CIVA SHM for guided waves simulation: Damping model and absorbing boundary layers

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Outline

- Introduction: Why simulation in SHM ?
- Implementation of guided wave SHM in CIVA
- Additional features for simulation accuracy and efficiency
  - Attenuation modelling
  - Absorbing boundary layers
- Conclusion

Why simulation in SHM ?

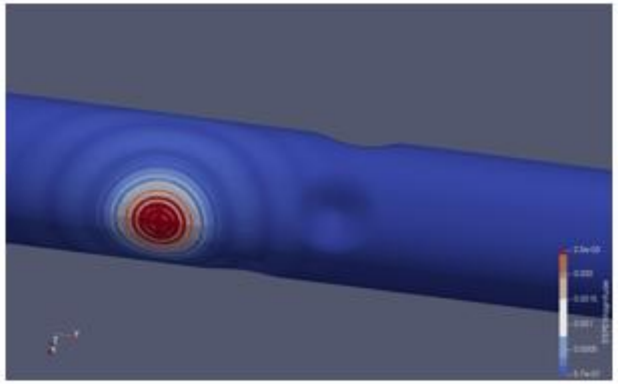
- Simulation shall help the industrial deployment of SHM strategies:
  - To reduce time and cost at the **design** stage:
    - Needs to optimize the monitoring setup to find the best compromise “Cost / Number of sensors” vs “Detection performance”
    - Virtual prototyping shall help to :
      - Try and select some sensors (Size ? Frequency ? Signal processing ?)
      - Optimize the number and location of sensors
    - Without having to invest “before” in many costly sensors, physical prototypes and instrumented mock-ups.
    - Once a monitoring scenario looks promising, start the physical implementation and tests

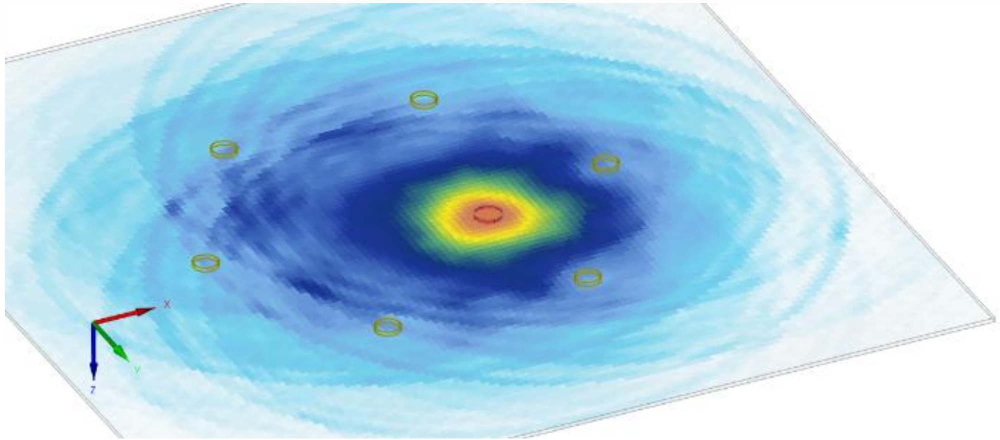
Why simulation in SHM ?

- Simulation shall help the industrial deployment of SHM strategies:
  - To support **certification/performance demonstration** tasks
    - Reliability study needs to rely on large dataset representing field variability
    - Simulation is a solution to run relevant designs of experiments for many influential parameters, typically:
      - Defect parameters defect sizes, types, locations and orientations
      - Materials/geometrical uncertainty/variability
      - Environmental and operational conditions (with adapted models)
    - Some other influential parameters still need to studied experimentally (such as contact/transmission conditions, electronic and ambient noise),
    - However, a full experimental approach would need to build and instrument too many flawed mock-ups, which is just too costly :
      <u>A rigorous demonstration performance could not be achieved</u>.

Why simulation in SHM ?

