Simulating for Innovation: Exploiting the Capabilities of Simulation in Non-Destructive Testing

Stéphane LE BERRE, CEA-List, France

Roman FERNANDEZ, EXTENDE, France

OUTLINE

- Introduction to modelling benefits and capabilities of the simulation,
- NDT Simulation challenges :
  Multi-scale, multi-physics : a large set of simulation strategies and models
- Highlight on UT modeling
  - Semi Analytical models,
  - FEM and Hybrid models,
  - Metamodeling.
- New applications,
  - Simulation for Data Science and AI,
  - Digital twins,
  - Simulators for skill maintenance.
- Some application cases,
- Conclusion.

Modelling benefits and capabilities of the simulation

Numerical modelling is increasingly used in the world of non-destructive testing:

- Industries
  - Energy (nuclear, Oil & Gas, wind, hydro, etc.)
  - Aeronautics and aerospace sector,
  - Metallurgy,
  - Railway,
  - Inspection company,
  - Design of testing equipment…
- Universities and R&D centers
- Training centers

Modelling benefits and capabilities of the simulation : Types of models

- Pure finite elements (FEM):
  - + : Accurate and reliable
  - - : time consuming, in general, no dedicated GUI
- Semi-analytical (SA):
  - + : accurate and reliable for a wide range of applications, dedicated GUI, fast calculation and intensive calculation capabilities,
  - - : Limits of models linked to calculation algorithms
- Pure analytical / ray tracing-based models:
  - +: easy to use, dedicated GUI, fast
  - - : Not accurate
- Hybrids SA / FEM
  - + A complement to SA models, good compromise between FEM calculation time and SA limits

Modelling benefits and capabilities of the simulation

Why using simulation in NDT ?

- Evaluate **feasability**, **design** and **optimize** inspections
  Better understanding, less iterations before physical tests on mock-ups

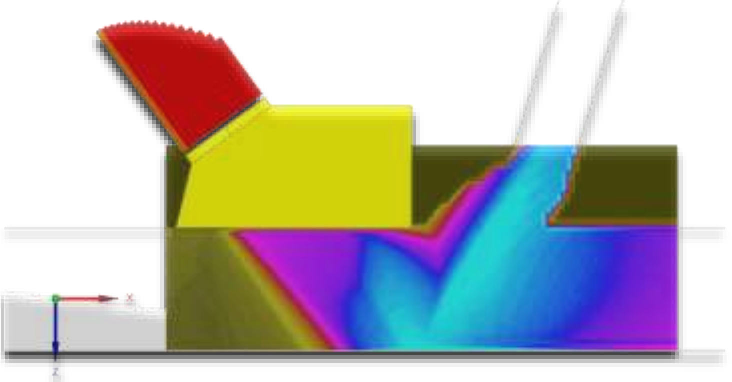
- Support **performance demonstrations**:

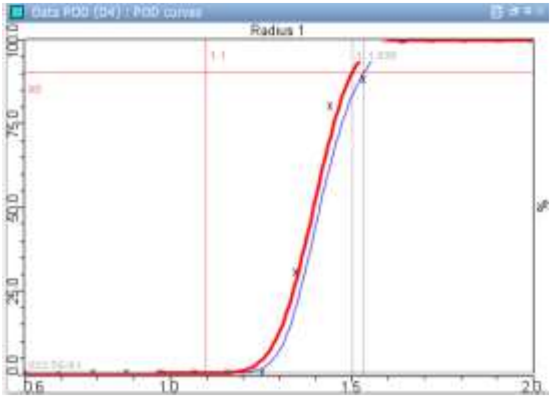
  Capacity to run large parametric studies to provide
  data for technical justifications /reliability/POD studies

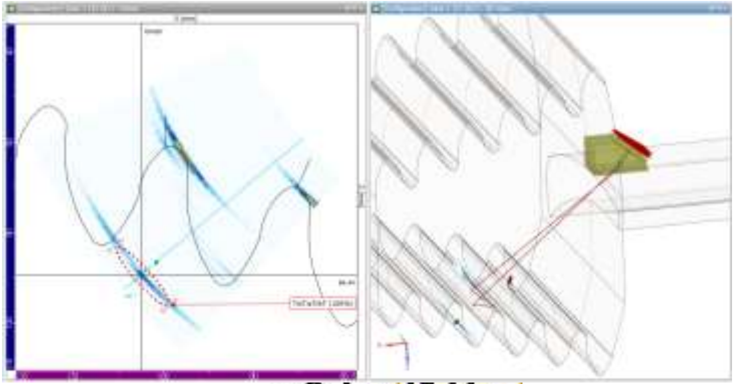
- **Expertise**:

  To explain complex situations and confirm or disprove a diagnosis

- **Convince** and **train :**
  Illustrate inspections set-up to support technical discussions



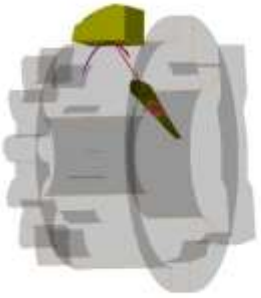


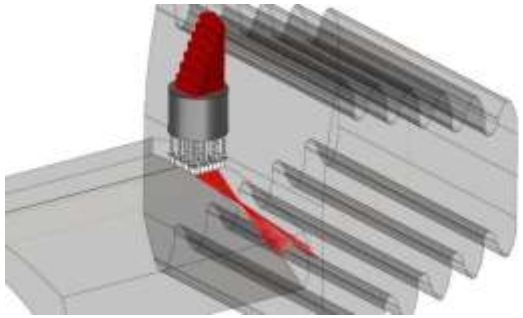


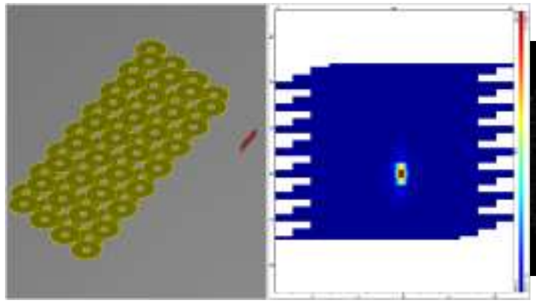
Modelling benefits and capabilities of the simulation

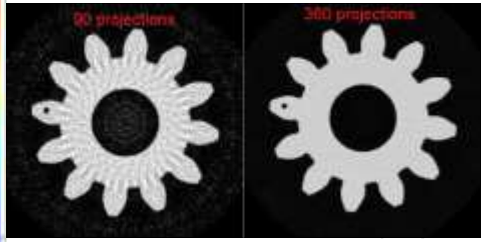
DESIGN, OPTIMIZE AND PREPARE THE INSPECTION :

- Easy control of different parameters: Create a wide range of test scenarios at low cost before investing in a prototype and physical testing to converge on the optimum solution with fewer iterations,
- Design probes and select the relevant one,
- Optimize focus settings,
- Predict the response of different defects and their detectability,
- Predict the suitability and performance of the system on the part to be inspected before going on site,
- Check the controllability of an inspection procedure.

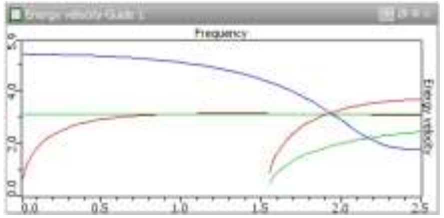






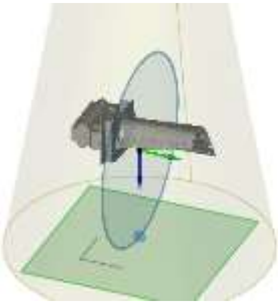


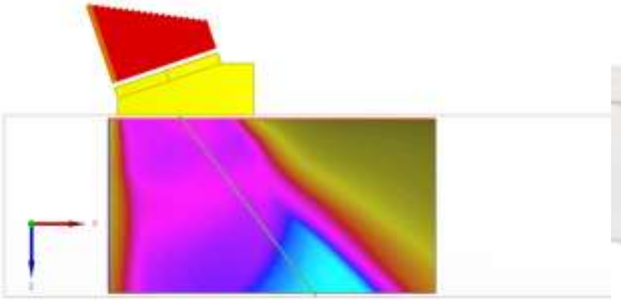
Modelling benefits and capabilities of the simulation

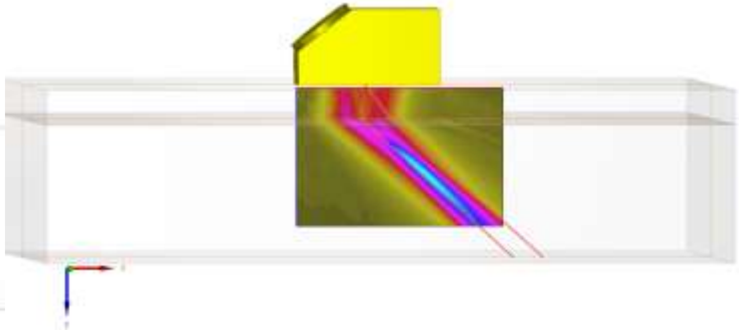


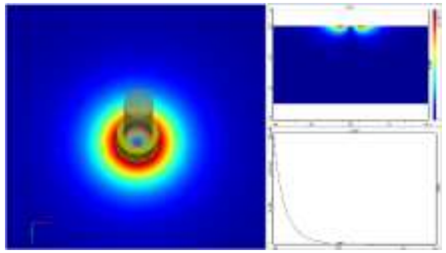
UNDERSTAND AND MASTER :

