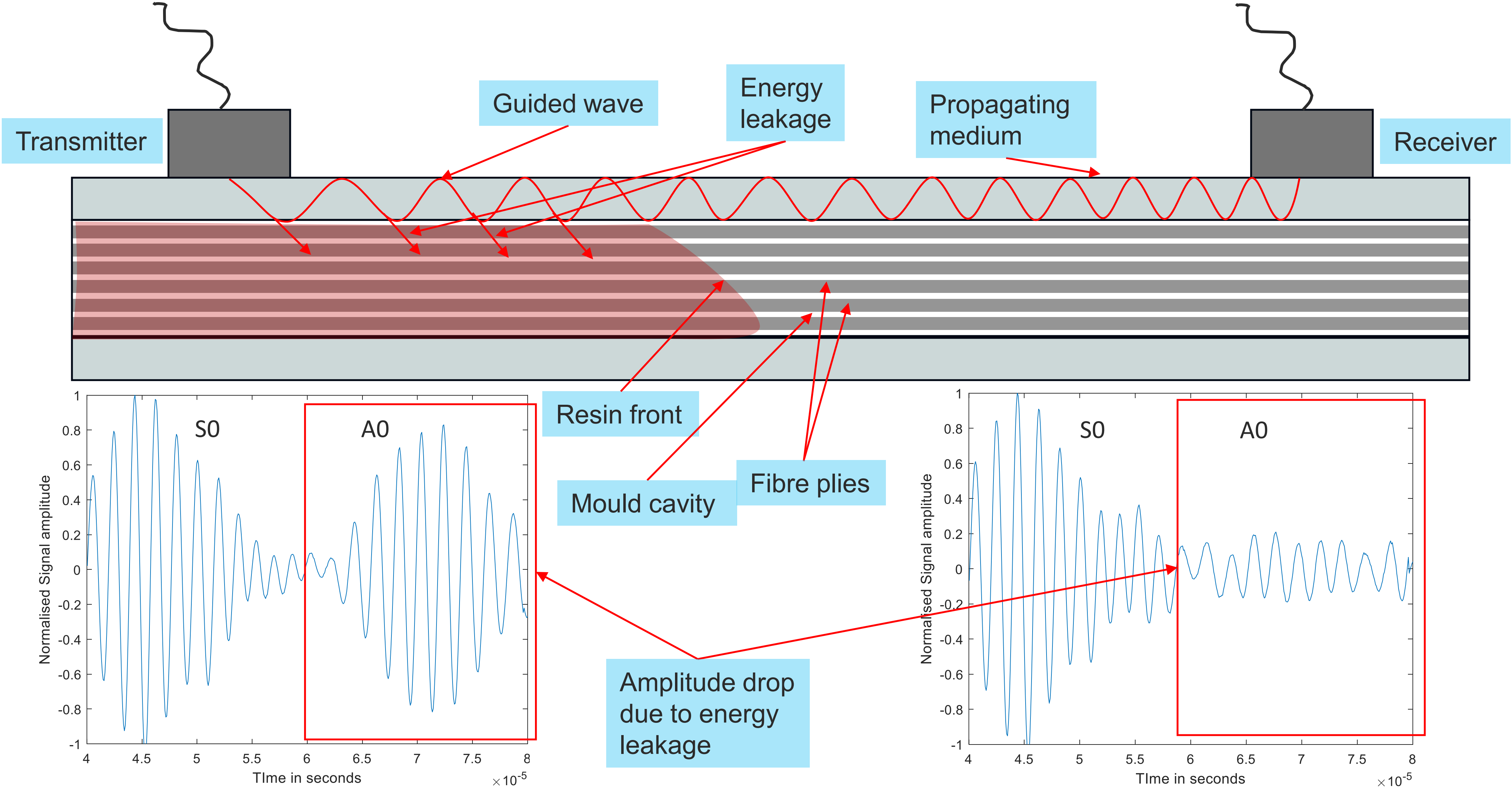
Russia's Aero Composite and Boeing reported a 20-40% price reduction by using OoA processes [3]

Alternative:

- Use of dry fabrics
- Infusion with resin
- Curing done **out-of-autoclave (OoA)**
- Sustainable and affordable

