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SIMULATION OF ULTRASONIC INSPECTIONS OF COMPOSITE STRUCTURES IN THE CIVA SOFTWARE PLATFORM

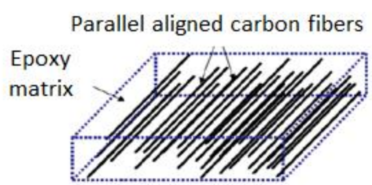
WCNDT 2016 | Jezzine Karim

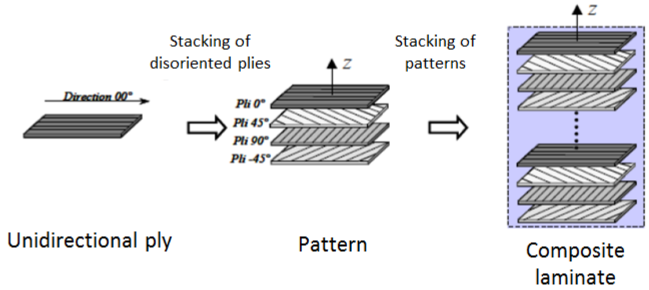
- *Context: CIVA-COMPOSITE*
- *Hybrid modelling for the simulation of composite inspections*
- *Simulation results and validations*
- *Conclusions & Perspectives*

NDT OF COMPOSITE LAMINATES

Carbon Fiber Reinforced Polymers

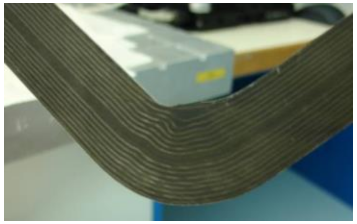
- Used to reduce the weight of the structure while maintaining high mechanical performance
- Highly heterogeneous and anisotropic





Typical defects

- Ply waviness
- Delaminations
- Matrix crackings
- Porosities

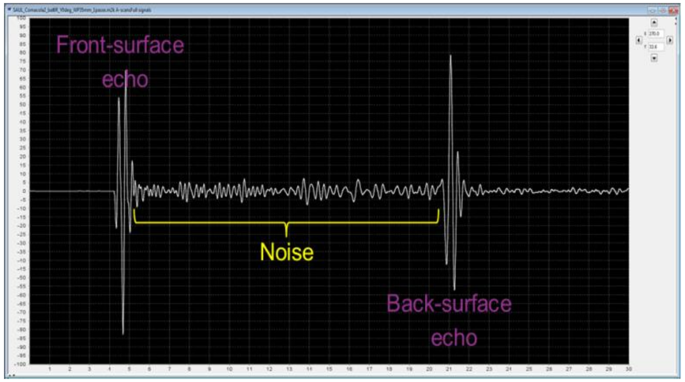


HOMOGENIZATION OF COMPOSITE LAMINATES (1/2)

Scale of inhomogenities

- Fiber diameter: ~ 5 to 10 µm
- Intermediate epoxy layers: ~10 to 25 µm
- Ply thickness: ~ 100 to 200 µm

Typical UT signals (pulse-echo Ascan)



Presence of structural noise due to intermediate epoxy layers

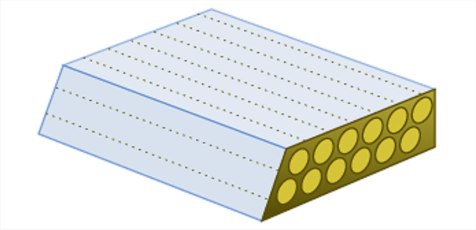
Necessary to homogenize the structure to apply ultrasonic propagation models

HOMOGENIZATION OF COMPOSITE LAMINATES (2/2)

Homogenization at ply scale (based on multiple scattering)

S. Lonné PhD thesis, 2003

Fiber density 60 %
Fiber diameter 0.007 mm
Algorithm Yang Mal
Min frequency 1 MHz
Max frequency 10 MHz



Name: Homogeneous material
Density 1.494 $g.cm^{-3}$

Properties

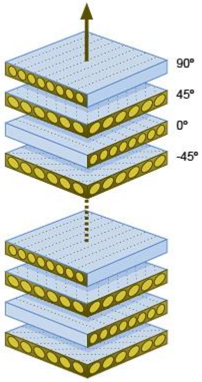
Symmetry: Transversely isotropic

Stiffness matrix (GPa) - elastic properties

141.952	5.286	5.286	0	0	0
5.286	12.432	5.81	0	0	0
5.286	5.81	12.432	0	0	0
0	0	0	3.311	0	0
0	0	0	0	5.089	0
0	0	0	0	0	5.089