- Better control of a technique, visualize :
  - The ultrasonic field for a given probe UT, UTPA…
  - The currents induced by a coil in a given component,
  - The suitability of an X-ray source for the material to be inspected,
  - The guided waves modes generated in a specific component...
- Verify the behavior of ultrasound, currents, photons in components with complex, variable geometries or materials (pitting, cross-section changes, bimetallic welds, anisotropic welds, …)





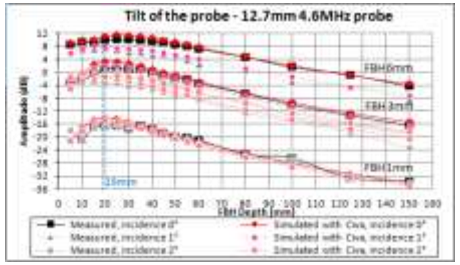


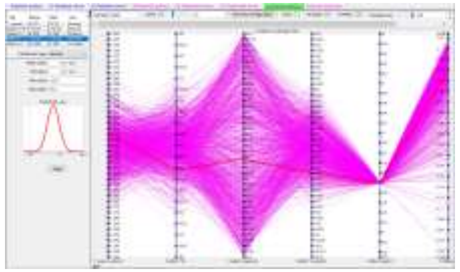


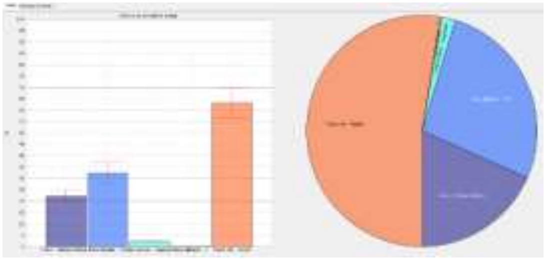
Modelling benefits and capabilities of the simulation

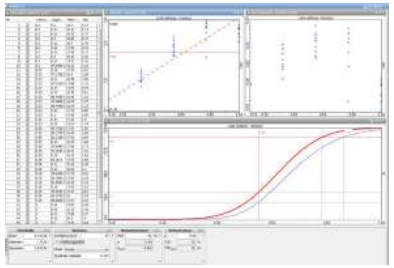
QUALIFY, DEMONSTRATE PERFORMANCE AND ASSESS CONTROL RELIABILITY :

- Predict unfavorable scenarios, worst case
- Better understanding of influential parameters, uncertainties and variability to improve control reliability,
- Perform sensitivity analyses, calculate POD curves to improve the reliability of qualification by multiplying the number of scenarios evaluated and defining the experimental tests and mock-ups that are really relevant.









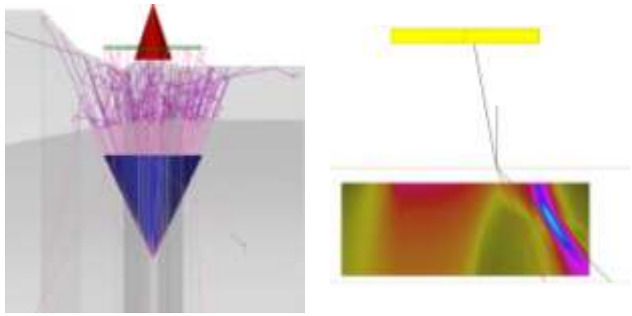
Modelling benefits and capabilities of the simulation

EXCHANGE AND CONVINCE :

- Ease technical discussions between all “players” (inspector, manufacturer, client, etc.) thanks to graphic illustration and predictive results, and convince them before investing in prototypes and tests..

TRAIN / TEACH:

- Illustrate physical phenomena,
- Explain basic concepts,
- "See the invisible”,



EXPERTISE :

- Reproduce and compare with real test and inspection results to understand complex situations and help confirm/infirm a diagnosis.

Modelling benefits and capabilities of the simulation

- Simulation is not a full substitute for experimental testing, but it can help to reduce the number of tests and improve the choice of models,

- It's important to keep a critical eye on results, and (if possible) to go through a validation stage (experimental validation, cross-validation with different modelling approach, etc.),

- Knowing this and once the models have been validated :
  - Simulation in NDT helps ensure the effectiveness and efficiency of inspections, leading to safer and more reliable components across various industries,
  - It is an extremely powerful tool that allow to break down barriers,
  - And even in complex cases having representative tendencies can be more than enough.

.

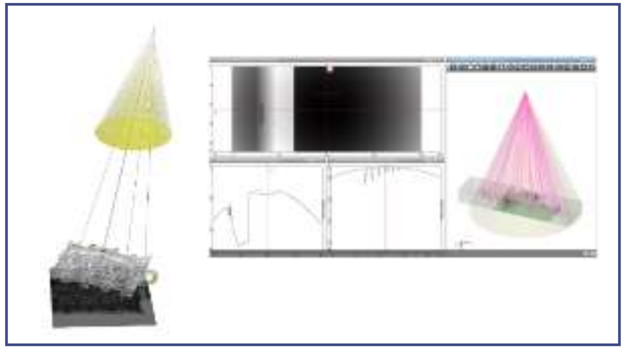
OUTLINE

- Introduction to modelling benefits and capabilities of the simulation,
- NDT Simulation challenges :
  Multi-scale, multi-physics : a large set of simulation strategies and models
- Highlight on UT modeling
  - Semi Analytical models,
  - FEM and Hybrid models,
  - Metamodeling.
- New applications,
  - Simulation for Data Science and AI,
  - Digital twins,
  - Simulators for skill maintenance.
- Some application cases,
- Conclusion.

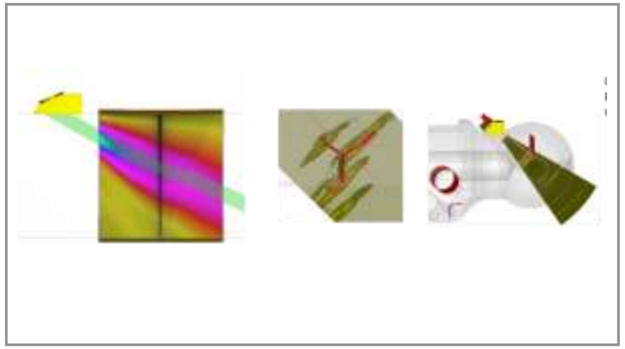
NDT Simulation challenges :