- Lack of research
- Uncontrolled resin flow
- Lower pressures

Ultrasonic Guided Waves



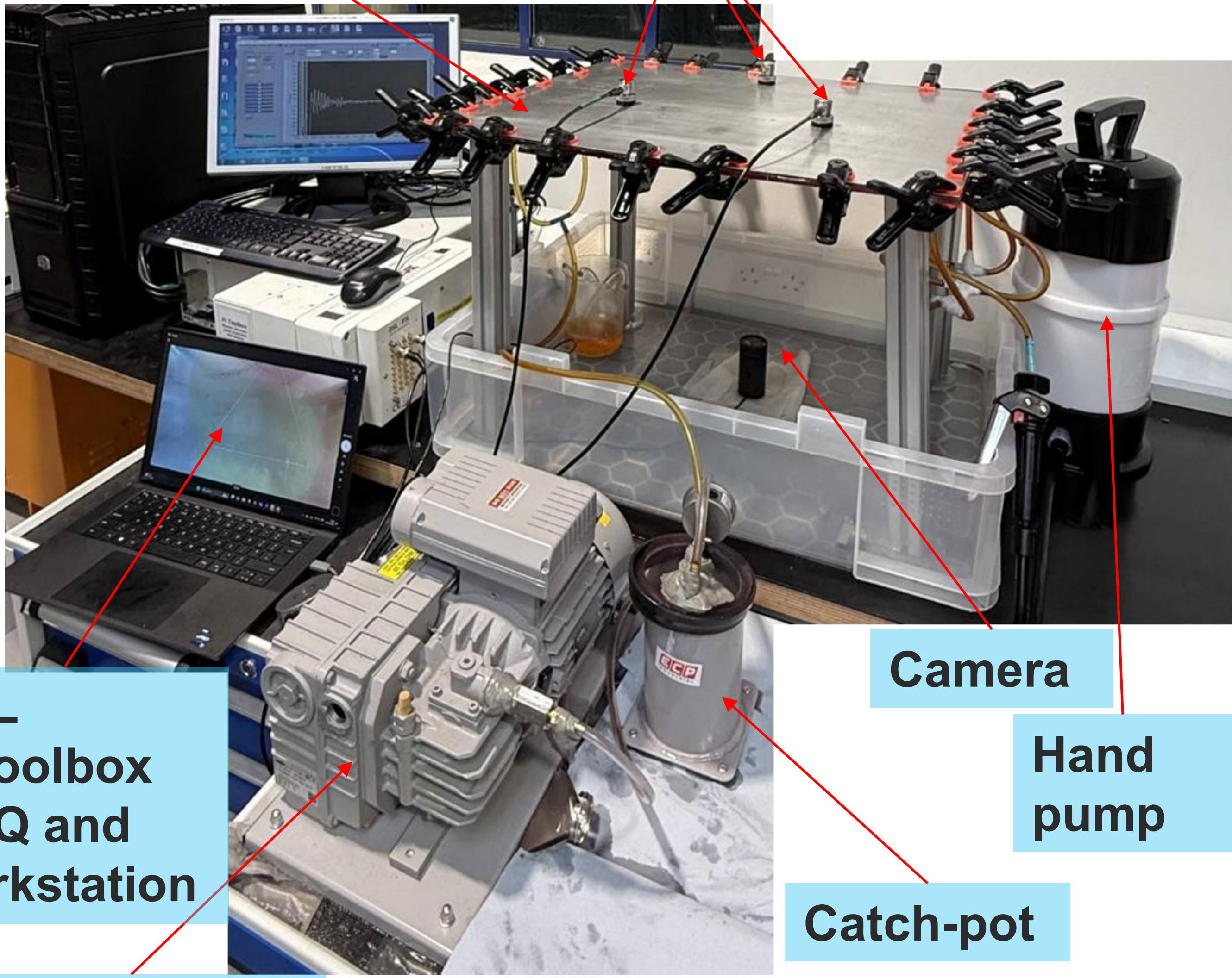
Experimental Setup

Methodology:

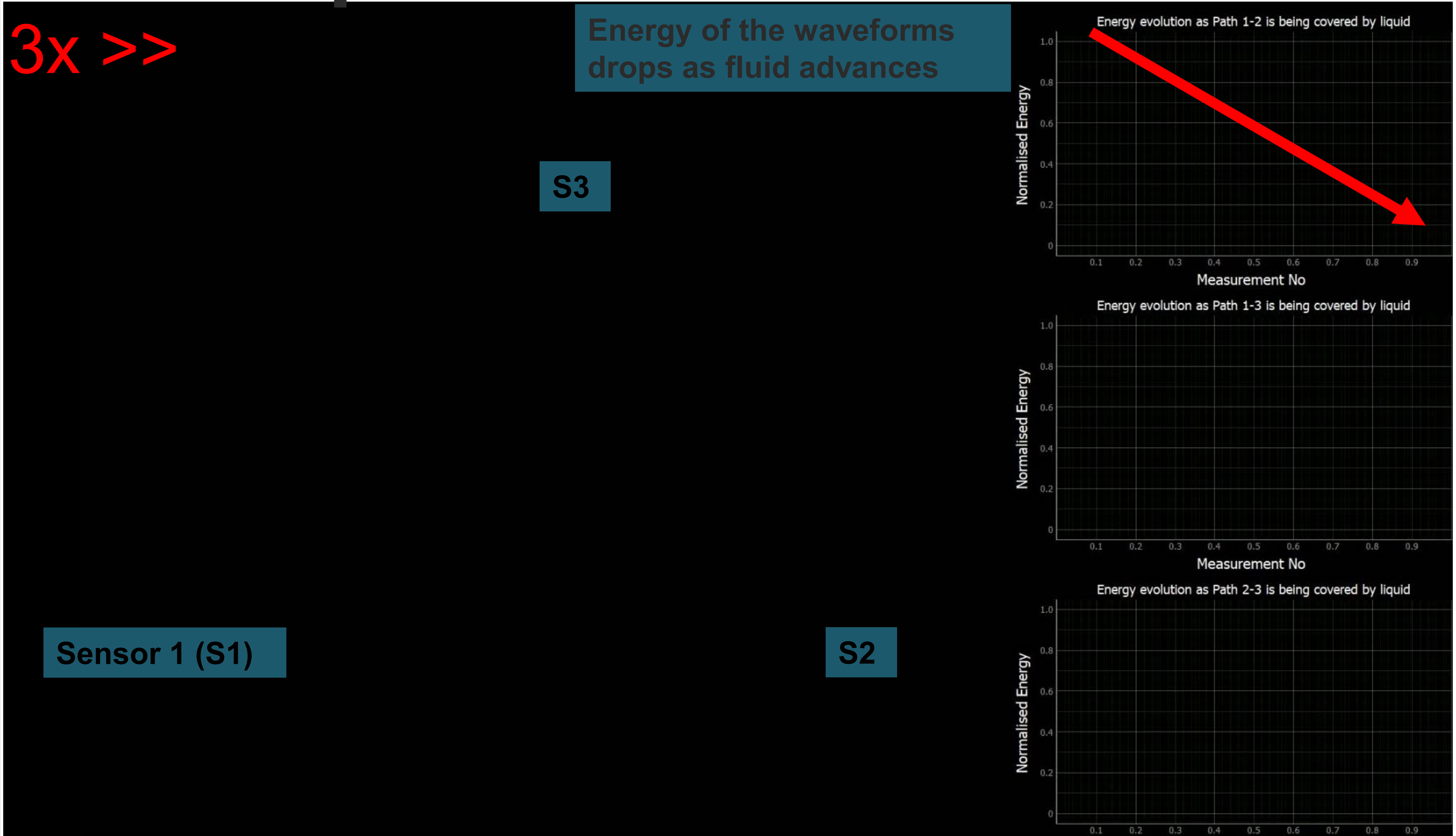
- Simple infusion setup
- Hand pump used to advance the fluid
- Measurements taken by DAQ every second
- Remove oil using a vacuum pump and catch-pot

