New tools in CIVA for Model Assisted Probability of Detection (MAPOD) to support NDE reliability studies

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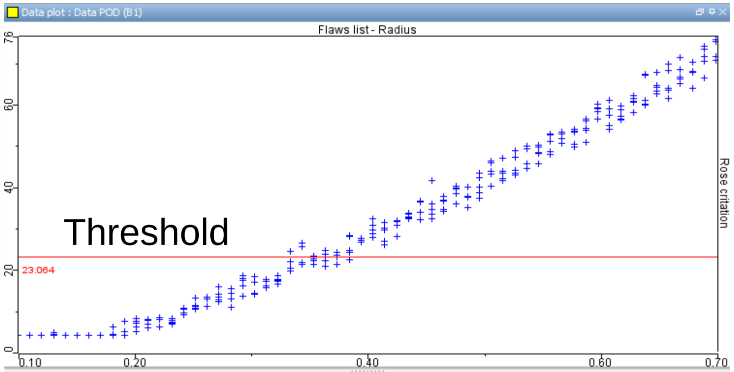
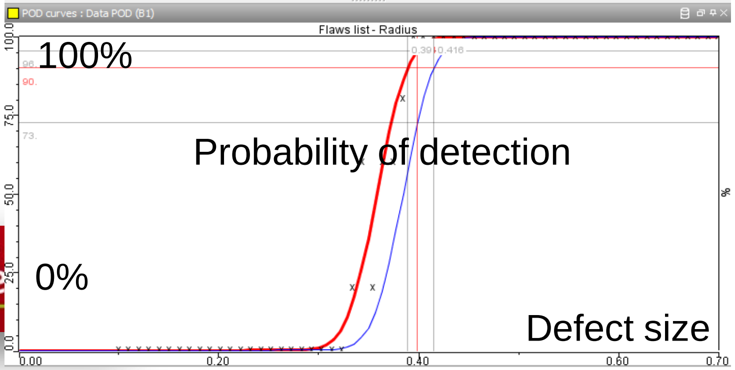
Outline

- Introduction
- MAPOD methodology & benefits of modeling
- CIVA features in this context
- Examples:Illustrative cases
  - HF ET
  - UT inspection of engine disks
  - UT inspection of titanium billet
- Conclusion

Reliability in aerospace

- Context:
  - Damage tolerance rules: Aircraft maintenance intervals driven by the knowledge of detectable flaw sizes
  - Probability Of Detections campaigns are required in order to evaluate statistically the maximum flaw size that can be missed by a given inspection procedure:
    - Military Handbook 1823-A methodology: Parametric approach of POD (Berens models) and PFA
    - Involves knowledge of influential parameters to define relevant Design Of Experiments
    - Quite large amount of data necessary to provide reliable POD curves
  - Quite long & costly: Why not doing a part of this work with simulation ? MAPOD approach (Model Assisted POD)





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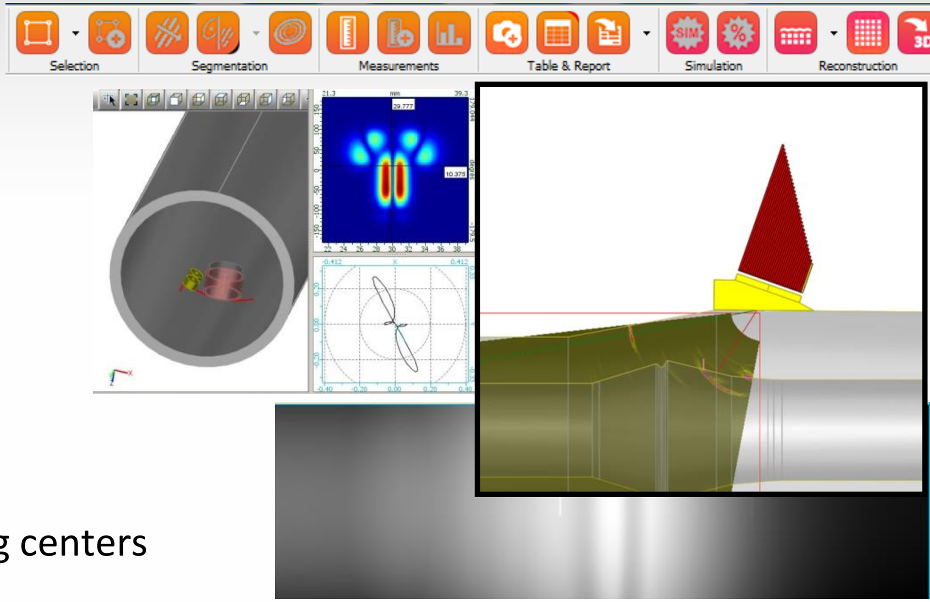
CIVA

- Leading industrial software dedicated to NDE Simulation & Analysis
  (more than 270 customers in 42 countries)
- Multi-techniques:
  - ✓ UT :
    - Ultrasounds Testing modelling
    - UT Acquisition Data Analysis tools
  - ✓ GWT: Guided Waves
  - ✓ ET : Eddy Current
  - ✓ RT : Radiography
  - ✓ CT: Computed Tomography



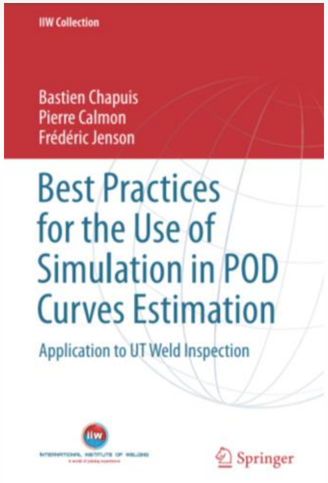
- CIVA Education: For universities and training centers
  - Help to understand the physics behind NDT
- Mostly based on semi-analytical models (fast), connection with numerical ones (FEM, FDTD,…)
- Developed by CEA (French Atomic Energy commission):
  25 years of experience with models & validations
- Distributed by EXTENDE (EXTENDE Inc in USA, VA)

MAPOD methodology

- US MAPOD Working Group (2003-2011) driven by USAF has been a pioneer in developing a MAPOD approach

MAPOD WG

- Efforts have been done to fix an accepted methodology:
  - 2016 : IIW publication « Best practices for the use of simulation in POD Curves Estimation »



- Different stages in a MAPOD process:
  - Define a nominal configuration
  - Identify and characterize the sources of variability which will be accounted for by the POD:
    - Select "aleatory parameters" among the input parameters in the model
    - Assign a statistical distributions to them
  - Sample the statistical distributions of aleatory parameters (MC) and run the corresponding simulations.
  - Compute POD curve from obtained results with relevant statistical models
  - Evaluate the reliability of the POD curve

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Benefits of Using Simulation

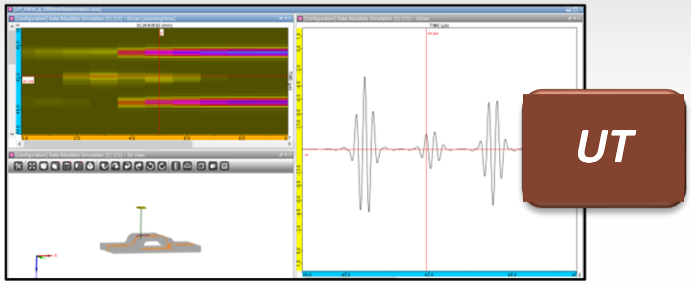
- In the context of reliability studies:
  - Easy and precise mastering of parameters variation:
    Not always the case experimentally
  - Easy and fast to generate large amount of data (required for POD analysis)
  - Less mock up & less trials : Lower cost
  - Insights for physical understanding
- Modelling also useful also in other contexts
  - Inspection method design, expertise, training....
- Some limitations & challenges:
  - Models capture a part of the variability but maybe not all (human factor, structural noise, etc.)
  - Needs to define a priori in the model the sources of variability: Can be difficult
  - Requires sufficient modelling accuracy (needs for validation) and acceptance by stakeholders