Symmetry: X' / Y' / Z'

Full homogenization



Name	Thickness (mm)	Angle /Z (deg)
Ply n° 0	0.125	45
Ply n° 1	0.125	0
Ply n° 2	0.125	-45
Ply n° 3	0.125	90
Ply n° 4	0.125	45
Ply n° 5	0.125	0
Ply n° 6	0.125	-45

S. Deydier PhD thesis, 2006

Properties | Visualization

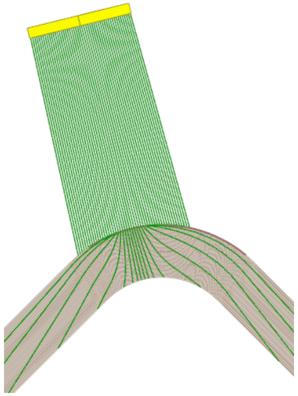
Symmetry: Orthotropic

Stiffness matrix (GPa) - elastic properties

111.709	70.666	4.697	0	0	0
70.666	111.709	4.697	0	0	0
4.697	4.697	12.432	0	0	0
0	0	0	4.128	0	0
0	0	0	0	4.128	0
0	0	0	0	0	20.521

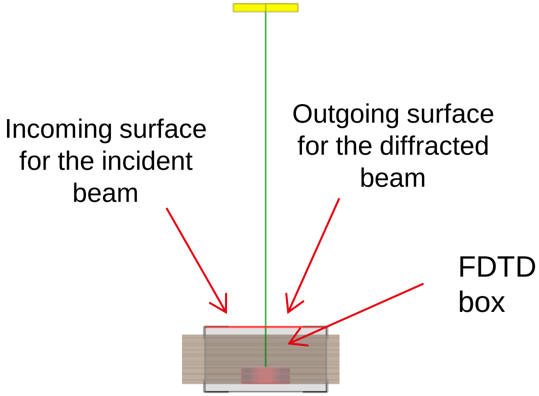
SIMULATION APPROACHES IN CIVA FOR COMPOSITE LAMINATES

Semi-analytical ray based approach



- Requires full homogenization of the laminate (structural noise cannot be taken into account)
- Very fast computations for flat specimens (rays travel in straight line), even for 3D.
- Ray tracing and amplitude computation are slower for curved anisotropic media but remain fast compared to numerical methods.
- Available in CIVA for 2D and 3D computations