Experimental parameters:

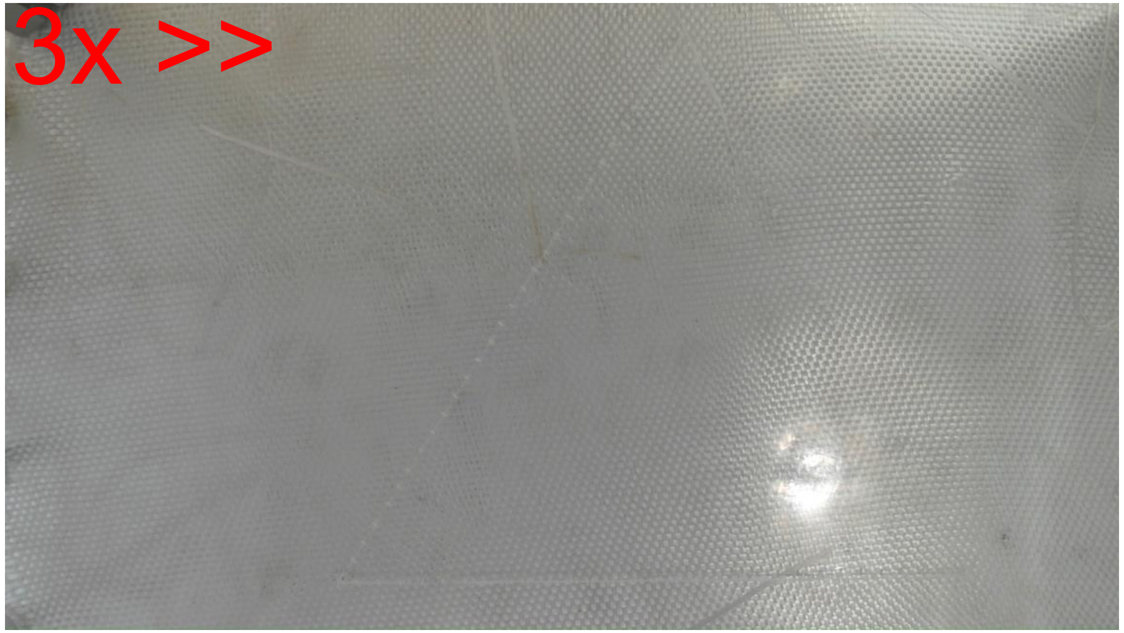
- 500kHz single element Sonatest ultrasonic piezoelectric sensors.
- **Tx:** 60V 5-cycle square pulse train
- **Gain:** 52dB, fixed
- **Temporal range:** 80μs
- **Sampling frequency:** 12.5MHz
- **No of samples:** 1000



Data Acquisition



Experimental Setup (Why liquid only?)

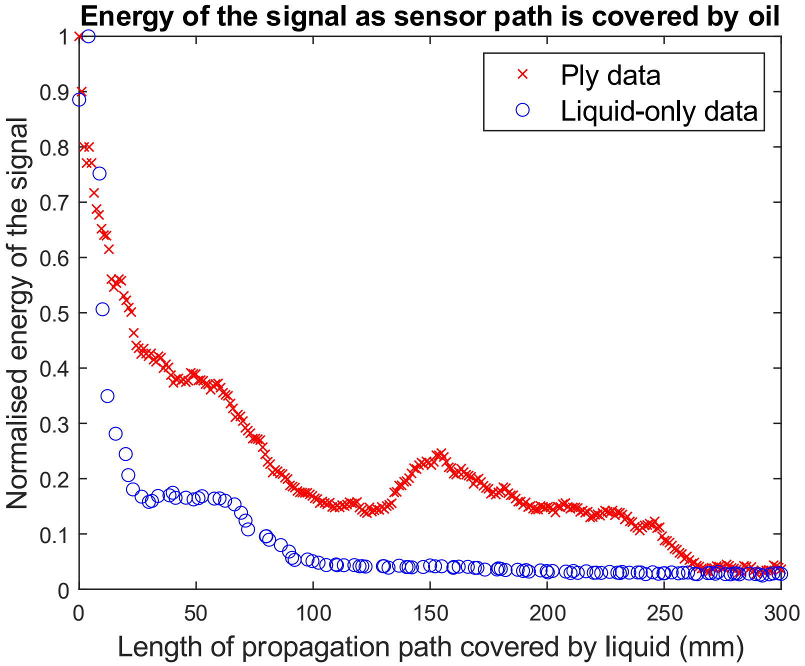


Disadvantages:

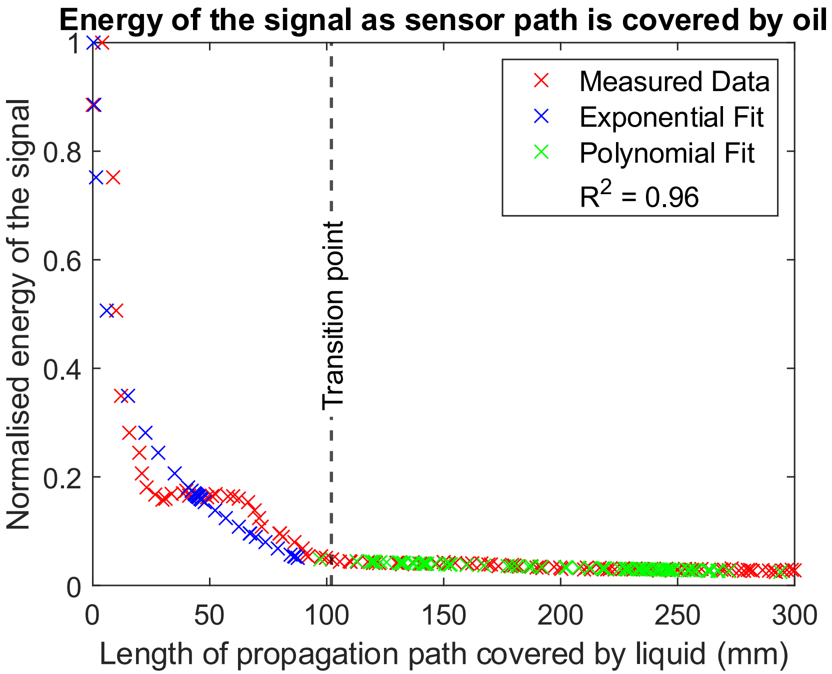
- Longer infusion time.
- More difficult to clean.
- More pumping pressure needed.
- More difficult to label data using Machine Vision.

Comparison to liquid only:

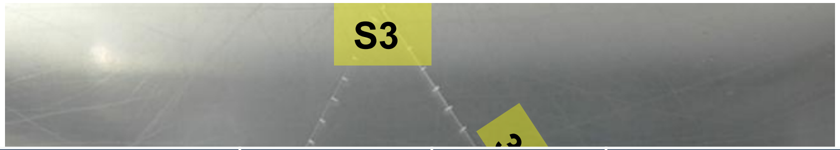
- Waveform behaviour is not significantly affected by the presence of the plies.
- Differences mainly present due to improper liquid pumping into the mould.



Fluid Front Position Approximation



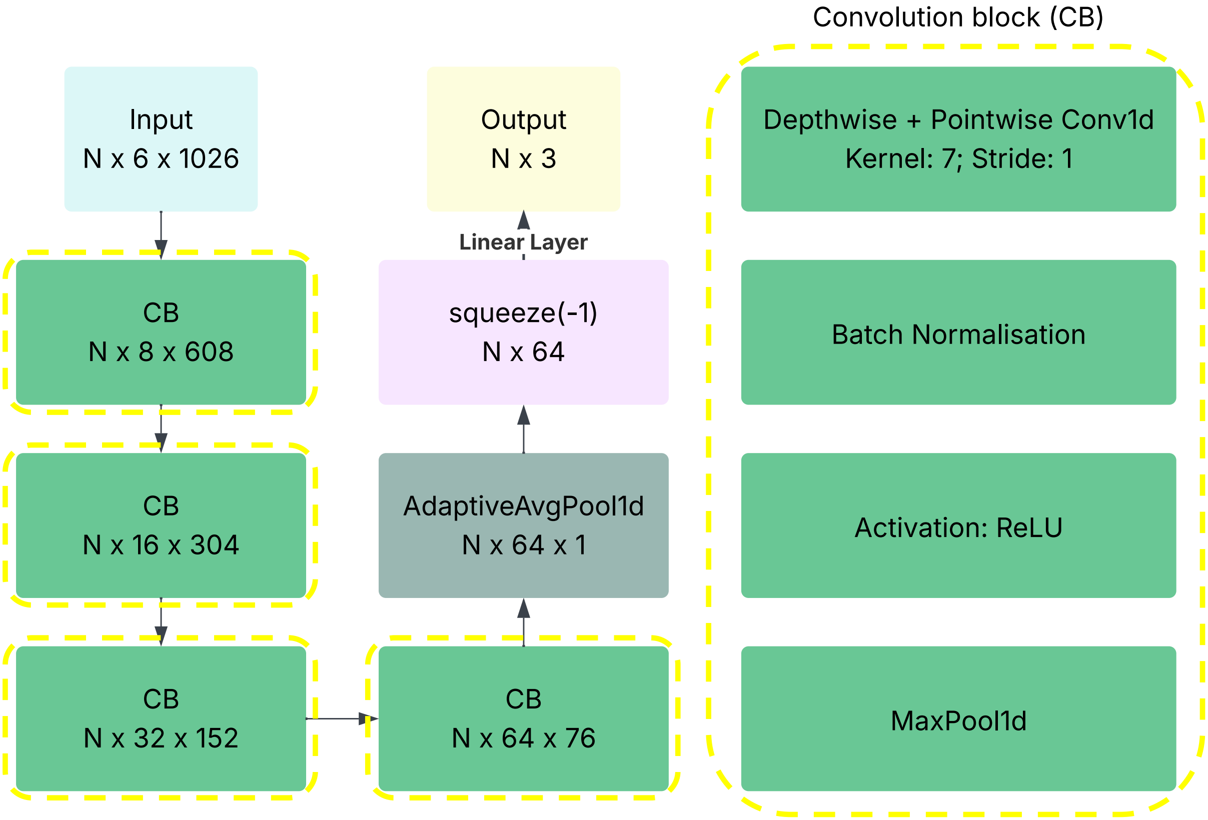
- Piecewise function fits the energy drop well.
- Determined three models and predicted flow position using three sensors.
- Front position is reconstructed using approximation from each path.



