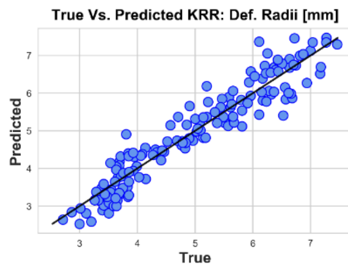
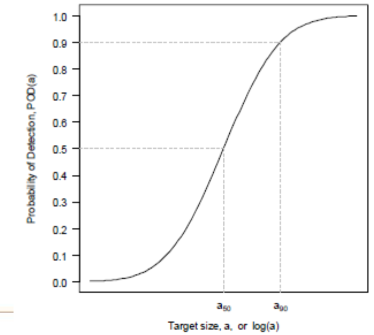
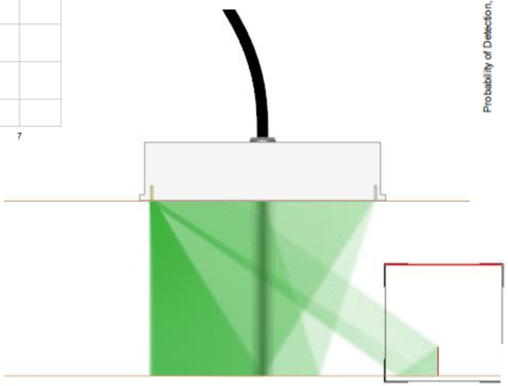
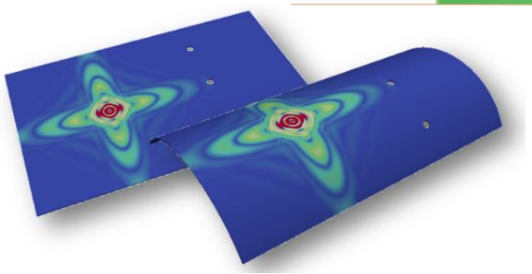
NDE & SHM computational tools for enhanced diagnostics and reliability assessment

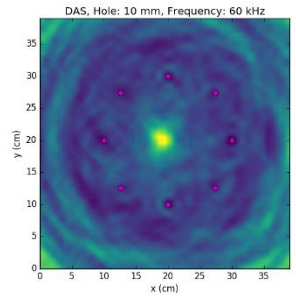
Pierre Calmon, Christophe Reboud, Edouard Demaldent, Olivier Mesnil, Stéphane Leberre











NDE & SHM COMPUTATIONAL TOOLS FOR ENHANCED DIAGNOSTICS AND RELIABILITY ASSESSMENT

Pierre CALMON, Christophe REBOUD, Edouard DEMALDENT, Olivier MESNIL, Stéphane LEBERRE

10th International Symposium on NDT in Aerospace | Dresden

NDE @ CEA LIST

- **NDE Department**
  - 110 staff members (20 PhD)
  - Located in Paris-Saclay

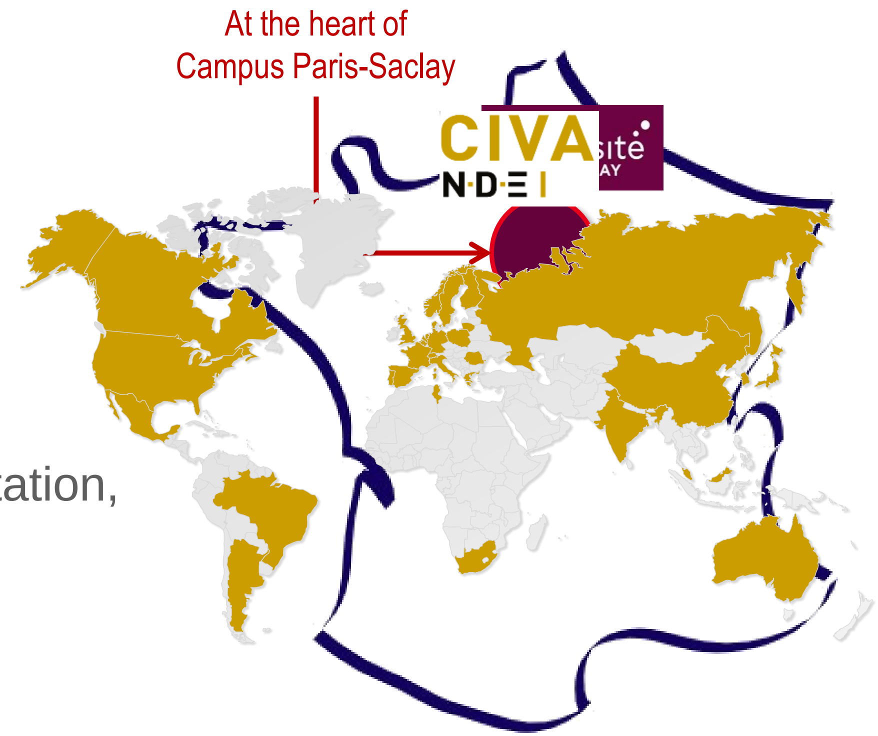
- **RESEARCH AREAS**

Development of innovation in NDE-SHM

→ Modelling Simulation Data

→ Instrumentation Methods

Technological transfers to the industry



- **COLLABORATIONS**
  - Industrial partnership : Energy, transportation, manufacturing, …
  - International academic partnership

NDE TECHNOLOGICAL CHALLENGES

Numerical tools
Tailored & Efficient

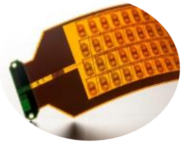
Complex geometries and advanced materials

Artificial intelligence for diagnostics

NDE Reliability assessment

Robotized, adaptive and reconfigurable NDT

Array imaging & smart sensors



Structural Health Monitoring (SHM)

OUTLINE

A glimpse on current *computational* activity at CEA LIST.

- Challenges and recent advances on **numerical modelling**:
  Illustration on **CFRP simulation**

- Computational tools for Reliability assessment:
  MAPOD and Meta-models

- Computational tools for enhanced diagnostics:
  Illustration on **advanced array imaging**

- A focus on a growing field: SHM
  Simulation & analytics for GW-SHM

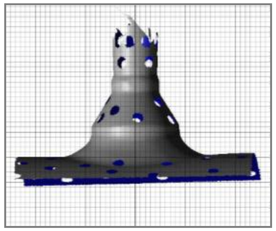
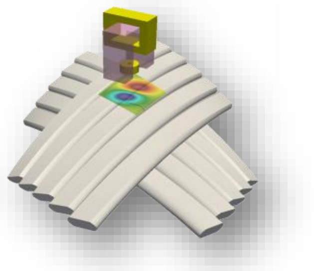
A choice: To limit the talk to UT/GW applications.

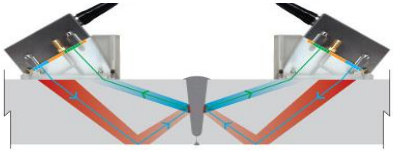
Numerical simulation

New approaches and potentialities

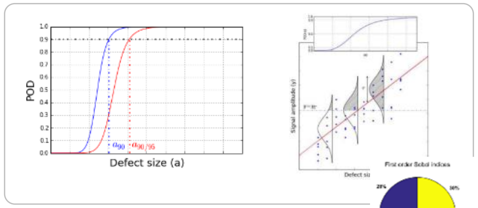
GOALS FOR NDT SIMULATION TODAY

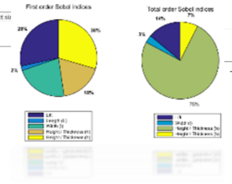
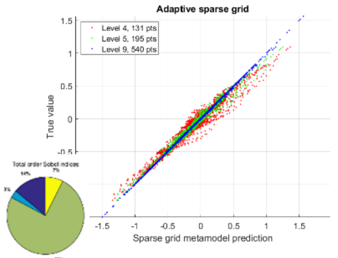
- **Need to handle always more complex cases**
  - Materials: assemblies, multi-layer, AM
  - Defects : scale, shape, location,…
  - Complex geometries, accessibility, surroundings
  - Inspection systems : phased array, multi-probe, SHM

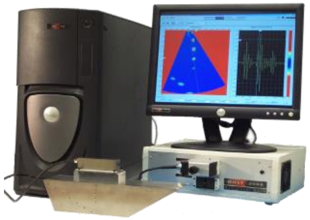
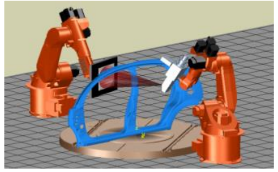


- **New uses implying intensive computations**
  - Statistical analysis & reliability assessment
  - Diagnostics & inversion: flaw characterization



- **Needs for "on line" computational tools**
  - Implementation in inspection systems
  - Automatic diagnostic, process monitoring
  - Optimization of robotized trajectories

NEW CHALLENGES FOR SIMULATION

To fulfill these needs a two-fold modelling strategy is needed:

➡ **One way to address complexity : Hybrid codes coupling numerical-semi-analytical models + dedicated application oriented meshing strategies**

- Combines the advantages of different models and optimize the computational efficiency.
- Requirement/challenge: Fast (executable on personal computer)
- Requirement/challenge: Easy of use (“automatic” meshing, transparency)

➡ **Development of meta-modelling strategy for intensive or on-line computations.**

- Surrogate models for ultra-fast computations
- Statistical data analysis and automated diagnostics (inversion)
- Challenges: Accuracy and easiness of use

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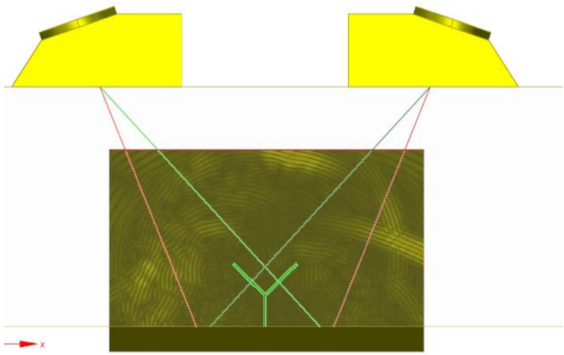
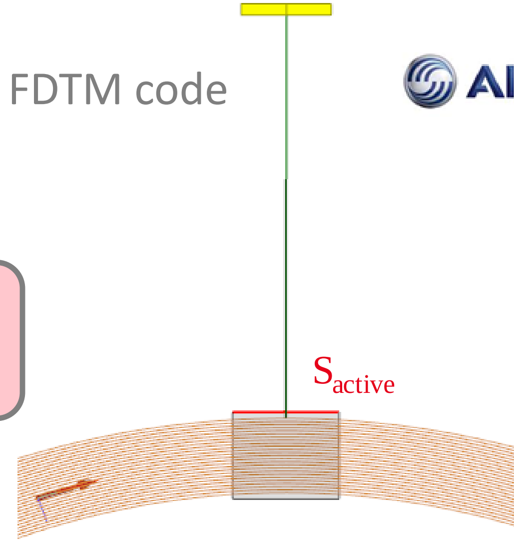
HYBRID 2D SOLUTIONS FOR UT-GW SIMULATION

Coupling between Ray-based/modal models with numerical codes

- ***ATHENA*** FEM code

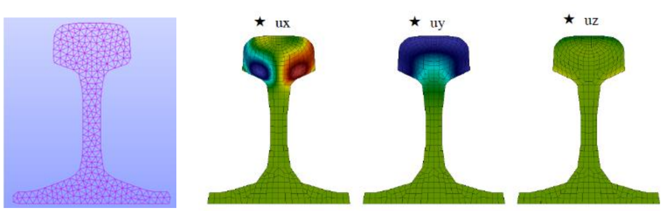


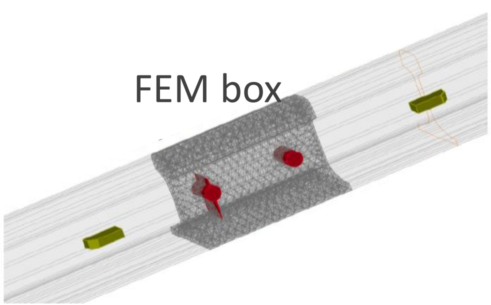
- ***FDTD*** FDTM code

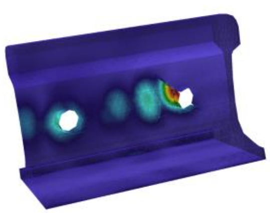


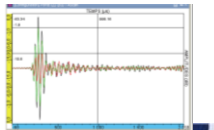
Efficient but today limited to 2D

- **GW**: Hybrid model SAFE+FEM





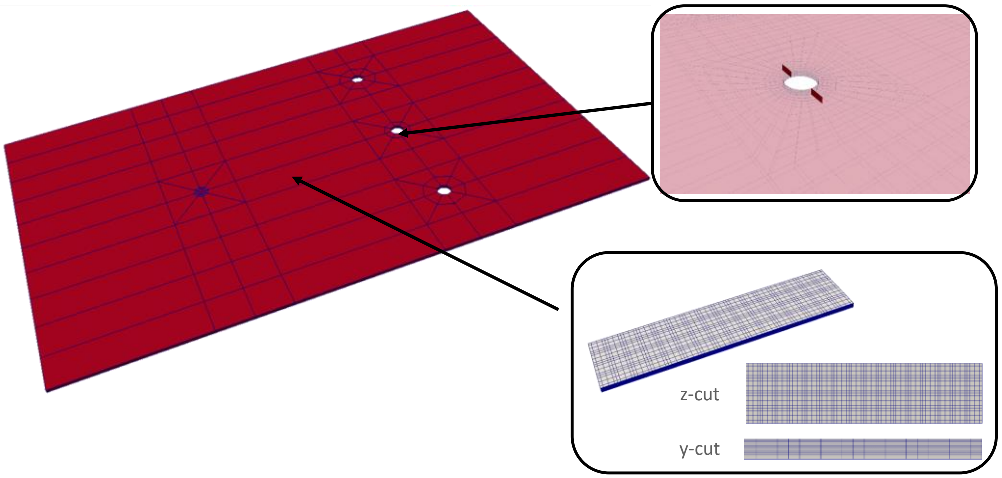




FULL 3D SOLUTIONS IN PROGRESS

Strong Requirement: FAST and EASY TO USE !