- Simulation shall help the industrial deployment of SHM strategies:
  - To help the **understanding and data analysis**:
    - Complex signals (many modes, dispersive, etc.) to interpret : Simulation provides insights to improve understanding
    - Simulation provides databases of various scenarios from which:
      - Signal/Image processing techniques can be evaluated to help raw data treatment for flaw detection/characterization and avoid false alarms
      - AI models can be trained for assisted/automated pre-diagnostics





Implementation of guided wave SHM in CIVA

- **CIVA** is a modelling and analysis platform dedicated to **NDT** and **SHM** :
  - Multi-technique :
    - UT: Ultrasounds
    - RT-CT: Radiography (Gamma and X Rays) & Computed Tomography
    - ET: Eddy Current
    - GWT: Guided Waves
    - SHM-GWT: Structural Health Monitoring by Guided Waves
    - TT : Thermography Testing
  - Developed by CEA List
  - EXTENDE is the exclusive distributor of CIVA and provides NDE consulting services.

Implementation of guided wave SHM in CIVA

- You need one model, but which model ?
  - Several simulation strategies available :
    - **Semi-analytical** (SA) methods efficient for large propagation distances in “perfect” and long “waveguides” (pipe, rails, etc.) : Unidirectional propagation
    - **Hybrid:** SA can be potentially **coupled with local FEM computations** to account for local perturbations (flaws, geometrical discontinuities): Adapted for long range applications addressed with CIVA GWT
    - **Full Finite Elements** approach can tackle more complex configurations (several “perturbations”, several sensors, more complex geometries, etc.):
      - But can require large computation times
      - Can be faster if parallelized with GPU but needs specific hardware
      - Can benefit from a tailored **spectral elements** method to enable “low cost” computation on standard hardware: <u>Strategy implemented in CIVA SHM</u>

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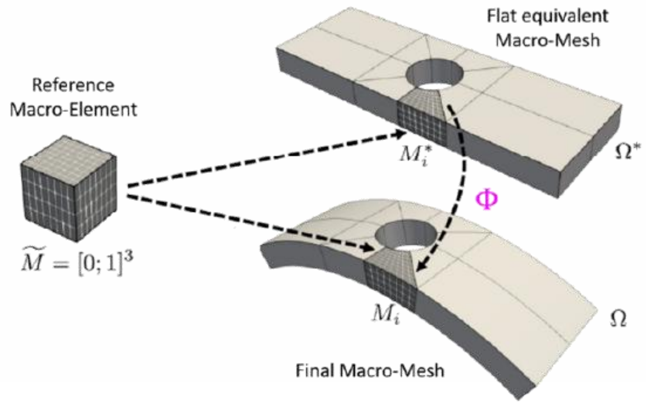
Implementation of guided wave SHM in CIVA

- You need one model, but which model ?
  - CIVA SHM is based on a High Order Spectral Finite Elements method*
  - Mesh is parametrized vs geometric features (specimen, sensors, defects)
    → “Macro-Mesh” from which the FEM mesh is automatically generated
  - Benefits :
    - Parametrized mesh and high order discretization leads to a reduced number of d.o.f
    - Mass matrix is diagonal :
      - Fast to inverse at each time step
      - Stiffness matrix does not need to be assembled

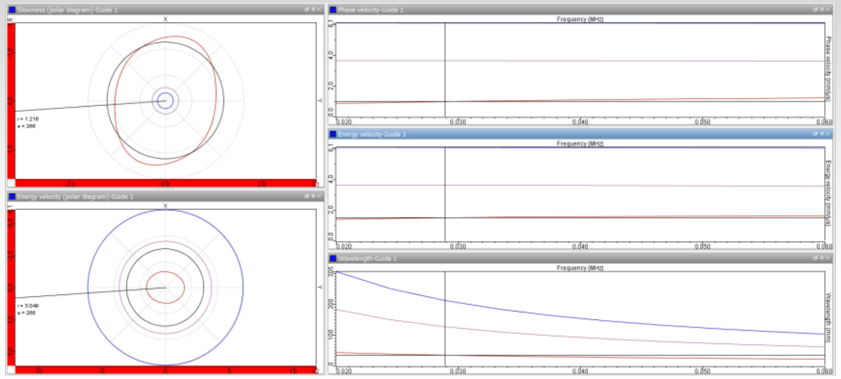
    → Faster computation time and low memory footprint compared to traditional FEM
  - Drawbacks/Challenges:
    - Parametric geometry/mesh: Not fully generic. Needs to progressively implement new use cases
    - Simulation time step strongly dependent on mesh and viscoelastic parameters