Propagation paths	MAE (mm)	Max Error (mm)	R^2 (-)
1-2	11.8	38.3	0.97
1-3	26.9	62.8	0.80
3-2	22.0	62.2	0.91

- Different factors influence each path → sources of error.
- Each model is tailored to return minimum error.

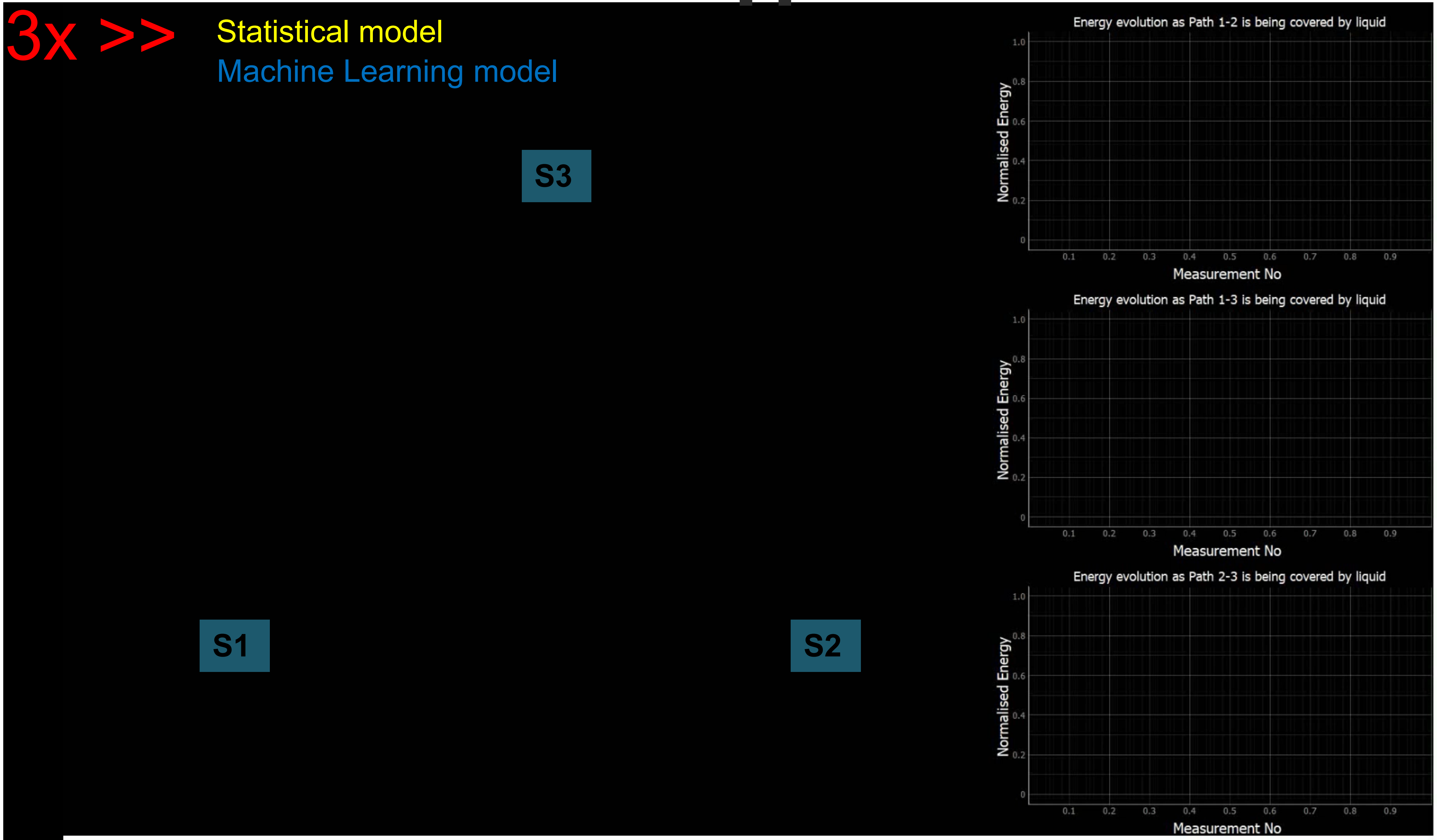
Fluid Front Position Approximation



- Experimental data collected is collated for machine learning training.
- Input: A-scans and Hilbert envelopes.
- Output: Distance readings.
- One CNN model for all three paths.

Propagation paths	MAE (mm)	Max Error (mm)	R^2 (-)
1-2	5.7	24.6	0.99
1-3	12.5	37.2	0.99
3-2	10.9	67.94	0.97

Fluid Front Position Approximation



Fluid Front Position Approximation

- Full methodology detail for the ML approach and improved results → IEEE Xplore.
- Full experimental setup, data acquisition and functional approximation model → NDT&E International.