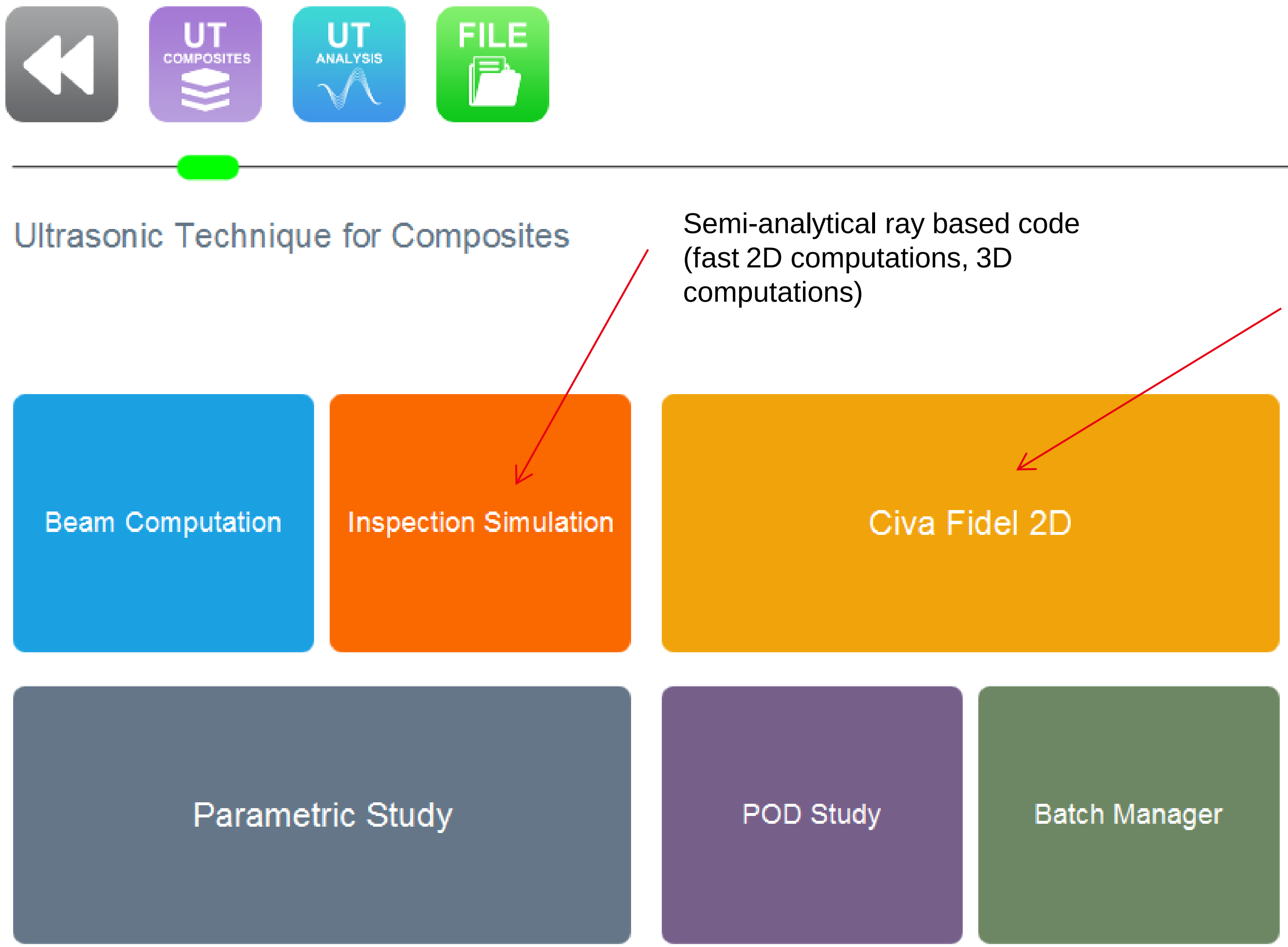
Hybrid modelling (ray based/ Finite Difference Time Domain)



- Only requires homogenization at ply scale (structural noise is taken into account)
- Computation time reduced in comparison to a full FDTD computation
- Computation time increases with frequency
- Available in CIVA for 2D computations

PRESENTATION OF CIVA-COMPOSITE (1/3)

Module dedicated to composite materials released in 2016



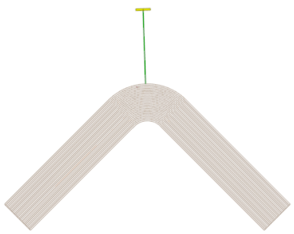
Semi-analytical ray based code (fast 2D computations, 3D computations)

Hybrid ray based/ FDTD code

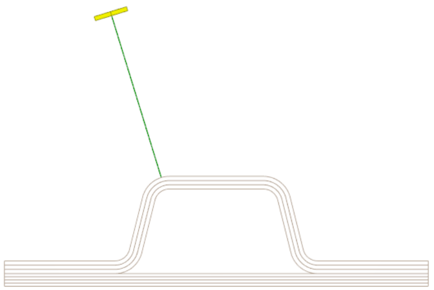
(Accurate 2D computations)

PRESENTATION OF CIVA-COMPOSITE (2/3)

