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Transitioning ultrasonic ply-tracking algorithms from academia to industry

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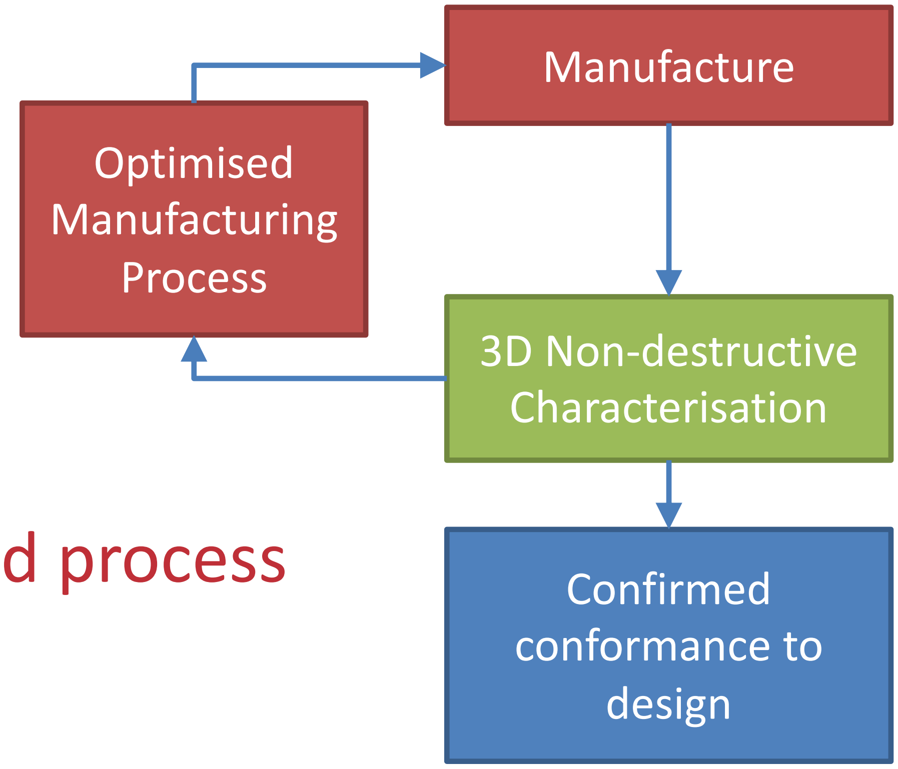
EPSRC
Engineering and Physical Sciences Research Council

Content

- Introduction
- Stage 1: Analytic-signal and instantaneous parameters
- Stage 2: Ply tracking
- Stage 3: Ply wrinkling
- Stage 4: In-plane waviness, Stacking sequence, 2D and 3D woven composites
- Transitioning algorithms to industry
- Conclusions

Introduction - Motivation

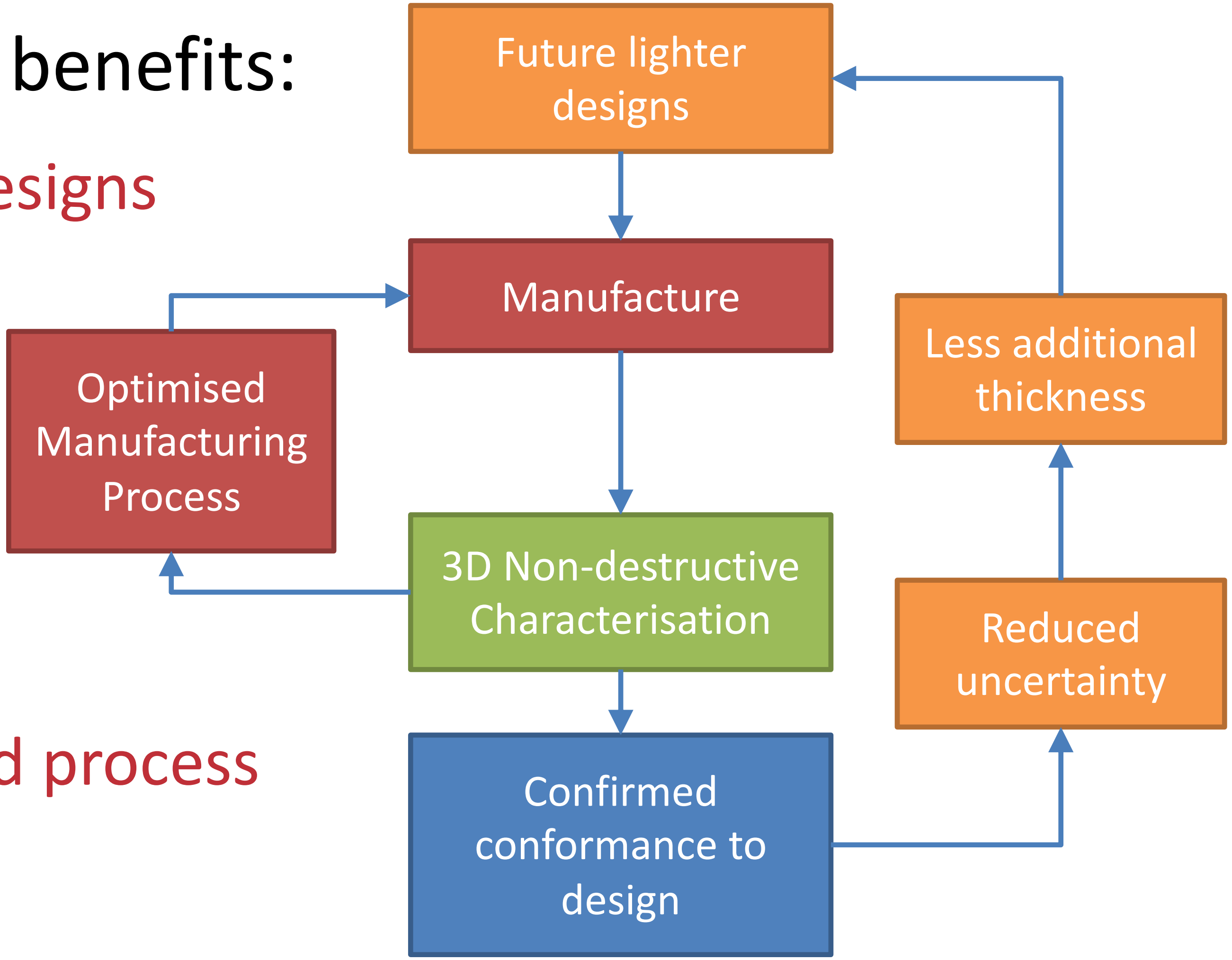
- Long-term benefits:



  - Optimised process

Introduction - Motivation

- Long-term benefits:
  - Lighter designs



  - Optimised process

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Technology Transitioning

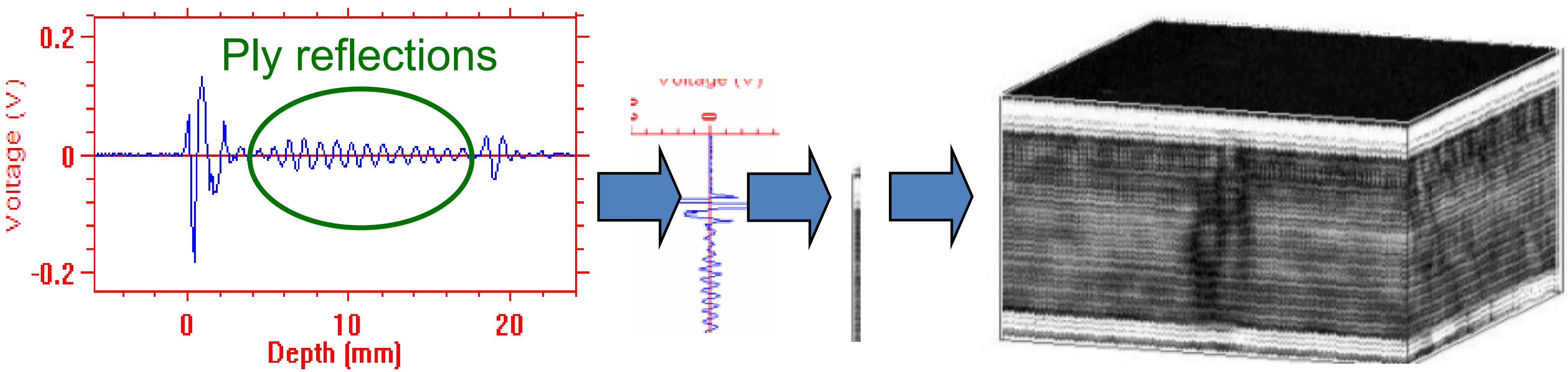
- Using MTC's Algorithm Deployment Support Service
  - Transitions *Software Engineering Documents*
  - Currently transitioning into supply chain:
    - Stage 1: Analytic-signal and instantaneous parameters
    - Stage 2: Ply tracking
    - Stage 3: Out-of-plane ply orientation and wrinkle mapping
    - Through: Ultrasonic Sciences Ltd, Wavelength NDT/UTEX
  - Planning the project consortium for:
    - Stage 4: 2D woven composite classification and mapping
    - Through DolphiTech (all four stages) for DolphiCam2.