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A step towards ultrasonic guided wave monitoring for resin infusion front position estimation in composites manufacturing

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ARTICLE INFO

Keywords:
Ultrasonic leaky Lamb waves
Resin infusion process monitoring
Model-based estimation of resin front
Piezoelectric transducers

ABSTRACT

Resin infusion paired with Out of Autoclave (OoA) curing offers an alternative to infrastructure-heavy autoclave-based manufacturing. However, lower fibre volume fractions and increased porosity from uneven resin flow limit the adoption of OoA processes in safety-critical applications. Consequently, there is demand for in-situ monitoring tools to track resin progression and ensure full permeation. Prior methods, including optical fibres and electromagnetic sensors, can infer front position but are intrusive or hard to scale. This research investigates leaky Lamb waves generated by ultrasonic transducers embedded in the top lid of an infusion mould. To isolate wave-fluid interactions, liquid-only measurements in a 2.0 mm thick infusion box are collected, removing laminate heterogeneity and enabling acquisition of controllable consecutive measurements, enabling the development and validation of predictive models under well-defined conditions. Attenuation of the fundamental antisymmetric mode (A0) as resin reaches the sensing region was demonstrated through theoretical and simulation-based analysis, highlighting the potential of Ultrasonic Guided Waves (UGW) for real-time fluid tracking. A custom experimental setup enabled consistent repeatable measurements of an advancing liquid front. A parametric study investigated the effects of geometry and fluid on signal amplitude, determining sensor spacing for sensitivity and areal coverage. Ultrasonic measurements were correlated with time-stamped images of the resin front through a machine-vision algorithm. Several functional approximation methods were applied to estimate liquid position from ultrasonic data, capturing the general trends in flow behaviour. The models yielded robust predictions, with mean errors of 5–7 % of the sensor spacing, despite environmental variations and system nonlinearities contributing to data variability.

1. Introduction

Carbon Fibre Reinforced Plastics (CFRP) are advanced composite materials consisting of a polymer matrix, typically thermoset or thermoplastic, embedded with high-strength carbon fibres. This configuration produces a highly anisotropic material in which key properties such as the tensile strength, stiffness, and fatigue resistance depend on the fibre orientation within the composite lattice [1]. These characteristics can be tailored to produce components with exceptionally high strength-to-weight ratios, a feature that has driven their adoption in high-value, safety-critical industries with a clear need for lightweight components such as automotive, sports equipment, renewable energy, and aerospace [2]. In aerospace applications, the advantages of CFRP extend beyond their superior mechanical performance. Their inherent design flexibility allows the creation of complex, aerodynamically optimised structures that contribute to significant weight reductions [2]. Reducing mass does not only enhance overall aircraft performance, but it also improves fuel efficiency, since lighter aircrafts consume less fuel, leading to lower emissions and more sustainable operations. The integration of CFRP into aerospace began in 1964 [3], and their usage has

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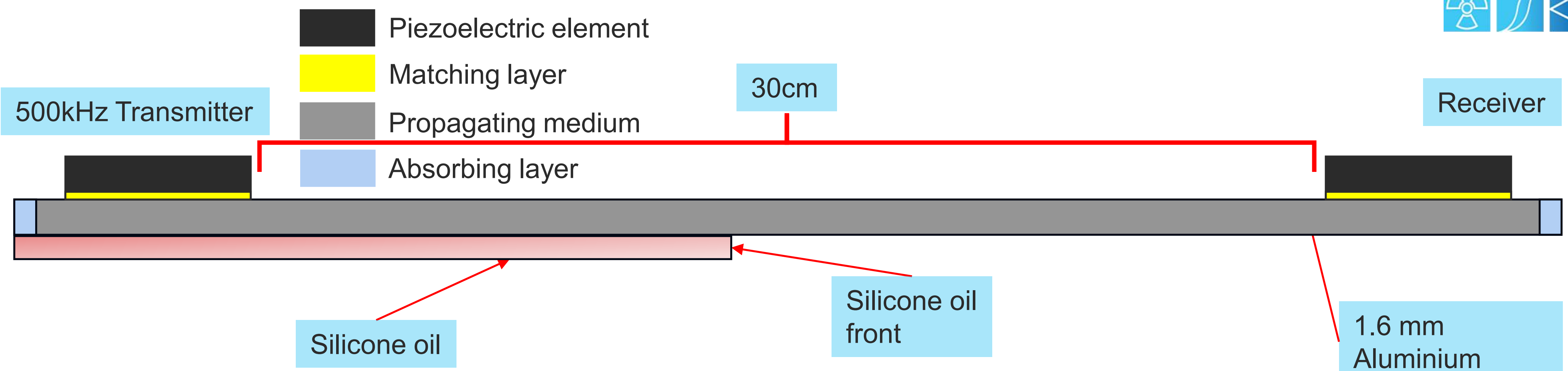
are consolidated and preformed either through externally applied pressure in closed moulds or by vacuum bagging in

readings corroborated the ultrasonic results. The latest study [9] achieved full-field monitoring of resin flow and dry spot

COMSOL Simulation



Simulation:

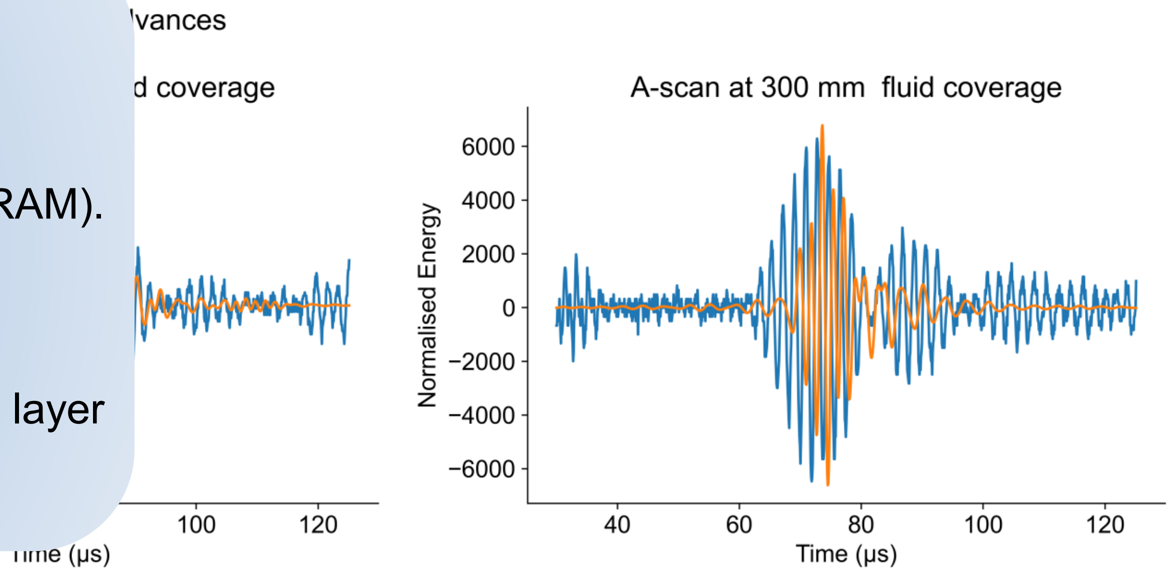
- Energy leakage in pure fluid.
- MATLAB LiveLink used for parametrisation.
- Frequency domain to reduce computation time.

	Physics Module	Material	Mesh Generator
Piezoelectric element	Solid Mechanics; Electrostatics; Piezoelectric Effect	PZT-5H	Mapped (2D)
Matching layer	Solid Mechanics	Polymer ($\rho = 1260\ kg/m^3$; $c_p = 3000\ m/s$; $c_s = 2450\ m/s$)	Mapped (2D)
Propagating medium	Solid Mechanics; Pair Acoustic-Structure Boundary	Aluminium alloy 1100	Free Triangular (2D)
Liquid layer	Pressure Acoustics, Frequency Domain; Pair Acoustic-Structure Boundary	Silicone oil	Free Triangular (2D)

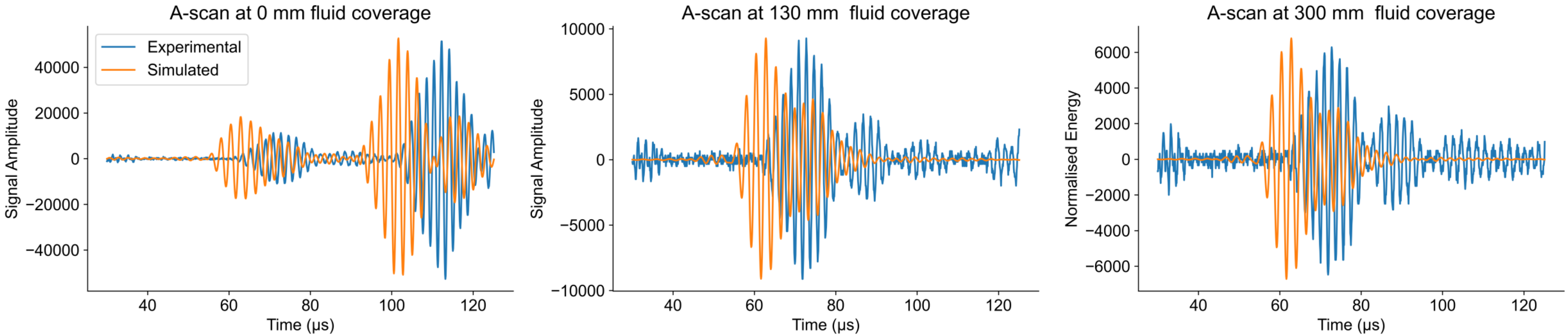
COMSOL Simulation → Results

Running the simulation:

- 6521 mesh elements (0.66 minimum element quality).
- Ran on CPU (24-core AMD Processor and 128 GB of RAM).
- Under 3 minutes per front location.
- Reduced computation time allows finetune of matching layer conditions and damping ratios.



b) Signal Energy as Fluid Advances (tuned parameters)

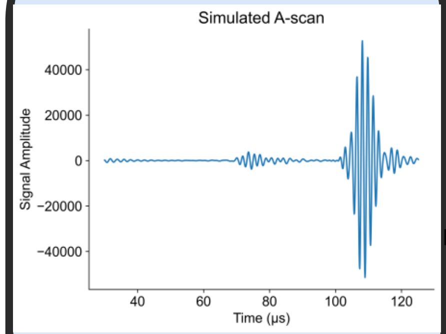


GAN for Domain Adaptation

Motivation:

- Bridge the gap between experimental and simulated.
- Create synthetic dataset for front position mapping.
- Avoid data bleeding and accurately represent observed behaviour.