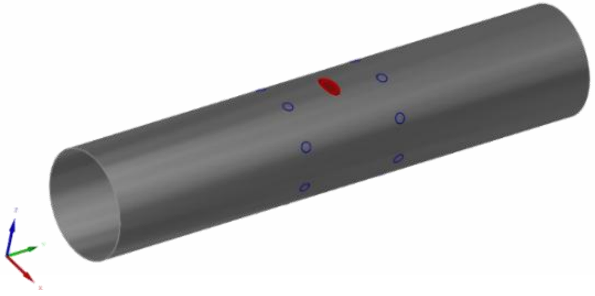


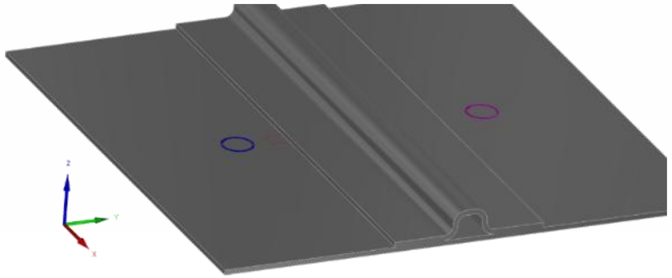
*Imperiale, A., Demaldent, E. (**2019**). A macro-element strategy based upon spectral finite elements and mortar elements for transient wave propagation modeling. Application to ultrasonic testing of laminate composite materials. Int. Journal for Numerical Methods in Engineering, vol. 119(10), pp. 964–990.

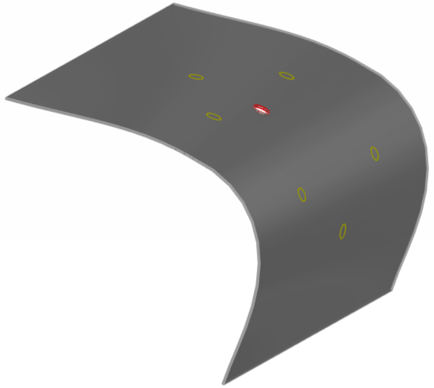
Implementation of guided wave SHM in CIVA

- Applications covered:
  - Metallic and composite plates, pipes and elbows
  - Account for curvatures, stiffeners, sleeves
  - Defects: Holes, Cracks, Delamination, Corrosion/Erosion, Inclusion







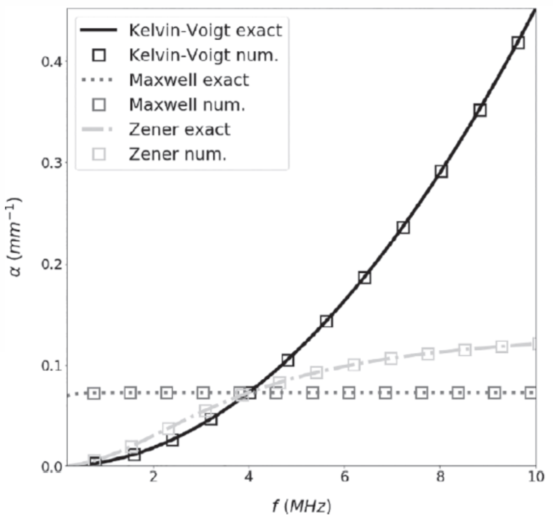


- New features recently implemented:
  - Damping model for more accurate simulation, especially for composite materials
  - Absorbing layers boundary conditions for more efficient simulations

Damping models

- Three attenuation models (Maxwell, Zener, Kelvin-Voigt) have been implemented in CIVA relying on different hypotheses and thus different numerical implementations:

Model	Hypothesis	Impact on numerical implementation* vs no damping model	Cost	Physical representativeness
Maxwell	Constant attenuation vs Frequency	• Double unknowns • Smaller time step needed • Time step linearly dependent on mesh size	+	+
Zener	Locally linear attenuation vs Frequency	• Double unknowns • Even Smaller time step needed • Time step linearly dependent on mesh size • 2 applications of the stiffness matrix et each time step	++	++
Kelvin Voigt	Quadratic attenuation vs Frequency	• No need for double unknowns • Smaller time step needed • Time step quadratically dependent on mesh size • 2 applications of the stiffness matrix et each time step	+++	+++