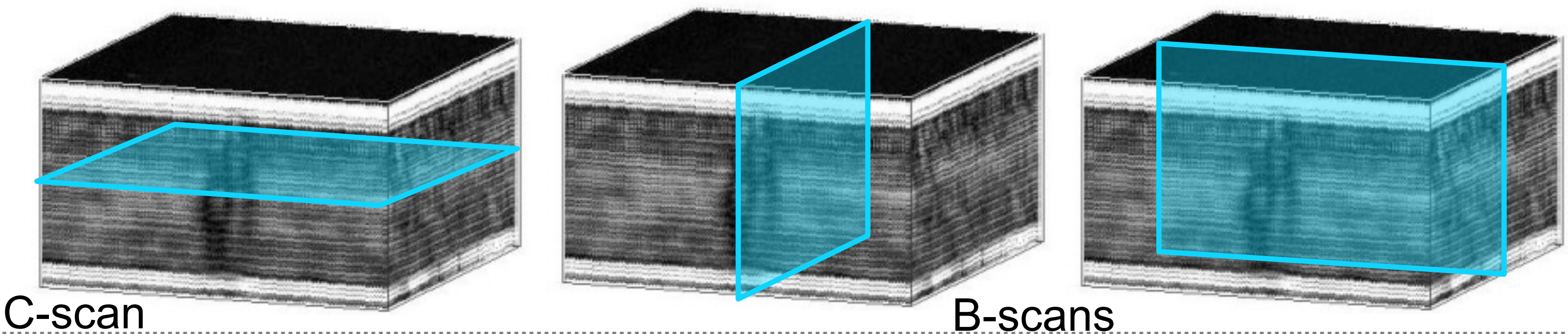
Stage 1: Analytic-signal and instantaneous parameters

3D Characterisation Methodology

Ultrasound 3D data sets

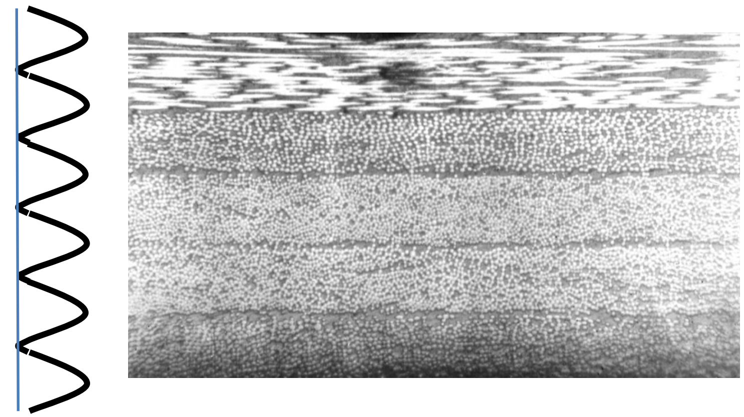
- Normal incidence focused probe – focused on mid-plane

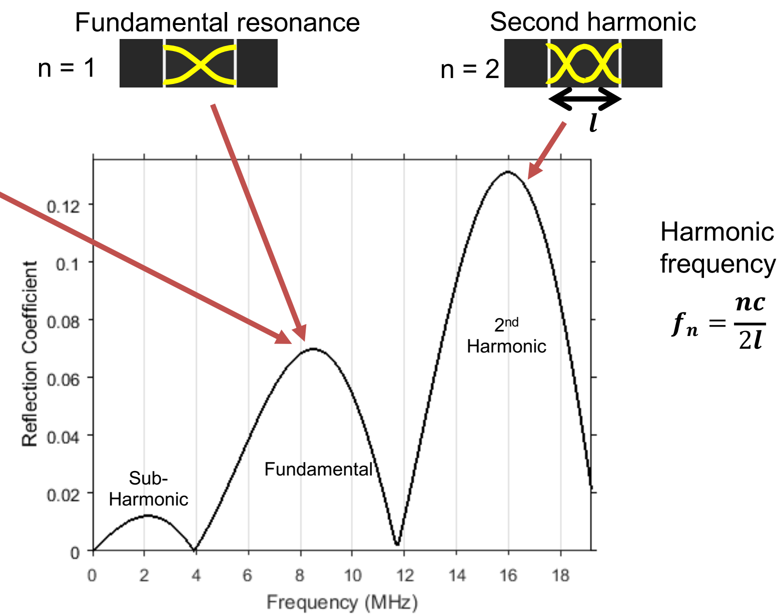




Ultrasonic Propagation in CFRP

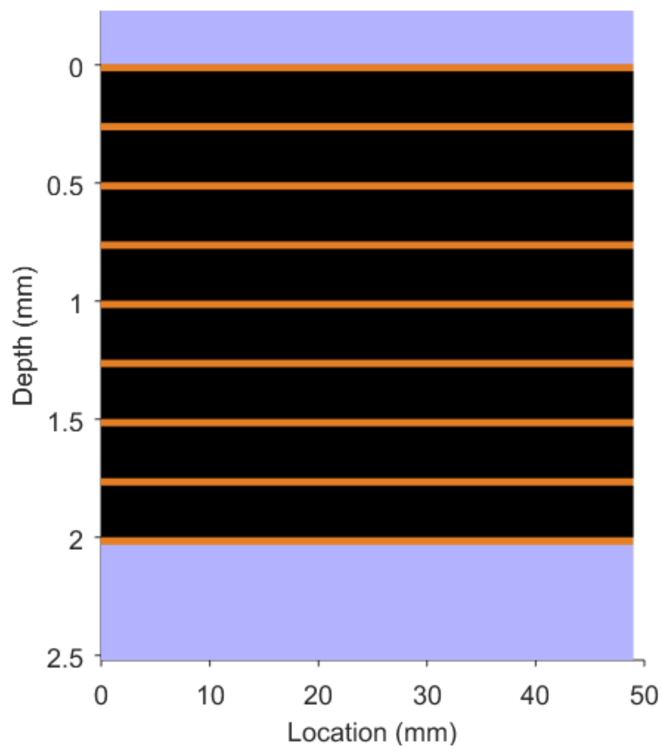
- CFRP
  - Resin layers reflect
  - Interference between reflections
  - Weak resonances, eg
    - 8 MHz for 0.189 mm plies
  - Resonances disrupted by:
    - Ply thickness variations
    - Material property variations
  - Localised response
    - Reflections are only weak

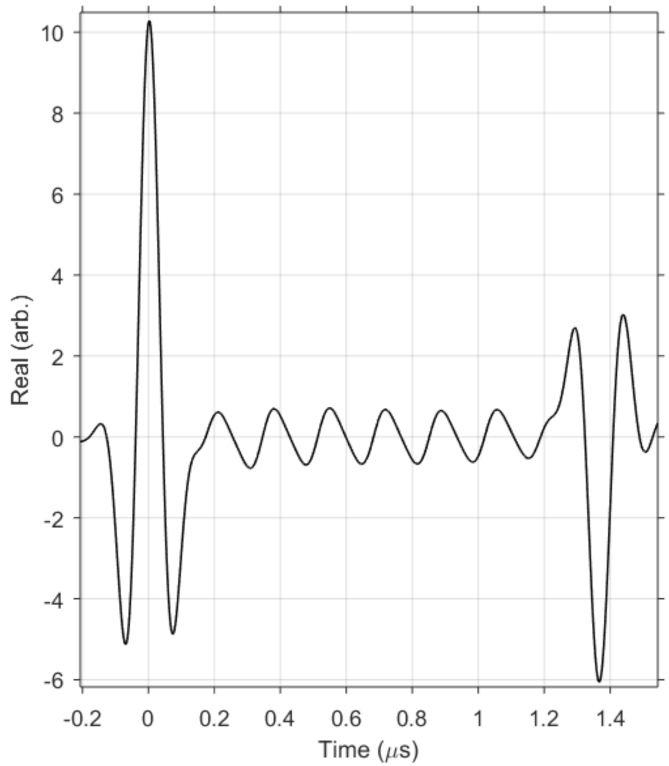




Analytic Signal Formulation

- 8 plies in water – normal incidence pulse-echo

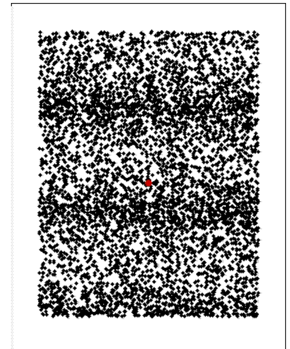


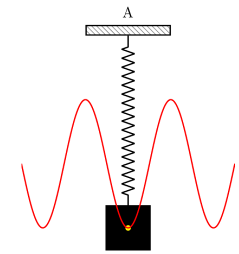


Measured parameter is usually acoustic pressure (proportional to particle velocity)

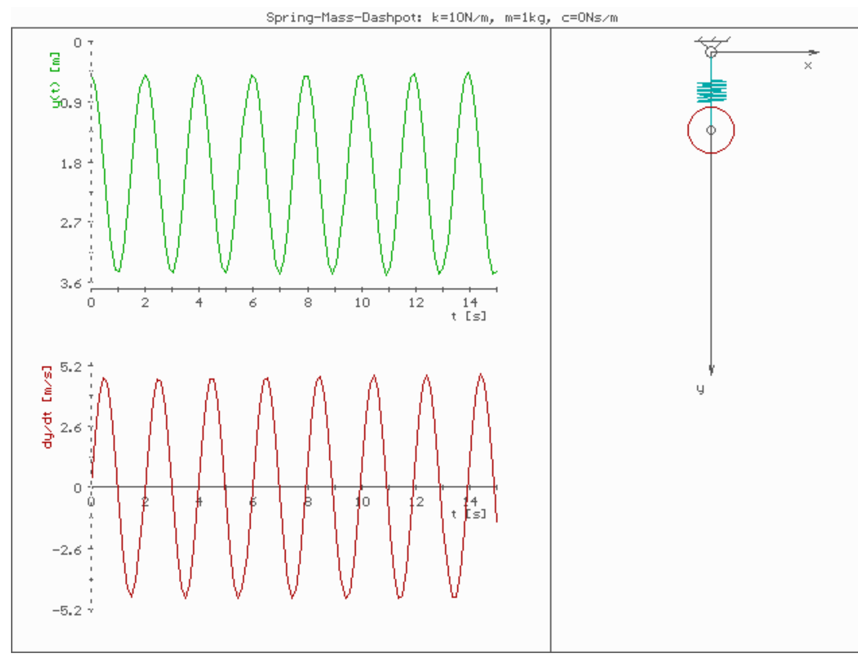
Analytic Signal Formulation

- Analytic signals
  - Mass-spring analogy





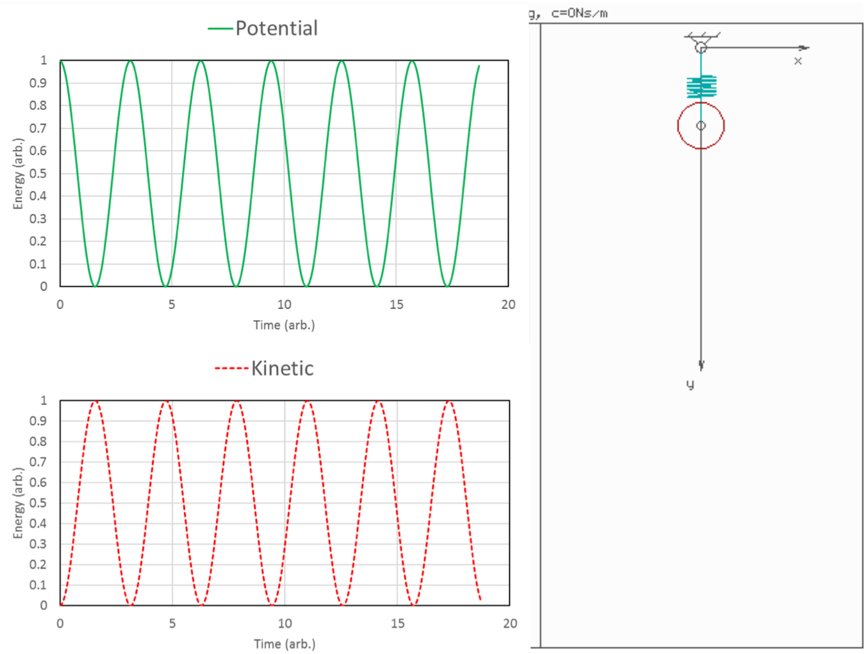
  - Particle Displacement.
  - Particle Velocity
    - 90° (π/2) out of phase with displacement