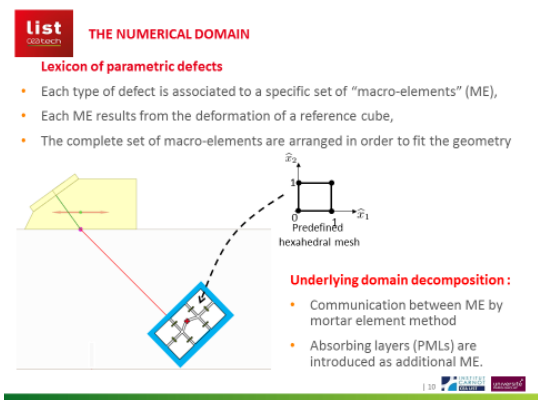
Based on the use of 3D SEM (Spectral Element Method) + Domain decomposition



SEM: High order Finite Element

✓ Requires less degrees of freedom for the same accuracy than conventional FEM

First introduction in CIVA to model crack scattering by hybridization with ray model



Decomposition in sub-domains

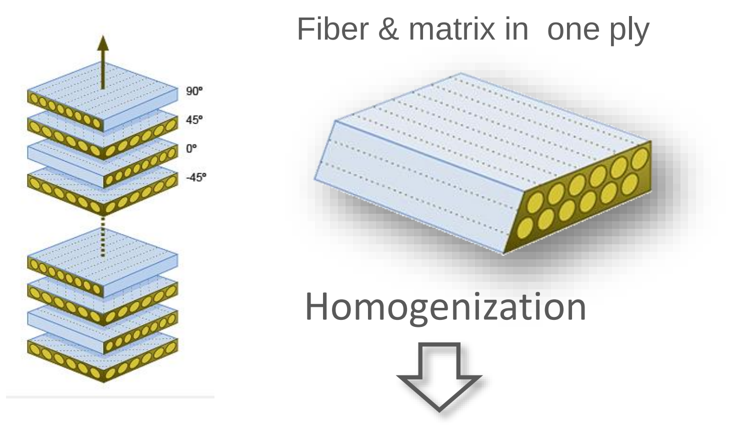
- **Macromesh strategy:** Macro-elements with predefined mesh
- Macro-elements carry geometrical + physics information
- Automatic meshing (no intervention of the operator)
- Possibly : different models in the ≠ subdomains

A. Imperiale, Set al., *UT simulation using a hybrid model based upon Spectral Finite Element and domain decomposition methods*, WCNDT 2016, Munich

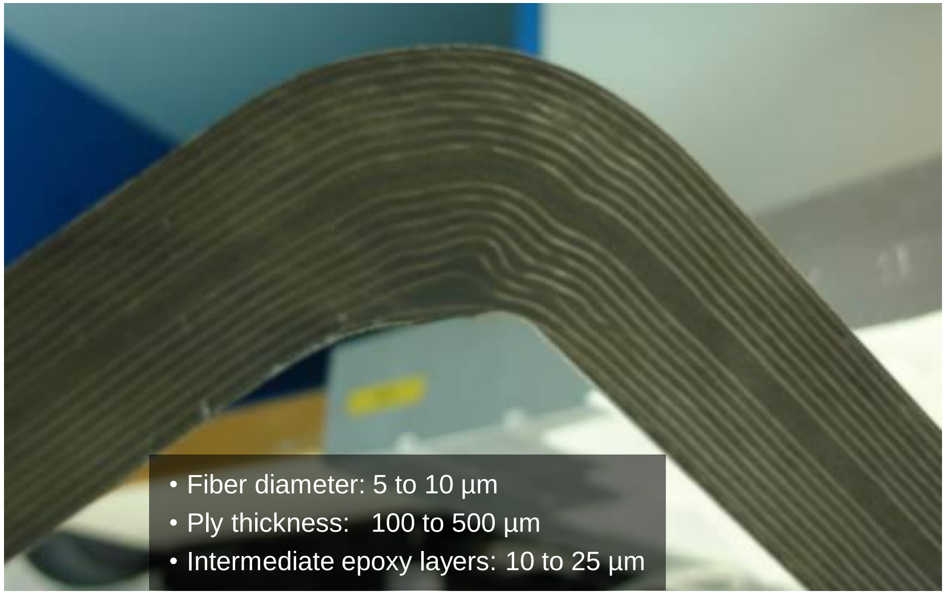
19th WCNDT 2016 World Conference on Non-Destructive Testing June 13 – 17 in Munich Germany

EXAMPLE: SIMULATION OF CFRP INSPECTIONS

- Modelling the UT of curved carbon fiber reinforced composite structures
  - **Stratified anisotropic** structure
  - **Continuously variable orientations**



- Elastic constants of one ply: (isotropic transverse)
- Attenuation coefficients (post-processing)



Targeted configuration

- From a **computational** point of view it requires:
  - To associate the local orientation to every node of the mesh
  - To ensure a discretization fine enough fine to account for the stack in the curvature

EXAMPLE: SIMULATION OF CFRP INSPECTIONS

- Modelling the UT of curved carbon fiber reinforced composite structures
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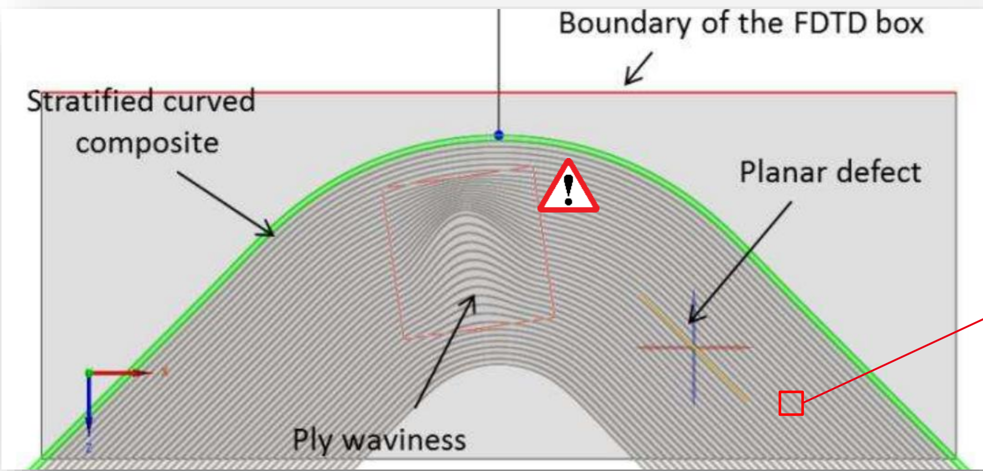
Drastic limitation of computational performances !
(3D, parametric studies…)



N. Dominguez & F. Reverdy, *Simulation of Ultrasonic Testing of Composite Structures*, ECNDT 2014

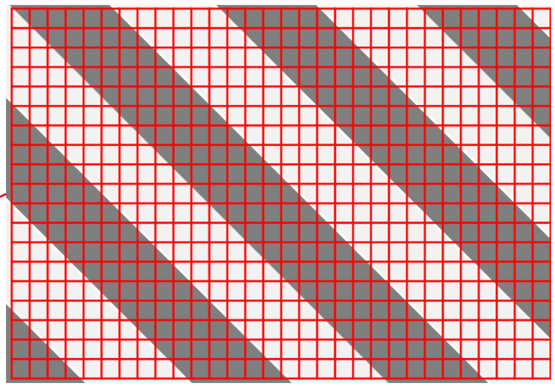


Illustration of a FDTD cartesian grid

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EXAMPLE: SIMULATION OF CFRP INSPECTIONS

Application of the *macro-mesh strategy*

- Macro-elements contain the information on fibers orientation
- Deformation of macroelement to account for curvature
- Minimal storage of data :**3D computations become feasible on a PC !**
- **Makes possible fully transparent construction of the numerical scene**

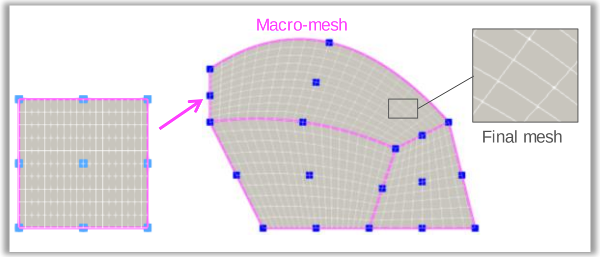
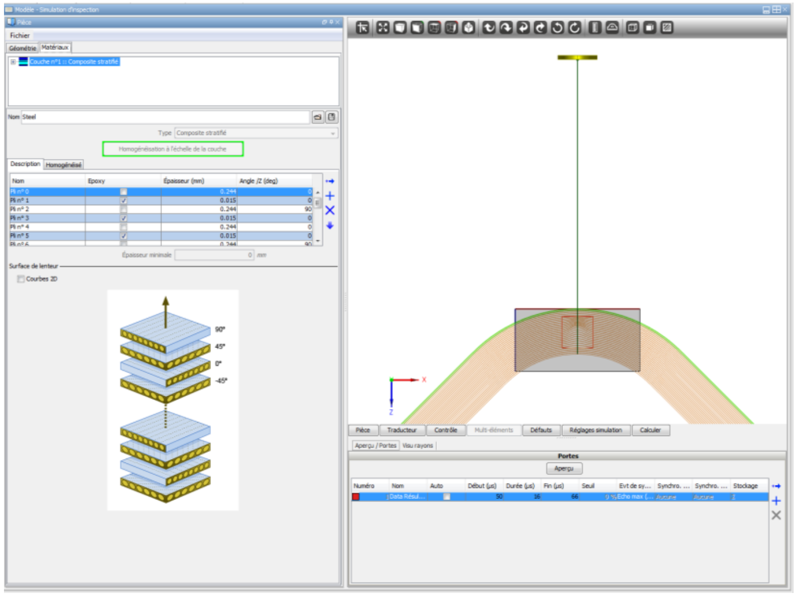
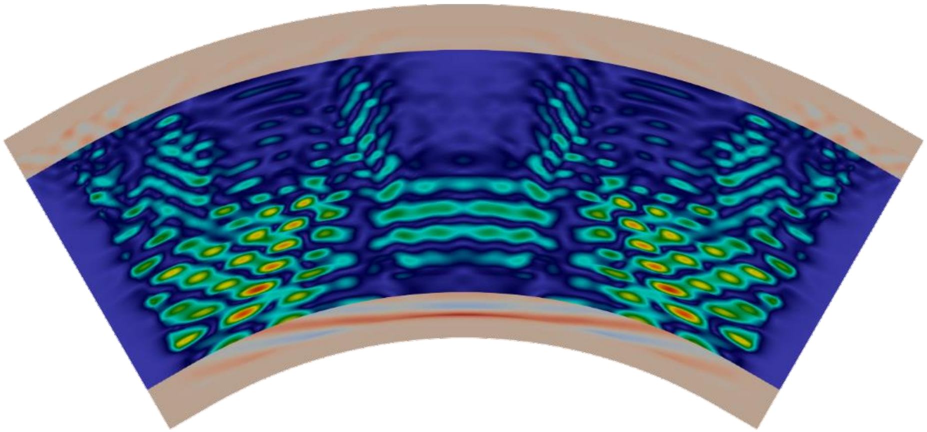


Illustration: UT 2 MHz, 55-layers + Waviness



Incident field from ray-model

Fluid-solid coupling: PML + mortar elts



E. Demaldent et al, in QNDE 2018 Proc.

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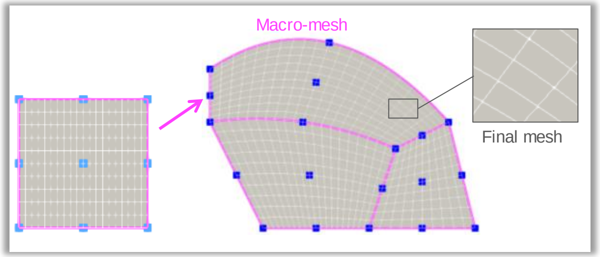

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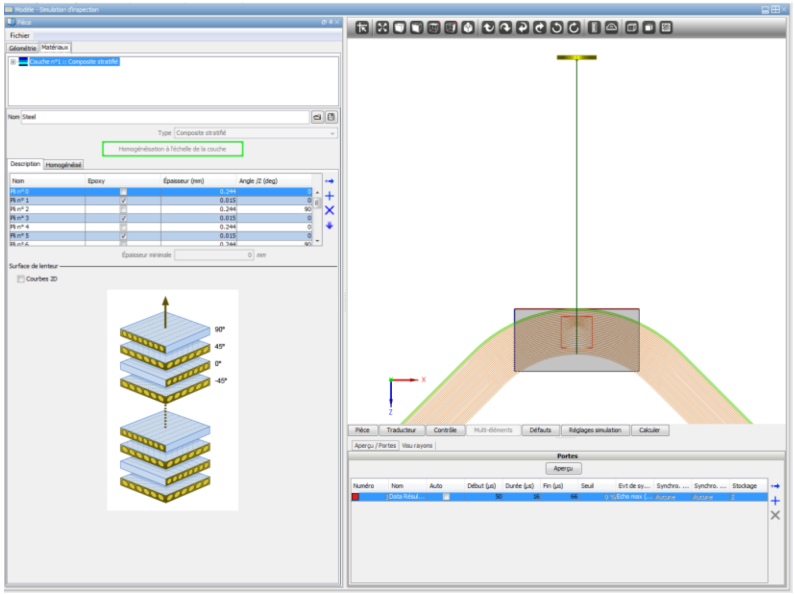
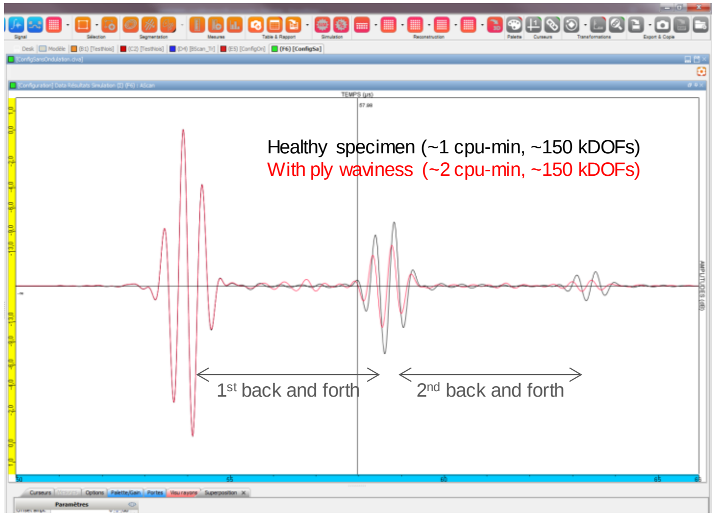