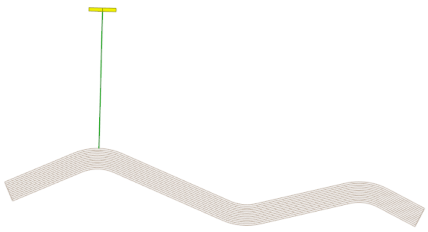
SPECIMENS



Curved composite laminates



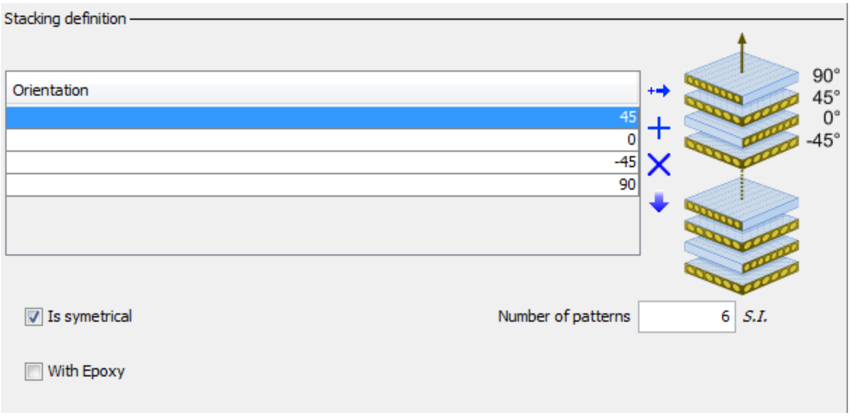
Stiffeners



Complex shaped composite laminates

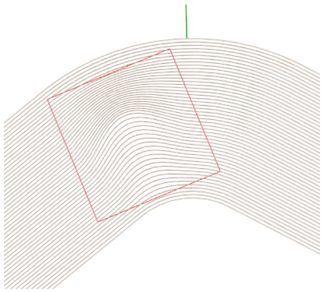
MATERIALS

Specific GUI to define stacking sequence

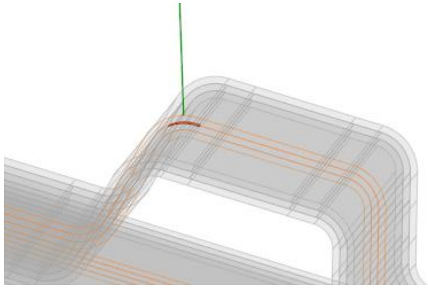


PRESENTATION OF CIVA-COMPOSITE (3/3)

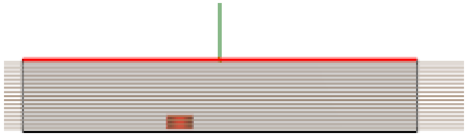
SPECIFIC FLAWS



Ply waviness

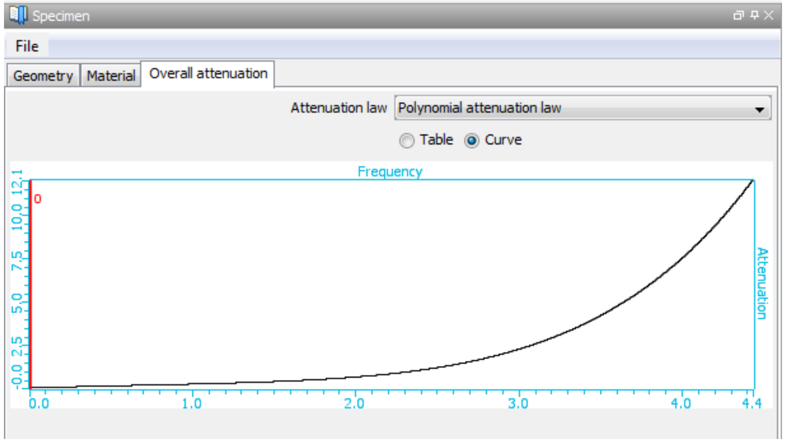


Delaminations



FBH (filled with fluid)

ACCOUNT OF ATTENUATION BY POST-PROCESSING



- Obtained from experimental data
- Accounts for viscoelasticity of the resin, scattering by carbon fiber, porosities
- Sliding FFT window algorithm

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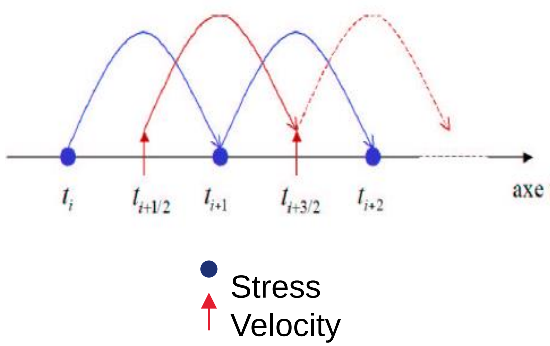
FDTD MODEL DEVELOPPED BY AIRBUS