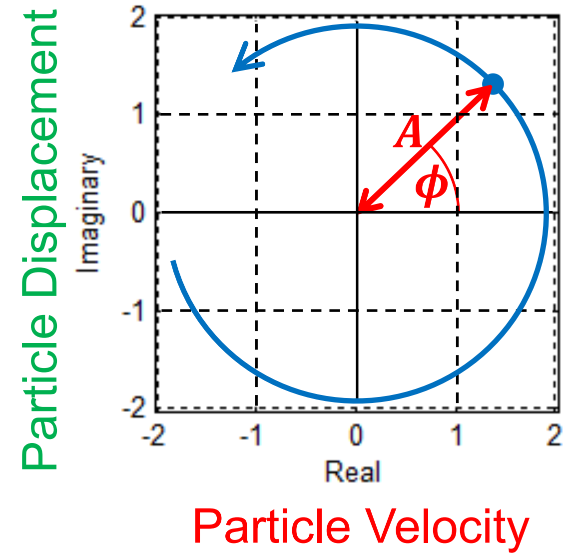
Analytic Signal Formulation

- Analytic signals
  - Mass-spring analogy
  - Energy transfer

  - Particle Displacement.
    - Potential energy = $\frac{1}{2}kx^2$
  - Particle Velocity
    - Kinetic energy = $\frac{1}{2}mv^2$



Instantaneous parameters



- Analytic Signal $\boldsymbol{a(t)}$

$$\boldsymbol{a(t) = A(t)e^{i\phi(t)}}$$

where: A(t) is <u>instantaneous amplitude</u>

ϕ(t) is <u>instantaneous phase</u>

$\frac{1}{2\pi}\frac{\mathrm{d}\phi}{\mathrm{d}t}$ is <u>instantaneous frequency</u>

(local phase gradient)

- Use a **Hilbert Transform** to create imaginary part from real waveform.

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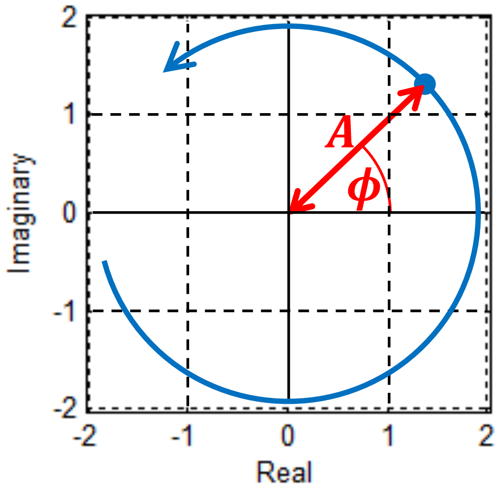
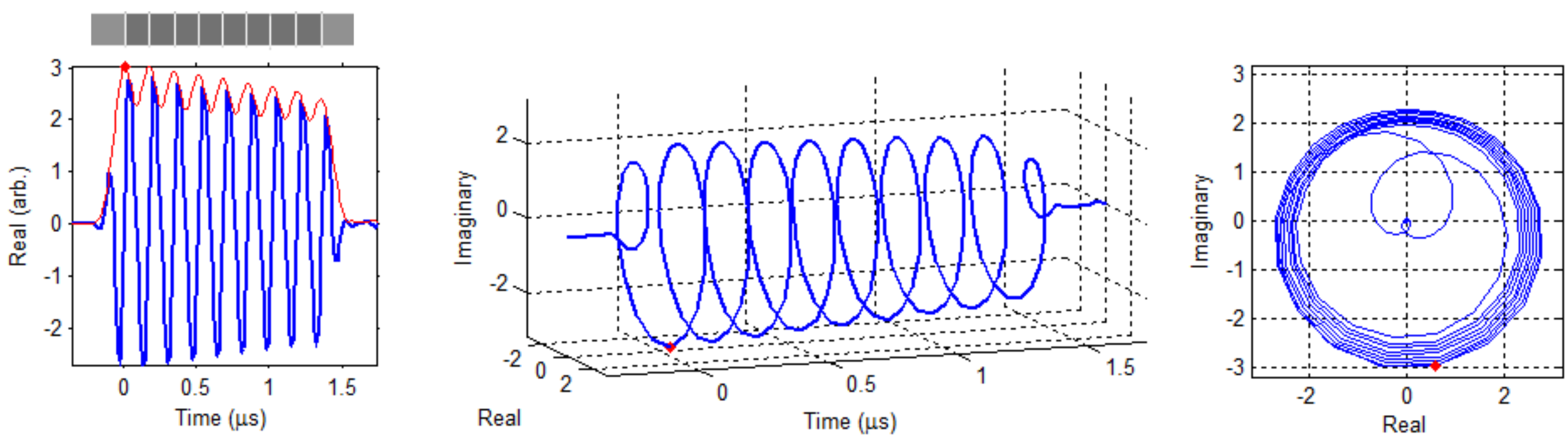
Analytic Signal Response

$$a(t) = A(t)e^{i\phi(t)}$$

- At resonance, a particular phase is *locked* to resin layers between plies.