E. Demaldent et al, in QNDE 2018 Proc.

Simulation of Ascan



E. Demaldent et al, in QNDE 2018 Proc.

EXAMPLE: SIMULATION OF CFRP INSPECTIONS

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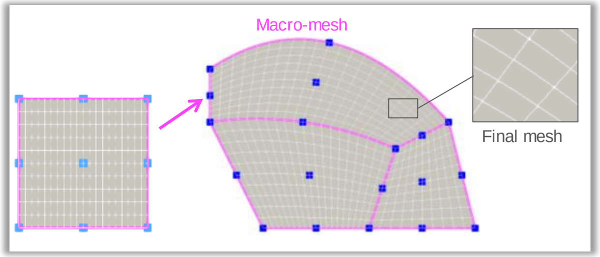
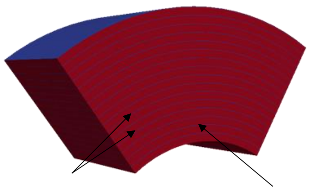
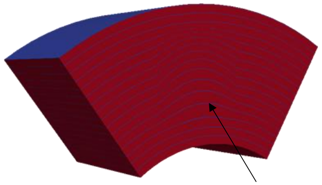


Illustration: 16-layers + Waviness



Layers: [0°, 90°] 0.298mm isotropic transversal

Intermediate 15µm epoxy layer

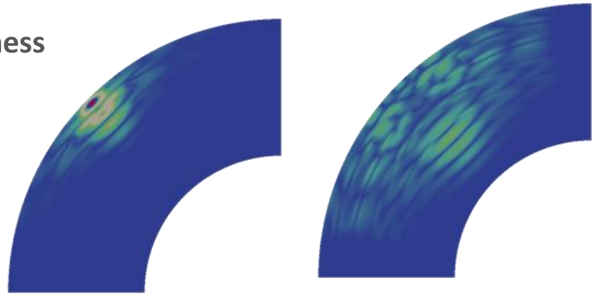


Central ply waviness defined as an additional deformation (same number of M.E.)

The local fiber orientations follow the ply deformation

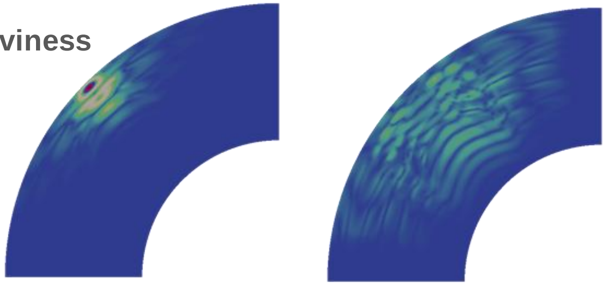
3D Computations

No waviness



Computation time : 10 mn on standard PC

With waviness



Snapshots of the wave propagating in the part

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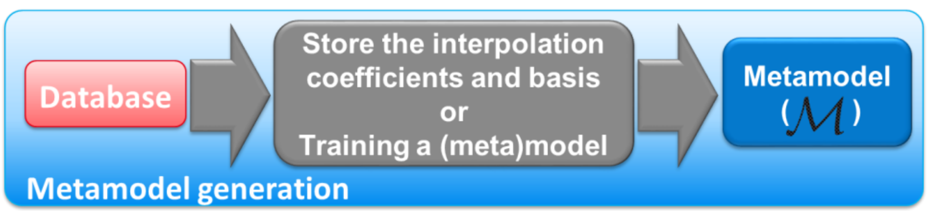
METAMODELLING STRATEGY

Metamodel: “Smart interpolator” of a numerical data base substituted to a physical model

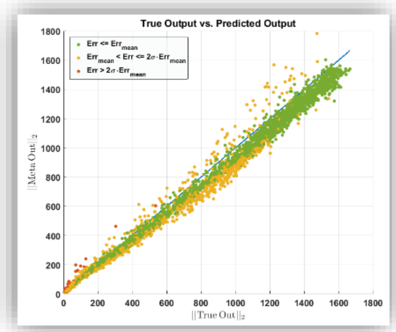
- "**Off line" phase**: Possibly time consuming

Data base generation

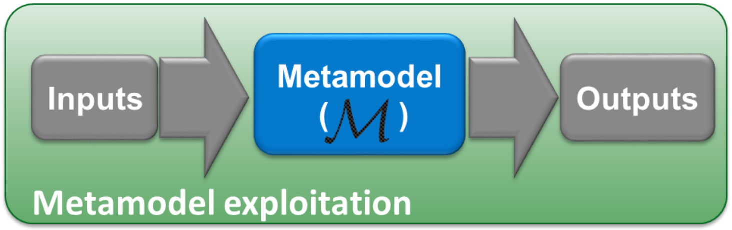


Creation of the metamodel (Kriging, RBF, SVR, ...)

Cross-validation



- **"On line" phase:** Possibly almost real-time



Exploitation of the metamodel

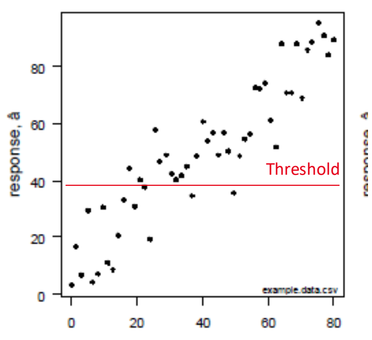
COMPUTATIONAL TOOLS FOR NDE RELIABILITY ASSESSMENT:

MAPOD, Simulation assisted POD

BACKGROUND: RELIABILITY ASSESSMENT AND POD

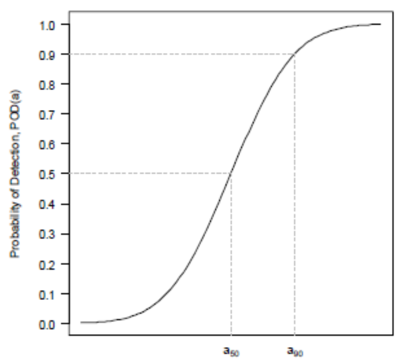
- NDE reliability assessement : A key challenge
  - More and more request for higher level of performance demonstration
  - Deterministic (worst case) vs probabilistic approaches (POD).
- Probabilistic approach: Estimation of POD

Scattering of the results



From ENIQ Rep. 41

Probability of detection



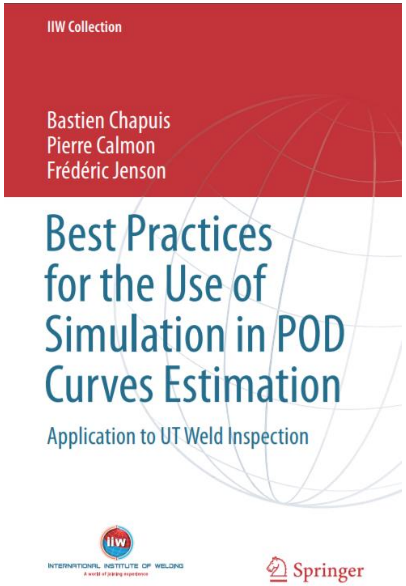
Flaw size

Statistical analysis framework in reference documents: MIL-HDBK-1823A, ENIQ-R41, …

Based on a statistical analysis of laboratory trials: Needs samples & resources

MODEL ASSISTED POD

- Emergence in the early 2000s of the **MAPOD** concept
- **First idea:** To replace expensive and sometimes uneasy to implement experimental trials by numerical simulation
- **Active R&D on this topic during the last decade :**
  - MAPOD Group driven by USAF at CNDE (2003-2011) MAPOD WG
  - European Project PICASSO (2009-2013) PICASSO
    + French national projects projets ANR
  - **In 2010 First POD module in CIVA** CIVA N·D·E
- In 2016 publication of a **IIW** Recommanded practice



- ***Second idea:*** *Thanks to simulation it becomes possible to overcome the assumptions of the "standard" (experiment-based) methodology.*

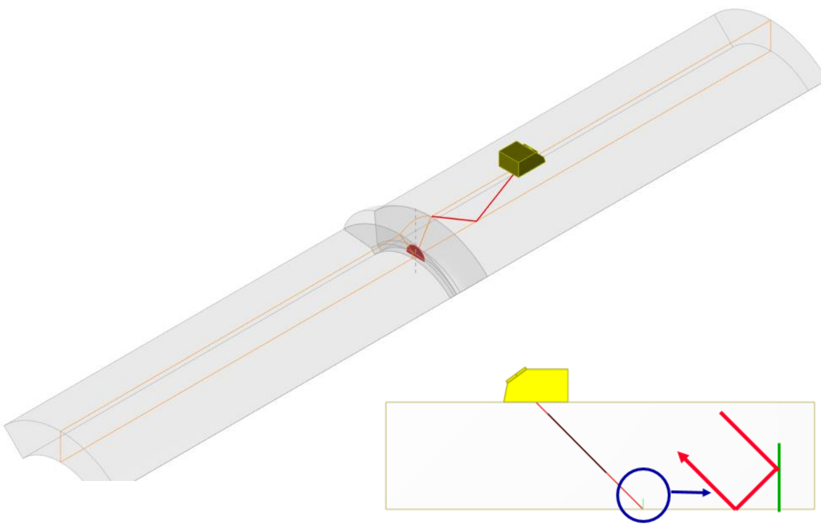
METHODOLOGY ILLUSTRATED ON ONE EXAMPLE

- **The methodology:**

Key idea: To introduce variations in the input parameters of the model and to analyze the variability induced on the output of the simulation.

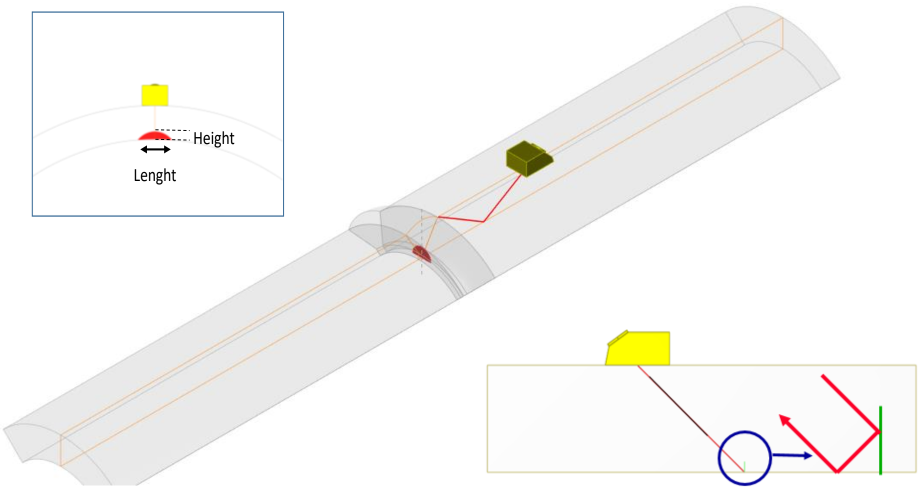
- **The example: from REDUCE European project**

REDUCE



- Context: RI-ISI quantification of risk reduction
- POD inputted in Structural Reliability models
- Manual UT of pipes
- 6 cases of study (≠ géométries)
- Breaking fatigue crack detected by corner echo TTT

METHODOLOGY ILLUSTRATED ON ONE EXAMPLE



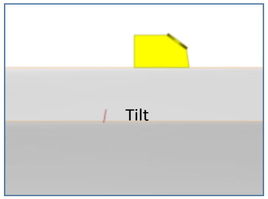
1. Nominal configuration

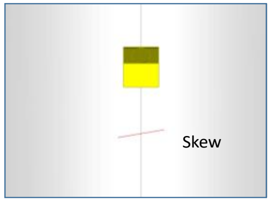
- Manual UT of pipes, 2.25 MHz
- Breaking fatigue crack
- Corner echo TTT
- 6 cases of study (≠ géométries)

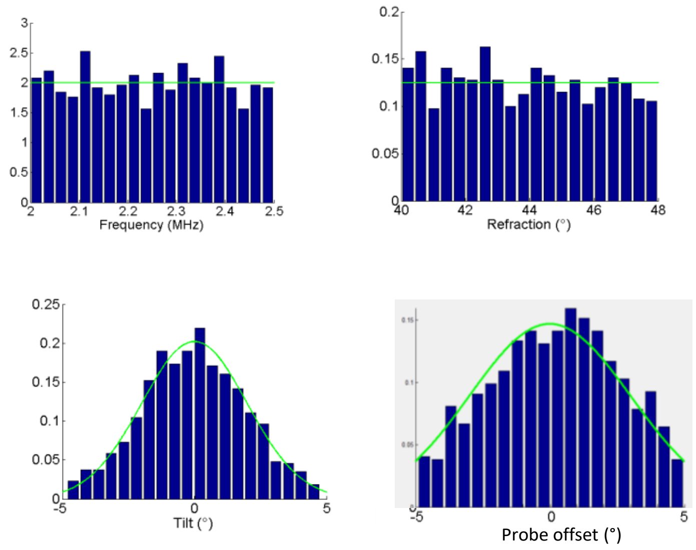
2. Variability inputted in the estimation

Aleatory parameters

- Frequency, *Uniform*
- Angle of refraction, *Uniform*
- Tilt, $N(0,\sigma_{tilt})$
- Skew, $N(0,\sigma_{skew})$
- Probe offset, $N(0,\sigma_{skew})$