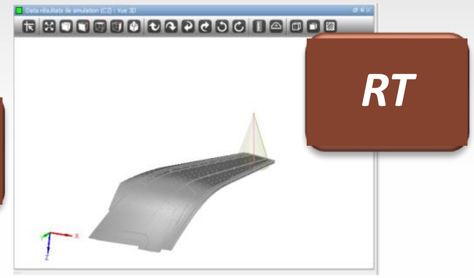
CIVA features in this context

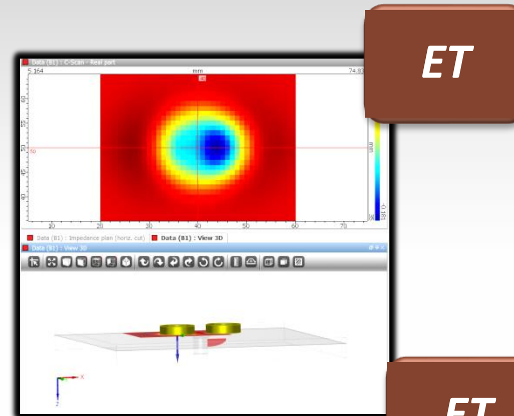
1. Versatile & fast physic-based models, a user-friendly GUI:

Adapted for parametric studies

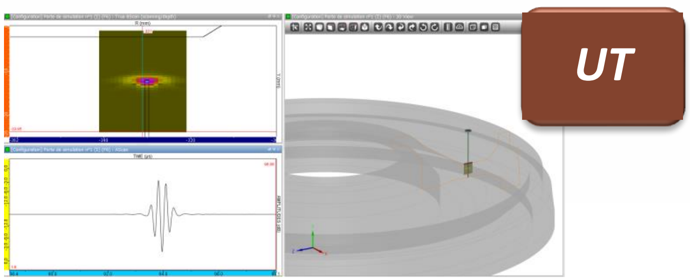
- For aeronautical structures

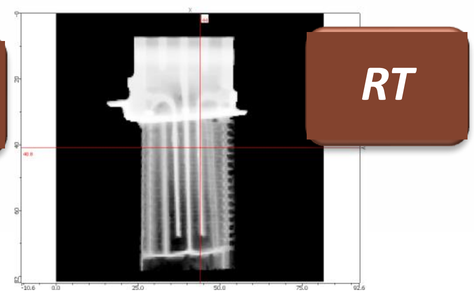


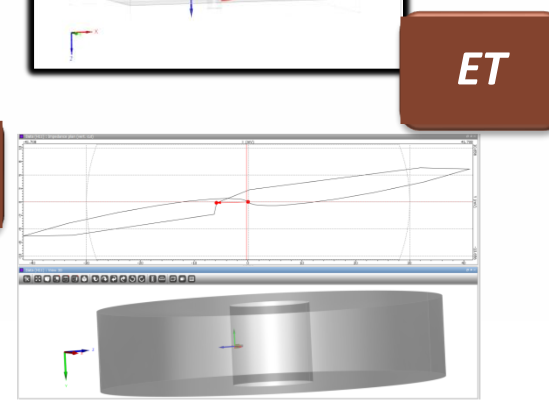




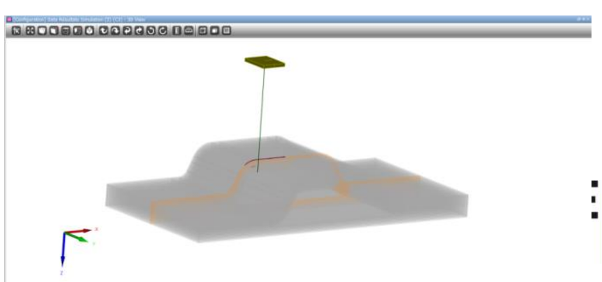
- For engines manufacturers

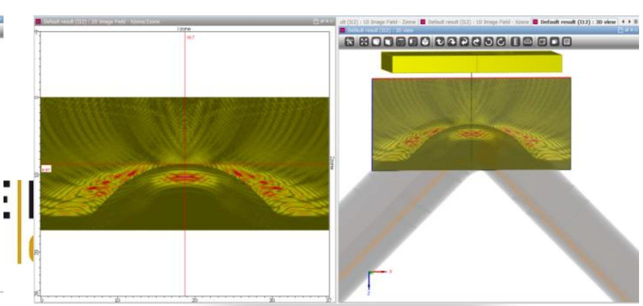






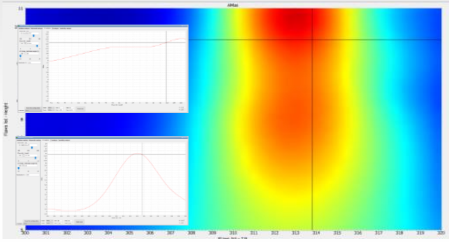
- For metallic or composite parts

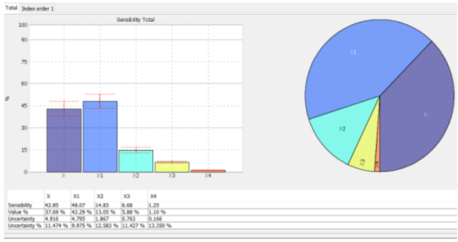




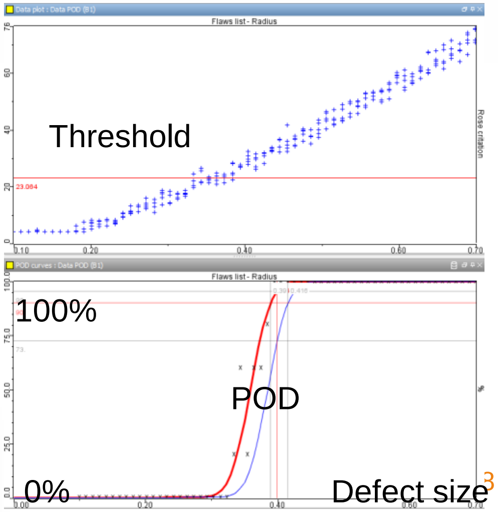
CIVA features in this context

2. Implementation of « metamodels » or « Surrogate models:
    - Smart Interpolators
    - Built from a set of physic-based model results
    - Can replace (after validation) the physic-based models:
        - For an ultra-fast exploration of the full range of parameters variation and « on demand » resampling
        - Generate even larger amount of data:
            - Makes possible sensitivity analysis (Sobol Indices)
            - Can « feed » POD requirements





3. Built-in POD Analysis tools:
    - Signal Response or Hit Miss Berens models
    - Data transform tools (log, lin, box-cox)
    - Non parametric curves
    - Array of PODs
    - Import/Export data
    - …



Model validation

- To be able to rely quantitatively on simulation, models reliability and accuracy is of first importance.

- CIVA software development goes along with extensive test & validation campaigns:
  - To demonstrate applicability of new models when they come out
  - Quality Assurance and Non regression tests between each release
  - Annual participation to WFNDEC benchmarks presented at QNDE conferences
  - Targetted validation works performed in the frame of EXTENDE / CEA a collaboration, then published on EXTENDE website:

    www.extende.com
  - Overview of CIVA validation efforts to be presented in the upcoming ECNDT conference (Goteborg, Swe):

F. Foucher, S. Lonne, G. Toullelan, S. Mahaut, S. Chatillon, "AN OVERVIEW OF VALIDATION CAMPAIGNS AROUND THE CIVA SIMULATION SOFTWARE", Monday June, 11th 2018, ECNDT conference