Multi-technique issues : A large set of physical models and modeling strategies

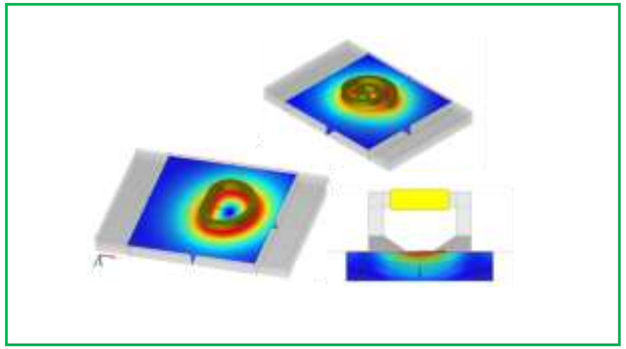
X-Ray



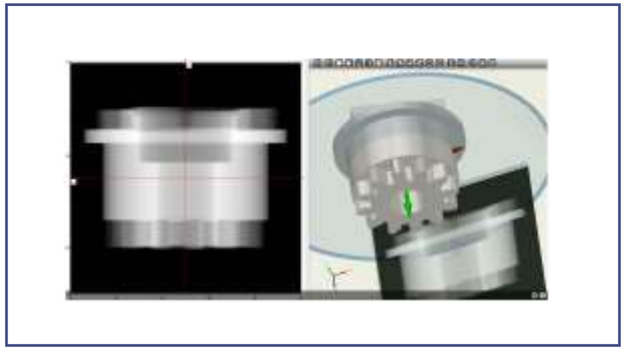
Volume waves ultrasound



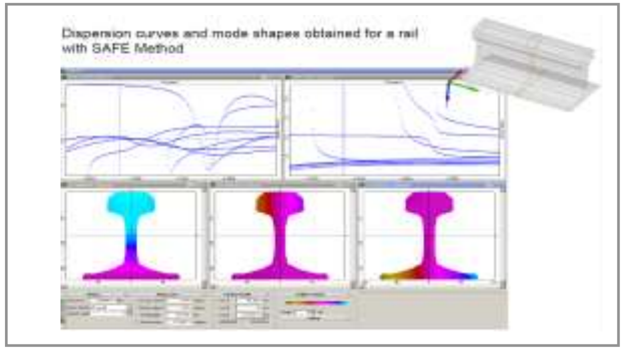
Eddy Current



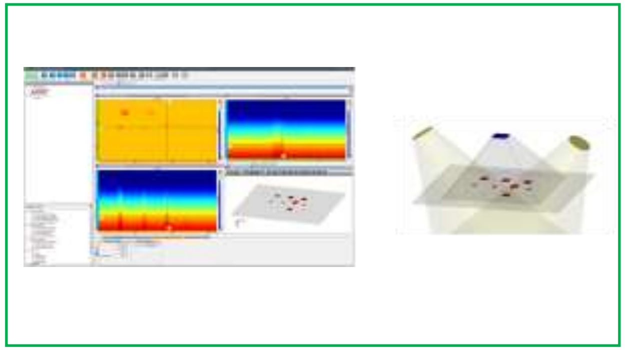
X-Ray Tomography



Ultrasound by Guided Waves



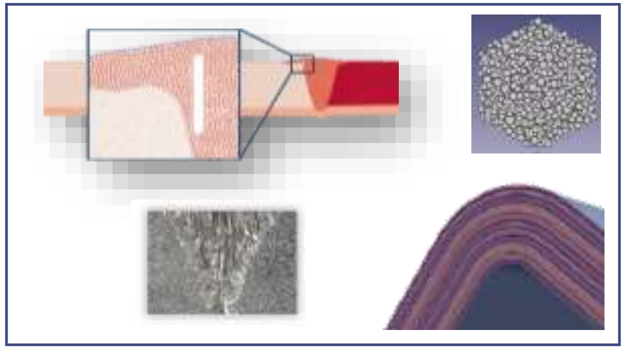
Thermography



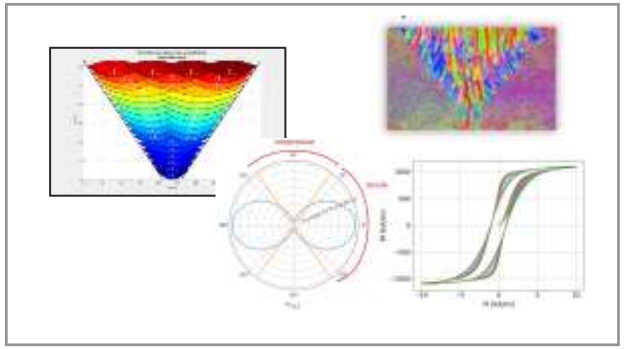
NDT Simulation challenges :

Multi-scale issues : Material characterization and properties

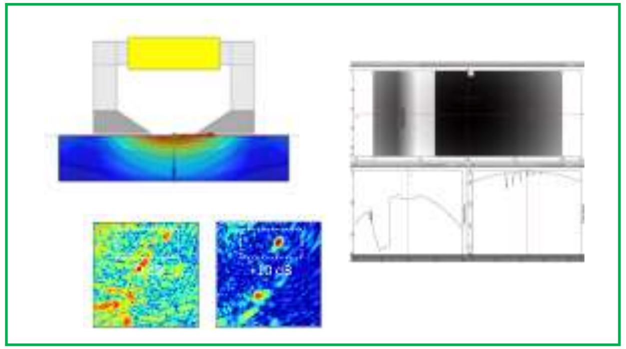
Material complexity at different scales



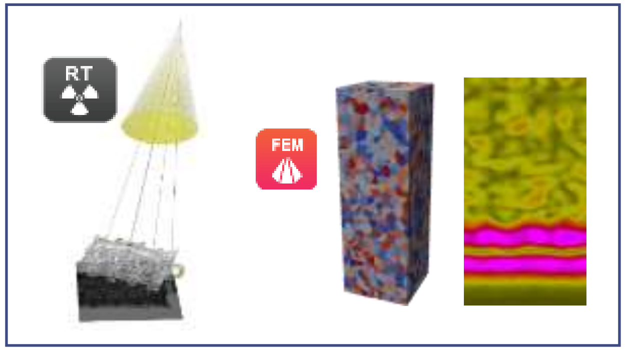
Material Properties & Parametric models



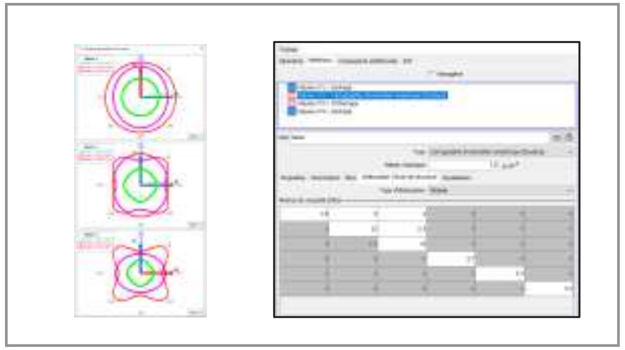
NDT Simulation & Reconstruction



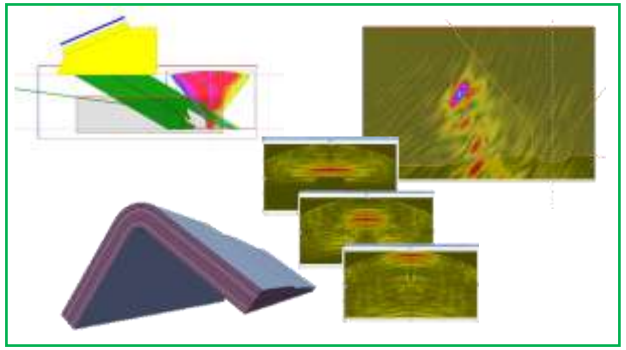
Simulation at micro-scale



Material Properties & Parametric models



NDT Simulation



CIVA Software

NDE Simulation and analysis

- Integrate research achieved at CEA List
- Release annual versions containing new tools
- Collaborative plat-form, Plug-In technology for customized or external solutions





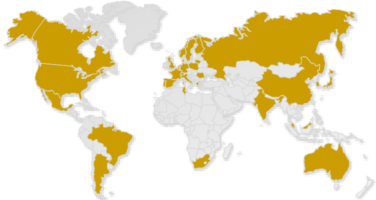

Digital Twin

Developed by CEA-List
Distributed by EXTENDE

A multi-technique software platform

Main Industrial sectors

World leader in NDT simulation



330 companies in 40 countries

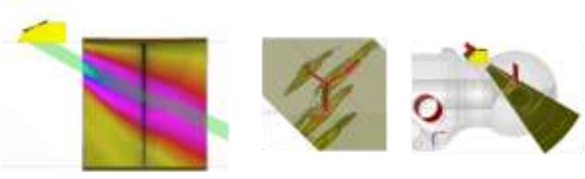
- **Design and optimization** (Probes, Inspection's Methods)
- **NDT Performance Demonstration** (Parametric Studies, Zone Coverage, POD)
- **Diagnosis** (Analysis, Reconstruction, Simulation / Experimental data, Data Bases, Machine learning, Inversion)
- **Training**

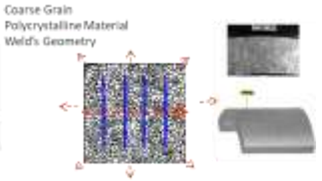


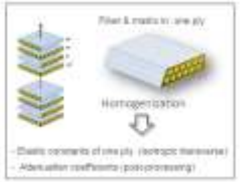
For all techniques : Common **NDT GUI ENVIRONMENT**
PROPAGATION AND INTERACTION (Material-geometry-defect)
Semi Analytical, FEM and Hybrid strategies of simulation – **FAST COMPUTATION**
IMAGING and reconstruction

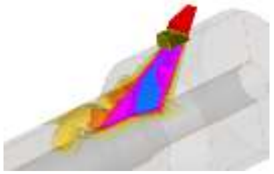
Simple Cases : under 1 minute
Complex Cases : under 1 hour
Very Complex Cases : under 1 day