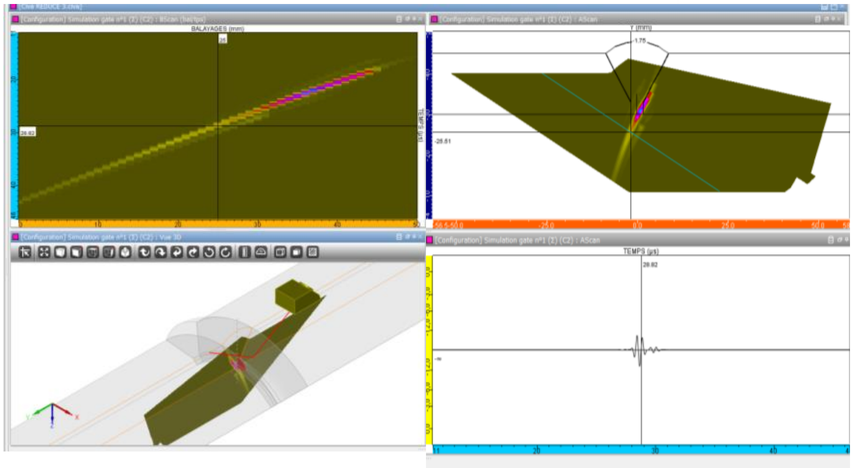


METHODOLOGY ILLUSTRATED ON ONE EXAMPLE

3. Sampling of distributions (MC) + Run the simulations

- Generation of a set of scenarii
- Use of Ultrasonic semi-analytical models of the CIVA software
- Automatic extraction of the Signals amplitude (after calibration)

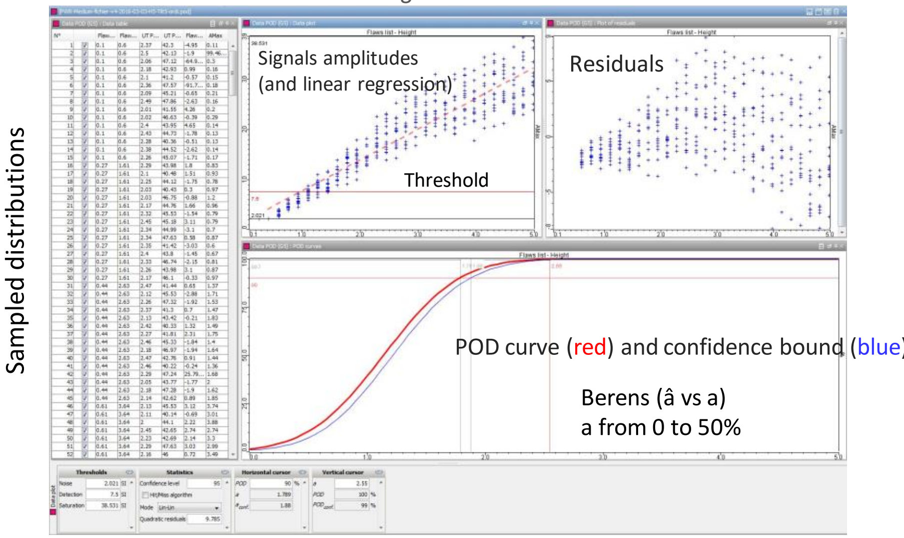
CIVA



4. Calculation of POD curves

Application of statistical analysis on the simulated amplitudes

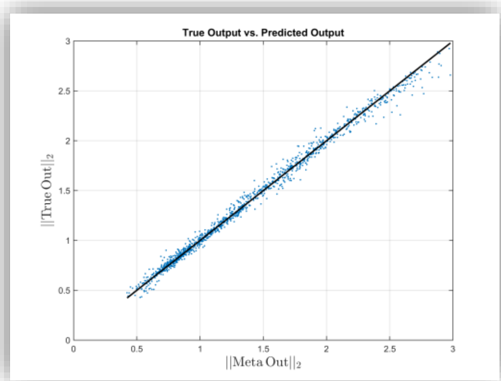
*One **REDUCE** case: « BWR Large »*



THE USE OF METAMODELS FOR PODS

Creation of the meta-model CIVA

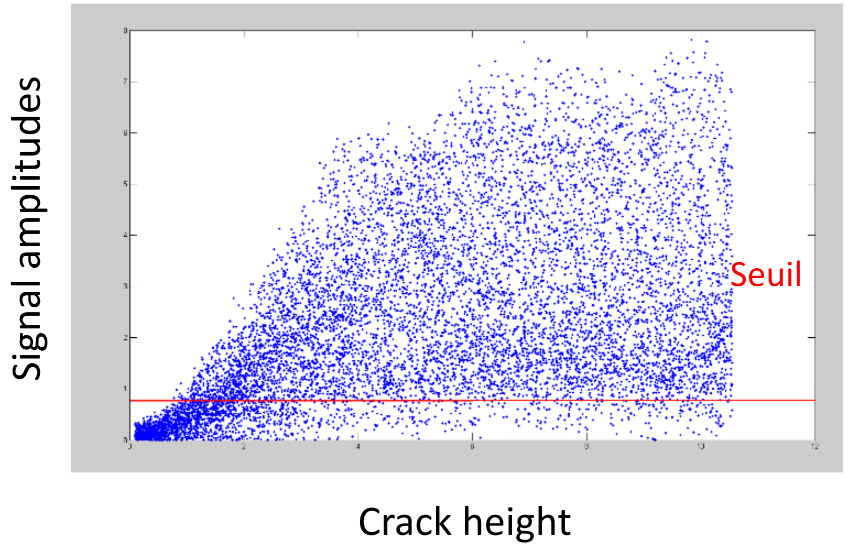
- Construction of a Numerical data base
  - 2500 points
  - Takes 10 h on a 30 nodes cluster
- Meta-model
  - Input: The “aleatory” parameters
  - Output: The amplitude of the signal
  - Radial basis functions



Cross-validation

Exploitation in the CIVA POD module

- Computation of **100 000 values (!)** for the calculation of one POD



Takes around 4s on a PC

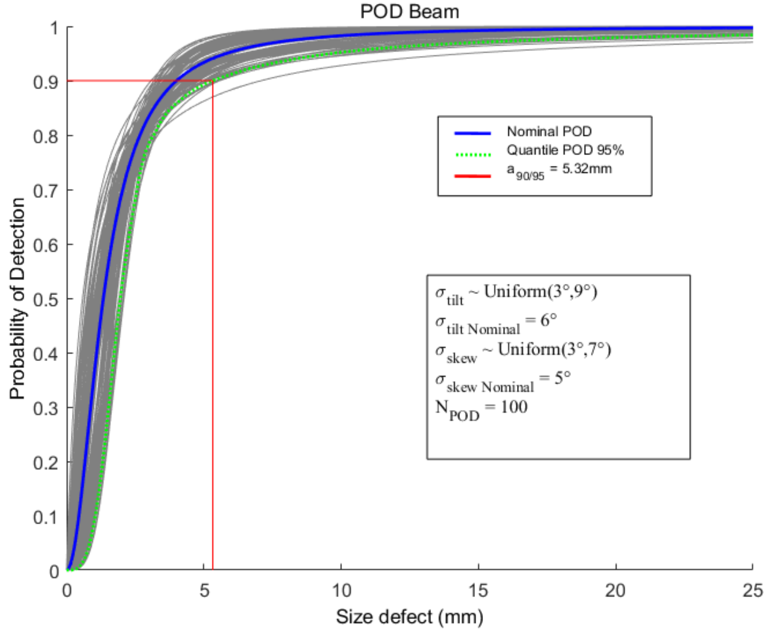
THE USE OF METAMODELS FOR PODS

New estimation of the confidence bound on POD curve

- Fast simulation of large data-sets makes possible the calculation Calculation of ***Beams of POD curves*** [1].
- Every POD curve corresponding to one set of statistical distributions.
- Evaluation of the sensitivity to the inputted statistical distributions

Illustration on one ***REDUCE*** case

REDUCE



[1] Dominguez, N. and al, A new approach of confidence in POD determination using simulation, Rev. of prog in QNDE, VOL 32B, 1749-1756 (2013)

THE USE OF METAMODELS FOR PODS

To go beyond the « standard » statistical analysis

- Possibility to overcome the hypothesis of standard analysis: **Direct evaluation of Hit/miss ratio** (« non parametric » POD).
- be used to assess and if necessary to replace a POD estimated according to the « standard » analysis.

Hit-miss logit link — Floor-ceiling link — ●●●●●● POD non paramétrique

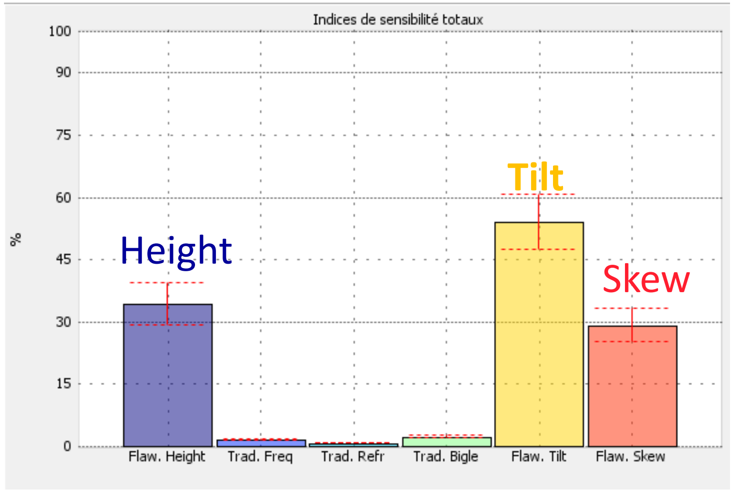
In case 1 the standard Hit-miss analysis is valid. Not in case 2!

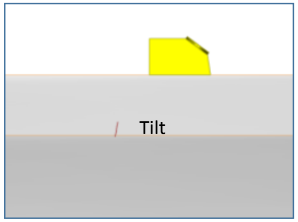
METAMODELS: SENSITIVITY ANALYSIS

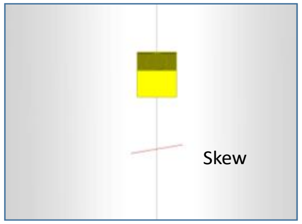
- Simulation of large data-sets makes possible multiple and versatile sensitivity analysis.
- Quantification of the relative influence of the parameters (Sobol indexes).

➡ Illustration on the ***REDUCE*** case study:

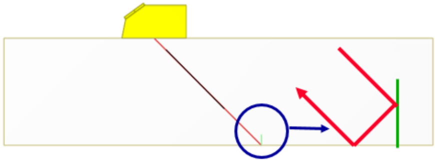
Sobol index for cracks (0 < H < 10 mm)





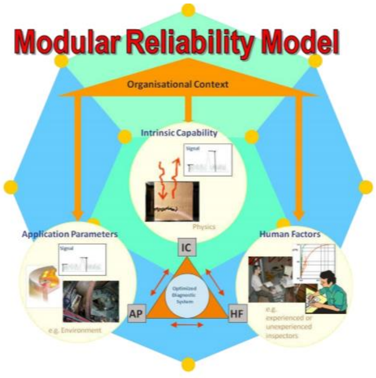


➡ Strong influence of tilt and skew.

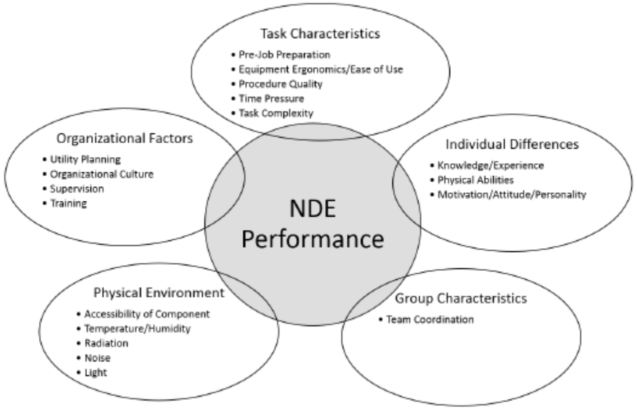


HUMAN FACTORS, SIMULATION AND NDE RELIABILITY

- Pioneers works at BAM, (M. Bertovic,and coll.) and in UK (PANI projects)
- Growing interest over the world.



From European-American workshop on NDE reliability and BAM works



From A. D'AGOSTINO, NRC, 2017

From G. Selby, EPRI, ICNDE 2016

- In France, National funded project launched in 2017 ANR FOEHN

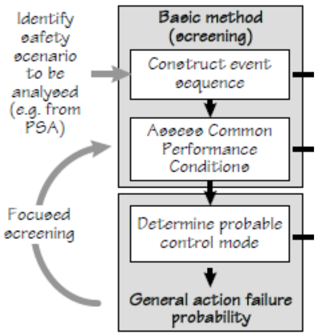
HUMAN FACTORS, SIMULATION AND NDE RELIABILITY

FOEHN

- Modelling of HF influence on NDE performance

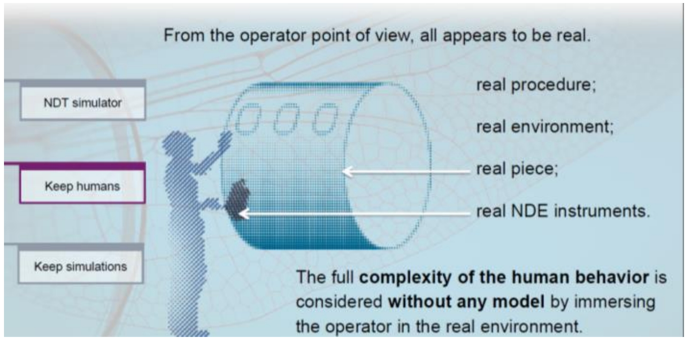
MINES ParisTech

Cognitive **R**eliability and **E**rror **A**nalysis **M**ethod (Hollnagel, 1998)



- Monitoring the inspection to capture gesture variability (UT) .