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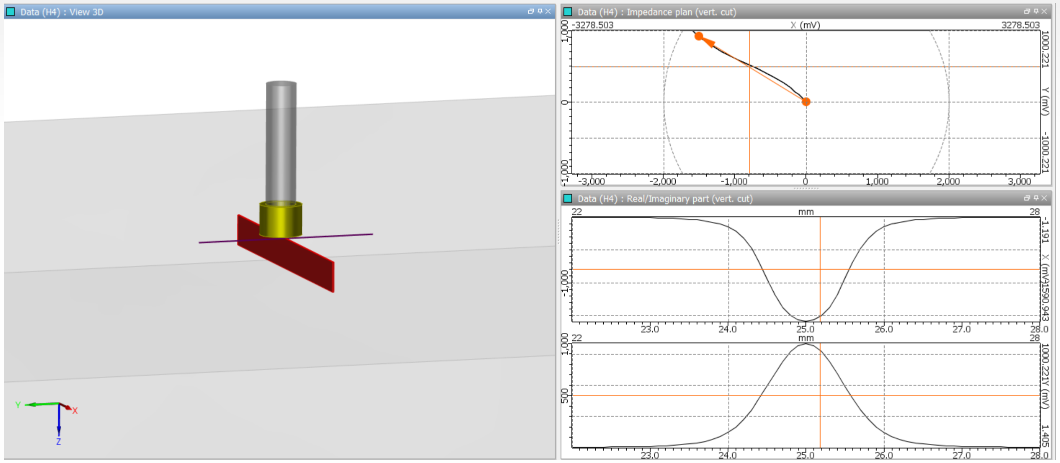
Illustrative examples

- Sample case: High Frequency Eddy Current Testing model
  - Aluminum slab with surface breaking notch
  - Pencil ET sensor Φ1,4mm with Ferrite core, common mode function operating at 1MHz
  - Simulation results of the calibration case on a reference defect, 10mm long and 1mm high :



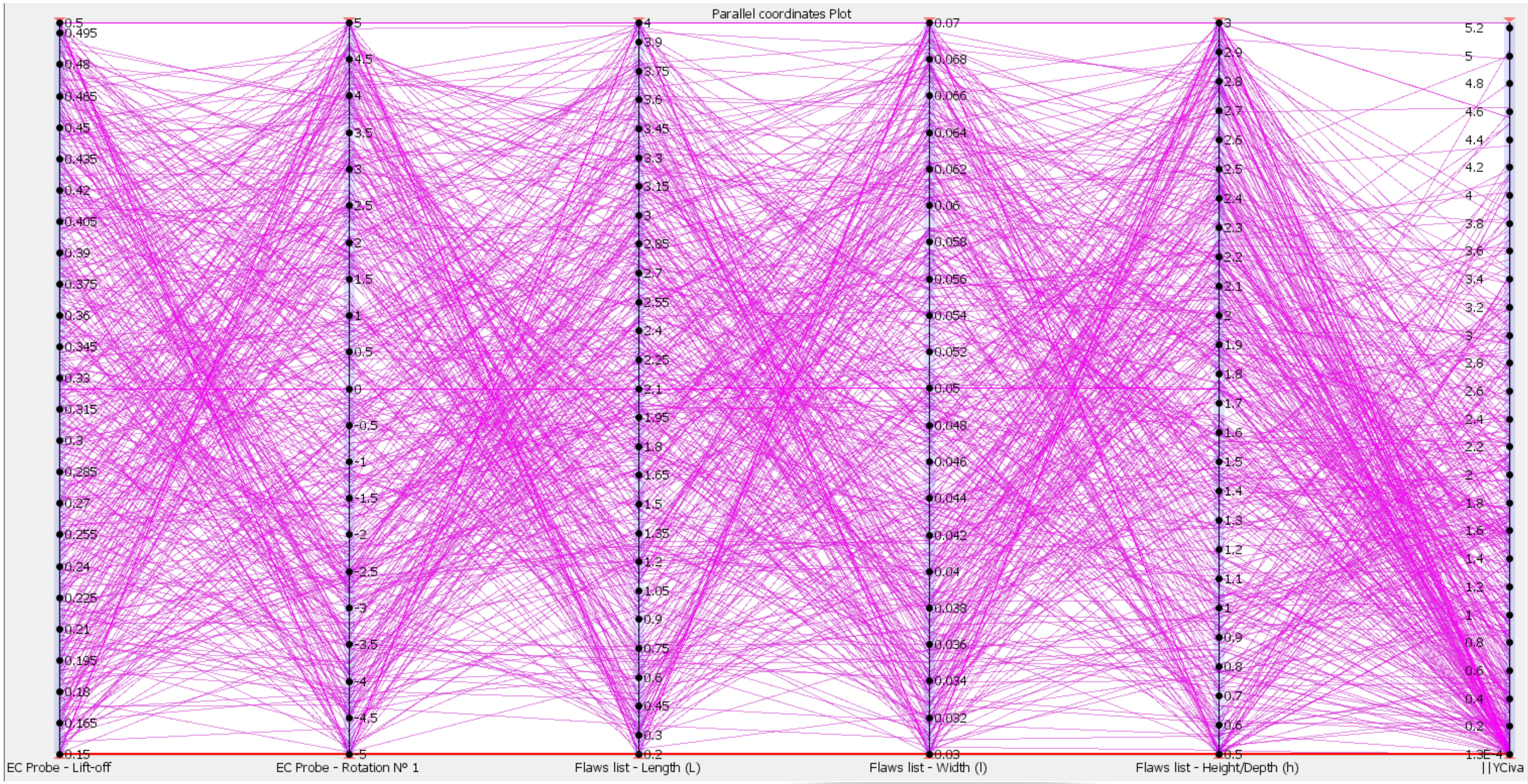
  - 4 main essential variables kept in the design of experiment:
    - Lift-off: [0,15mm; 0,5mm]
    - Sensor orientation: [-5° ; +5°]
    - Defect Height [0,5mm; 3mm]
    - Defect aperture [0,03mm; 0,07mm]

Defect length considered as defect size parameter

Illustrative examples

- Building of the metamodel :
  - Built from a database of 500 CIVA simulations
  - Sobol sampling schemes to fill the space of parameters variation
  - Overview of the DOE and results in a parallel plot

Probe Lift-off | Probe orientation | Flaw length | Flaw width | Flaw height | Signal Amp.