**Imperiale, N. Leymarie and A., Demaldent, E. (2020)*. Numerical modeling of wave propagation in anisotropic viscoelastic laminated materials in transient regime: Application to modeling ultrasonic testing of composite structures. Int. J. Num. Meth. Eng., 121(15):3300–3338, 2020

Damping models

- Validation case :
  - Comparison with experimental measurements (Laser Doppler vibrometer) of normal displacements amplitude for different attenuation models
  - 500mm*500mm CFRP composite panel, 12 plies of 0.125mm, Excitation at 75kHz, 50% bandwidth at-6dB

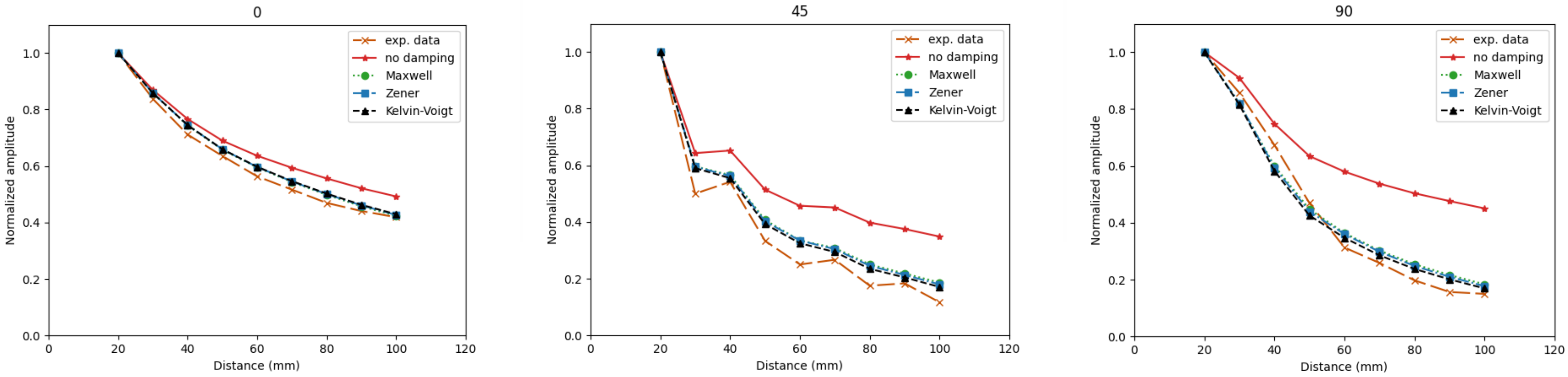
  - Elastic constants: Viscosity coefficients calibrated at 75kHz

Stiffness coefficients	**C11**	**C22=C33**	**C12=C13**	**C23**	**C44**	**C55=C56**
Values (Gpa)	147	9.8	0.41	0.69	3.31	5.3
Viscosity coefficients	**D11**	**D22**	**D33**	**D44**	**D55**	**D66**
Values (Pa.s)	155.2	248.1	248.1	341	185.8	185.8

Damping models

- Normal displacements amplitude:
  - At different distances from emitter (20mm to 100mm)
  - In 3 directions: 0° , 45° , 90°