+ Virtual mock-up
& real time simulation

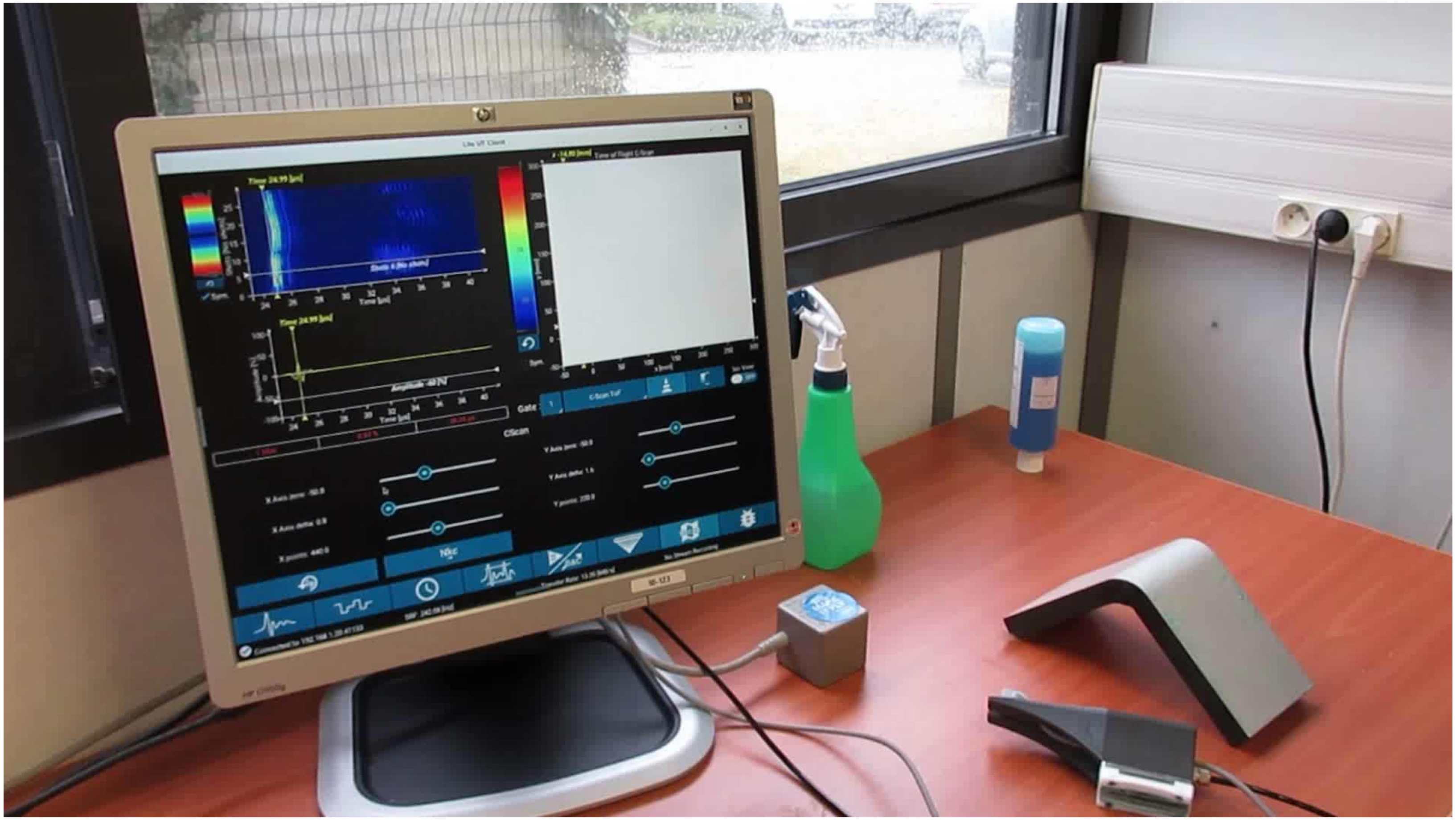


Operational simulator

AIRBUS GROUP

PROOF OF CONCEPT

Damien Rodat's PhD
Saclay, Dec 6th



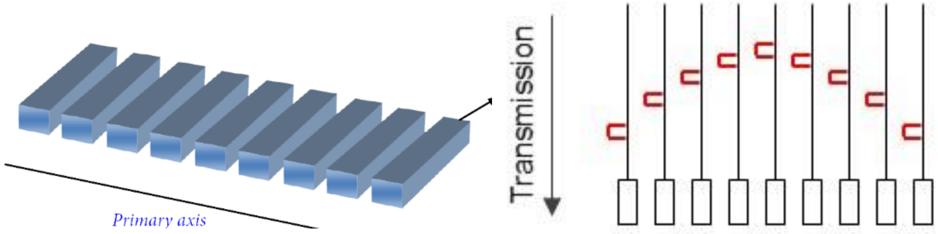
COMPUTATIONAL TOOLS FOR ENHANCED DIAGNOSTICS:

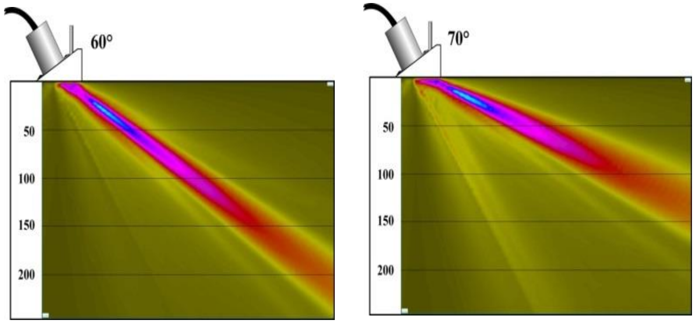
Advanced ultrasonic array imaging

BACKGROUND: PAUT & FMC-TFM

- Tremendous development of PAUT techniques

Principle: Application of **electronic delays** to an array in order to steer the beam





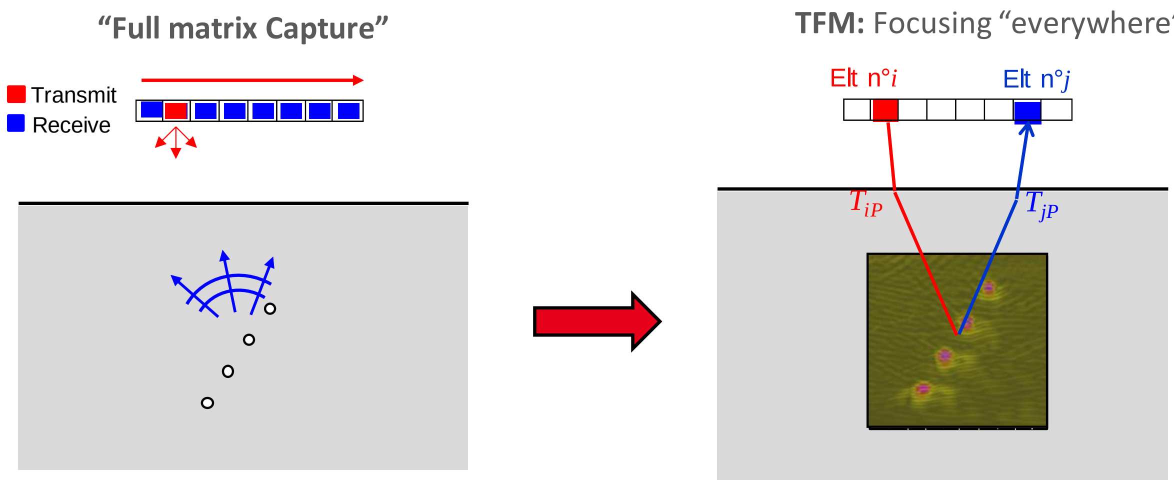
Faster acquisitions / Higher performances / Limited Access Compensation

But … The full potential of arrays is not exploited !

→ **Advanced array imaging: FMC-TFM methods**

BACKGROUND: PAUT & FMC-TFM

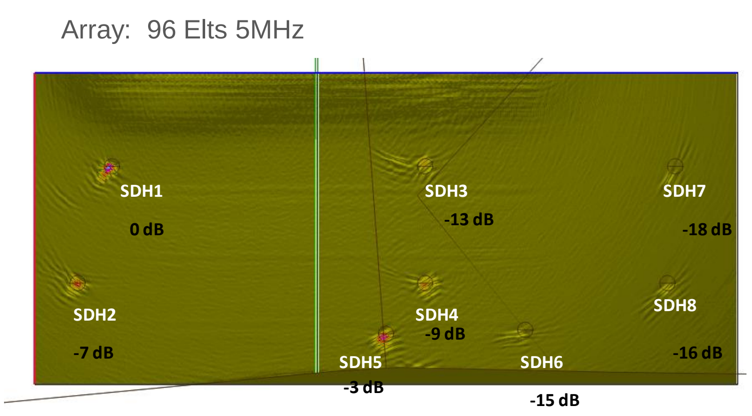
- Principle



- **FMC**: Acquisition of the signals for all the pairs of T-R elements
- **TFM**: Processing based on the computation of TOF for all the pixels in the image

Advantages of FMC-TFM:

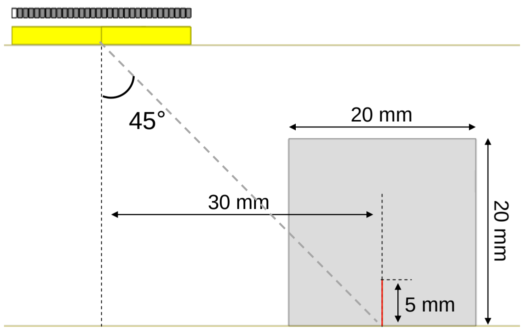
- Direct imaging of one large area in one probe position
- Optimized focusing and spatial resolution everywhere
- Relative insensitivity to the orientation of the defect
- Intuitive imaging : Easy interpretation
- Enhanced imaging of crack-like defect by corner effect
- Possibility of 3D imaging with 2D arrays.



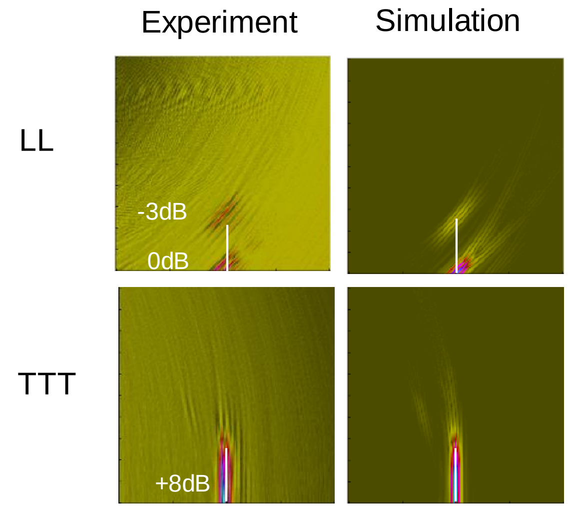
MULTIMODAL TFM

Direct imaging of crack-like defects by corner effect

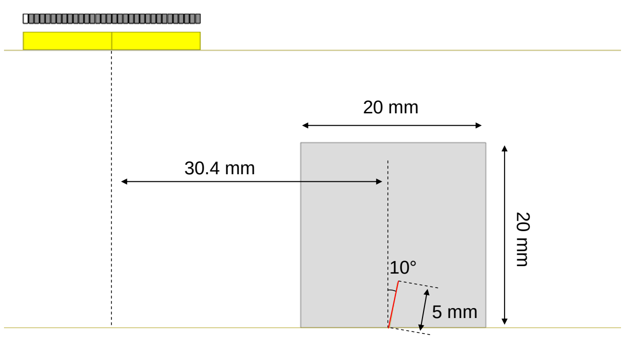
Linear array : 32 elements, 5MHz



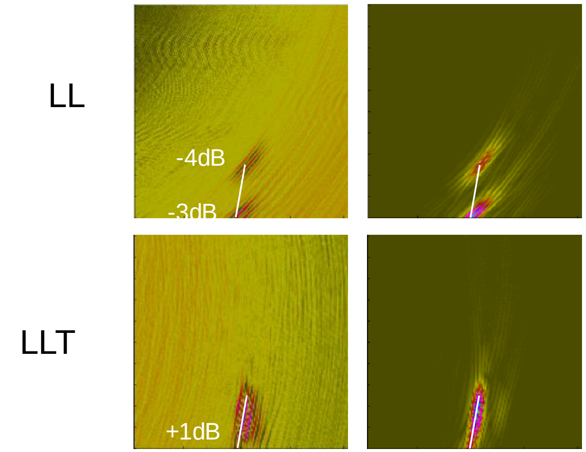
Steel block with notch
H = 5 mm,Tilt = 0°



Calibration: 0db SDH Ø2 mm



Steel block with notch
H = 5 mm, Tilt = 10°

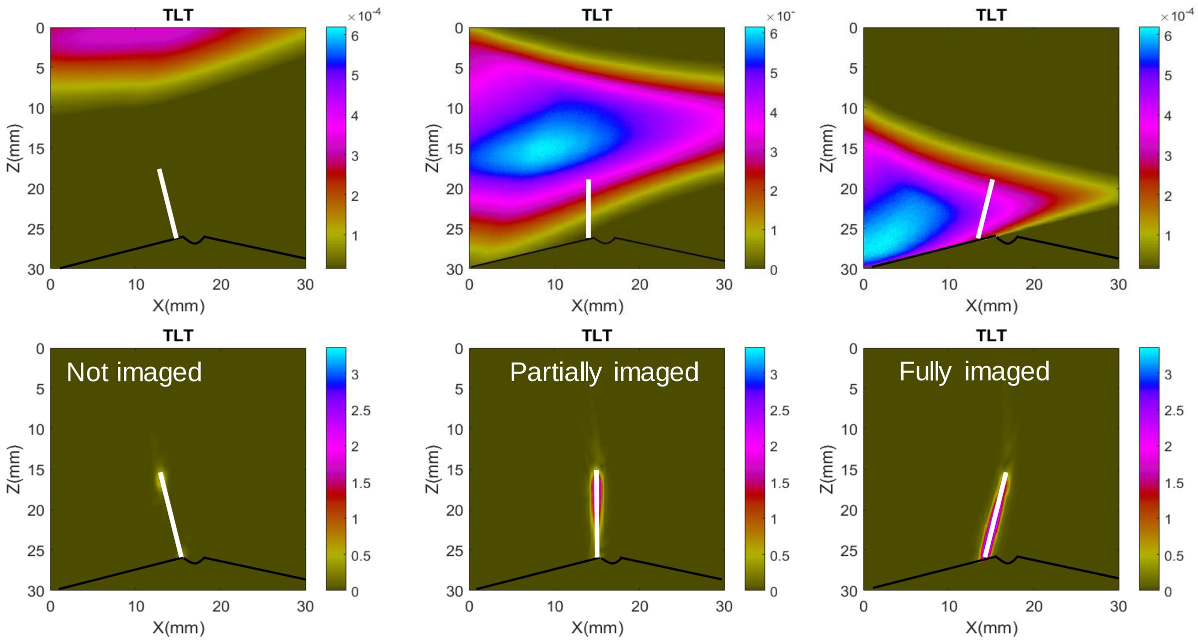


COMPUTATIONAL TOOLS FOR FMC-TFM

Modelling embedded in tools assisting the TFM inspection :