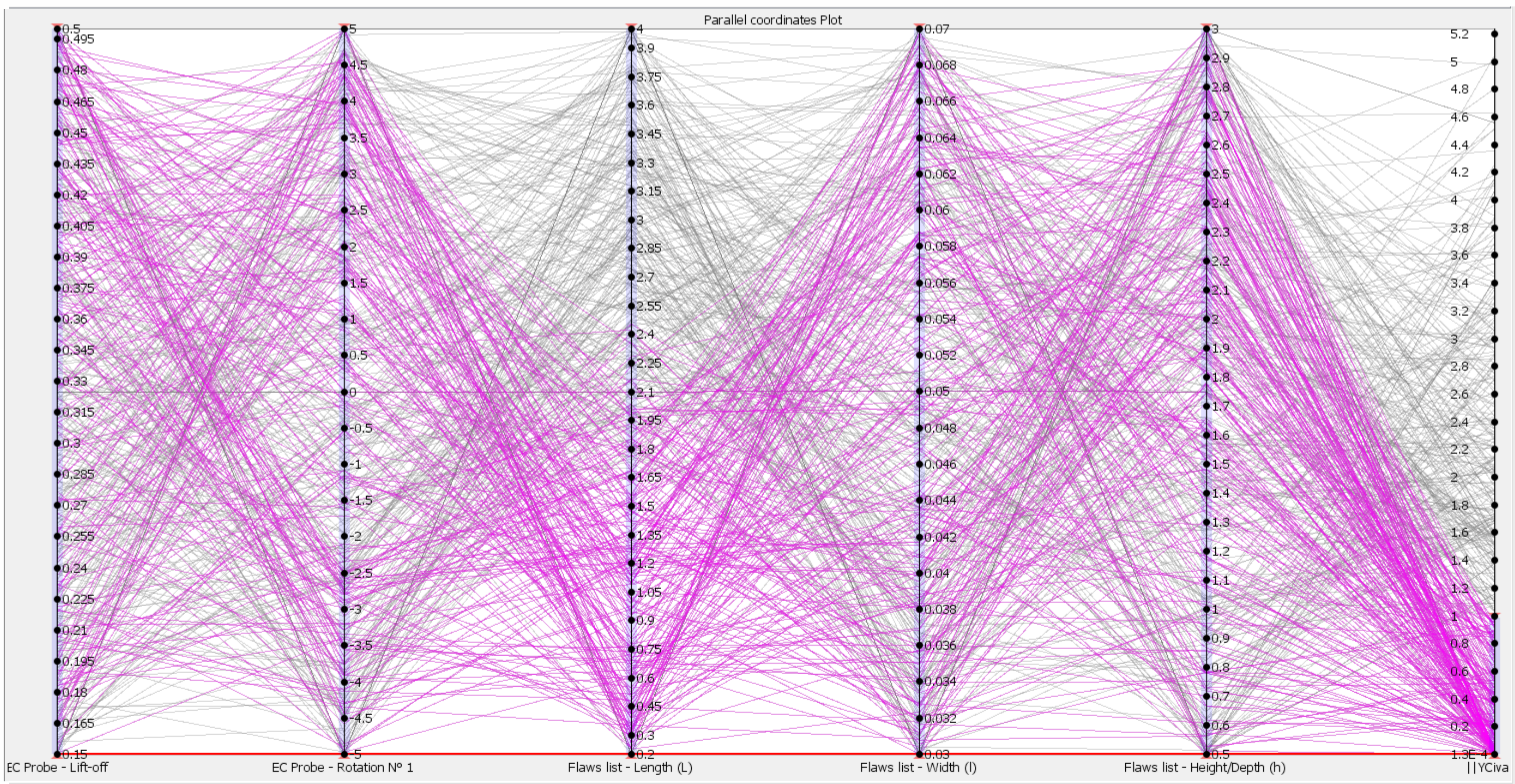


Illustrative examples

- Building of the metamodel :
  - Built from a database of 500 CIVA simulations
  - Sobol sampling schemes to fill the space of parameters variation
  - Overview of the DOE and results in a parallel plot

Selection of worst cases

Probe Lift-off | Probe orientation | Flaw length | Flaw width | Flaw height | Signal Amp.

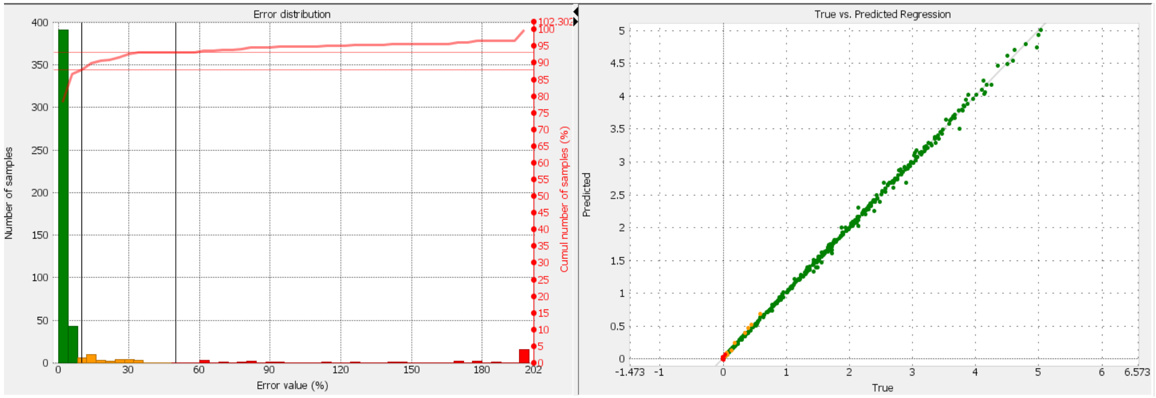


Illustrative examples

Analysis of the metamodel : Validation

Based on Cross validation methodology:

- Division of the physic-based samples database in k folds
- Comparison of metamodel results obtained from k-1 folds with the remaining samples.
- « Error measurement »:
  - Histograms of « errors » between metamodels and samples
  - « True vs predicted » plot

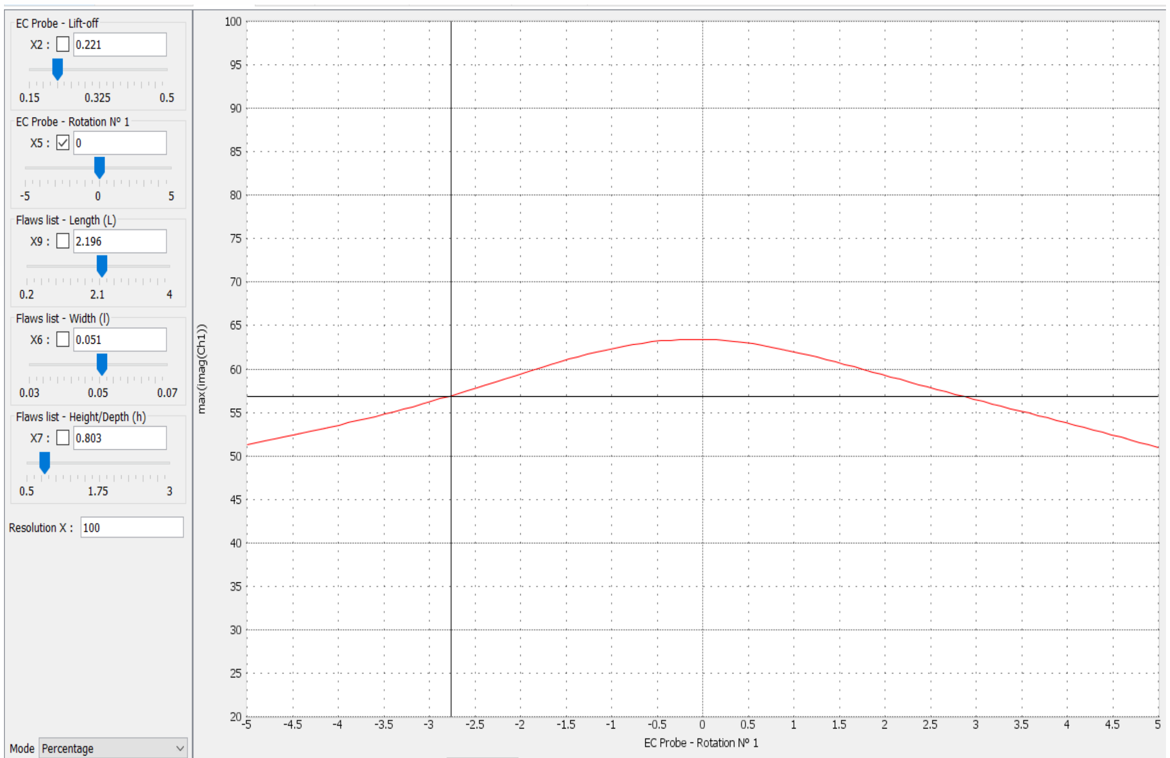


- Several interpolators available to build the metamodel (Kriging, Linear, RBF)

Evaluation of the metamodel "fit" and selection of the best interpolator

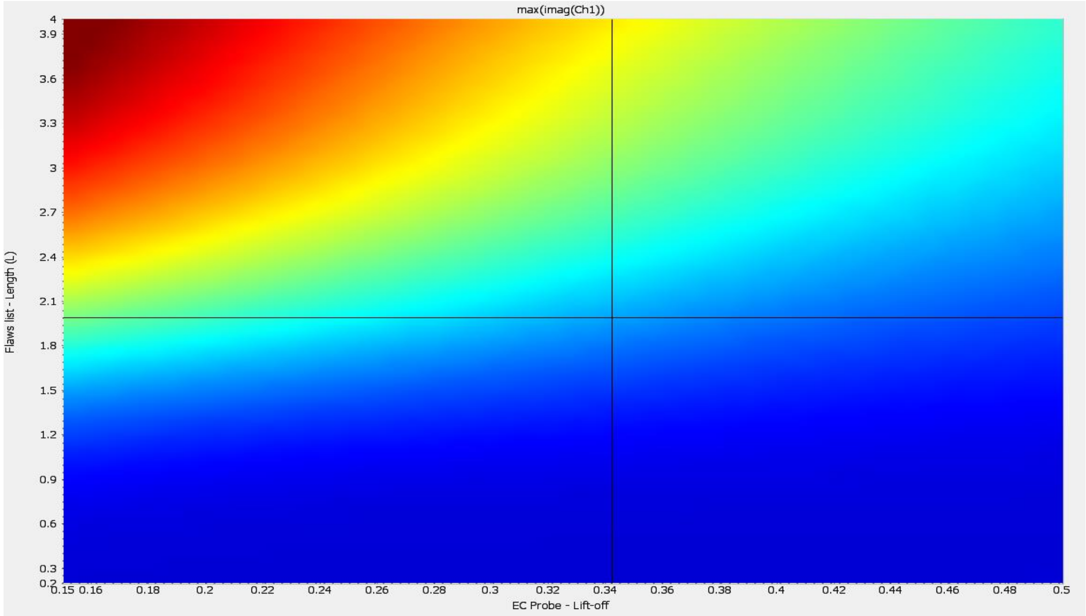
Illustrative examples

- Parametric analysis from metamodel data:
  - Access to 1D or 2D plots built with metamodel data (and not only the 500 results grid)
  - Really fine sampling and exploration of the full range of multi-parameters variation:
    - Impact of sensor orientation (-5° ;+5°) when other parameters fixed to a selected value



