Using Modeling and Metamodels for Reliability Study in Non-Destructive Evaluation

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Abstract: As in any other measurement process, NDE is subject to variability whose impact can be assessed to guarantee a given level of performance. Once NDE prevents catastrophic failures, deaths and environmental damage, identifying uncertainties and variability in NDE help to design more reliable inspections, therefore is a process that saves lives. This is the goal of a reliability study. Statistical indicators such as Probability of Detection (POD) curves give insights to allow building of mechanical designs with enough « secure margin » for structural integrity and to also define appropriate maintenance & inspection cycles. Simulation is very useful to support performance or reliability demonstrations that require a lot of data (such as POD studies and qualification campaigns), and where simulation can help by reducing the number of necessary mock-ups and experimental trials. In addition to physical models, the NDE simulation software CIVA now offers meta-modelling techniques. Built from an initial set of physical simulations, such surrogate models give the user the possibility to generate a massive amount of data while combining and exploring multi parametric variations. This is particularly efficient in the context of reliability studies, when you have to find the best settings, track the worst-case scenario or build POD curves. This paper illustrates the use of this meta-modelling approach for the reliability study of a longitudinal weld AUT inspection. Real pipe mill inspection data are provided and compared to modelling and meta-modelling results.

Keywords: reliability, Simulation, ultrasound, PoD, MAPOD

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Using modelling and metamodels for reliability studies in NDE

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Outline

- Context / Motivation / Methodology
- Pipeline Longitudinal Weld Inspection and model
- Sensitivity analysis
- POD Analysis
- Conclusion

Context/Motivation/Methodology

- **NDE is subject to variability:**
  Reliability in NDE shall be assessed to guarantee a level of performance to fulfil its role:
  - Source of safety improvement
  - Information for maintenance strategies and mechanical design.

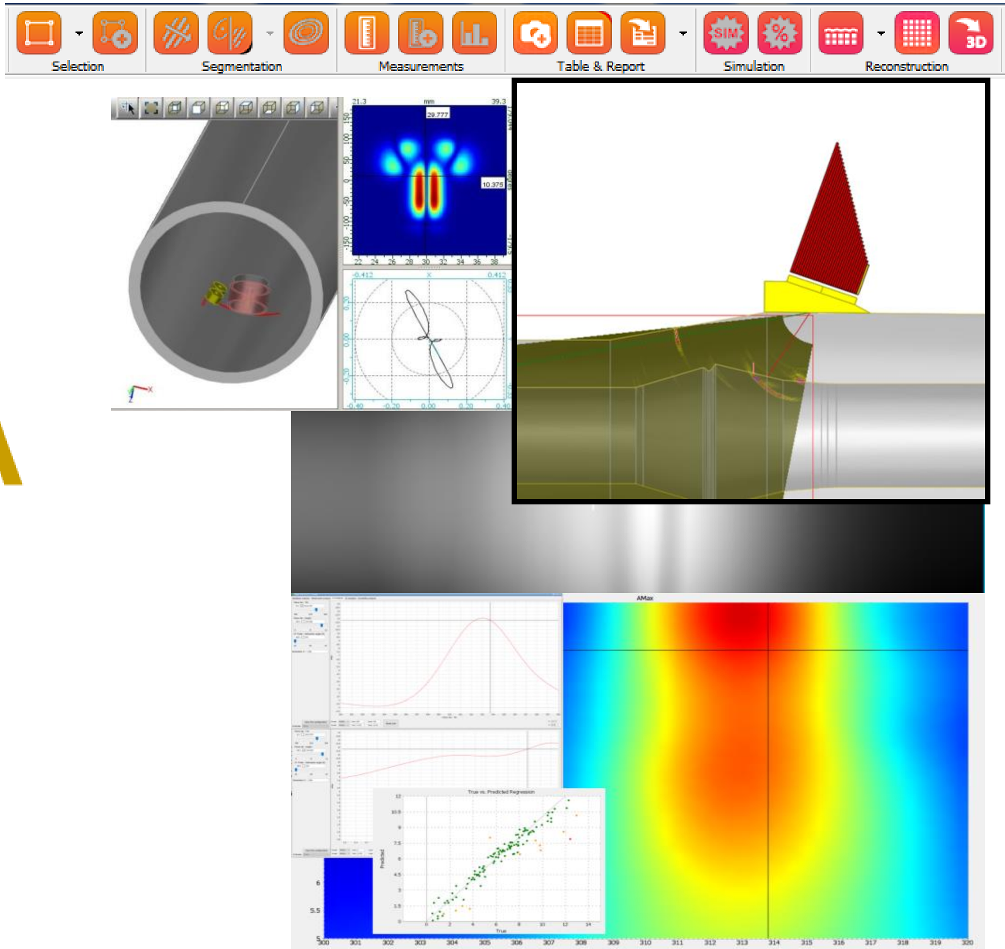
- Performance demonstrations require **extensive parametric studies**:
  - Which are the influential parameters ?
  - What is their impact ?
  - Build statistical indicators such as POD curves (need large enough data sets to provide acceptable confidence levels)