Input



+

Distance label

GAN

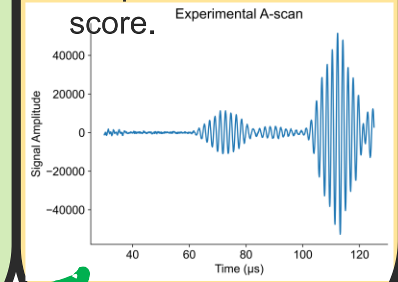
Score below threshold

Generator (CNN based)

- Transforms input signal.
- Incorporates physics-informed losses.
- Generates synthetic A-scan.

Discriminator

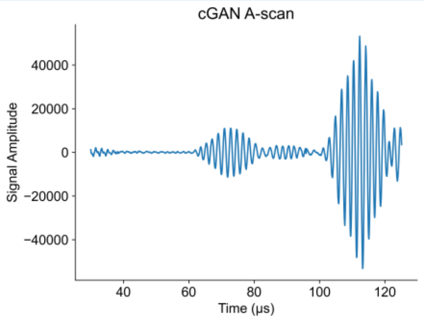
- Compares generated vs experimental.
- Outputs realism score.



Synthetic Signal

Score above threshold

Output



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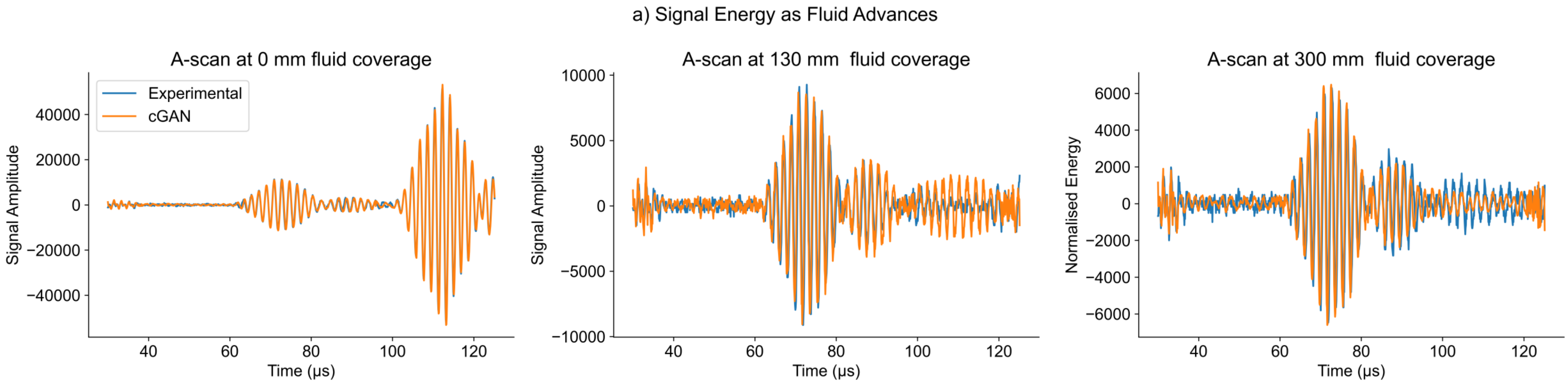
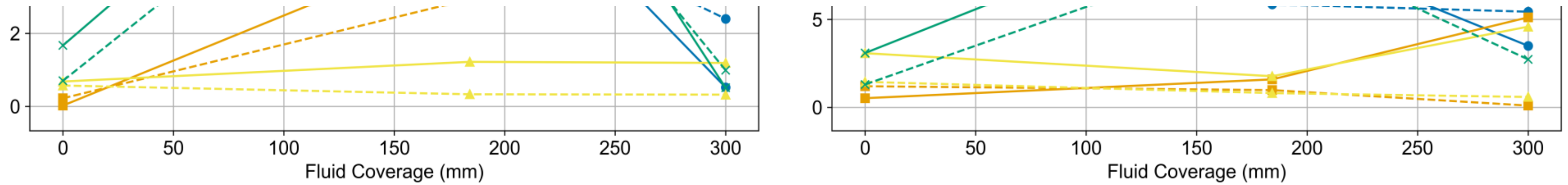
Distance label

GAN for Domain Adaptation

GAN Results:

- Signal is successfully reconstructed.
- Variation observed between experimental runs is preserved.
- Experimental dataset can be augmented using this technique.





GAN for Domain Adaptation → Results

Resin Front Position Results:

- Experimental and GAN used to predict position of the flow front in the infusion mould.
- A custom CNN is used to obtain the predictions.
- Adding GAN data to a limited training set significantly improves prediction results.

Training Set	MAE (mm)	Max Error (mm)	R^2 (-)
Exp	16.69 ± 0.86	86.72 ± 3.61	0.94 ± 0.01
Raw Sim	189.85 ± 19.78	298.53 ± 2.45	-2.50 ± 0.75
cGAN	23.47 ± 8.15	109.11 ± 30.42	0.89 ± 0.07
cGAN + Exp	**9.07 ± 1.11**	**45.42 ± 5.22**	**0.99 ± 0.01**

Concluding Remarks & Future Work

Conclusions:

- Gap between simulated and experimental data can be bridged using a custom GAN.
- 46% reduction in MAE when flow prediction models are trained on synthetic + experimental, demonstrating efficient data augmentation when experimental data is scarce.

Future work:

- Include plies, depth of flow and fault detection.
- Measurements at high temperatures.
- Increase number of sensors.

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Thank you | Any questions?

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