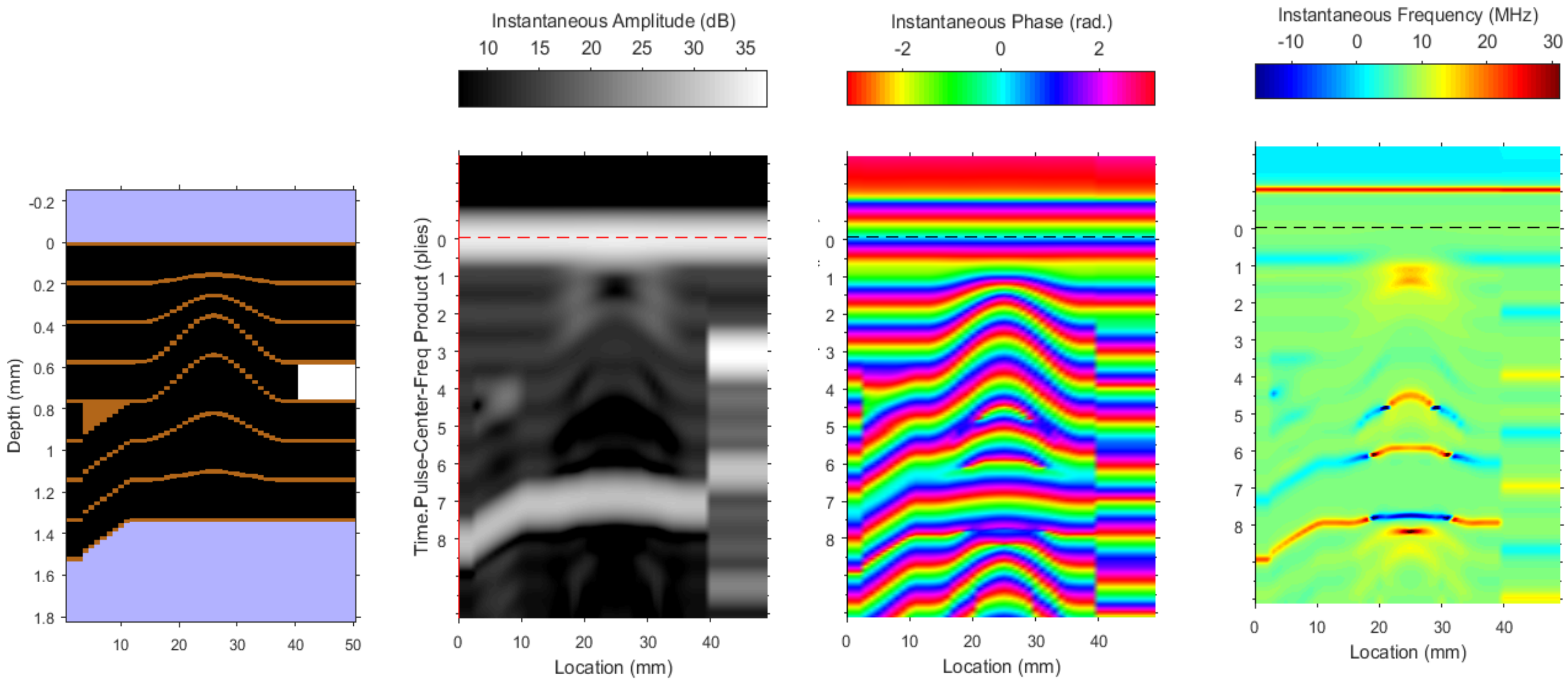


8-ply CFRP laminate, 0.25 mm ply spacing, between matching layers

Instantaneous parameters

- Simulated ply drop, wrinkle and delamination

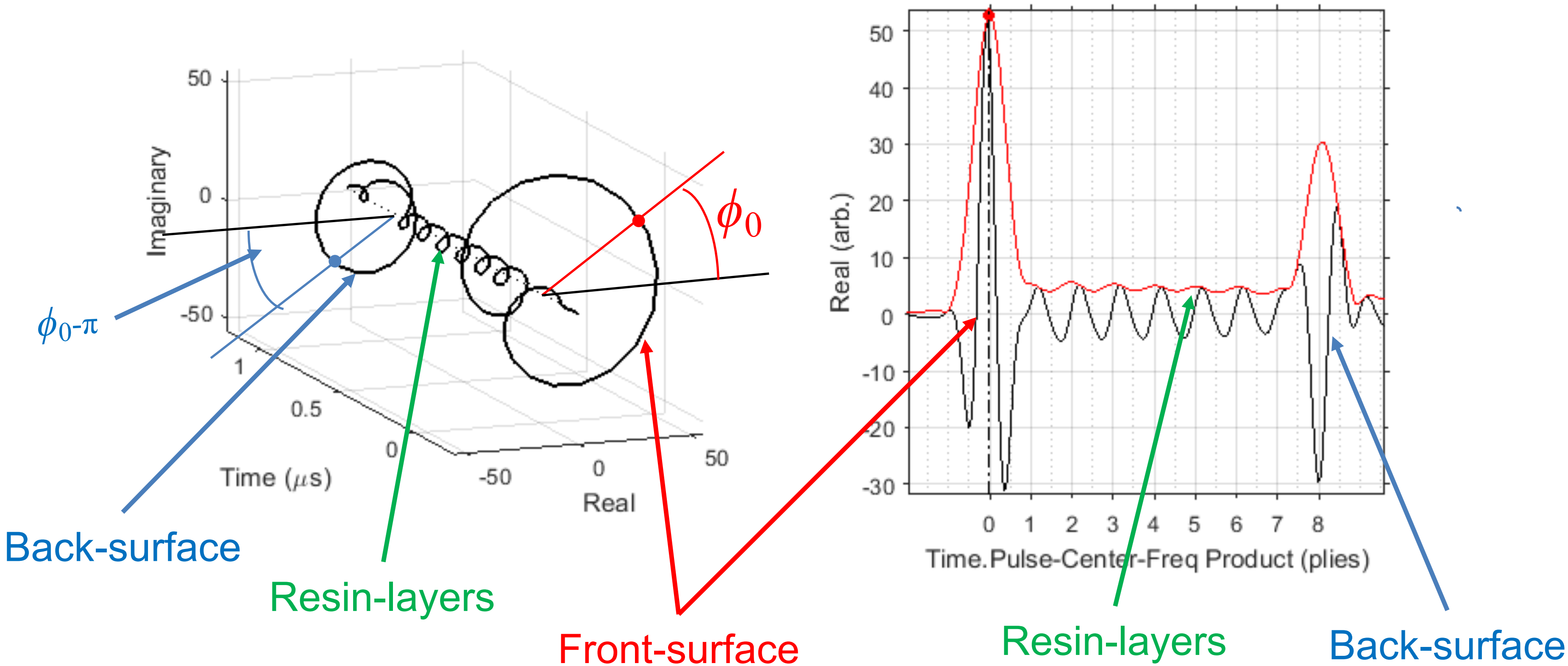
Simulation | Instantaneous Amplitude | Instantaneous Phase | Instantaneous Frequency



Stage 2: Ply tracking

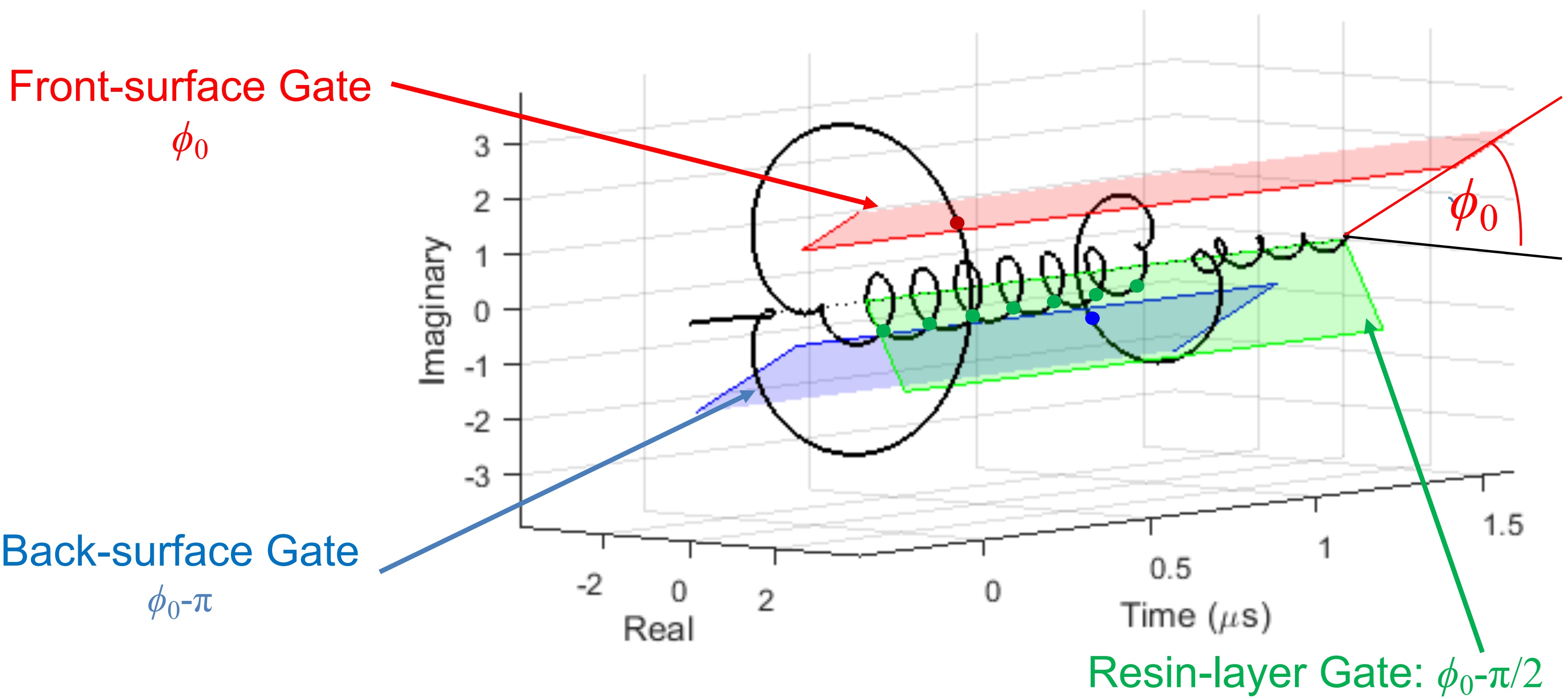
Ply Tracking

- Immersion scan with input-pulse phase: $\phi_0 = \pi/6$
- Front locked at: $\phi_{0,}$ back at: $\phi_0 - \pi$



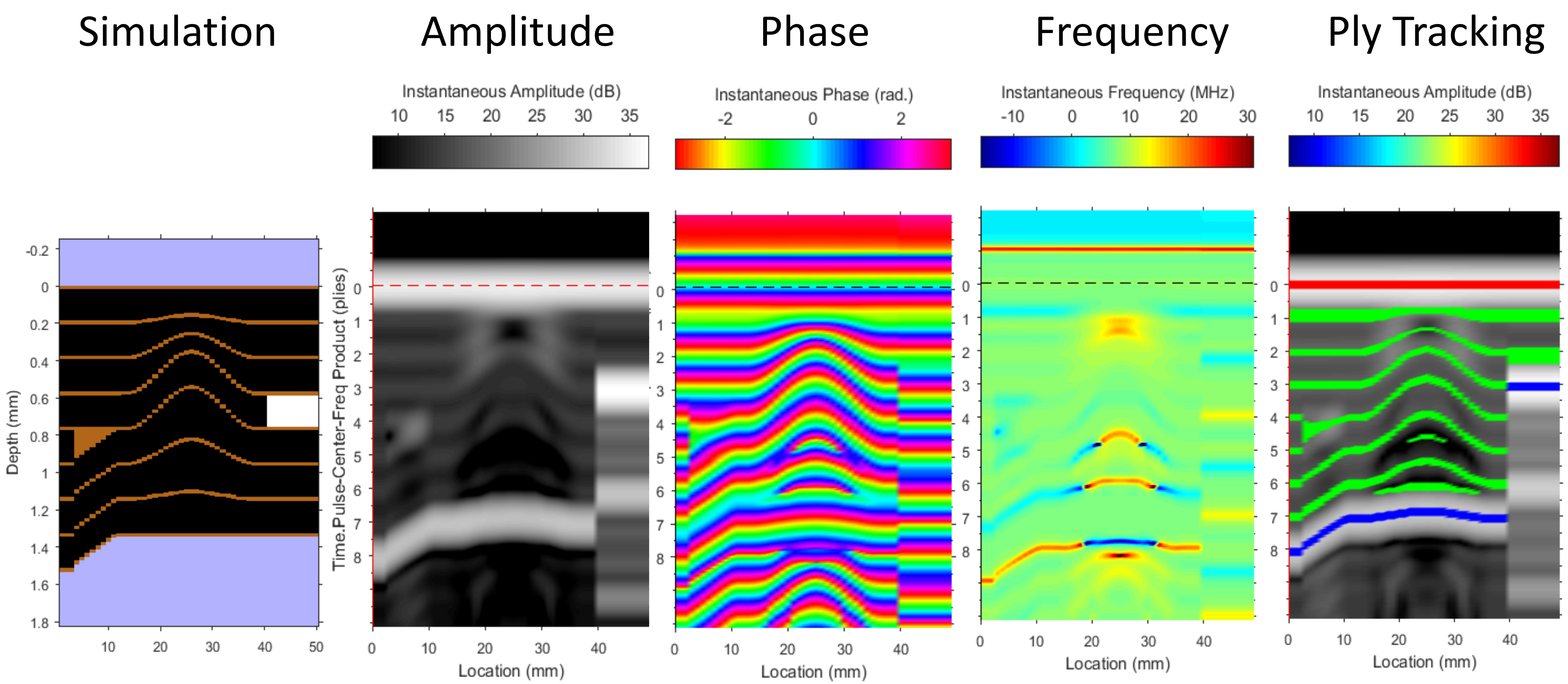
Ply Tracking

- Immersion scan with input-pulse phase: $\phi_0 = \pi/6$
- Front at: ϕ_0, back: $\phi_0 - \pi$, resin-layers: $\phi_0 - \pi/2$,