Fiber orientation at 0°: Stronger attenuation in 45° and 90° directions



No significant differences between the different damping models

All models are close to experimental references

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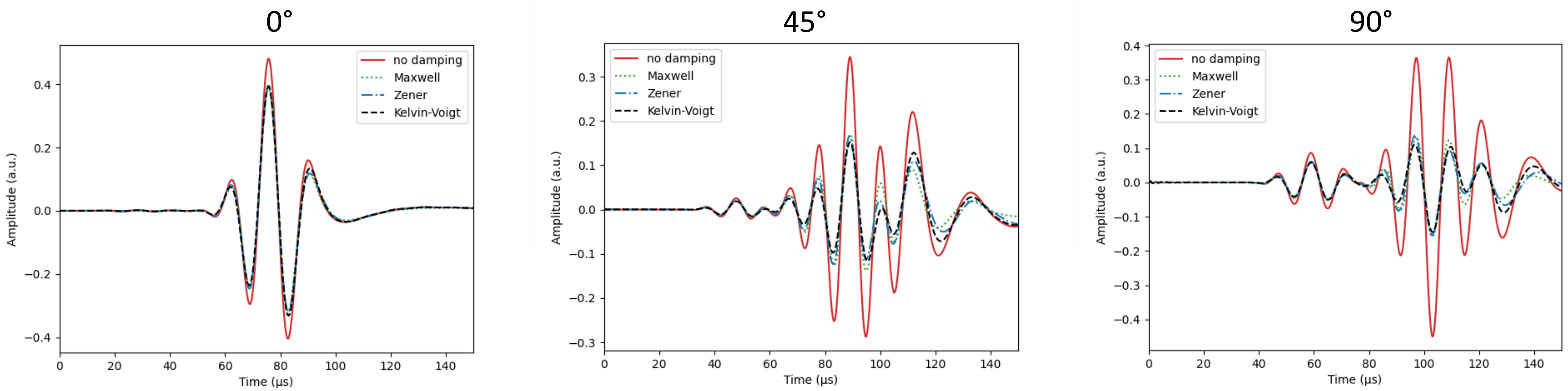
Damping models

- Simulated signals:
  - At 100 mm from emitter
  - In 3 directions: 0° , 45° , 90°

Pretty similar waveforms for the different damping models

Narrow bandwiwth (quite usual with SHM sensors), few impact of frequency dependence of the attenuation law

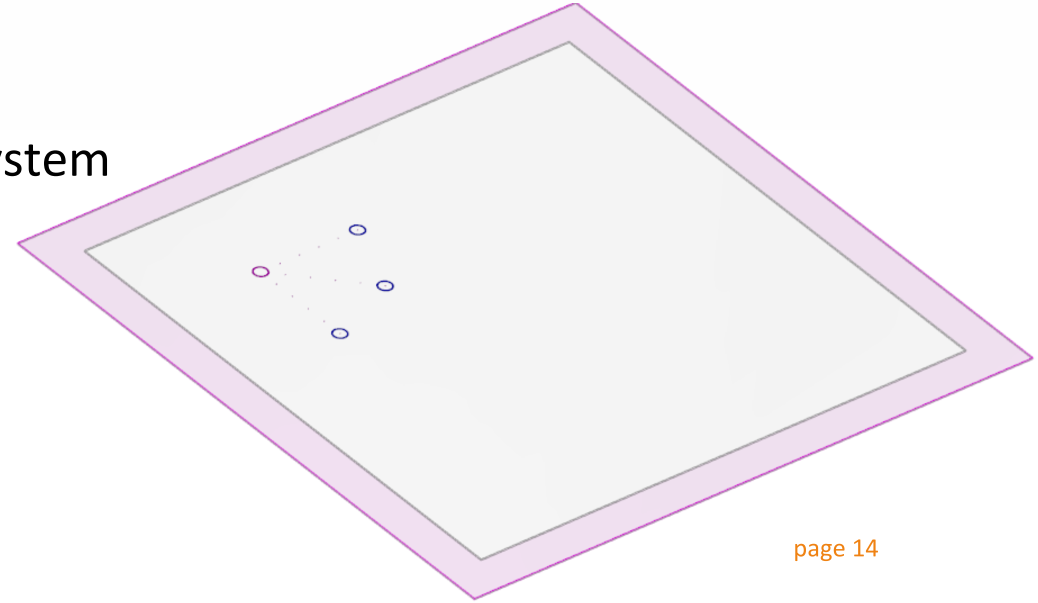


- Performances : In this case, more efficient to rely on the Maxwell model

Damping model	No damping	Maxwell	Zener	Kelvin-Voigt
Computation time	4’38’’	6’8’’	9’14’’	13’9’’