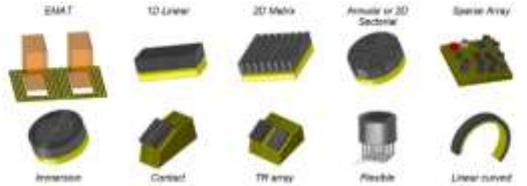
UT



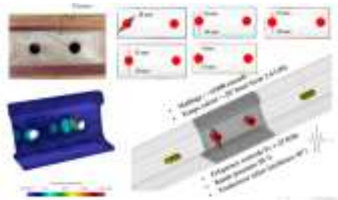


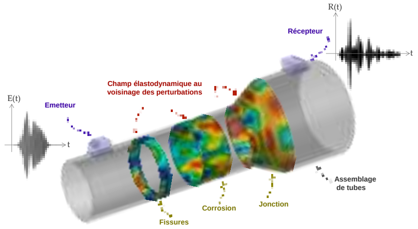




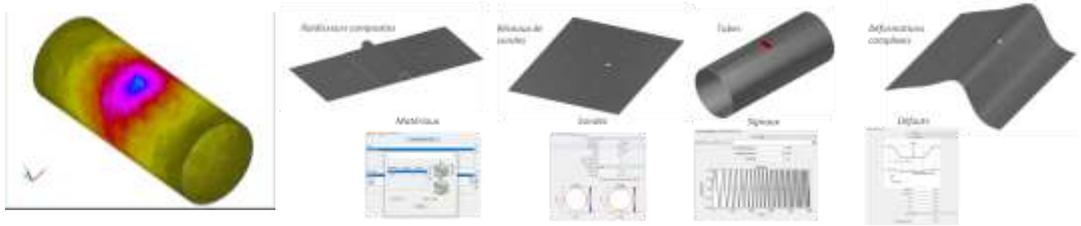


GWT

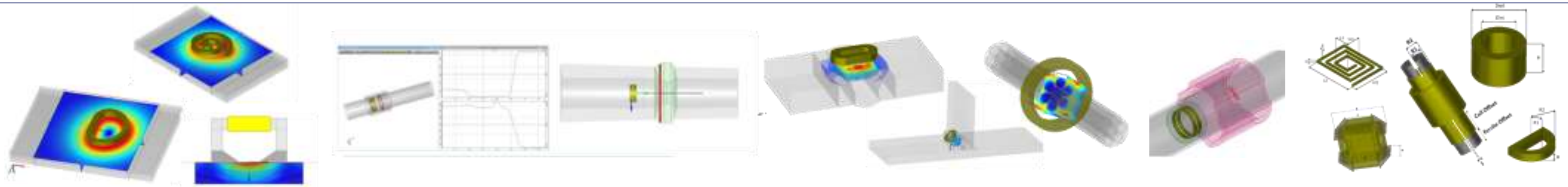




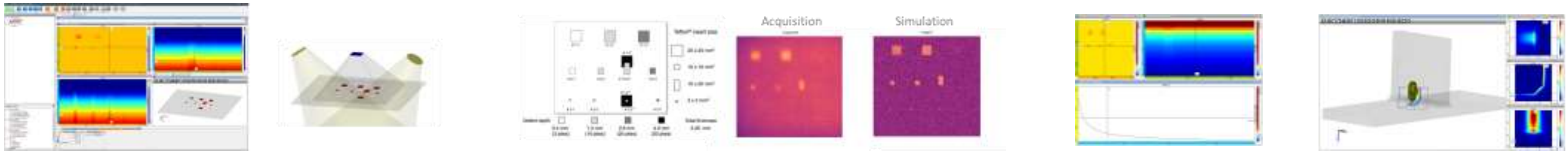
SHM



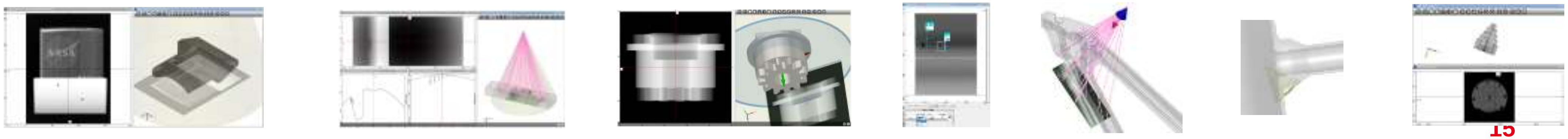
ET



TT

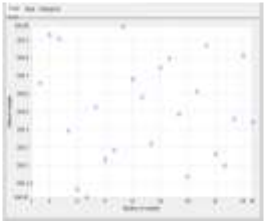


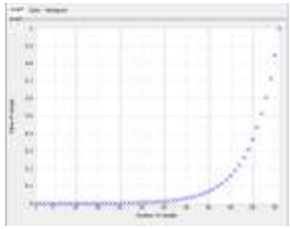
RT

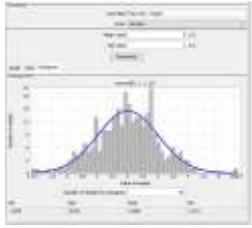


Parametric and statistical studies, metamodeling

Any parameter can be considered as “variable”







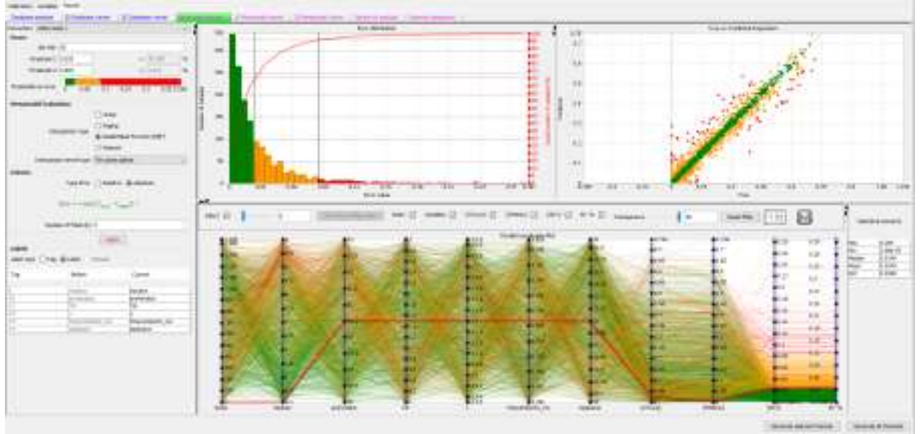
Easy setup for Parametric variations

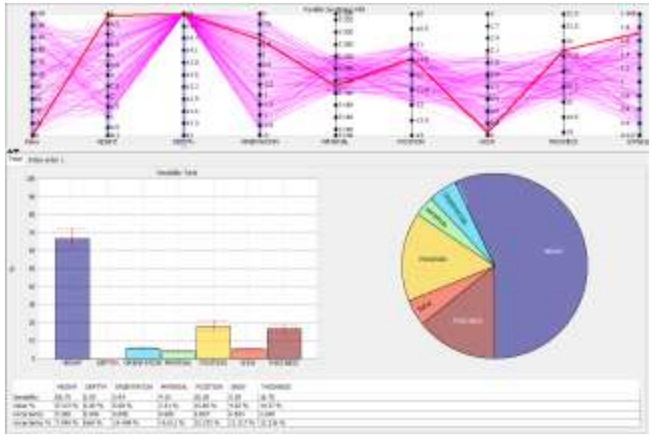
Metamodeling (real time simulation engine based on parametric study data base)

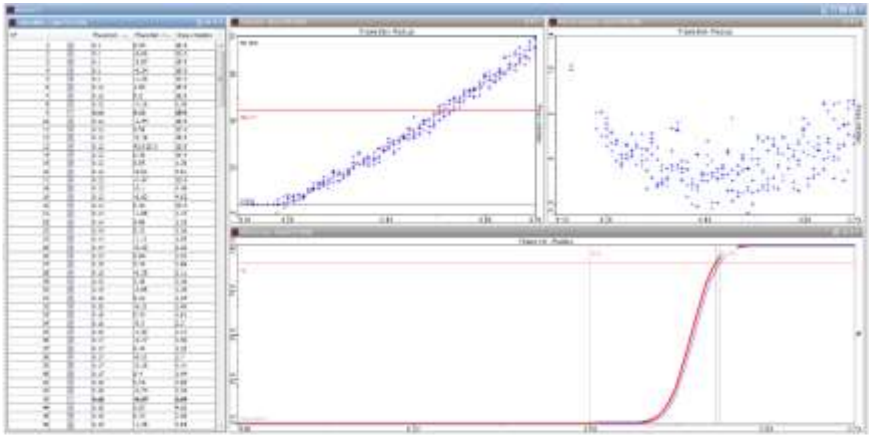
Sensitivity studies (sobol index – impact of essential variables)

POD (Probability of detection)

AI and learning data base generation for ML







EXTENDE CIVA

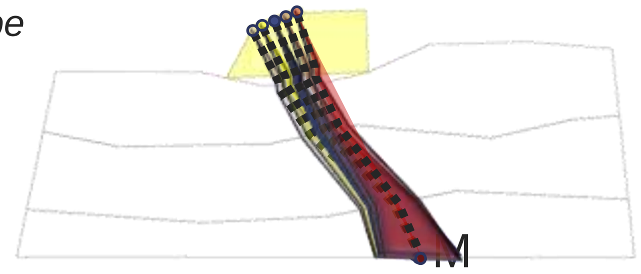
OUTLINE

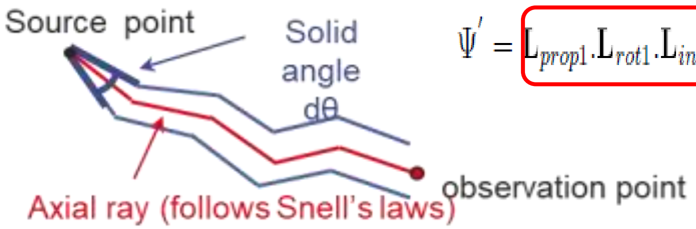
- Introduction to modelling benefits and capabilities of the simulation,
- NDT Simulation challenges :
  Multi-scale, multi-physics : a large set of simulation strategies and models
- Highlight on UT modeling
  - Semi Analytical models,
  - FEM and Hybrid models,
  - Metamodeling.
- New applications,
  - Simulation for Data Science and AI,
  - Digital twins,
  - Simulators for skill maintenance.
- Some application cases,
- Conclusion.

Semi analytical models for UT

- Beam computation :
  - Pencil models for beam propagation

Integration over probe surface on pencils' contributions to compute field at observation points

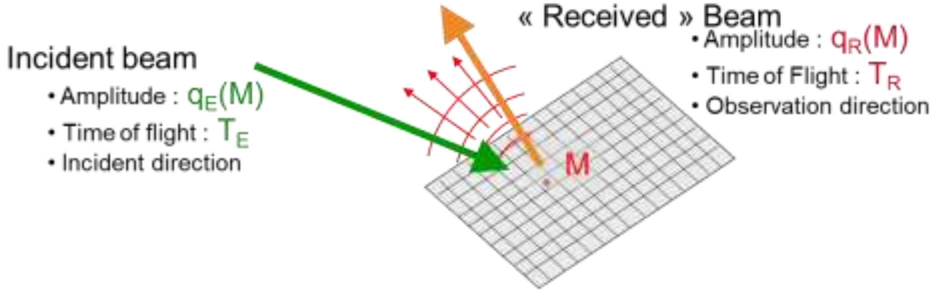




$$\Psi' = \boxed{L_{prop1}.L_{rot1}.L_{inter1}.L_{prop2}.L_{rot2}.L_{inter2}....L_{propn}.L_{rotn}.L_{intern}}.\Psi$$

Propagation matrix after N transmissions/propagations

- Defect Response principle: Tx Beam/Flaw scattering/Rx beam (by reciprocity) over the flaw mesh



$$S_{ER}(t) = \sum_{M} q_R(M) q_E(M) \{B(M).e^{i\phi_E}.e^{i\phi_R}\}.S(t-T_E-T_R)\}$$