Finite Differences in Time Domain (FDTD): Virieux scheme

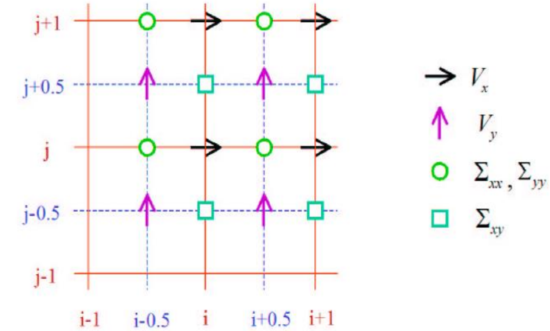
Stress-velocity formulation

$$\begin{cases} \dfrac{\partial v_i}{\partial t} = \dfrac{1}{\rho} div\sigma(v) + F_i \\ \dfrac{\partial \sigma_{ij}}{\partial t} = C_{ijkl}\dfrac{\partial v_k}{\partial x_l} \end{cases}$$

Leap-frog scheme in time



Staggered grid in space



Discretized equations

$$V_{x_{i,j}}^{n+\frac{1}{2}} = V_{x_{i,j}}^{n-\frac{1}{2}} + \frac{1}{\rho_{i,j}}\frac{\Delta t}{\Delta x}\left(\Sigma^n_{xx_{i+\frac{1}{2},j}} - \Sigma^n_{xx_{i-\frac{1}{2},j}} + \Sigma^n_{xy_{i,j+\frac{1}{2}}} - \Sigma^n_{xy_{i,j-\frac{1}{2}}}\right)$$

$$\Sigma^{n+1}_{xx_{i+\frac{1}{2},j}} = \Sigma^n_{xx_{i+\frac{1}{2},j}} + \frac{\Delta t}{\Delta x}\left\{C_{11_{i+\frac{1}{2},j}}\left(V^{n+\frac{1}{2}}_{x_{i+1,j}} - V^{n+\frac{1}{2}}_{x_{i,j}}\right) + C_{12_{i+\frac{1}{2},j}}\left(V^{n+\frac{1}{2}}_{y_{i+\frac{1}{2},j+\frac{1}{2}}} - V^{n+\frac{1}{2}}_{y_{i+\frac{1}{2},j-\frac{1}{2}}}\right)\right\}$$

FDTD stability conditions (2D):

$$\begin{cases} \Delta x \le \lambda_{\min}/20 \\ \Delta t \le \dfrac{\Delta x}{c_{\max}\sqrt{2}} \end{cases}$$

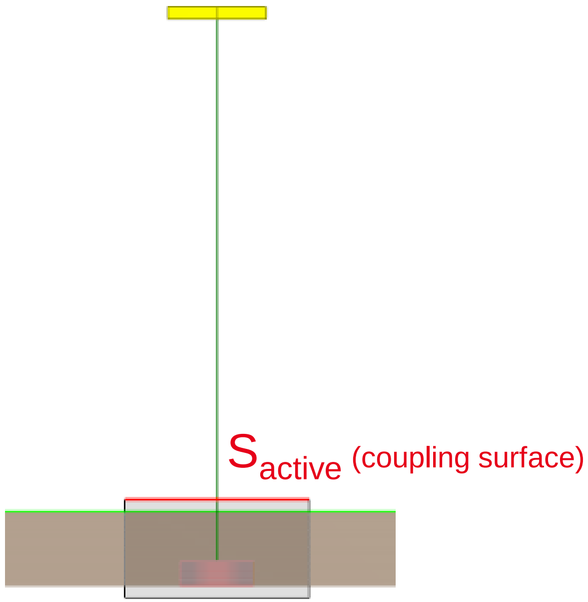
HYBRID MODEL

Echo response expression (Auld's reciprocity principle)

$$s(t) = \int_{S_{active}} \left(p^{(tot)} * \delta v_n^{(inc)}\right)(t) - \left(v_n^{(tot)} * \delta p^{(inc)}\right)(t)\, dM$$

Total wavefield (pressure/velocity) computed with FDTD

Incident wavefield (pressure/velocity) computed with CIVA (ray based model)



Use of PMLs (Perfectly Matched Layers) on the box boundaries (no reflections)