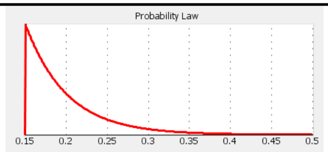
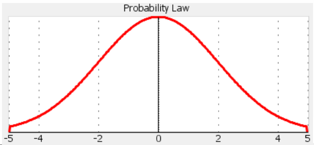
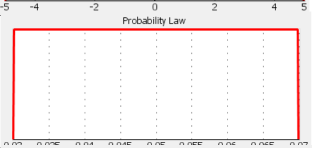
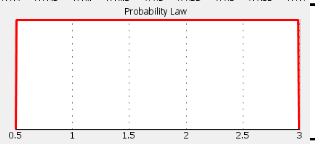
Illustrative examples

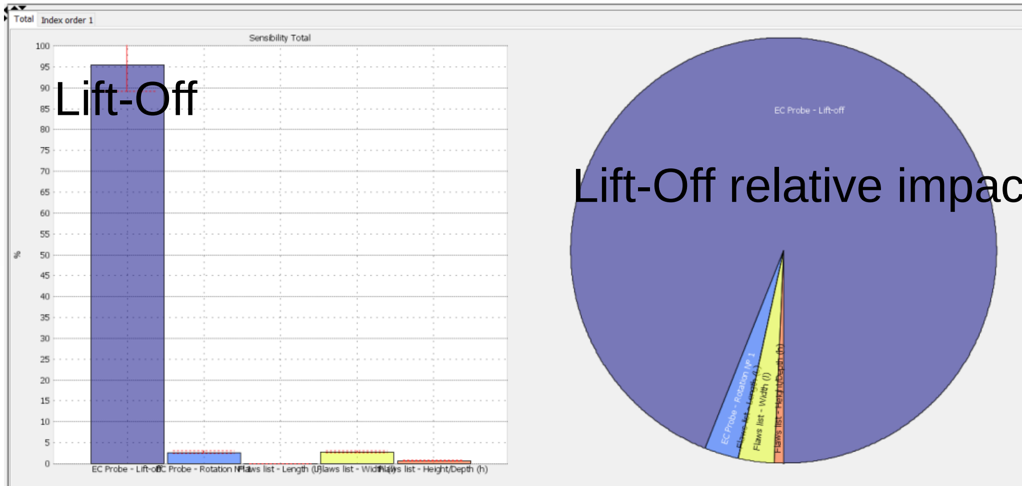
- Parametric analysis from metamodel data:
  - Access to 1D or 2D plots built with metamodel data (and not only the 500 results grid)
  - Really fine sampling and exploration of the full range of multi-parameters variation:
    - Impact of defect length (ordinate) and lift-off (abscissa) on the output signal (color level)



Illustrative examples

- Metamodel makes possible a statistical analysis of the parameters sensitivity:
  - Computation of Sobol Indices (Total Order, 1st order)
  - Obtained from variance decomposition computation
  - User defines assumed statistical distributions for variables
  - Sobol gives the relative influence of each parameters to the output

Lift-off	
Probe Orientation	
Defect Aperture	
Defect Height	
Defect length	Constant at 2 mm

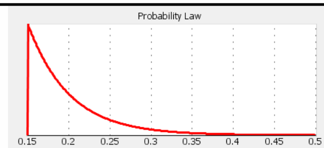
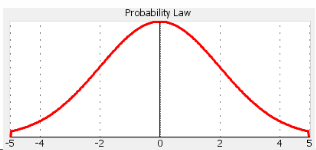
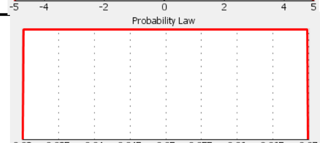
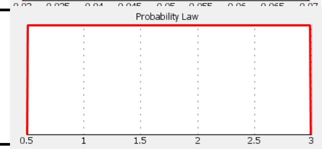


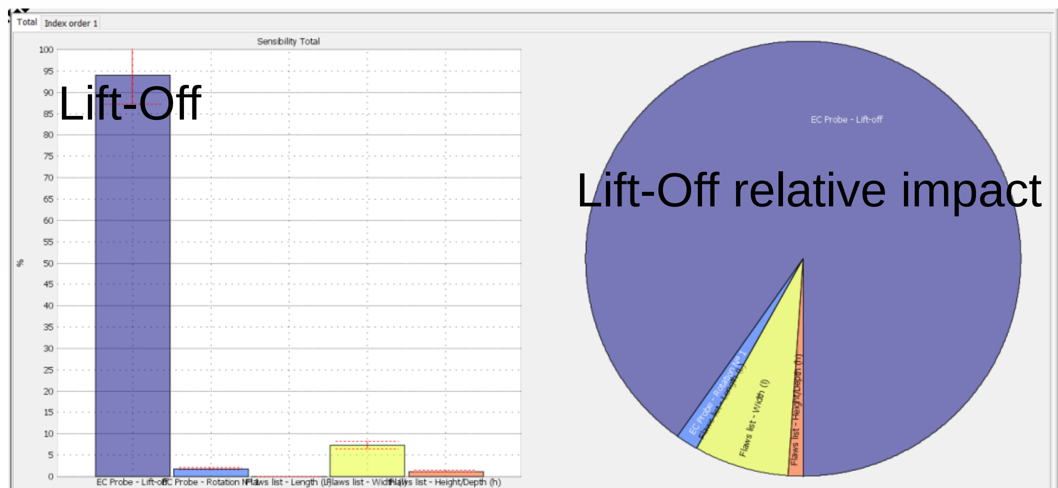
	EC Probe - Lift-off	EC Probe - Rotation N° 1	Flaws list - Length (L)	Flaws list - Width (l)	Flaws list - Height/Depth (h)
Sensibility	95.47	2.65	0.00	2.75	0.70
Value %	93.99 %	2.61 %	0.00 %	2.71 %	0.69 %
Uncertainty	6.416	0.299	0.000	0.297	0.091
Uncertainty %	6.721 %	11.312 %	NaN %	10.784 %	12.859 %

Helps for technical justifications and definition of a relevant Design Of Experiment

Illustrative examples

- Metamodel makes possible a statistical analysis of the parameters sensitivity:
  - Computation of Sobol Indices (Total Order, 1st order)
  - Obtained from variance decomposition computation
  - User defines assumed statistical distributions for variables
  - Sobol gives the relative influence of each parameters to the output

Lift-off	
Probe Orientation	
Defect Aperture	
Defect Height	
Defect length	Constant at 1 mm

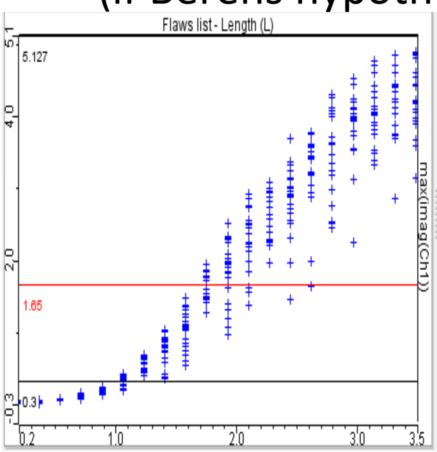


	EC Probe - Lift-off	EC Probe - Rotation N° 1	Flaws list - Length (L)	Flaws list - Width (l)	Flaws list - Height/Depth (h)
Sensibility	93.95	1.77	0.00	7.27	1.18
Value %	90.18 %	1.70 %	0.00 %	6.98 %	1.13 %
Uncertainty	6.903	0.223	0.000	0.871	0.147
Uncertainty %	7.348 %	12.568 %	NaN %	11.972 %	12.458 %