Flaw meshing

B_M : includes the (complex) diffraction coefficient ➡

- SOV
- Kirchhoff
- GTD
- Kirchhoff-GTD
- Born
- …

B(M) depends on:

- incident/scattered modes (L,T)
- Incident and observation direction
- Flaw properties

ADVANTAGES:

- Modal approach => each mode is computed independently => modal decomposition for a better understanding
- "**Very Fast**" simulations compared to fully numerical approaches,
- A lot of industrial "use cases" can be covered efficiently

DRAWBACKS:

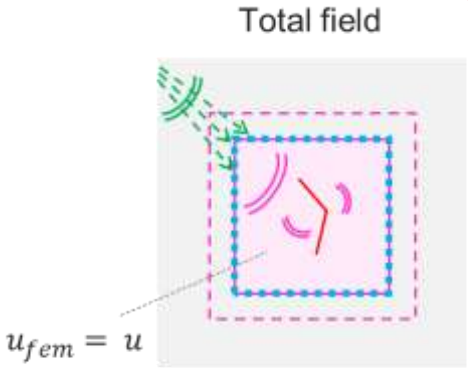
Some limitations in capacities and validity domain

EXTENDE CIVA

FEM and Hybrid SA/FEM strategy

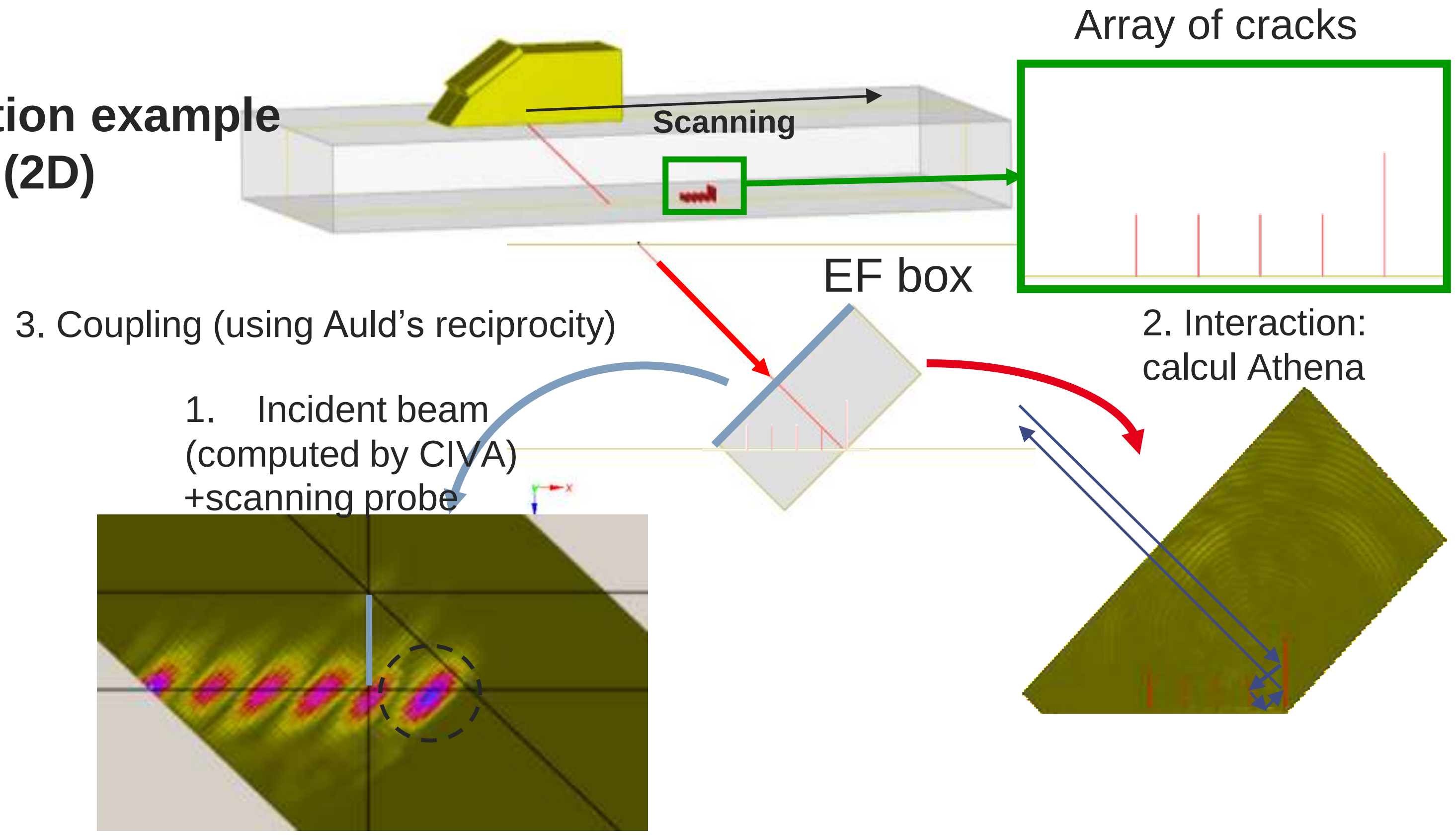
Several levels of hybridation are possible

2015



The “Box FEM” strategy

Application example (2D)



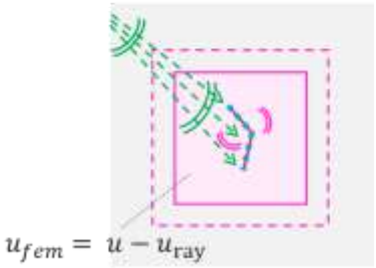
Athena 2D FE model (EDF)

FEM and Hybrid SA/FEM strategy

Several levels of hybridation are possible

CIVA NDE 2021

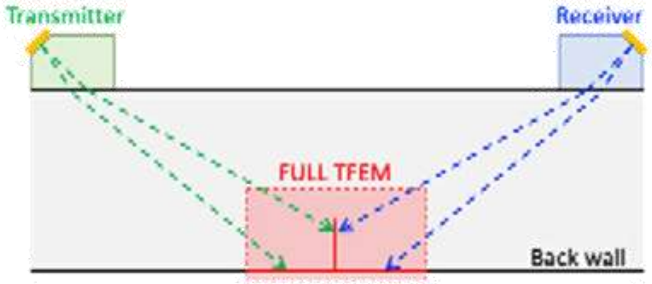
Diffracted field

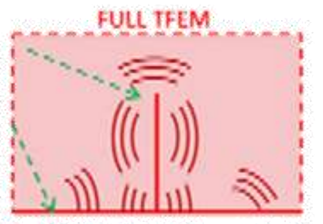


The "FE-Grid" strategy

- Principle : Sound propagation still modelled by pencil models + « local FE » box around discontinuities

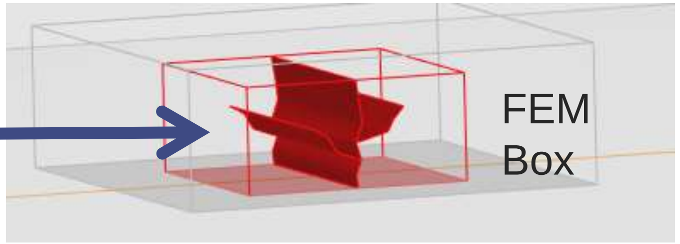
1. Incident beam (computed by CIVA) **on the defect and backwall** (inside the FE-Grid area)





2. FEM computation of the diffraction inside the FE-Grid area + PML boundary conditions at box edges (i.e., no reflections)

- Finite Element mesh automatically generated from flaw geometry and surrounding grid



ADVANTAGES:

Still quite fast. More accuracy to simulate flaws smaller than wavelength, specific waves phenomena around critical angles, interactions between flaws, etc.

...