Source terms in FDTD code

$$F_i = \frac{\Delta T}{\rho} \delta p^{(inc)} \Big/ \frac{\Delta x}{2}$$

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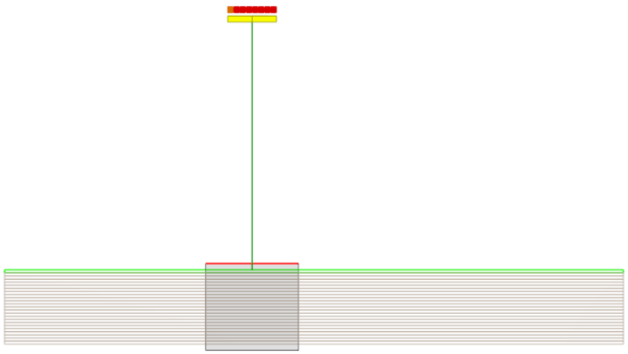
RESONANCE FREQUENCY (1/2)

Geometry

- Quasi isotropic laminated plate [0/+45/90/-45]
- Total thickness: 12mm (24 plies)
- Intermediate epoxy layers : 15µm thick



Material properties

- Epoxy : ρ = 1.23 g cm-3, V_L = 2500 m s^{-1}, V_T = 1140 m s^{-1}
- Unidirectional CFRP ply : ρ = 1.6 g cm-3

Hooke tensor:

$$\begin{pmatrix} 155 & 5 & 5 & 0 & 0 & 0 \\ & 13 & 7 & 0 & 0 & 0 \\ & & 13 & 0 & 0 & 0 \\ & () & & 3 & 0 & 0 \\ & & & & 6 & 0 \\ & & & & & 6 \end{pmatrix}$$

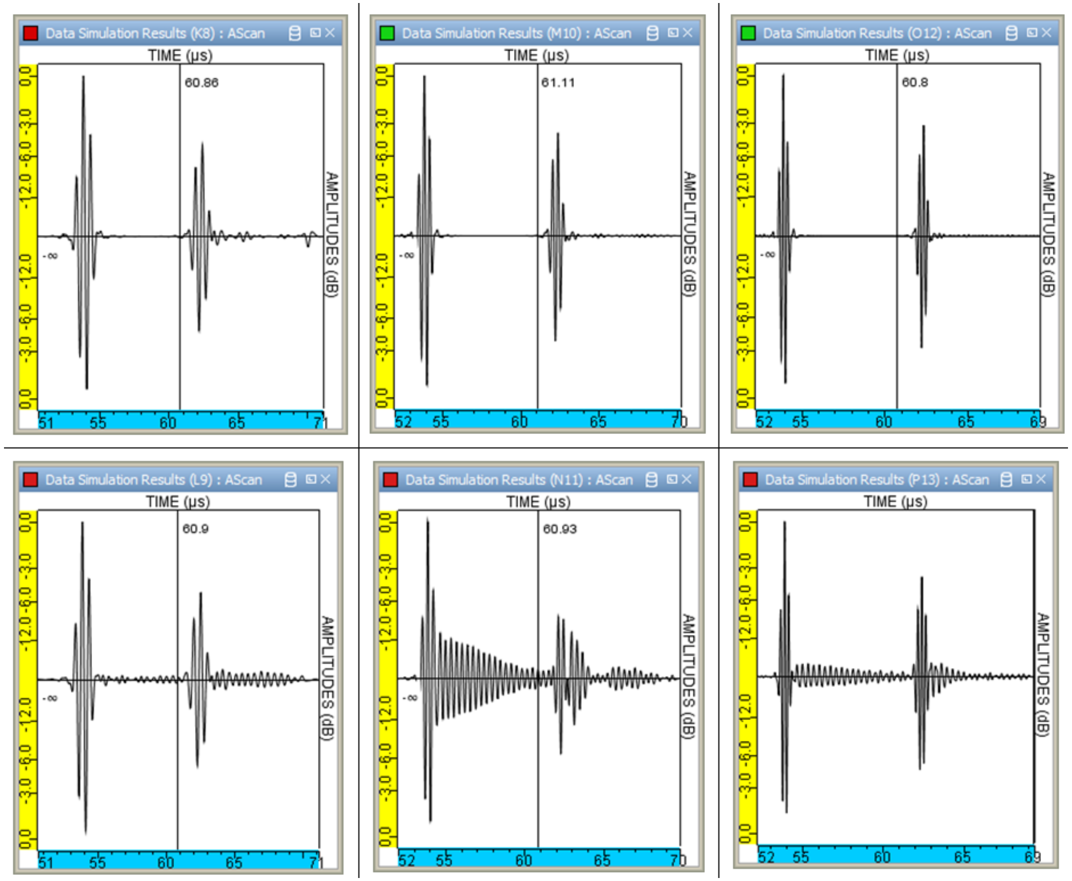
Theoretical resonance frequency ~ 3Mhz (V_{L0}/ply thickness/2)