- A priori selecting the most relevant images
- Correcting of possible artifacts
- Providing « enhanced diagnostics »: Size of the decfect + accuracy/uncertainty

One key idea: Sensitivity maps (operator « SEE ») defined for one orientation of the defect [1]



SEE: Estimation of the weighed number of T-R pairs in condition of specular reflexion

[1] K. Sy, Ph Brédif , E. Iakovleva , D. Lesselier, O. Roy, NDT&E Int., 2018

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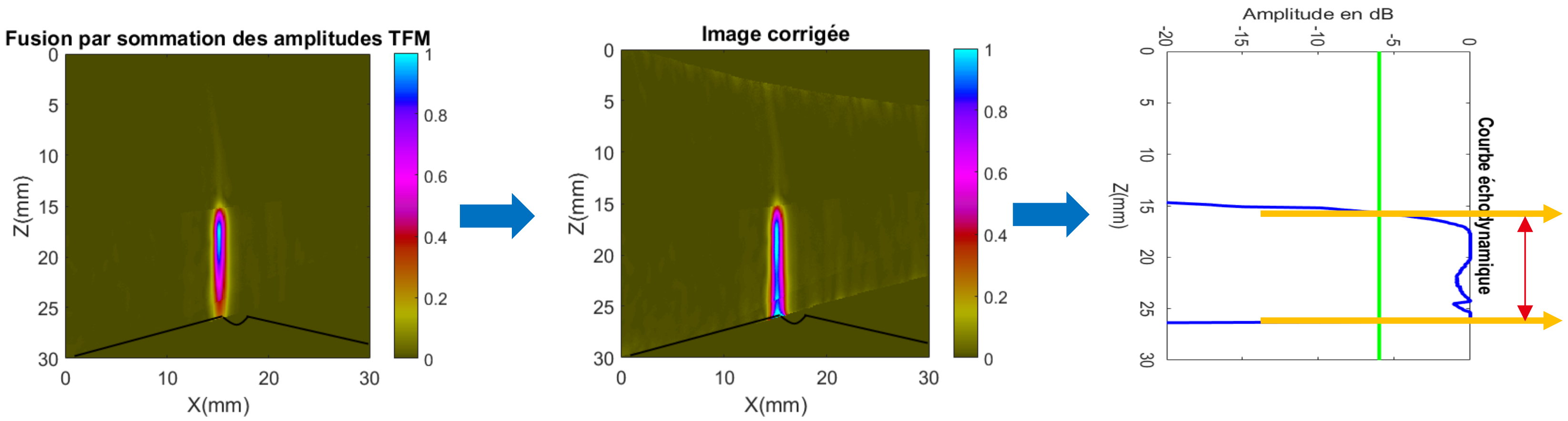

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COMPUTATIONAL TOOLS FOR FMC-TFM

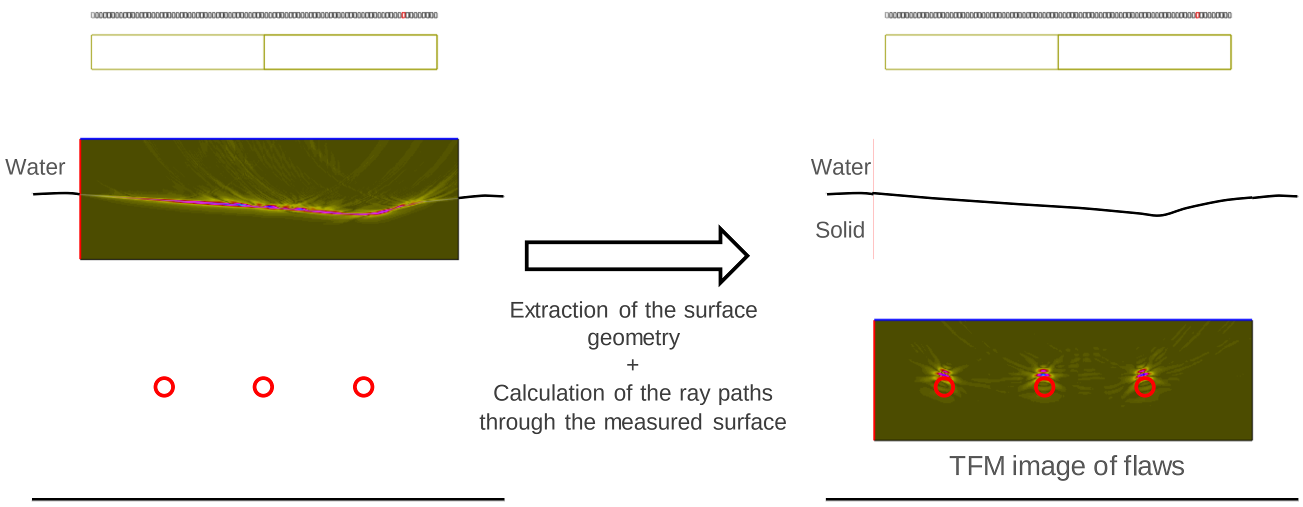
Sensitivity to « uncertain » parameters (geometry/material)

→ Development of adaptive algorithms based on a real time measurements (example of ATFM)

Principle of ATFM : Adaptive Total Focusing Method

At each position, from one same acquired data : two successive processing

1) Surface imaging **2) Imaging of the defects**



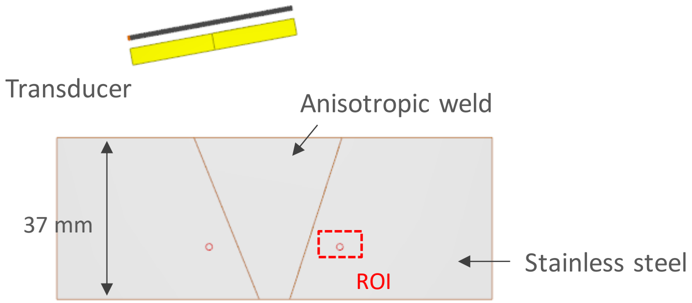
COMPUTATIONAL TOOLS FOR FMC-TFM

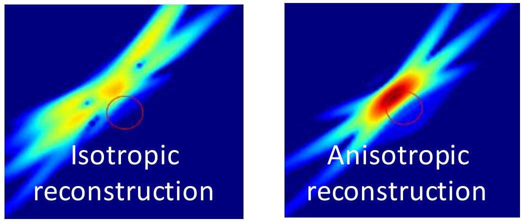
Sensitivity to « uncertain » parameters (geometry/material)

→ Optimization of the imaging : iterative process using metamodels

Sensitivity to the (unknown) material properties

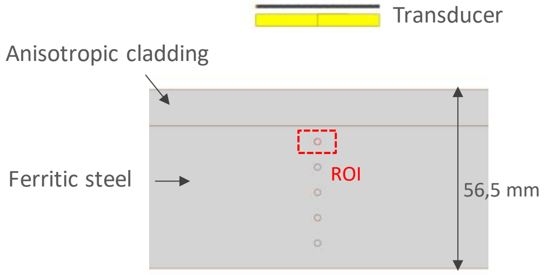
V-shape weld

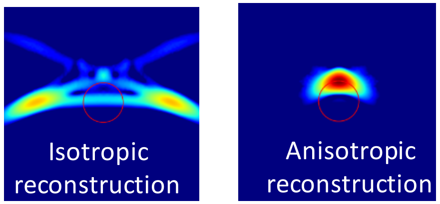




Simulated images

Cladding (steel)





COMPUTATIONAL TOOLS FOR FMC-TFM

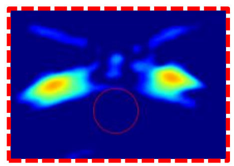
Principle of the optimization:

Acquisition matrix $\mathbf{K}(t)$

$$\mathbf{K}(t) = \begin{bmatrix} K_{11}(t) & K_{12}(t) & \cdots & K_{1N}(t) \\ K_{21}(t) & K_{22}(t) & \cdots & K_{2N}(t) \\ \vdots & \vdots & & \vdots \\ K_{N1}(t) & K_{N2}(t) & \cdots & K_{NN}(t) \end{bmatrix}$$

Exp. signals

Isotropic model



Initialization

Optimization algorithm

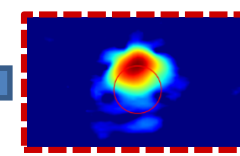
Inputs

C_{11}
C_{13}
C_{33}
...

Forward model (CIVA)

Focusing matrix $\mathbf{T}(P)$

$$\mathbf{T}(P) = \begin{bmatrix} T_{11}(P) & \dots & T_{1N}(P) \\ \vdots & \ddots & \vdots \\ T_{N1}(P) & \dots & T_{NN}(P) \end{bmatrix}$$



Estimators

Optimal image (Convergence test)

False : adjust C_{ij} parameters

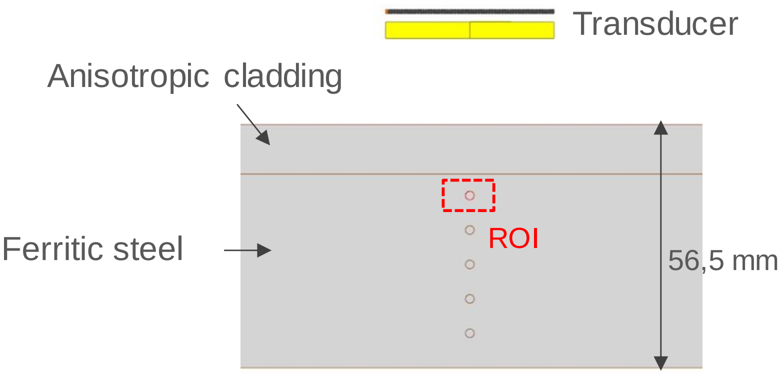
True

Optimization of the TFM image by iteratively adjustment of stiffness constants/welds parameters inputted in the TFM algorithm

ADVISE
Advanced Inspection of Complex Structures

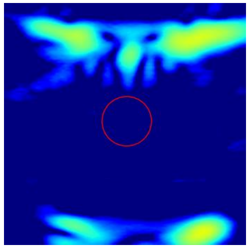
COMPUTATIONAL TOOLS FOR FMC-TFM

First results on experimental data (cladded component) :



Experimental data, 5MHz, 64 elts

Initial image

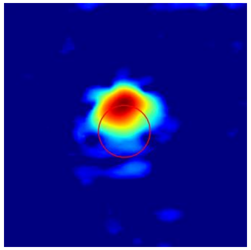


Initial guess

$$C_{ij} = \begin{pmatrix} 250 & 115 & 176 & 0 & 0 & 0 \\ 115 & 250 & 151 & 0 & 0 & 0 \\ 176 & 151 & 197 & 0 & 0 & 0 \\ 0 & 0 & 0 & 117 & 0 & 0 \\ 0 & 0 & 0 & 0 & 131 & 0 \\ 0 & 0 & 0 & 0 & 0 & 58 \end{pmatrix} \text{GPa}$$

Optimization scheme

Final image



Final guess

$$C_{ij} = \begin{pmatrix} 258 & 115 & 161 & 0 & 0 & 0 \\ 115 & 250 & 151 & 0 & 0 & 0 \\ 161 & 151 & 247 & 0 & 0 & 0 \\ 0 & 0 & 0 & 117 & 0 & 0 \\ 0 & 0 & 0 & 0 & 112 & 0 \\ 0 & 0 & 0 & 0 & 0 & 58 \end{pmatrix} \text{GPa}$$

ADVISE
Advanced Inspection of Complex Structures

SIMULATION- BASED ACCURACY ASSESSMENT

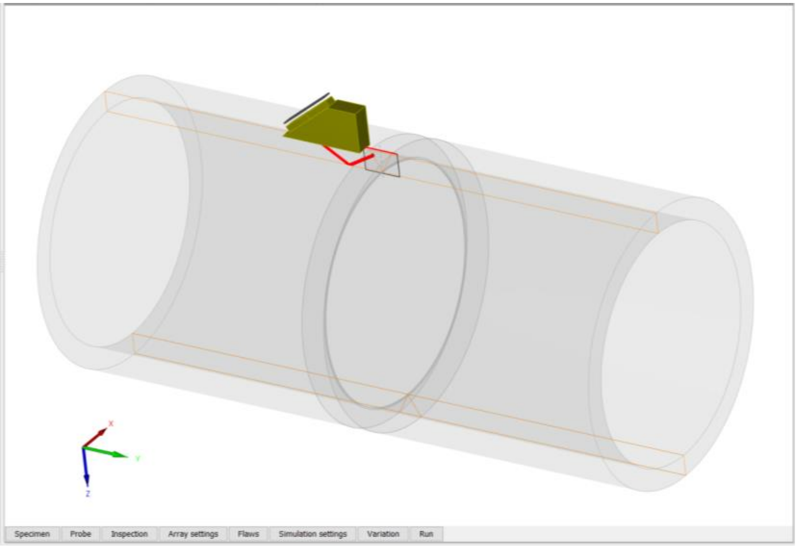
Performance demonstration:

- ***Reliability***: The ability of the technique to detect defects under realistic conditions
- ***Accuracy***: the effectiveness of the technique to size the defect

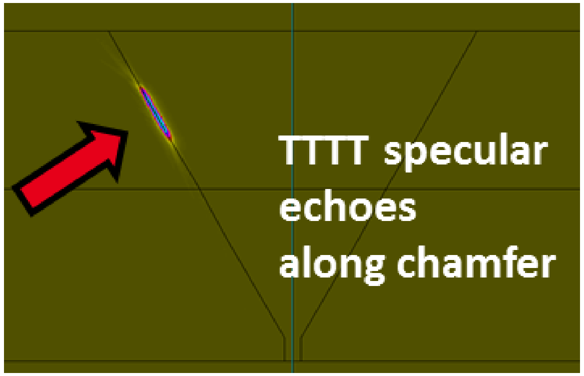
- Simulation has been proven to be helpful for reliability assessment (MAPOD)
- Can we imagine similar ***simulation-based accuracy assessment*** (accounting for « uncertainty/variability » of influent parameters) ?