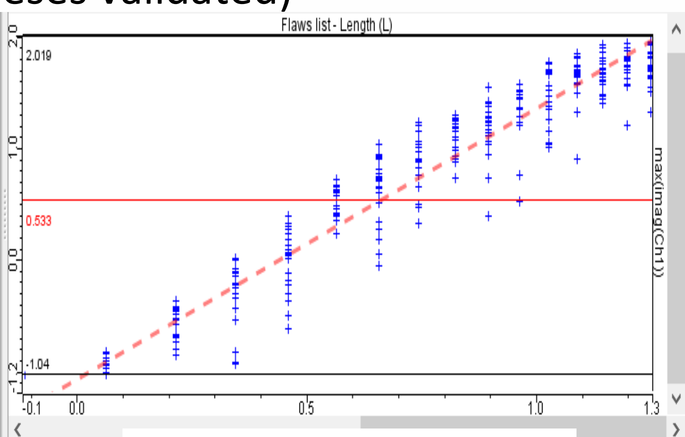
Helps for technical justifications and definition of a relevant Design Of Experiment

Illustrative examples

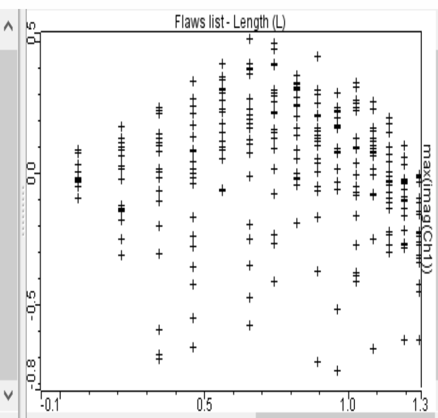
- A POD analysis can be created from the metamodel in a few seconds:
  - Selection of the « characteristic value » (e.g. length) for defect size
  - Selection of assumed statistical distributions for test variables
  - Data sampling definition (# of defect sizes, # of tests) :
    No limits thanks to metamodel
  - Definition of threshold
  - â vs a plot can be used to compute POD curve
    (if Berens hypotheses validated)



Â vs a plot in linear scale



Â vs a plot in log/log scale



Residuals from the linear regression computed by MLE

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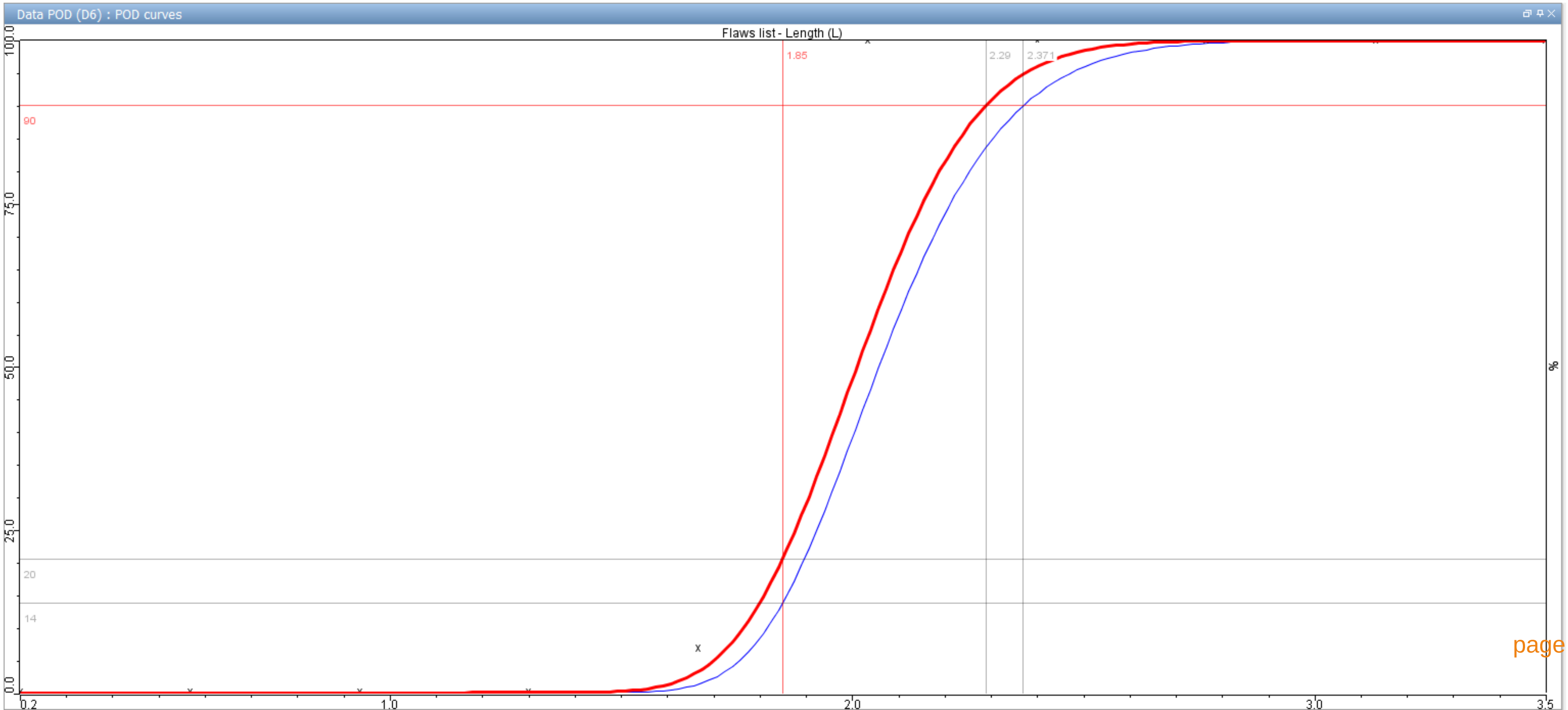
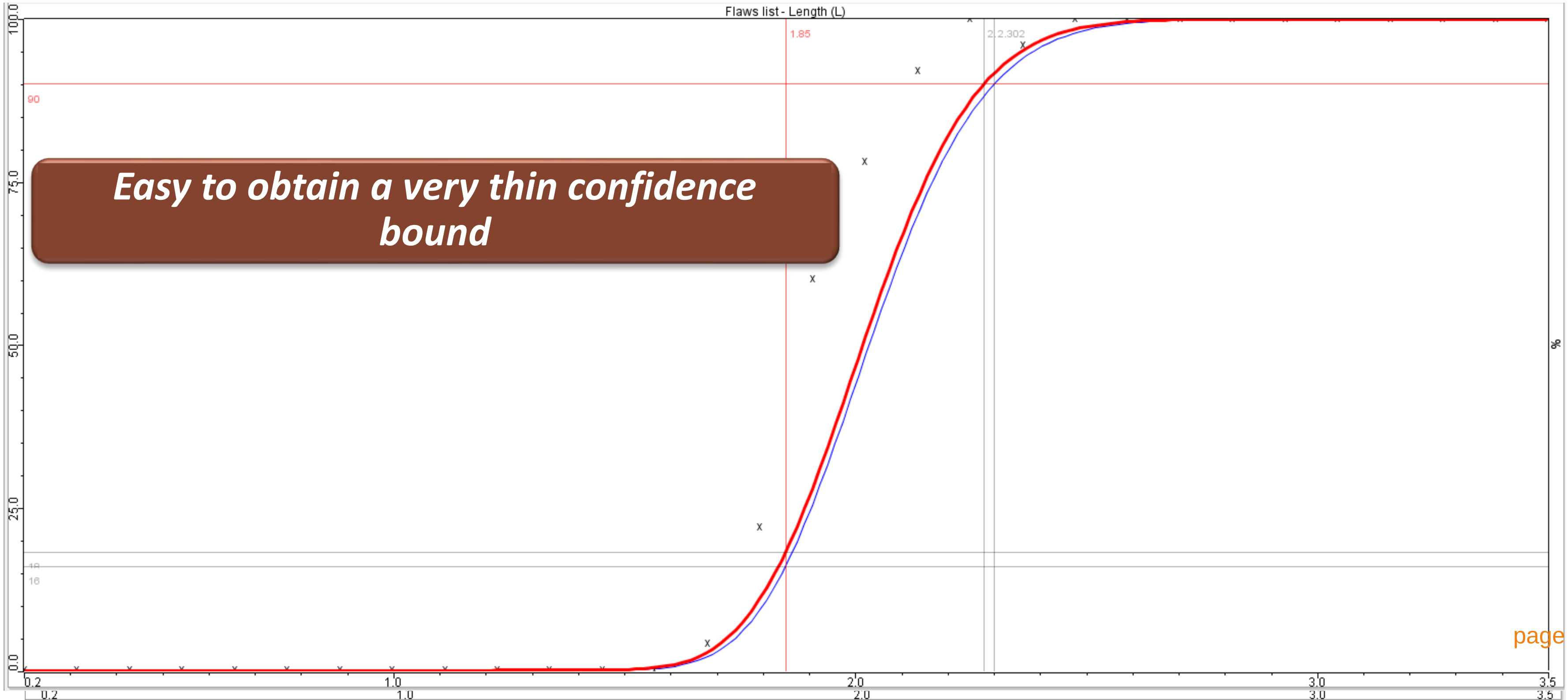
Illustrative examples