RESONANCE FREQUENCY (2/2)

Simulated Ascans

without intermediate epoxy layers

with intermediate epoxy layers



f= 2 MHz   f= 3 MHz   f= 4 MHz

EXPERIMENTAL VALIDATIONS (1/2)

Validation on a CFRP panel with two different transducers

Material type	Pre-preg
Material	CFRP n°1
Thickness of the area	7.23 mm (28 plies)
Total ply thickness (including resin interface)	0.259 mm
Resin interface thickness	15 µm

Theoretical resonance frequency ~5,8MHz

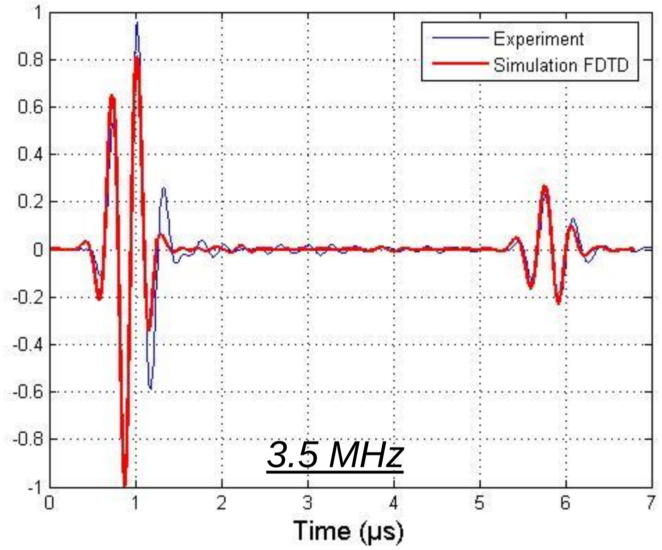
Material properties (Cij, ρ and α(F)) were measured by Airbus and used as input of the models

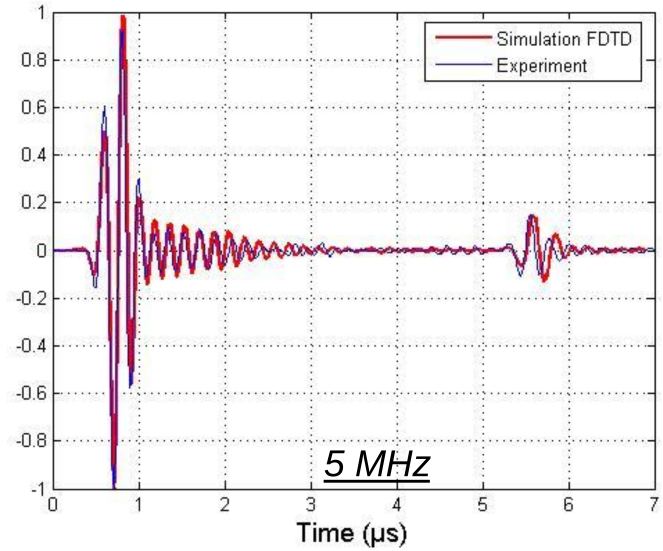
	Probe 1: Metalscan Aero C n°034801-4	Probe 2: Metalscan Aero C n°034801-2
Type	Single-crystal	Single-crystal
Crystal shape	Flat	Flat
Crystal diameter	6 mm	6 mm
Nominal freq.	3.5 MHz	5 MHz
Peak freq.	3.2 MHz	4.7 MHz
Bandwidth @ -6dB	60 %	55 %

EXPERIMENTAL VALIDATIONS (2/2)

Experimental and simulated Ascans

- Central frequency and bandwidth are adjusted to fit the frontwall echo
- Attenuation due to viscoelasticity is applied by post-processing using a sliding window over the signal.