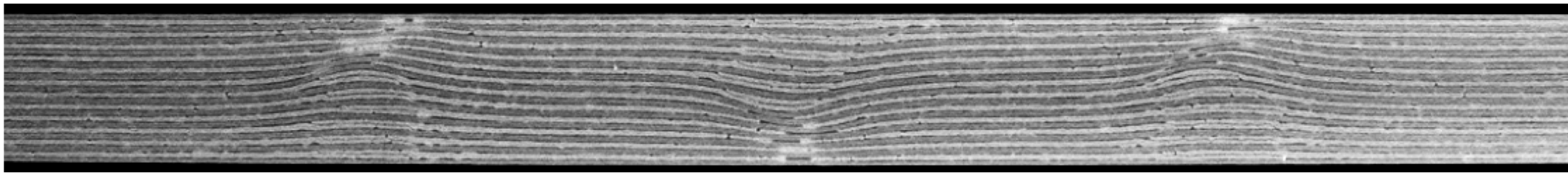
Ply Tracking

- Simulated ply drop, wrinkle and delamination

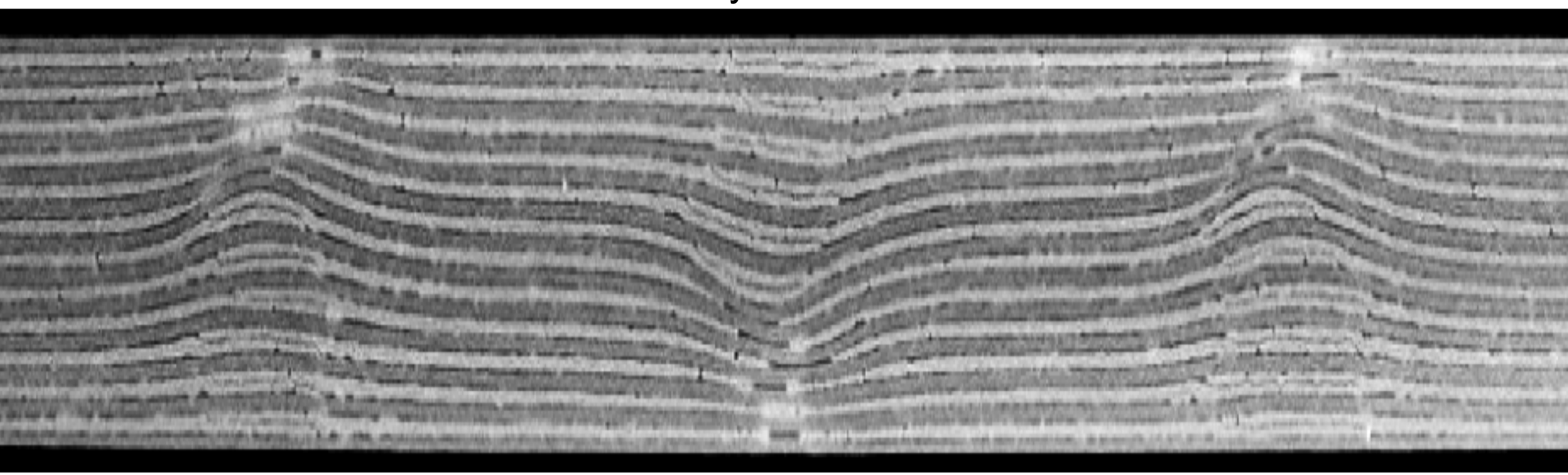


Ply tracking

- Tape gaps and overlaps to cause wrinkling

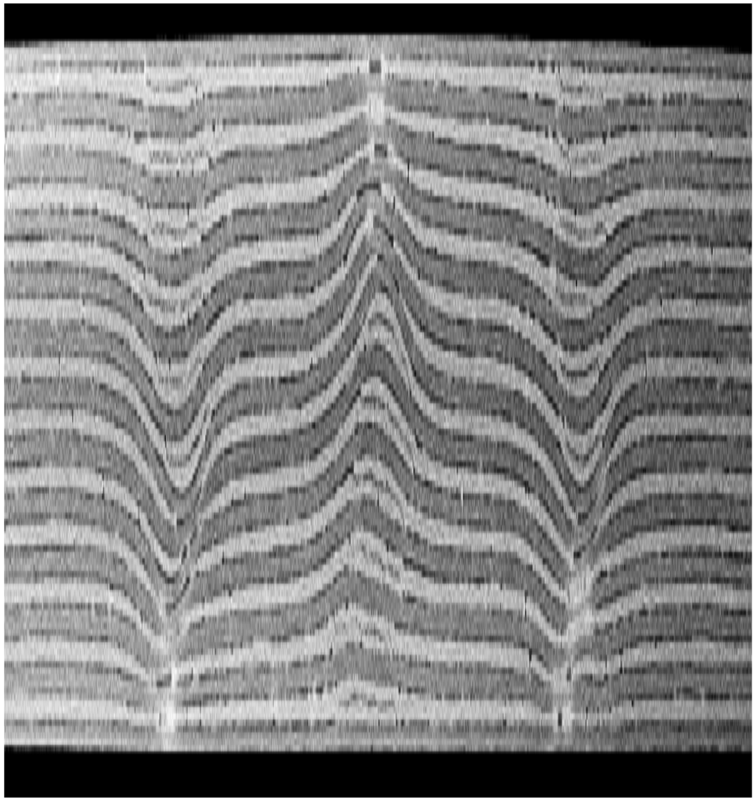


X-ray CT data

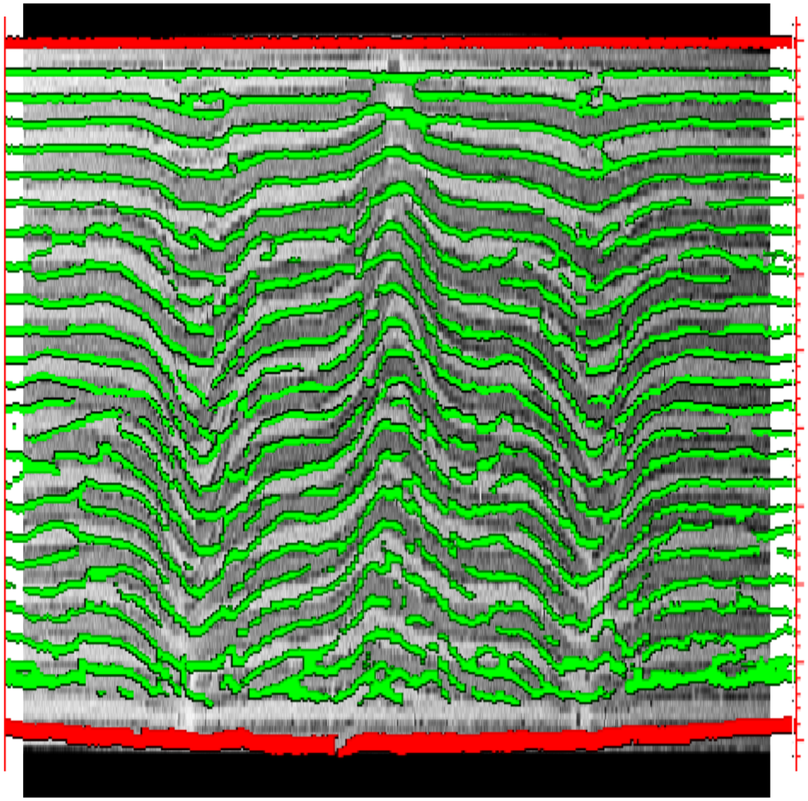


Ply Tracking

X-ray CT scan



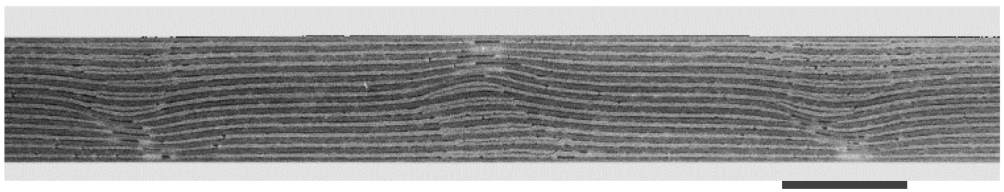
With ply-tracking overlay



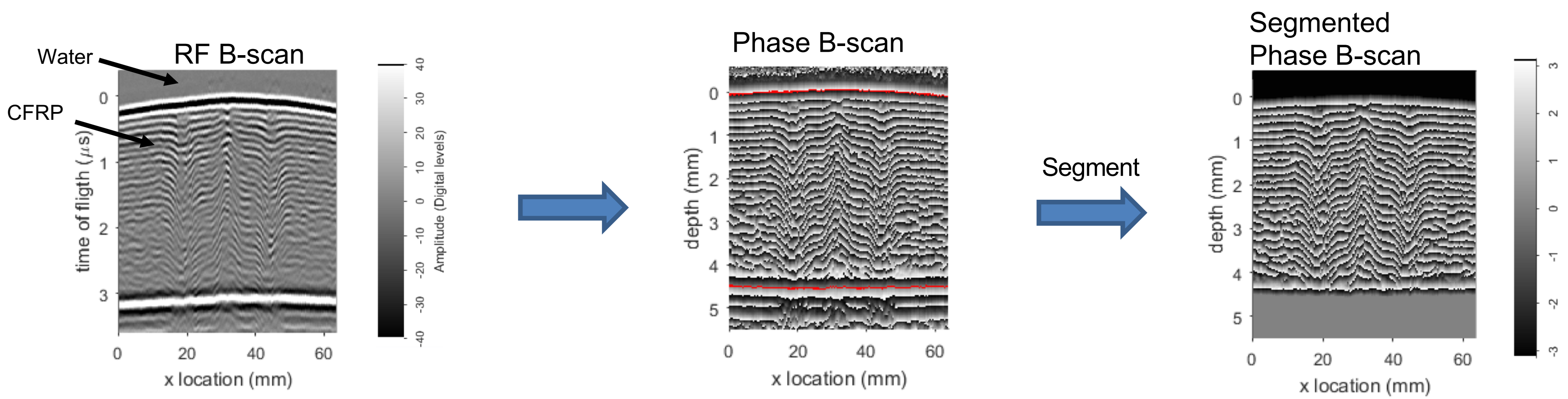
Stage 3: Ply Wrinkling

Ply Wrinkle Measurement

Validation by comparing ultrasonic-derived results to X-ray CT slices



X-ray CT of wrinkled test sample



Identify front and back surface

Convert time to depth, taking into account the different velocities

To retain true surface profile don’t interface gate, fit a plane to the front surface