- A POD analysis can be created from the metamodel in a few seconds:
  - POD curve obtained with a quite coarse sampling (150 samples with 10 different defect sizes) : a_{90}= 2,29mm ; $a_{90/95}$=2,37mm



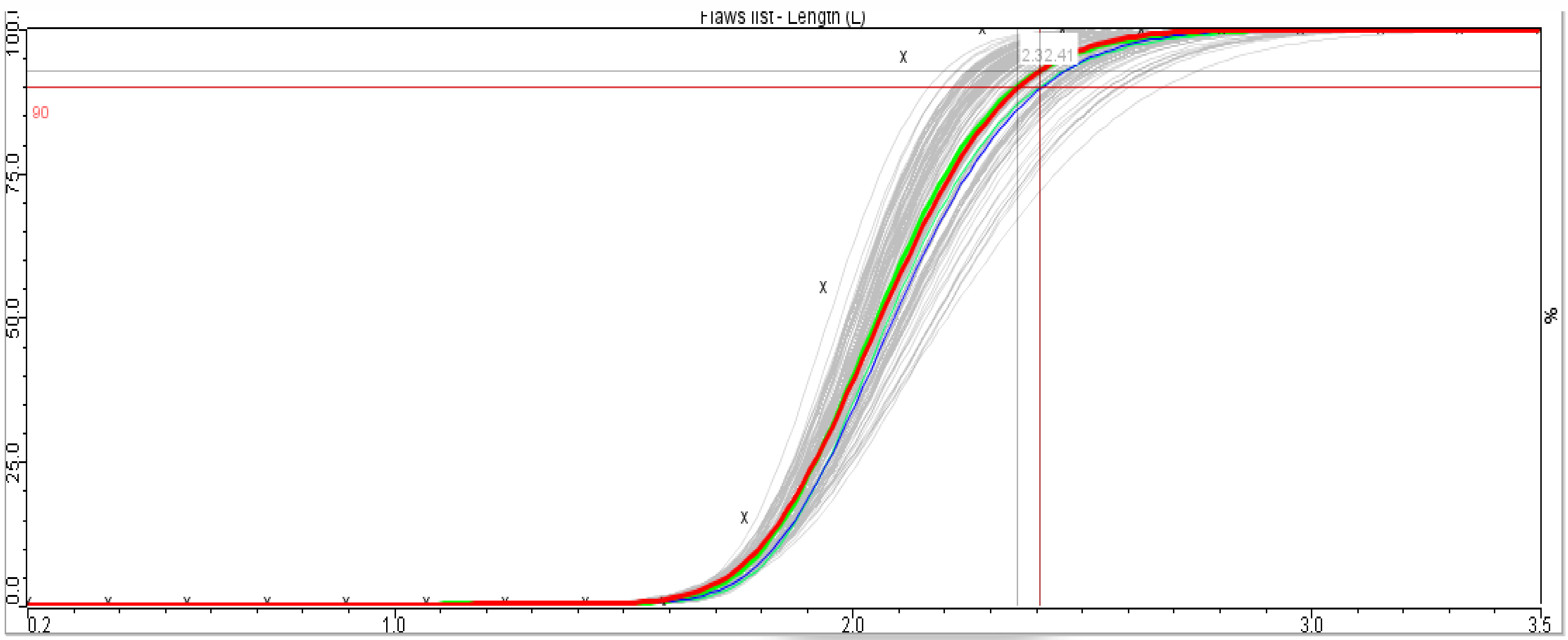
Illustrative examples

- A POD analysis can be created from the metamodel in a few seconds:
  - New POD curve obtained **in a second** with thinner sampling (1500 samples with 30 different defect sizes): a_{90}=2,28mm ;$a_{90/95}$=2,30mm



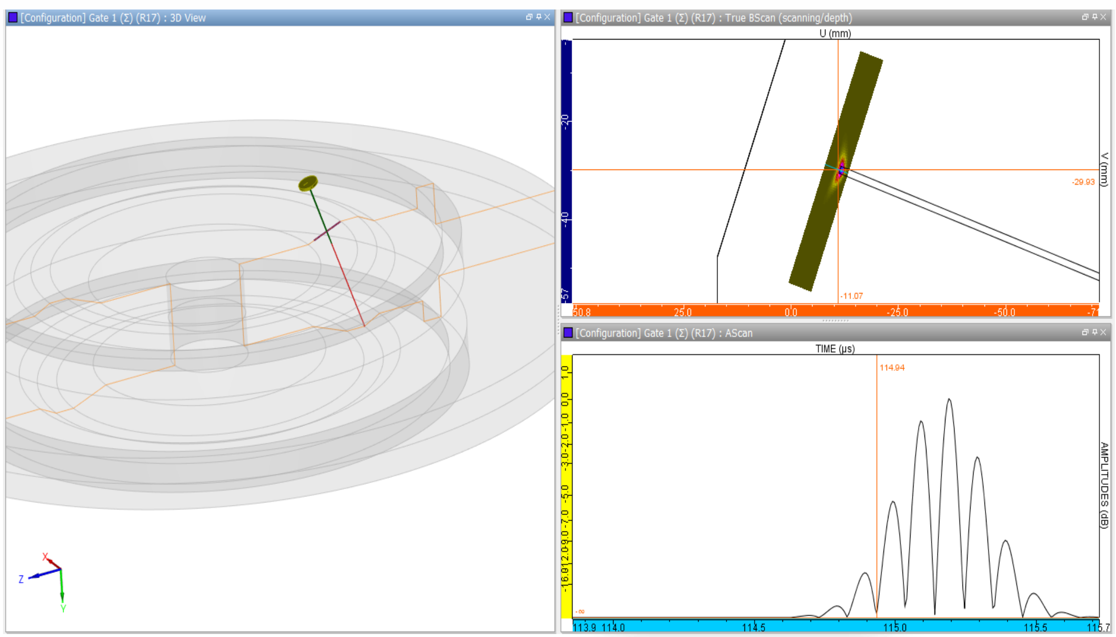
Illustrative examples

- Evaluation of POD curve reliability
  - In MAPOD: Main « error » is not due to a poor sampling but
    to the necessity to define input parameters value and statistical distribution
  - Evaluation of POD curve reliability possible by varying these distributions and assesing the impact. One tool to do this: Array of POD
    - A confidence level is given to statistical distribution parameters of the input variables.
    - Monte-Carlo sampling & generation of a set of POD curves instead of only one
    - Evaluation of the scattering of POD curves obtained