« ACCURACY ASSESSMENT »

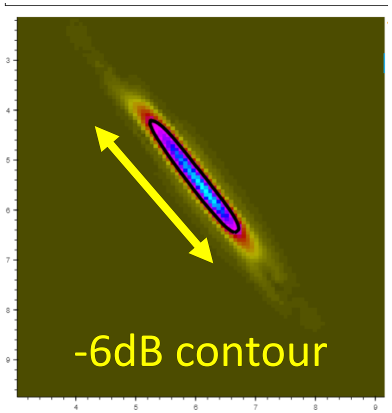
Proof of concept on one example [1] : TFM inspection of the V Bevel of weld



FMC - TFM Images



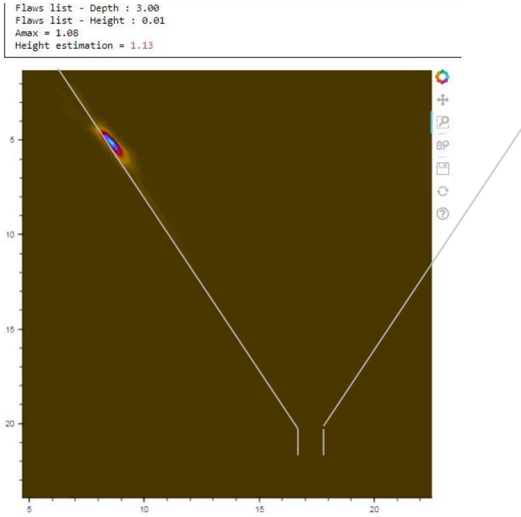
Array 64 elts 7 MHz
Steel welded pipe 21 mm, lack of fusion



Objective: To estimate the accuracy of the 6dB sizing procedure on the TFM image

[1] : S. Leberre et al, to be published in QNDE 2018 Proc.

SIMULATION- BASED ACCURACY ASSESSMENT

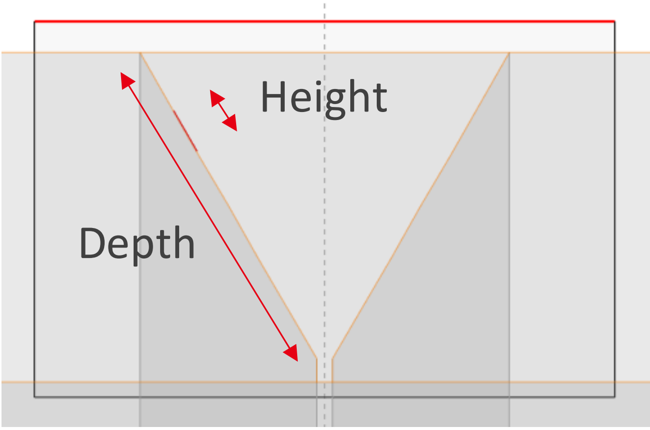


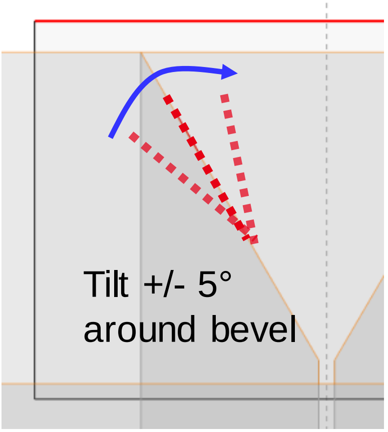
Methodology:

- Simulation/automatization of the sizing procedure
- Definition of a metric for the accuracy:

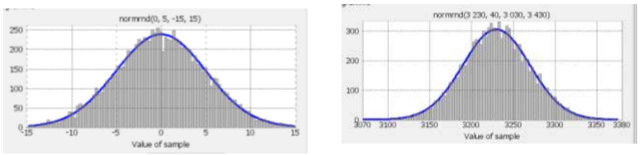
$$Probability\ of\ accuracy(x) = p[\|X_{Meas} - X_{True}\| \leq x]$$

- Use of metamodels + uncertainty propagation





Identification of uncertain parameters:
Here: tilt and on the velocity



$N(0,\sigma_{tilt})$ $N(3290,\sigma_{cT})$

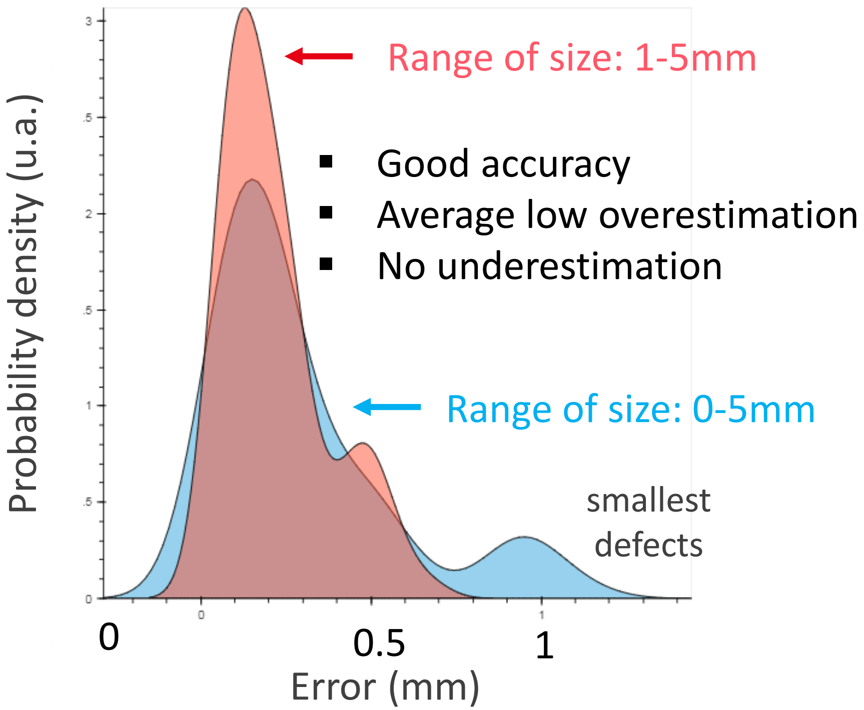
SIMULATION- BASED NDE ACCURACY ASSESSMENT

Metamodel output: Error of sizing

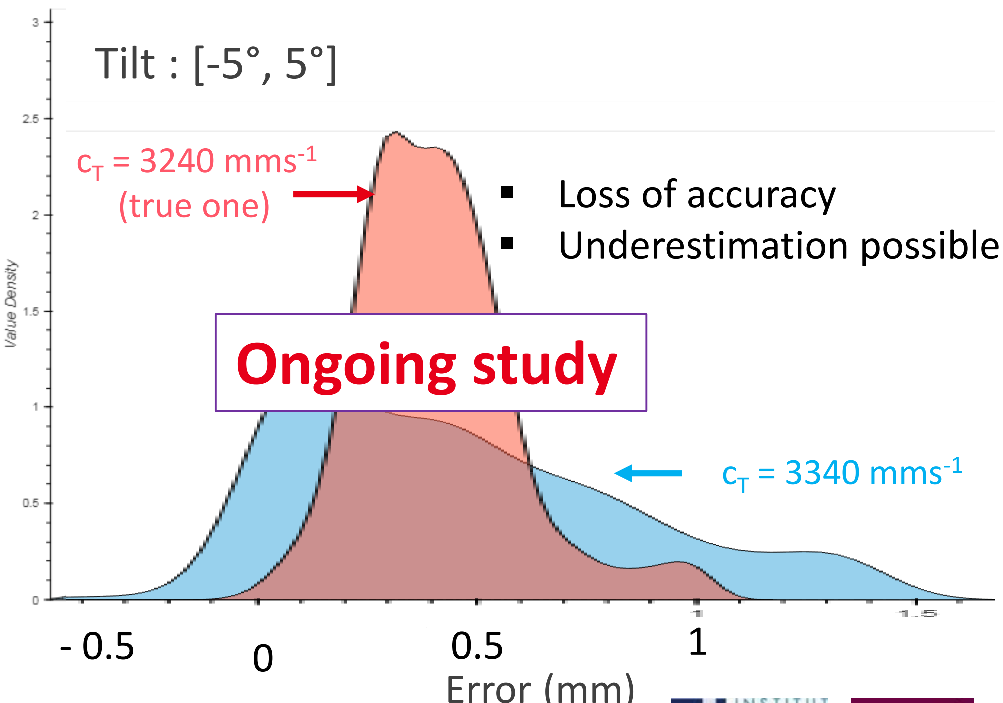
Statistical analysis:

- MC sampling + computations
- Estimation of the distribution of the error

1. In the « nominal » case
(no uncertainty on other parameters)



2. Accounting for uncertainties
(here on the tilt and on the velocity)



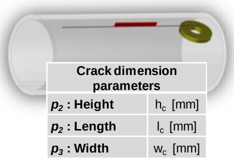
BEYOND IMAGING : INVERSE MODELS FOR DIAGNOSTIC

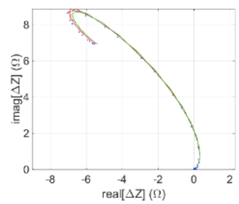
- Forwards and Inverse models

Forwards model

Flaw description → NDI result

CIVA NDE





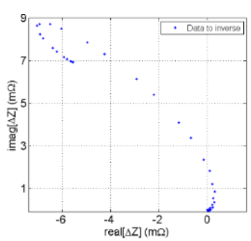
Many existing techniques to solve the inverse probem in the literature…

but not yet many applications in NDE

Inverse model

NDI result (Exp) → Flaw

CIVA NDE -1



Crack dimension parameters	
p_2 : Height	h_c [mm]
p_2 : Length	l_c [mm]
p_3 : Width	w_c [mm]

→ Iterative methods

Machine learning

- Solving the inverse problem for helped/enhanced/automatic diagnostics

A FOCUS ON SHM

New challenges & new opportunities

STRUCTURAL HEALTH MONITORING

Structural Health Monitoring = "The process of acquiring and analyzing data from on-board sensors to evaluate the health of a structure"

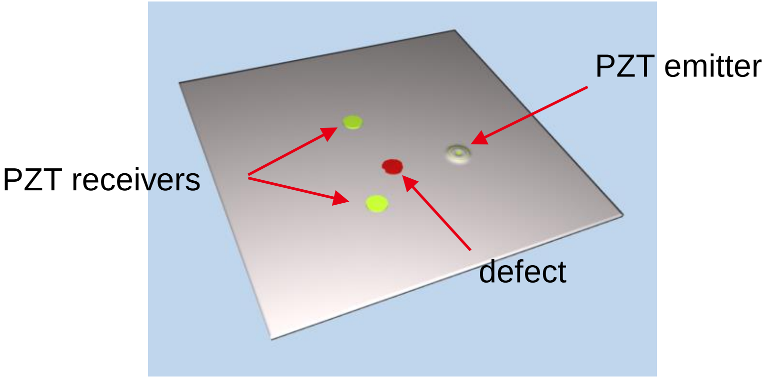
SAE INTERNATIONAL

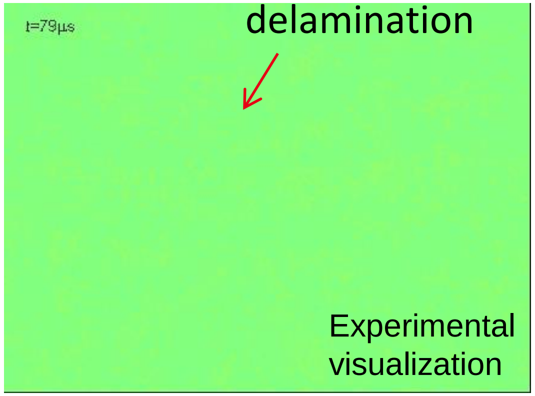
- Damage monitoring replaces periodic inspections
- Instrumentation of the structure
- Network of sensors of possibly different natures
- Decision making systems
- Evaluation of the remaining life

New challenges, new opportunities

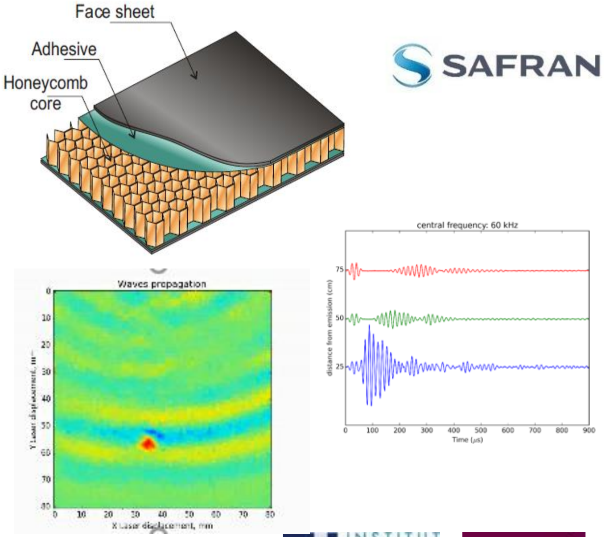
An even more central role for numerical tools