EXTENDE CIVA

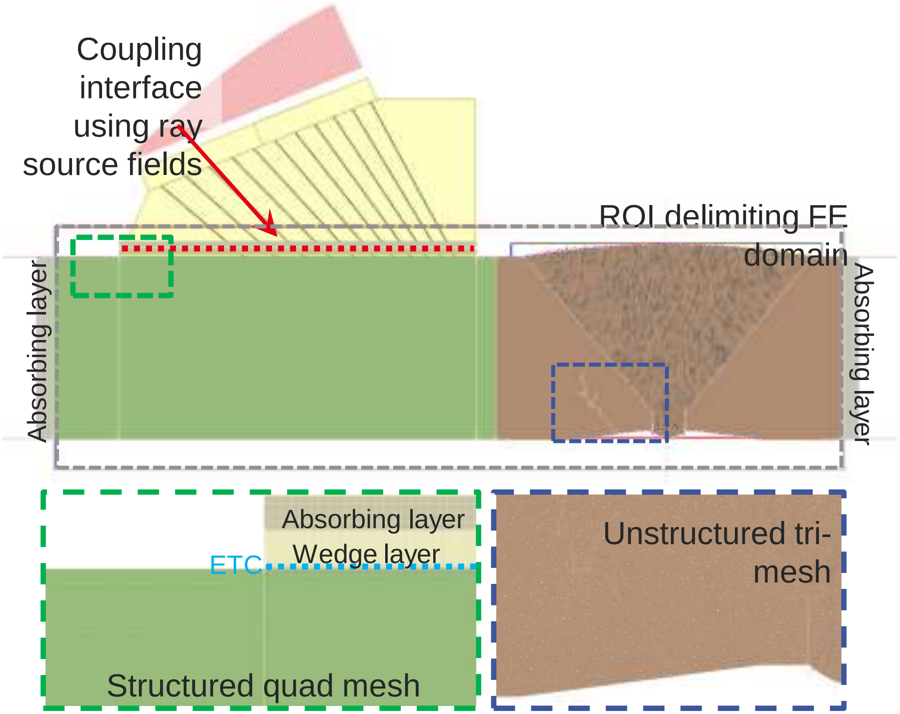
FEM and Hybrid SA/FEM strategy

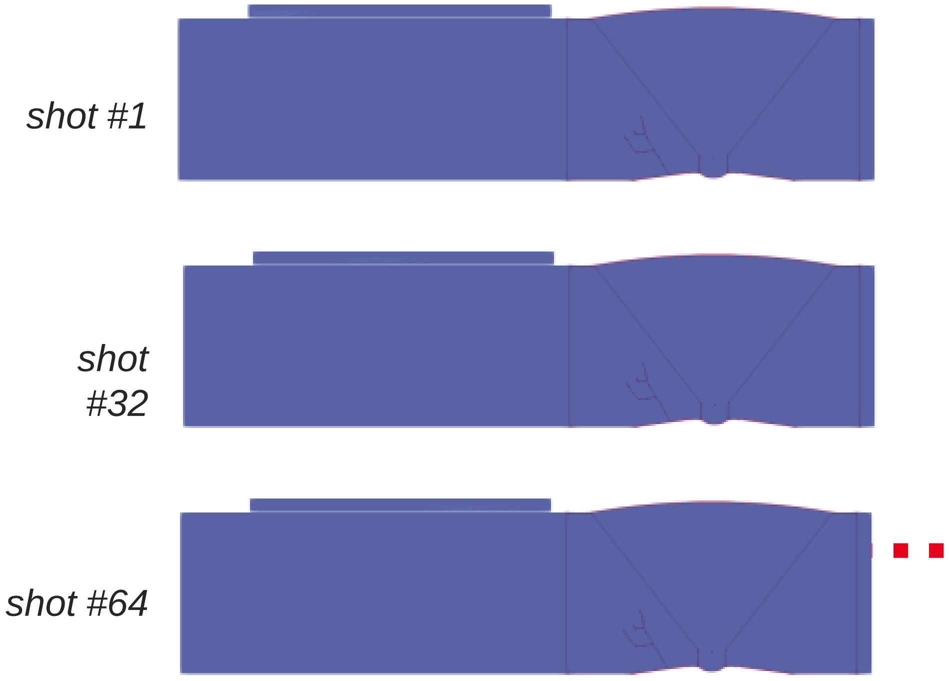
Several levels of hybridation are possible

CIVA NDE 2025

The “Full Component FEM” strategy

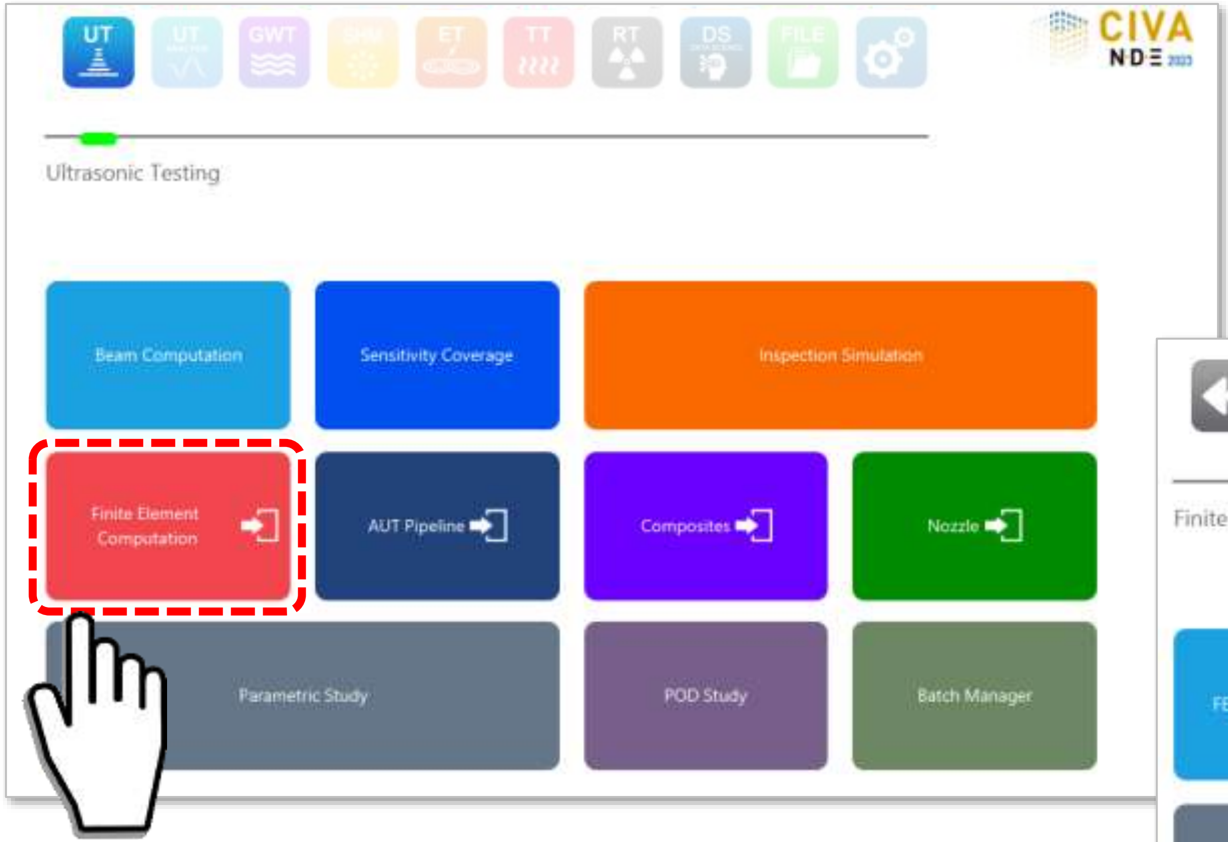
- Principle : Sound propagation still modelled by pencil models at the interface of the component
- Inside the component all is computed by FEM
- A smart strategy of domain decomposition allows to optimize the solution





EXTENDE CIVA

Incoming FEM module in CIVA



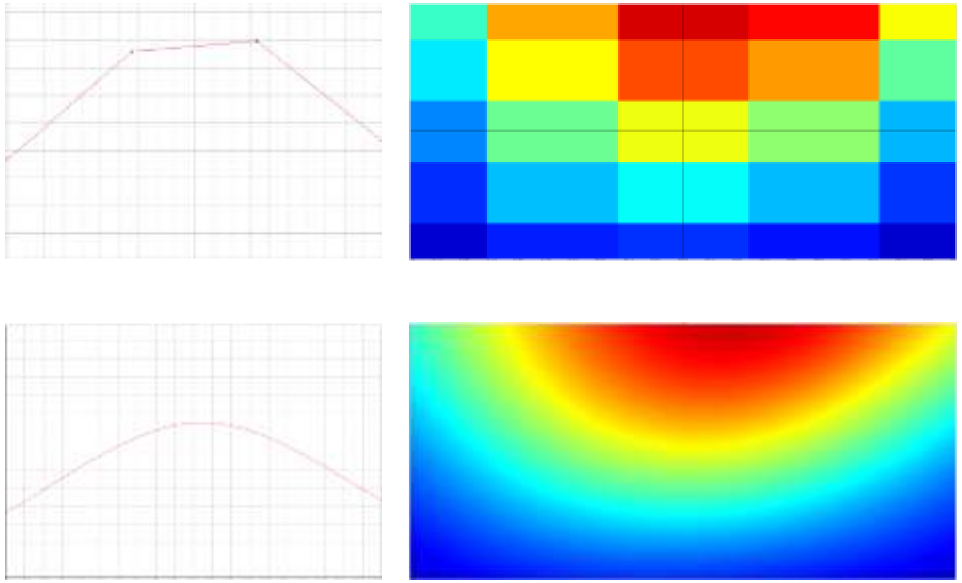
CIVA NDE 2025

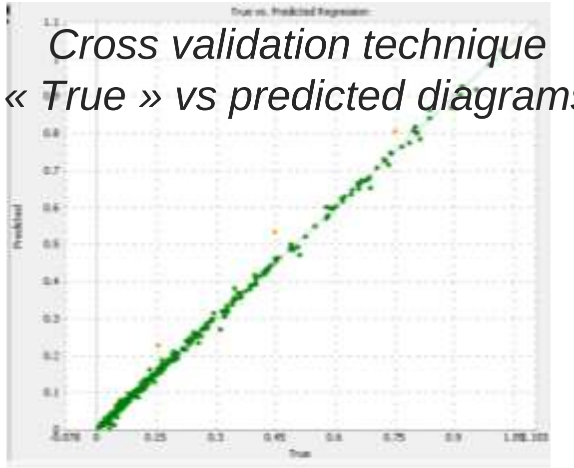
Metamodels

CIVA includes metamodelling capabilities

Compatible with all models (multi-technique):

- Based on an initial set of computed cases
- with variable parameters:
  The “database” (discrete grids)
- Application of multi-dimensional interpolation algorithms
  to build a **surrogate model**
  which provides a **continuum** of results
  for **all parameters combination**
- Once available, you can explore multiple scenarios
  in the defined range → **“Real time”simulations”, massive data** production
- Metamodels needs a simulation database based on physical models
  with enough samples.
- Metamodel “error” shall be assessed prior to use.