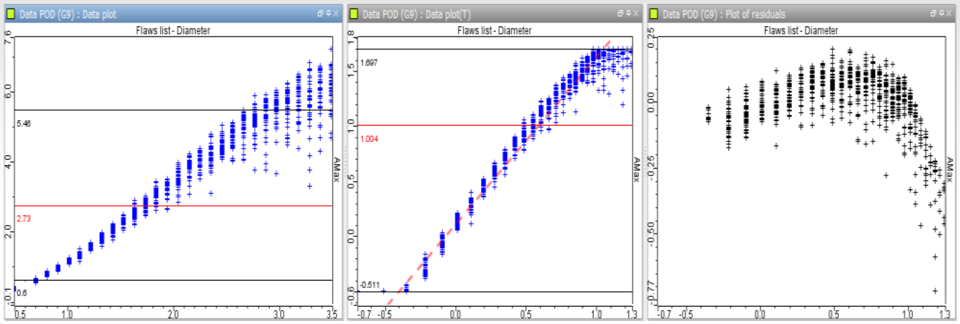
Illustrative examples

- Other examples: Engines Turbine Disk UT inspection
  - Nickel Super alloy disk at the mid-manufactured stage
  - Immersion, 5 MHz, Focused Single Element transducer
  - Flat Bottom Holes defect,
  - 4 main essential variables kept in the design of experiment:
    - Incidence Angle [-3° ; +3°]
    - Water Path [75mm; 85mm]
    - Attenuation level [40dB/mm; 60dB/mm]
    - Defect orientation [-5° ; +5°]



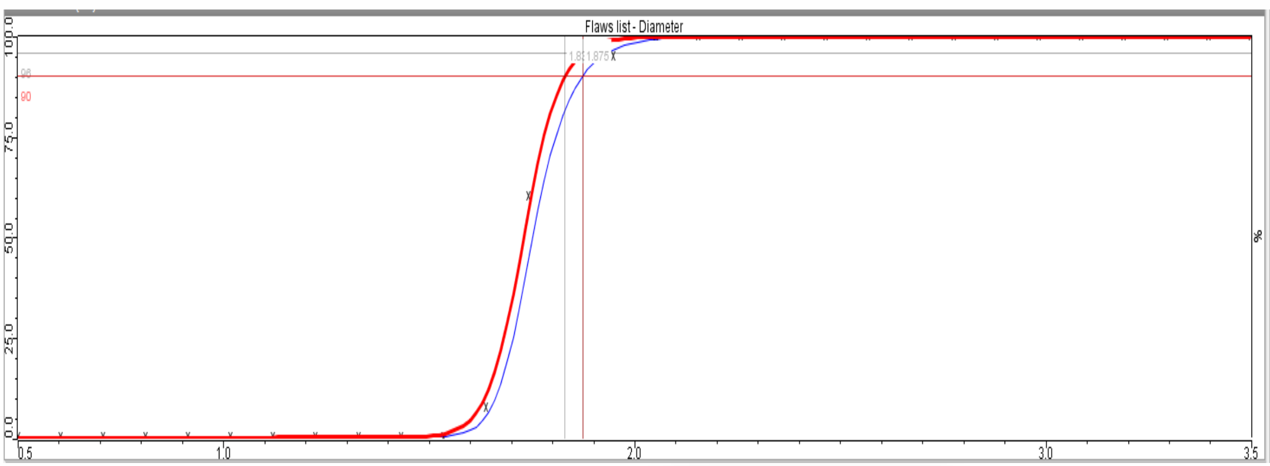
Illustrative examples

- POD analysis obtained from metamodels:
  - Here, Berens hypotheses not fulfilled for a signal response analysis



Statistical tests	
Quadratic residual	87.883E-3
Determination Coeff.	0.967
RMSE R^2	0.109
Normality	
Variance	

  - → Hit/Miss POD Curve: Obtained from 1200 samples with 30 different FBH diameters : a_{90}= 1,83mm ; $a_{90/95}$=1,88mm



Illustrative examples

Non parametric POD curves:

- Parametric models (Hit-Miss, Signal Response) have been created to tackle the difficulty to have enough data to generate POD curves with the binomial approach.

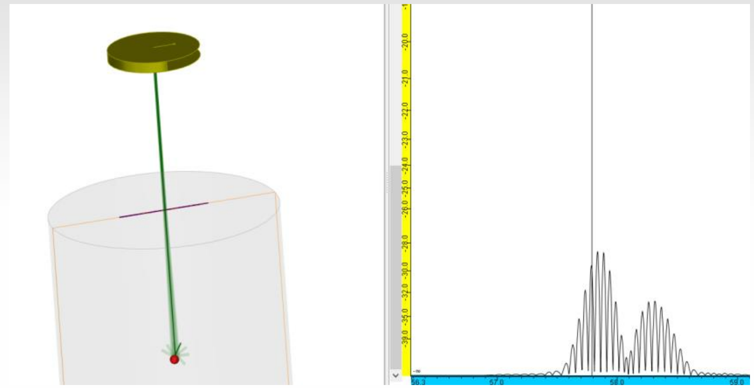
- With MAPOD & especially with metamodels, generate a large amount of data is not any more a real problem.

- Possible to directly plot piecewize POD curves, based on Hit/Miss ratio for each defect size (just requires to select a sampling with a sufficient amount of results for each defect size):
  - Able to describe non monotonic POD curves
  - Can be used to validate (or even replace) a POD curve obtained from with the standard parametric approach

Illustrative examples

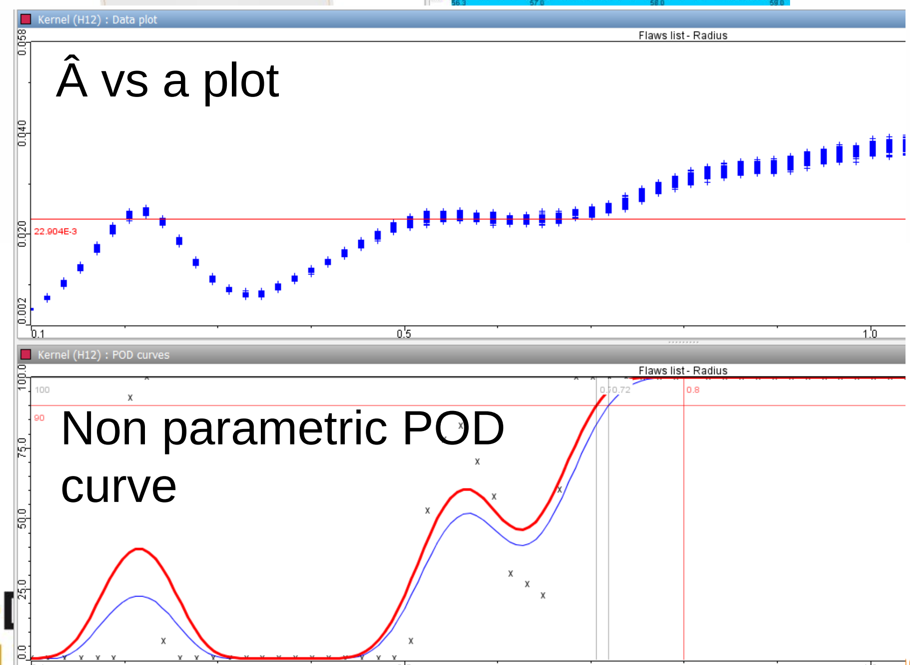
Non parametric POD curves:

- Examples of Titanium billet UT inspection simulation
- Alumina Inclusion



- Resonance phenomena* observed for several defect sizes, non linear â vs a plot
- Example of obtained non parametric POD curve

(80 samples for each defect size)



*Raillon, Schubert, *Simulation Supported POD Methodology and validation for mullti zone Ultrasonic testing procedure, NDT in Aerospace, 2012*

Conclusion

- MAPOD approach to support NDE reliability studies in aerospace: More data, Lower cost.
- General acceptance on the methodology: Recommended practices published by IIW in 2016.
- Validation with physical tests remain necessary at some stages.
- CIVA gives tools to fulfill required main steps of MAPOD method:
  - Versatile & Validated Physic-based models
  - Metamodels to help parameter sensitivity analysis and the definition of relevant Design of Experiment
  - Metamodels to easily generate a large amount of data required to « feed » POD parametric models
  - Embedded POD statistical tools
  - Array of PODs to evaluate POD curves reliability
  - Non parametric POD curves available

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