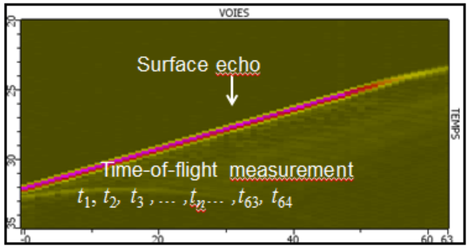


The amplitude of the backwall echo and the structural noise is well predicted by the model

SURFACE ADAPTATIVE ULTRASONIC (1/2)

Phase array inspections with SAUL

- SAUL is an iterative process that adapts the wavefront to enter the component with a normal incidence
- Delays laws are computed using the frontwall echo
- All the elements of the array are fired simultanously
- Time of flight measurement on each element in reception



Emission delay law ***E*** :

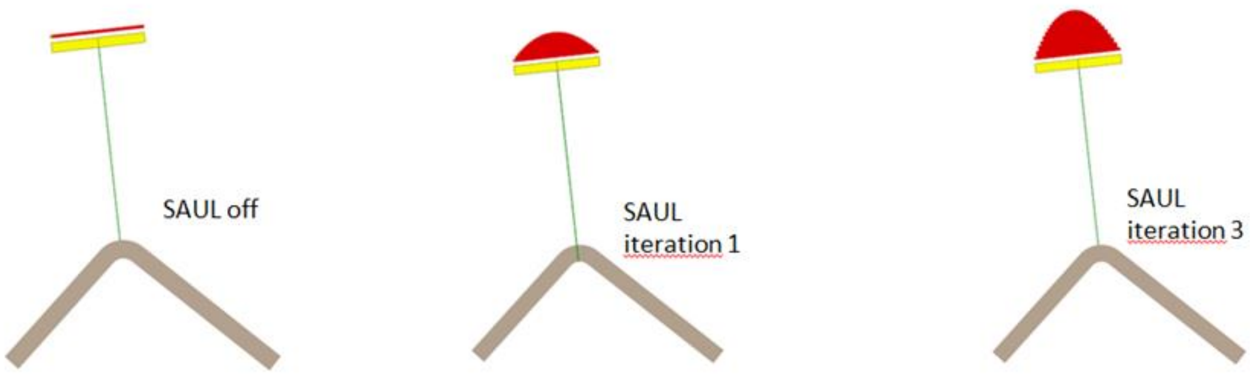
$$E_n^{(j+1)} = \frac{1}{2}\left[Max\left(t_1^{(j)}, t_2^{(j)}, \ldots, t_n^{(j)}\right) - t_n^{(j)}\right] + E_n^{(j)}$$

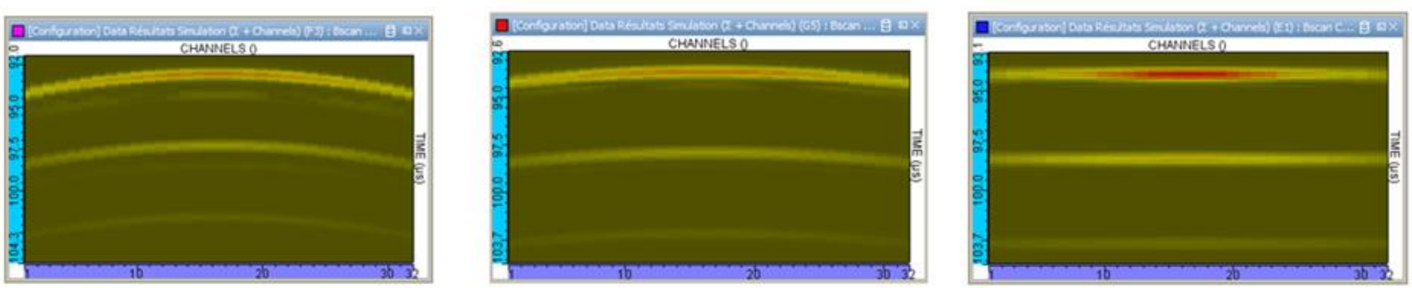
Reception delay law ***R*** :

$$R_n^{(j+1)} = Max\left(E_1^{(j+1)}, E_2^{(j+1)}, \ldots, E_n^{(j+1)}, \ldots, E_n^{(j+1)}\right) - E_n^{(j+1)}$$

SURFACE ADAPTATIVE ULTRASONIC (2/2)

- 32 elements probe, 4MHz,
- Delay laws computed from frontwall echo





SAUL gives a flatter echo with higher amplitude

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CONCLUSIONS AND PERSPECTIVES

- Airbus Group Innovations FDTD code has been integrated in CIVA for composite applications

- Dedicated GUI features have been implemented.

- Further improvements include
  - Account of dispersion
  - Integration of 3D code

- Contact and demonstration for CIVA: visit EXTENDE stand

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