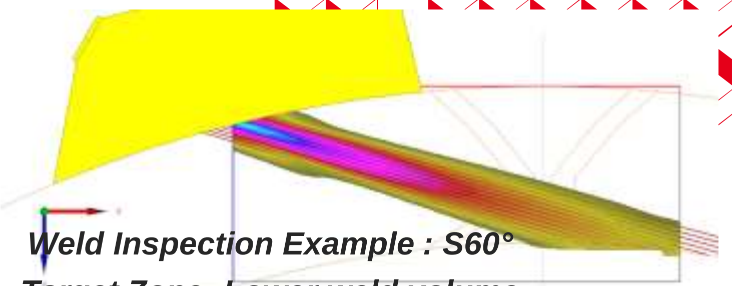




Cross validation technique
« True » vs predicted diagrams

EXTENDE CIVA

Metamodels: Applications



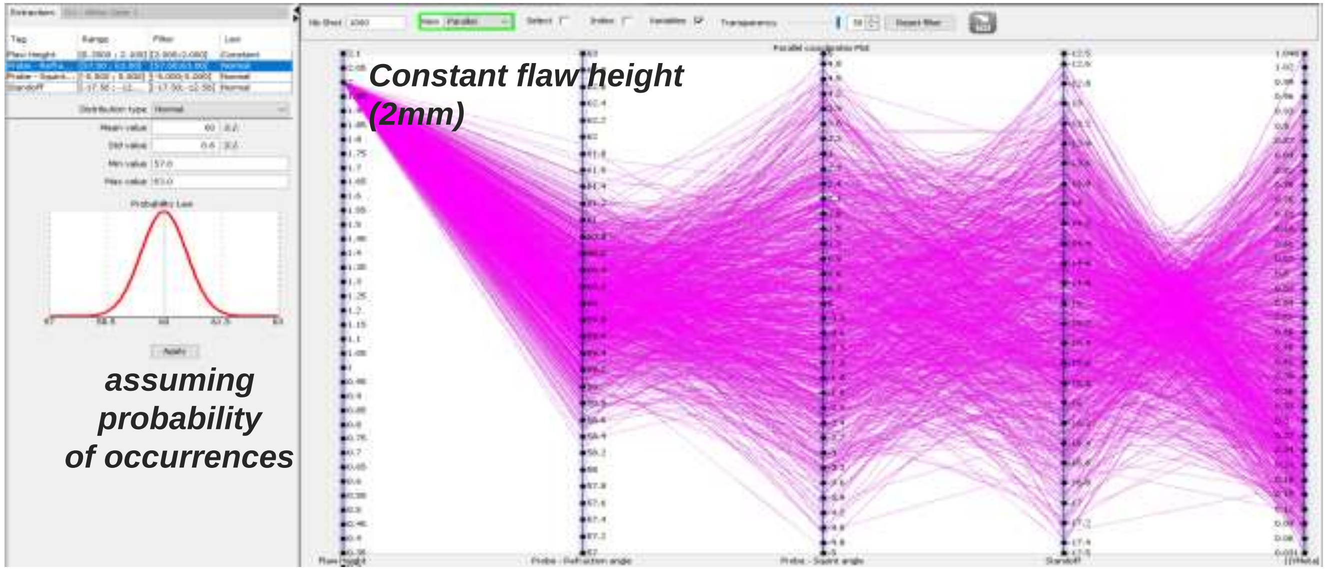
Weld Inspection Example : S60°

Target Zone: Lower weld volume

- **Design/Optimization and reliability studies :**

You can explore any combination of parameters' values, i.e., any inspections scenarios:

- **Multidimensional analysis** with parallel plots

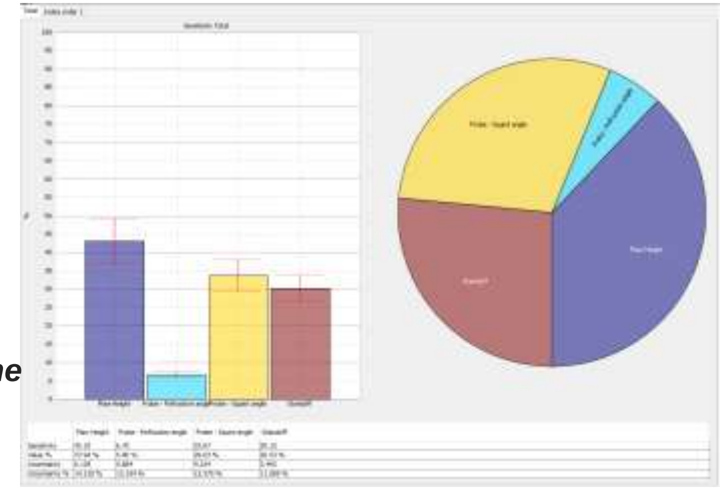


Outcome values

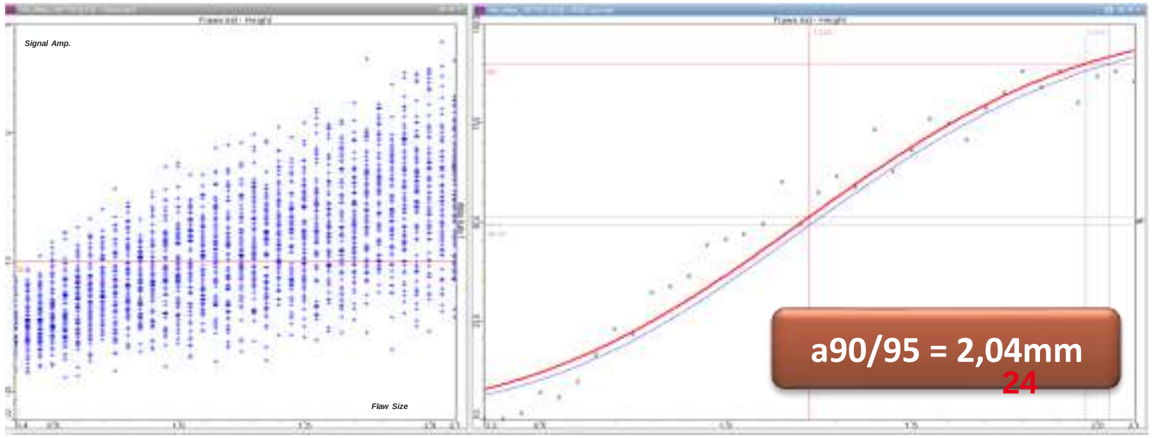
Gaussian laws for 3 other parameters)

Impact of 4 parameters on signal amplitude for N trials (here 1000)

- Influential parameters' "ranking" : Sobol Indices:



- **POD Curves**: You can try different hypotheses



OUTLINE

- Introduction to modelling benefits and capabilities of the simulation,
- NDT Simulation challenges :
  Multi-scale, multi-physics : a large set of simulation strategies and models
- Highlight on UT modeling
  - Semi Analytical models,
  - FEM and Hybrid models,
  - Metamodeling.
- New applications,
  - Simulation for Data Science and AI,
  - Digital twins,
  - Simulators for skill maintenance.
- Some application cases,
- Conclusion.

Data Science and AI

- Build learning database using simulation data or experimental data

- Merge, combine, post-process data

- Assess capabilities for Detection and Classification based on ML and AI

- What are the relevant criteria for my inversion process or training set ?
- Is my Training set adapted to machine learning ?
- Are my criteria sensitive to uncertainties ?
- What level of confidence can be expected due to uncertainties ?
- Can I complete or replace my Experimental Training set with Simulation ?

Model Assisted ML tools

Surrogate (meta)models allows intensive simulation

Sensitivity study (Sobol indices)   *Classification assessment tools*

Embedded in *CIVA Analysis* Tools and Templates

Digital Twins

Business Rules

Modeling business rules
Planning help

Knowledge and Skills

Digital Twin

Zones d’accessibilité
3D modeling
Robotic simulation
Collision detection
Path Planning

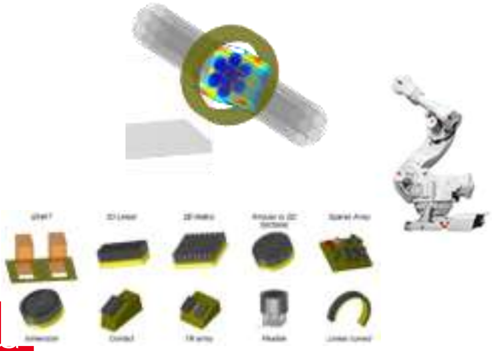
NDT Simulation

Area coverage
Optimization and performance demonstration

Simulation and Digital Twin at the heart of the testing process

Design and Optimization

NDT : Probes, Methods and Robotic

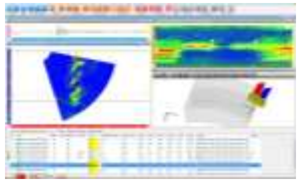


Performance demonstration

Testing and acquisition system parameters

Robotic Control
Driven by Digital Twin

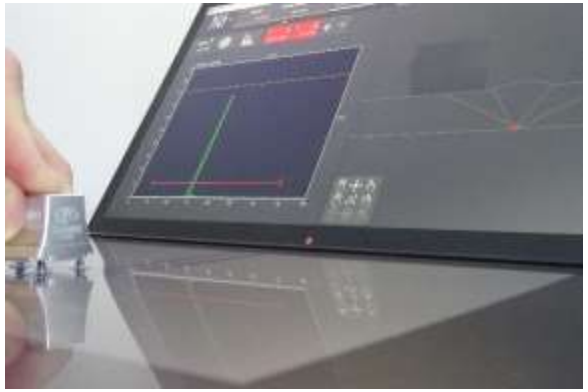
Automatic diagnosis
Learning on simulated data



Simulators for skill maintenance

And why not exploiting these capabilities for training and skills maintenance support for NDT?