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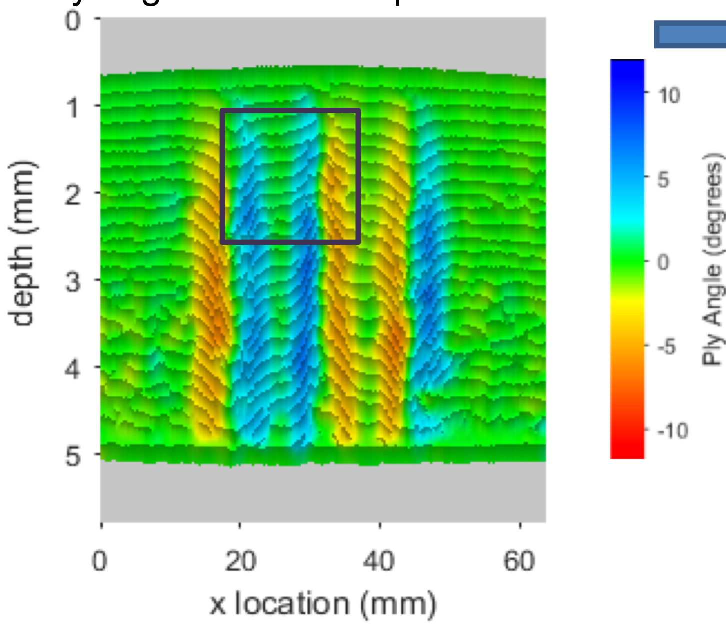
Ply Wrinkle Measurement

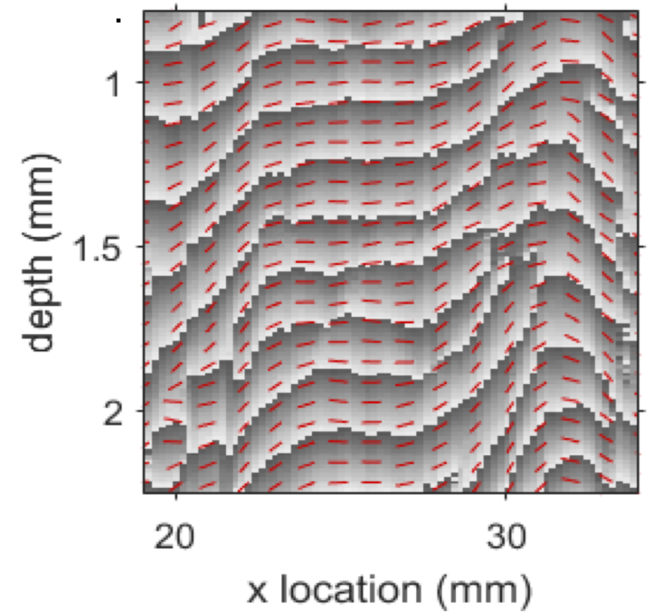
A **Structure Tensor** is used to determine gradients in the 3D phase

Ply angle overlaid on phase data.

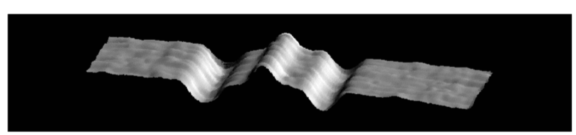


Do measurements map to CT data?

Vector lines (red) overlaid on phase data



- 'Colours' look correct.
- More quantification required.

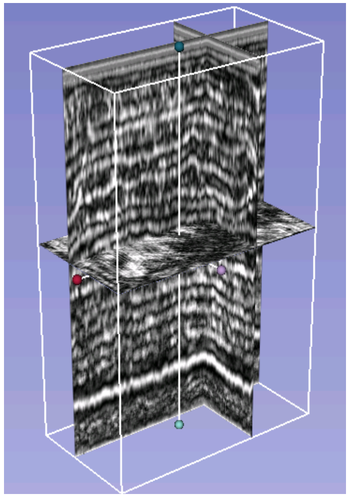


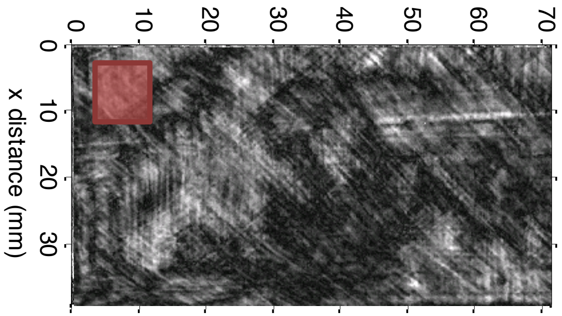
- Shows angles measurements accurately measure what is in the phase data

Stage 4: In-plane waviness, stacking sequence, 2D and 3D woven composites

In-plane fibre orientation

- Use amplitude data





In-plane amplitude C-scan at depth = 1.4 mm (approx. mid-laminate)

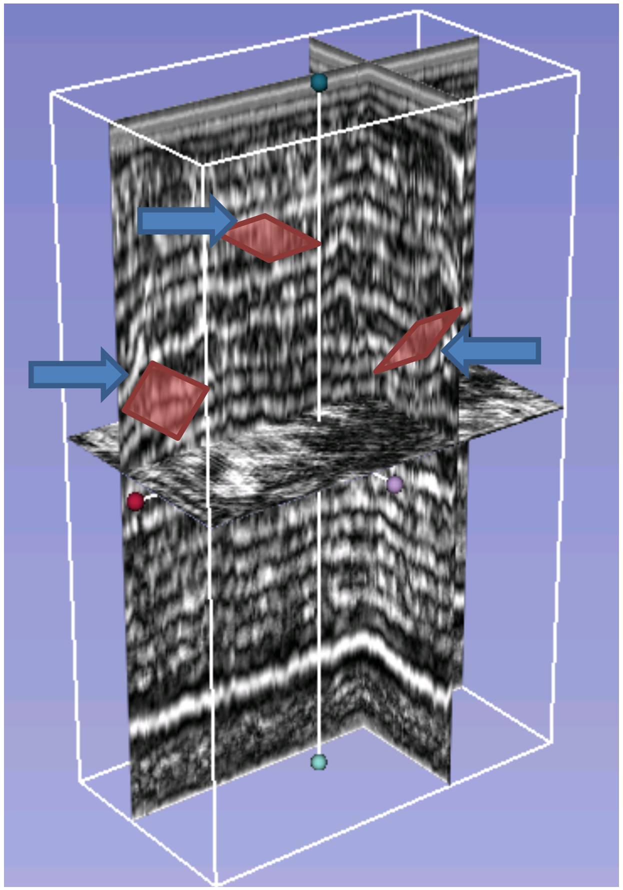
Fibre-tow sensitivity in ultrasound scan

- Thickness variations in resin layers produce amplitude variations which track fibre tows.
- Need focused probe
  - Centre frequency and bandwidth at approximately the ply resonance frequency
  - -6dB Focal spot size less than tow width

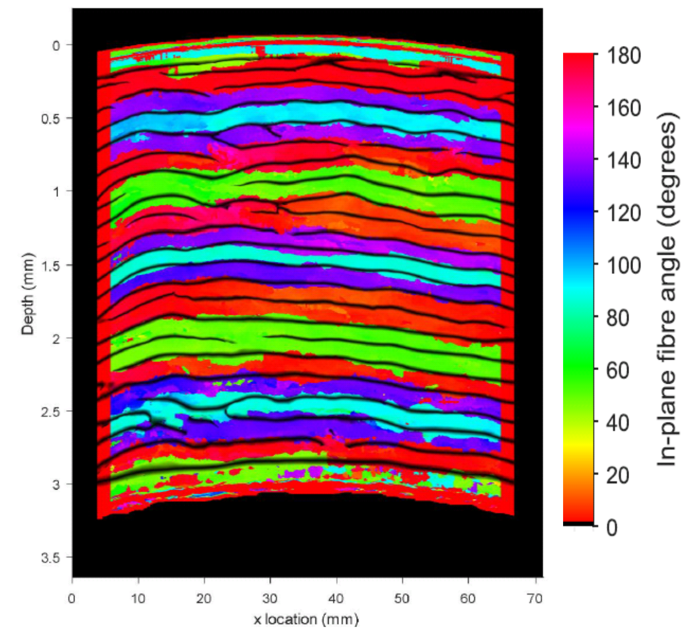
- Analyse 2D region and step in raster scan.
- Build up a 2D fibre-angle orientation map.
- Step to next depth and repeat so we perform at every 3D pixel location.
- In regions with ply wrinkling, x-y slice is inappropriate

In-plane fibre orientation

A **Radon Transform** is used to measure the dominant fibre-tow angle.



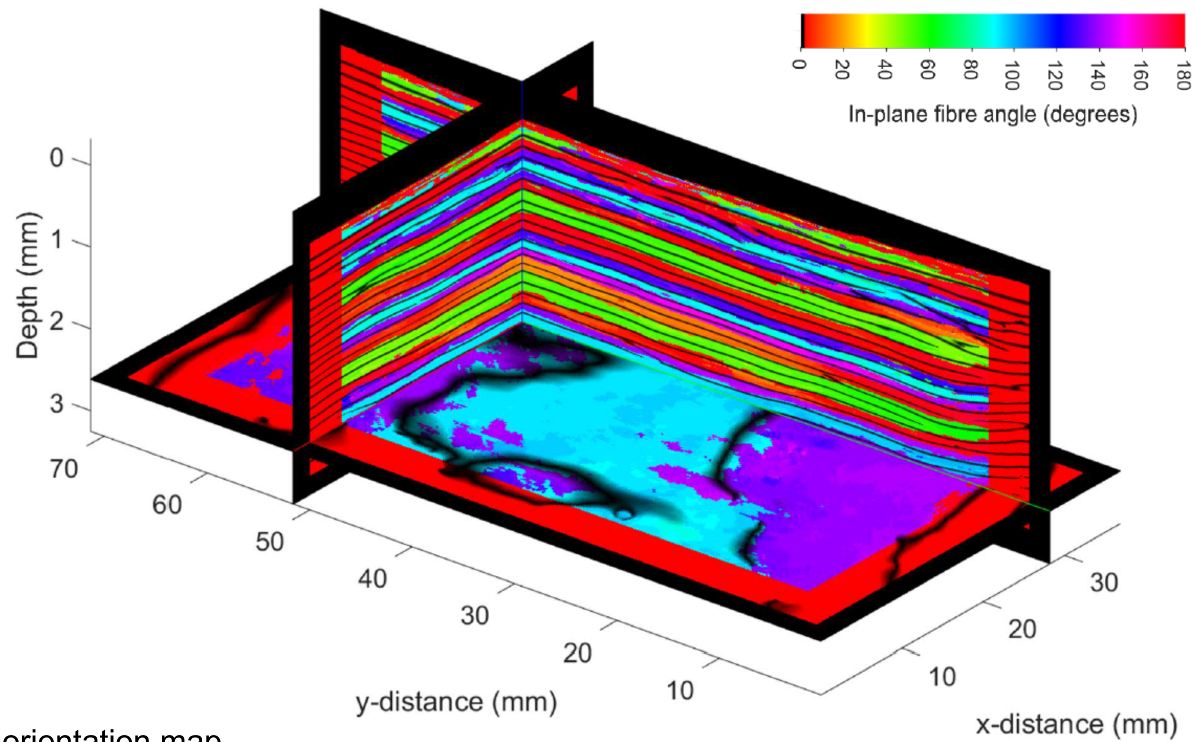
- We can measured the PLY orientation
- Since fibres are constrained to plies, use ply orientation to guide our 2D processing
- Perform at every 3D pixel location
- Smooth the phase data 'aligned to plies'