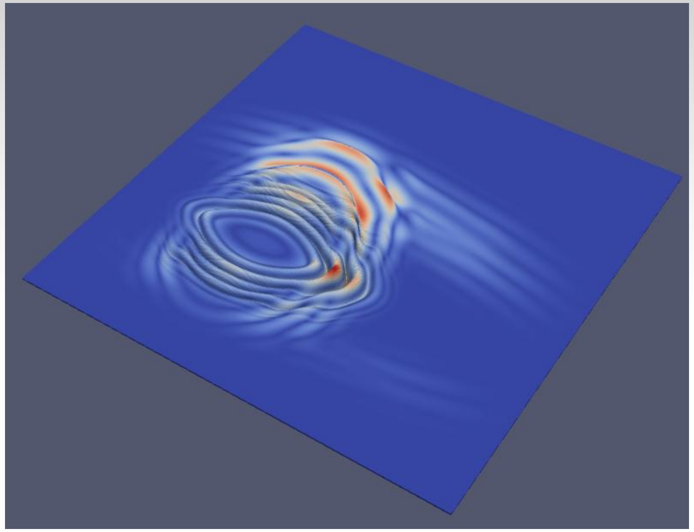
Absorbing boundary layers

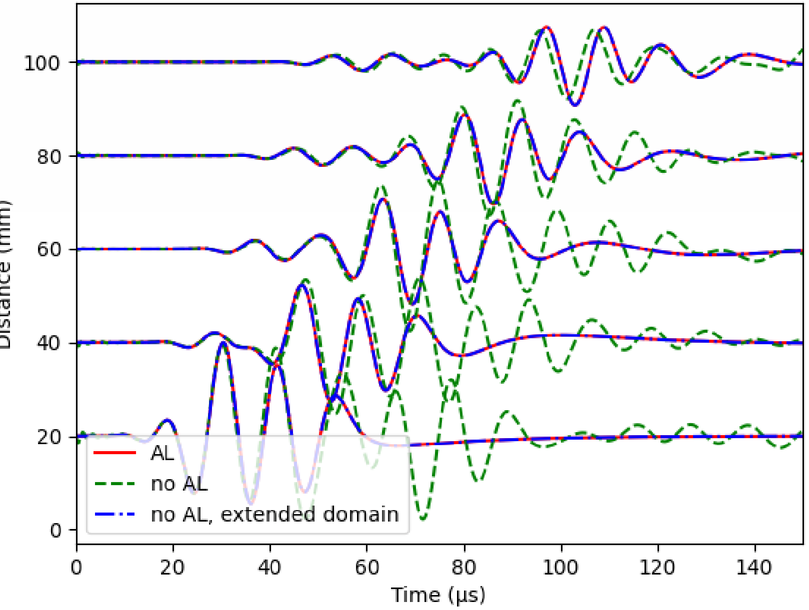
- SHM modelling with large components may lead to large study domain and mesh
- Reducing artificially the model size may introduce artificial edge reflections interfering with "signals of interest"
- Goal of absorbing boundary layers (AL) : Using a strong attenuation law on domain borders to strongly limit these reflections and limit the overall domain size
- AL versus PML (Perfectly Matched Layers):
  "Perfect" absorption for PML but less stable numerical system
- In CIVA SHM:
  AL band size is 2 * maximum wavelength in the model



Absorbing boundary layers

- Results and performance
  - Wave snapshots : Wave energy absorbed near the border
  - Comparison of results at different distance from an emitter located at 20mm from component border:
    - Large component size (500mm) and no Absorbing Layer (no AL)
    - Reduced component size (150mm) and no Absorbing Layer (no AL)
    - Reduced component size (150mm) with Absorbing Layers (AL)





Without AL and a reduced component size, additional « artificial » wave packets are visible

Case with AL matches very well the extended component model

- Performances (for this example) :

Case	Large specimen and no AL	Reduced Specimen With AL
Computation time	4’38’’	2’52’’

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Conclusion

- SHM simulation can allow more extensive parametric studies for virtual prototyping or demonstration performance studies at “low cost”.

- CIVA SHM implements a spectral FEM method allowing accurate simulation of complex situations for a quite wide range of application cases with quite fast computation times on standard computers.

- Three attenuation models have been implemented for more accurate simulation, especially for composite materials. One validation has been shown here with a good agreement with experimental data.
  In this case the “Maxwell” model was as accurate as other more complex and costly damping models (Zener, Kelvin Voigt).

- Absorbing layers, more stable than PML, have also been implemented to reduce the study domain size (thus the mesh and computation time), without introducing artificial edge reflections.

Thank you
for your attention !

- You wish a demo ?
- Visit our booth at the exhibition

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