- Benefits:
  - the ability to provide a highly portable way to gain hands-on experience,
  - Increase the number of inspections/cases covered per trainee,
  - Train and practice from everywhere,
  - For RT, no radiation issue
  - Justify some practice hours according to the required standard
  - NDT workforce dramatically needs to attract young professionals. Such digital tools can play a role to help such people to integrate the NDT world.
- With TraiNDE, the future of training is … now

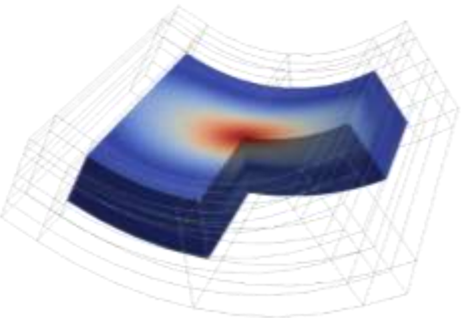


OUTLINE

- Introduction to modelling benefits and capabilities of the simulation,
- NDT Simulation challenges :
  Multi-scale, multi-physics : a large set of simulation strategies and models
- Highlight on UT modeling
  - Semi Analytical models,
  - FEM and Hybrid models,
  - Metamodeling.
- New applications,
  - Simulation for Data Science and AI,
  - Digital twins,
  - Simulators for skill maintenance.
- Some application cases,
- Conclusion.

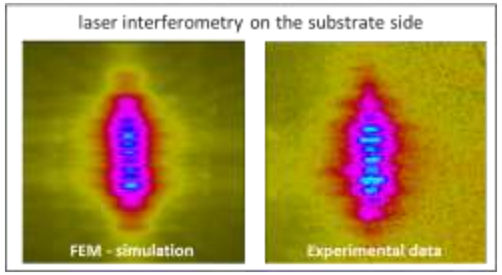
Examples of the use of simulation in the industry

- Application to downhole well inspection (UT)

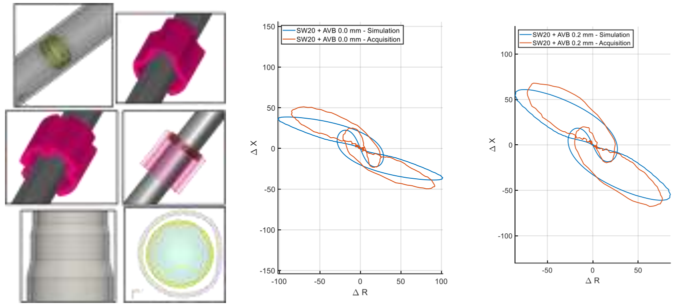


3D FEM Simulation

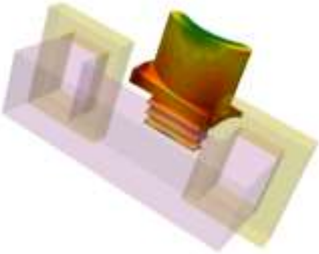
- Feasibility of UT of large high-quality WAAM samples
- Simulation study of the ultrasonic beam deflection



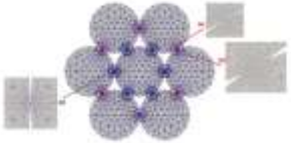
Modeling of wear under anti-vibration bars for eddy current inspection of SG tubes

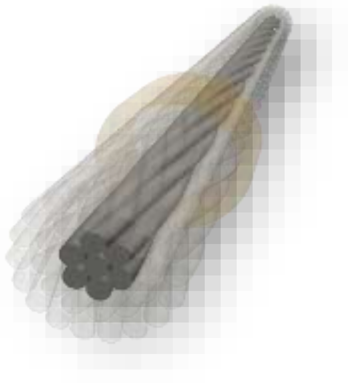


- Optimization of the inductor and the trajectory to ensure heating coverage

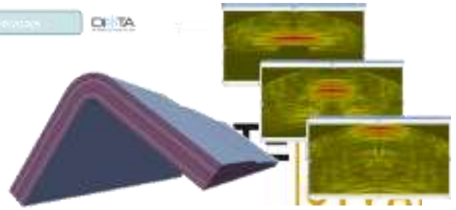


- Feasibility study of the generation and propagation of guided waves in the steel core



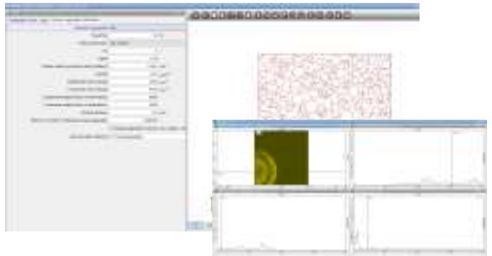


- L0 inspection of curved, stratified composites
- Field and signal simulation in presence of a delamination

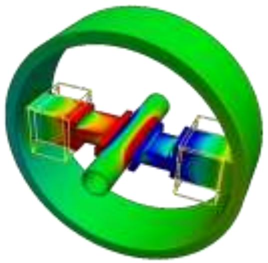


Examples of the use of simulation in the industry

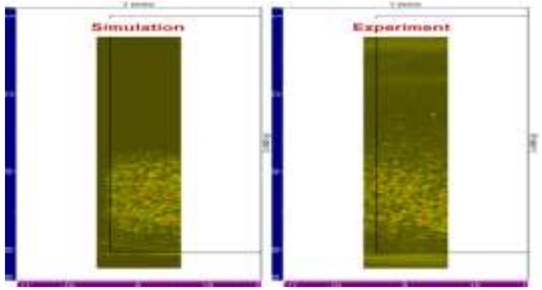
Nuclear applications:
UT inspection simulation plugin on complex welds and on concrete using
Full Finite Elements Models

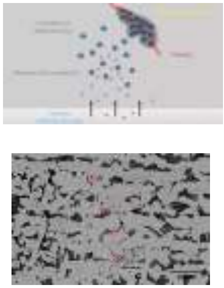


Magnetic Flux Leakage : Simulation Plugin (steel tube manufacturing control)
Exclusive early-stage distribution.
Roadmap CIVA 2026: “MFL” Technique

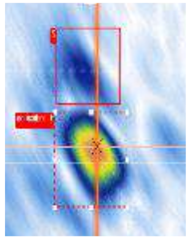


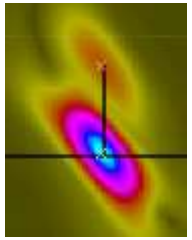
Oil & Gas applications: UT simulation of HTHA damaged specimen using UT advanced techniques : semi analytical Models of current CIVA version



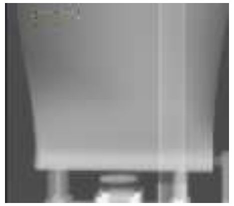


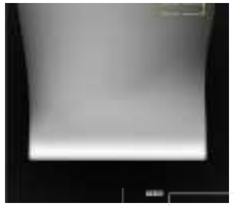
Nuclear applications:
Design of advanced ND **Nuclear applications**: T technic based on TFM reconstructions using a DLA probe

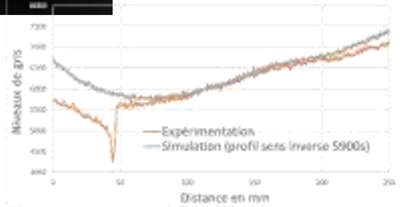




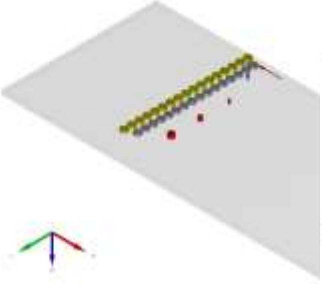
Aeronautical applications:
Study on the image quality of RT and tomographic volumes of a Fan Blade

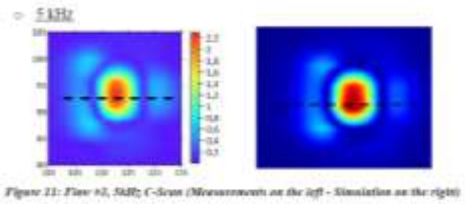






Nuclear application:
Eddy Current Array Modeling for Sub surface Flaw Detection





Conclusion

Simulation for NDT

- Increasingly adopted by the community
- Highly effective for design, optimization and performance demonstration
- An essential tool for the challenges of NDT 4.0: AI, Digital Twin, NDT-R, training of operators in new technologies

CIVA :

- Well established solution for NDT simulation,
- Recognized for its ability to **simulate efficiently a large scope of NDT applications**,
- Result of a strategy that priorized semi-analytical models and continuous research efforts that pushes these models to its limits,
- To overcome potential limitations and provide reference results, CIVA now includes more and more tools based on fully numerical models such as Finite Elements or hybrid approaches,

The CEA, as a major R&D center, actively works to continue to emphasize a global simulation innovation policy in NDT, EXTENDE, as partner promotes these innovations, and actively works on innovative solutions.