- Cross section with phase-derived ply-location overlay
- Shows double plies

In-plane fibre orientation

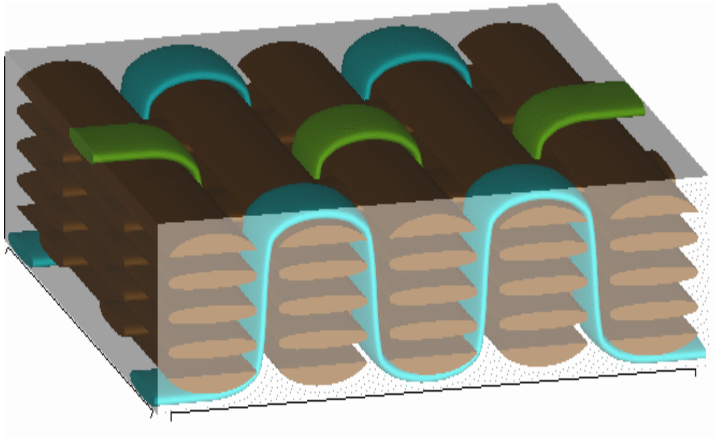
Fibre orientation Results



3D In-plane fibre orientation map

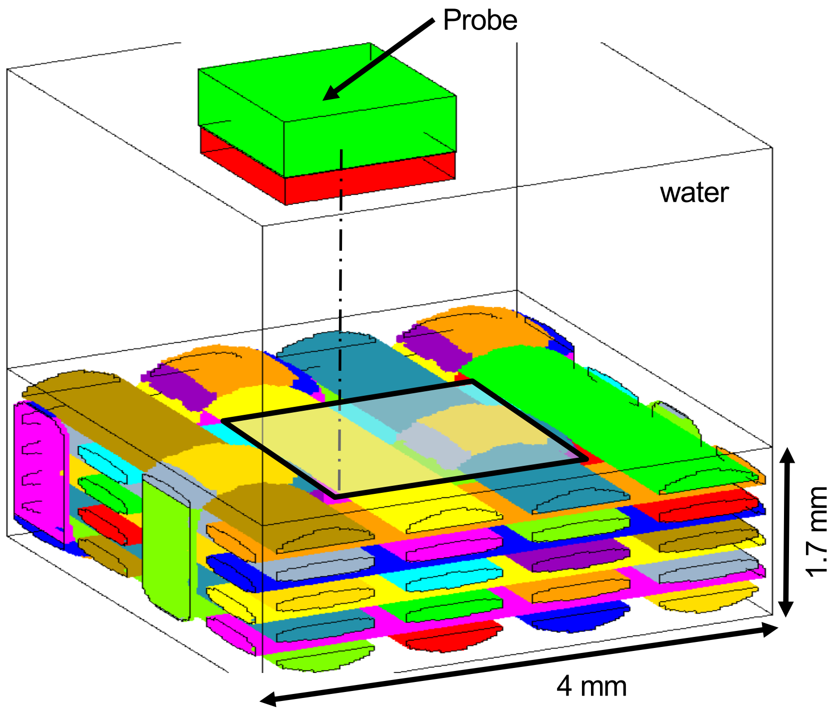
3D Woven Composites

Orthogonal weave example

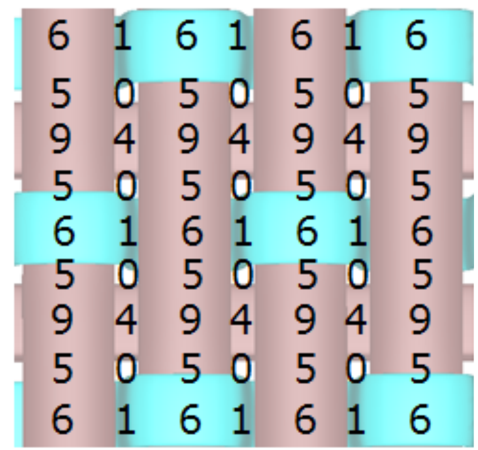


Orthogonal weave FE modelling

OnScale (PZFlex) Model

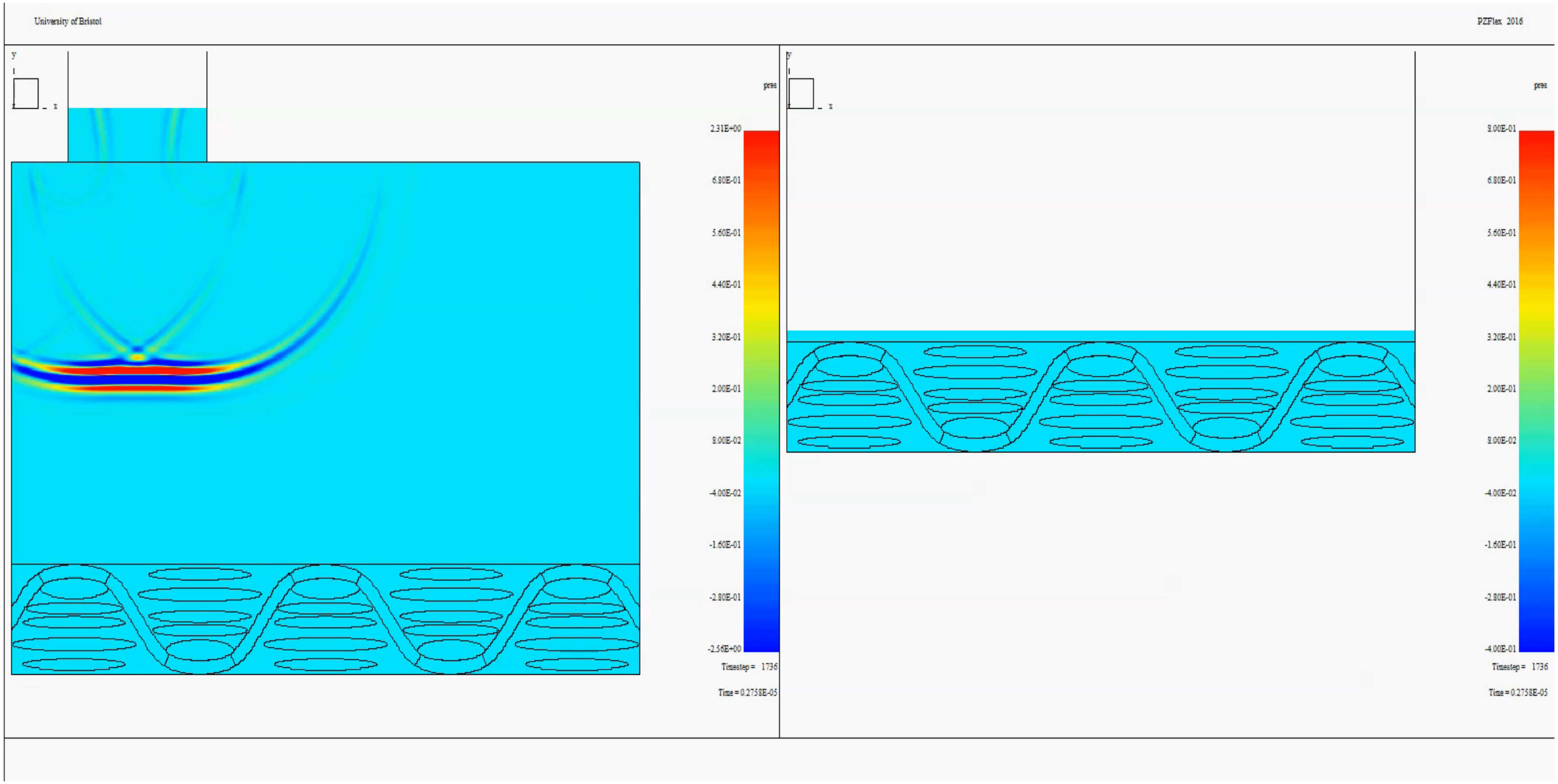


6 regions (yarns 0, 1, 4, 5, 6, 9)
with different velocities

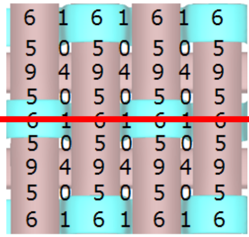


Each fibre orientation has a different color in PZFlex

Binding-yarn effect from FE modelling



Instantaneous parameters

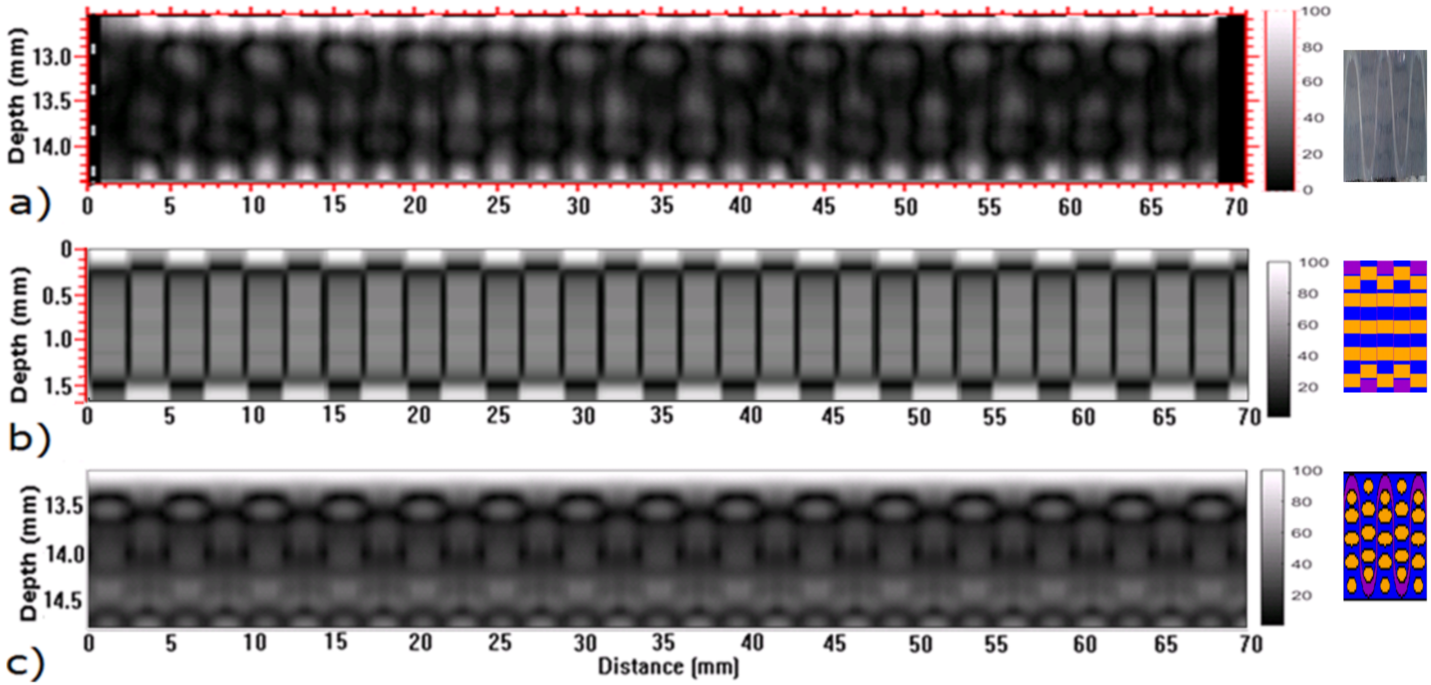


Binder-yarn region: 5 MHz Instantaneous. amplitude

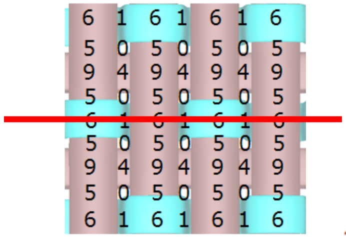
Experiment:

Analytical model:

Finite Element model:



Instantaneous parameters

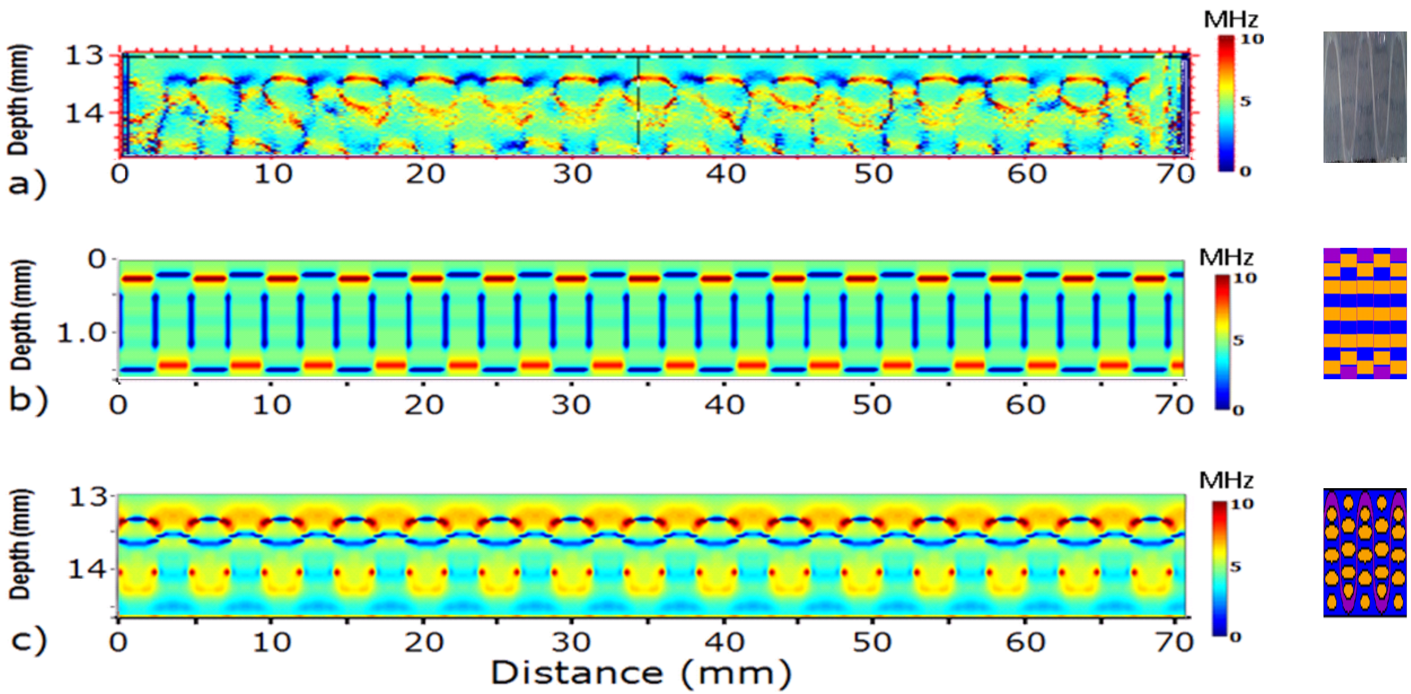


Binder-yarn region: 5 MHz Instantaneous frequency

Experiment:

Analytical model:

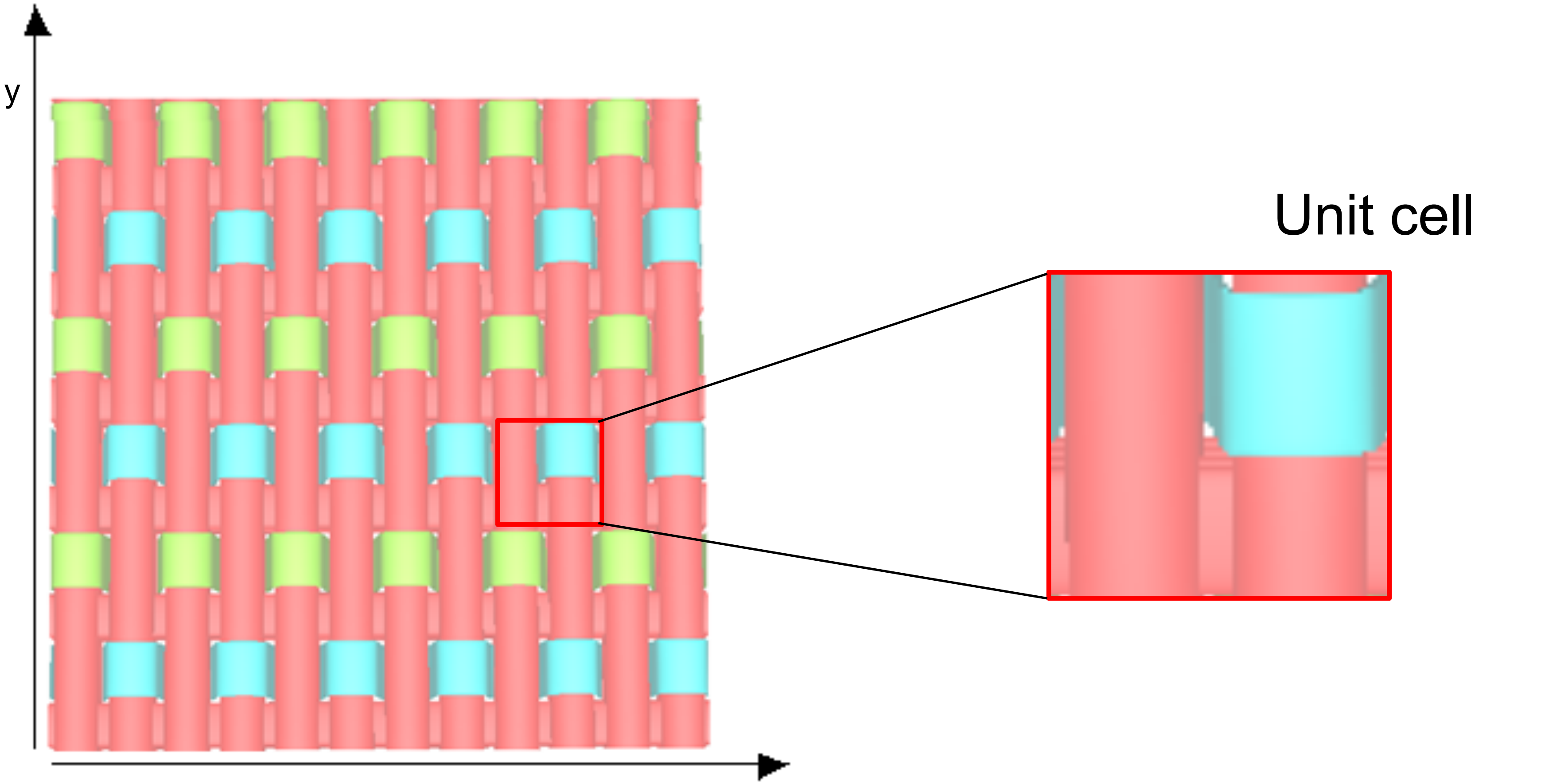
Finite Element model:



Conclusion: Level of compaction is important in modelling & in practice

Defect-detection Strategy

The Unit Cell



Unit cell is the smallest repetitive element in 2D or 3D

In-plane Benchmark Subtraction technique

For each depth below the surface, use the in-plane C-scan…

- Create a 'benchmark' pristine scan using a unit cell and cross-correlation in 2D
- Subtract the benchmark scan from the actual measured scan

Use of the instantaneous amplitude for these results, but should also work with instantaneous frequency

Method demonstrated using FE data, then applied to experimental data…