ELASTIC GUIDED WAVES FOR SHM





- Guided waves are good candidate for SHM of large structures
- Use of PZT sensors to emit and receive GW



SIMULATION OF GW-SHM: DESIGN + POD

- **One big challenge: SHM & POD**

It is already recognized that:

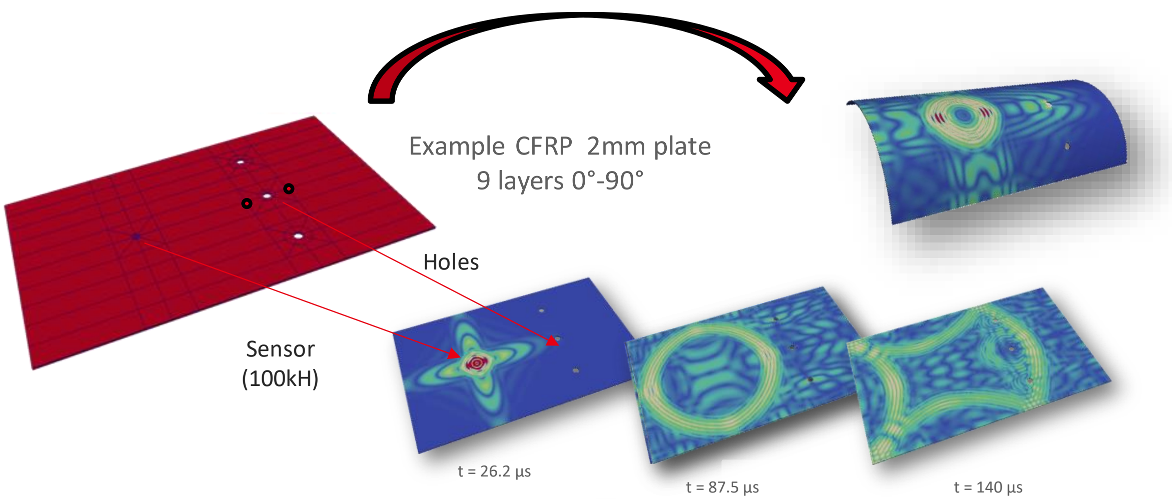
Acting WG on this topic at SAE INTERNATIONAL

- The **Standard POD methodology** (MIL1823) based on trials is **not directly applicable**

- **Simulation will be an unavoidable element of a methodology which is to be established**

- **Development at CEA of a CIVA-SHM module**

Based on the SEM code previously described :
High order FEM + Macromesh



- **Recent NASA benchmark (2018)**

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Simulation of guided-wave ultrasound propagation in composite laminates: Benchmark comparisons of numerical codes and experiment

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ABSTRACT

Ultrasonic wave methods constitute the leading physical mechanism for nondestructive evaluation (NDE) and structural health monitoring (SHM) of solid composite materials, such as carbon fiber reinforced polymer (CFRP) laminates. Computational models of ultrasonic wave excitation, propagation, and scattering in CFRP composites can be extremely valuable in designing practicable NDE and SHM hardware, software, and methodologies that accomplish the desired accuracy, reliability, efficiency, and coverage. The development and application of ultrasonic simulation approaches for composite materials is an active area of research in the field of NDE. This paper presents comparisons of guided wave simulations for CFRP composites implemented using four different simulation codes: the commercial finite element modeling (FEM) packages ABAQUS, ANSYS, and COMSOL, and a custom code executing the Elastodynamic Finite Integration Technique (EFIT). Benchmark comparisons are made between the simulation tools and both experimental laser Doppler vibrometry data and theoretical dispersion curves. A pristine and a delamination type case (Teflon insert in the experimental specimen) is studied. A summary is given of the accuracy of simulation results and the respective computational performance of the four different simulation tools.

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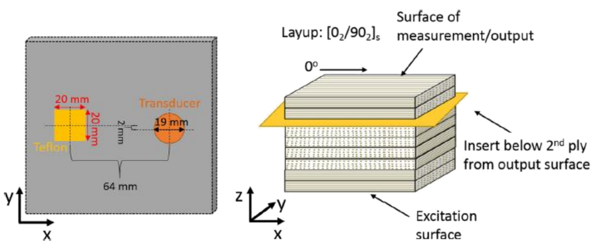
SIMULATION OF GW-SHM

Recent results (2018)

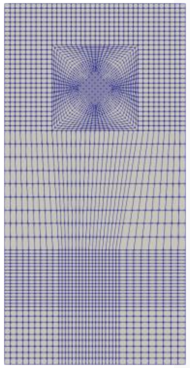
- **On the NASA benchmark** (wavenumbers)

Teflon insert in a CFRP plate, 300kHz

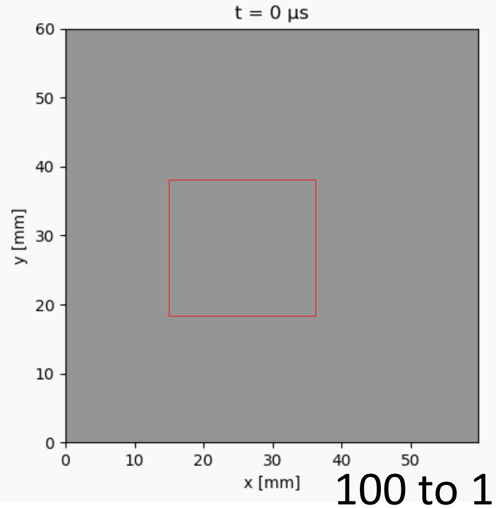
Benchmark
EFIT
COMSOL
ABAQUS/I
ABAQUS/E
ANSYS



Macromesh



Wave propagation (out of plane velocity, only A0)

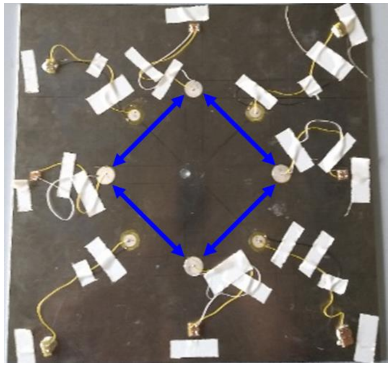


S0 ⟶ A0
then A0

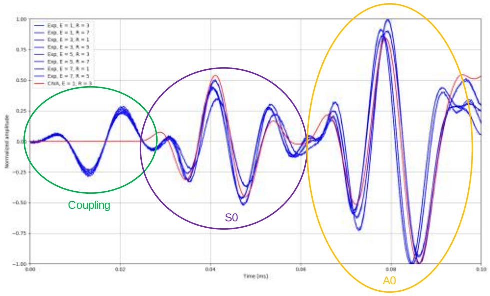
100 to 1000 x faster !

- **Experimental validation** (signals + images)

Al plate, 3 mm



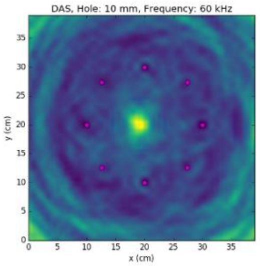
Comparison of signals in pristine



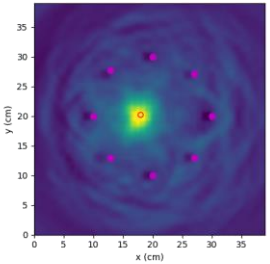
CIVA $40\ kHz$

Simulation of imaging algorithms

Experimental



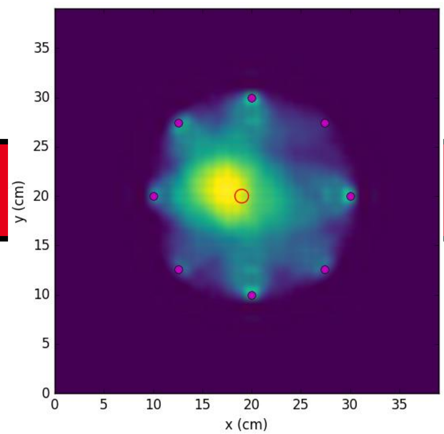
Simulated



O. Mesnil et al, Proc. Of QNDE conf. 2018

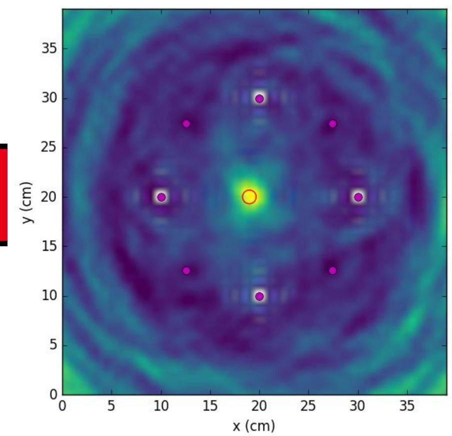
GUIDED WAVES IMAGING

- Imaging/detection relies on comparison to pristine (reference) signals
- Imaging algorithms embedding more or less sophisticated model



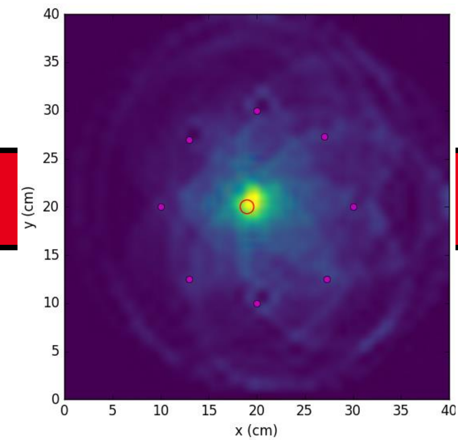
RAPID **(Reconstruction Algorithm for Probabilistic Inspection of Damages)**

Correlation between pristine and unknown state. **No model**



DAS **(Delay And Sum)**

Sommation of residual signals delayed by **theoretical times of flight**



Excitelet

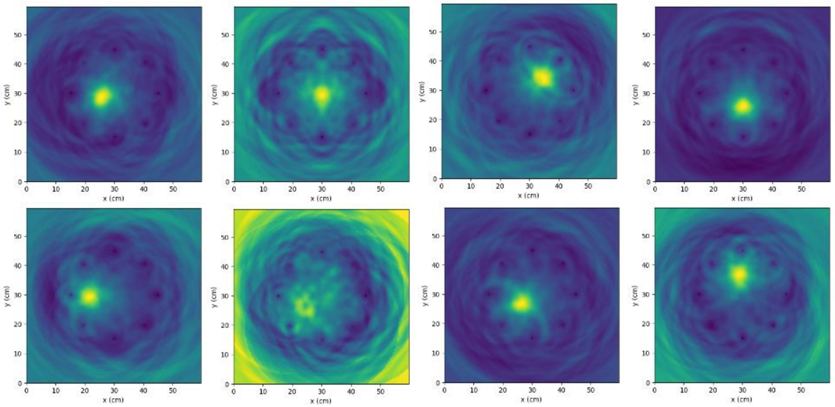
Correlation between residual signals and **theoretical signals at every pixel**

MACHINE LEARNING BASED INVERSION

Beyond imaging: Automatic characterization of the defect

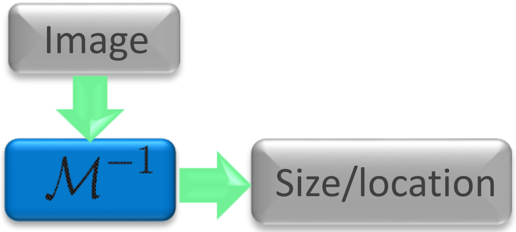
Method investigated: Machine learning based inversion

Offline phase: learning the « inverse model »



Numerical database (350 images)
Various defect size and position

Offline phase: learning the « inverse model »



- Data: Guided wave images (DAS, Excitelet) of holes
- **One required step:** Dimensionality reduction (here PCA)
- Construction of the « metamodel inverse »: Regression (SVM, KRR…) or classification

MACHINE LEARNING BASED INVERSION

Beyond imaging: Automatic characterization of the defect (size)

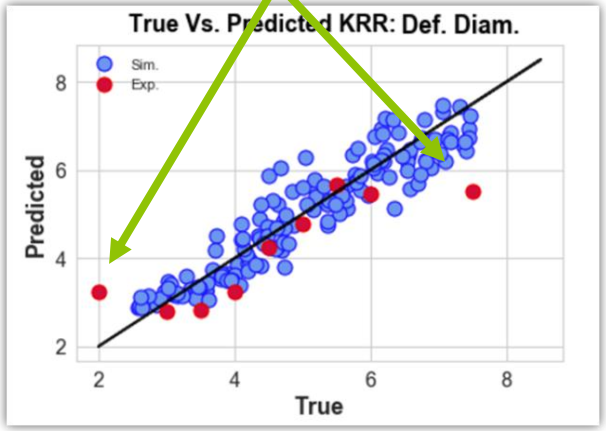
Method investigated: Machine learning based inversion

Online phase: Exploitation of the « Inverse metamodel »

Guided wave image
Unknown defect

→ $\mathcal{M}^{-1}$ →

Outliers



Predicted size VS true size

Blue: Numerical data
Red: Experimental data

Results

Proof of concept:

- Application to numerical data base (test base, 150 images)
- Average absolute error of 0,3mm in sizing

First results on experimental data:

- Excellent prediction (except outliers)

CONCLUSIVE REMARKS

CONCLUSIVE REMARKS

- A central role of simulation for fulfilling the challenges NDE and SHM are facing.
- Advances in numerical modelling coupled to NDE-oriented implementation allow to address always more complex situations. Example of composites
- In parallel the use of meta-modelling makes possible intensive computations.
- Simulation is for NDE reliability (POD, sensitivity analysis…). It will be even more true for SHM
- Model-based array imaging and inversion/optimization methods can improve diagnostics
- SHM and GW-SHM open new challenges and perspectives: Estimation of remaining life, reliability assessment, use of machine learning algorithms

Thank you for your attention

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