- **Simulation** can help !
  It cannot replace all real tests but are well suited to perform parametric studies at « low cost ».

- Illustrated here with the use of the CIVA Software

Context/Motivation/Methodology

- The CIVA software in a few words:
  - Developed by CEA LIST and distributed worldwide by EXTENDE
  - Multi-technique:
    - Ultrasound Testing
    - Guided Waves Testing and SHM by guided waves
    - Radiography (X & Gamma) – Tomography
    - Eddy Current Testing
    - Thermographic Testing
  - Parametric studies, Sensitivity and POD analysis
  - UT Analysis (of real acquisition data)
  - Data Science
    (to develop machine-learning based detection and classification tools)

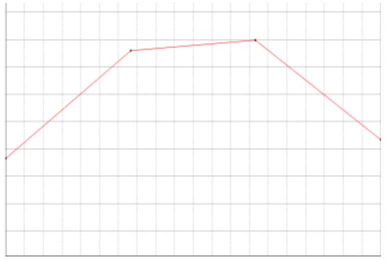


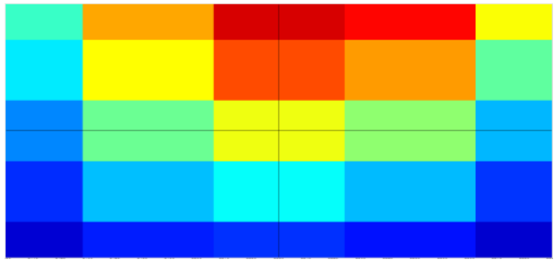
Context/Motivation/Methodology

- CIVA includes metamodelling capabilities.

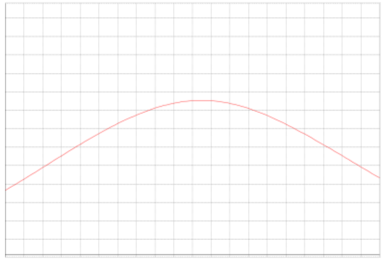
A metamodel provides an « augmented » parametric study:

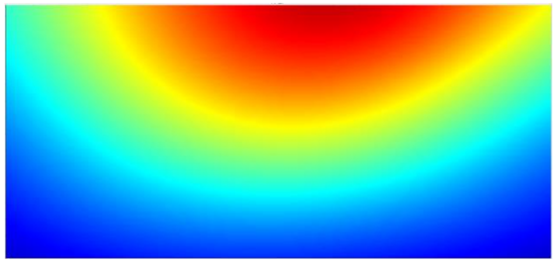
- Based on an initial set of computed cases, the "database" :





- Application of smart interpolation algorithms to build a surrogate model which provides a continuum of results for all parameters combination :

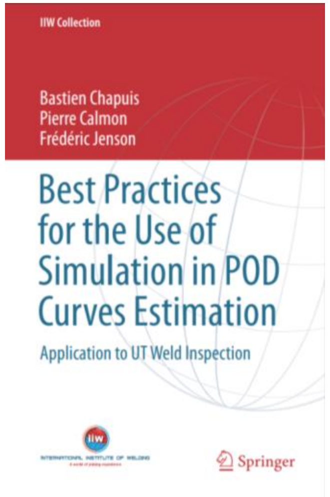


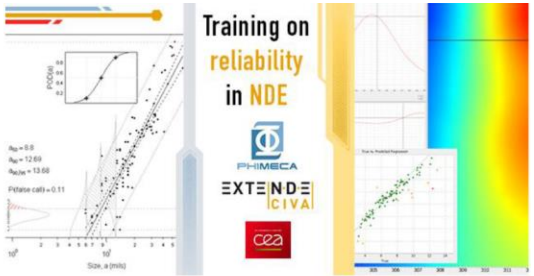


- Particularly useful for performance demonstration studies when you wish to explore multiple scenarios and need for large data sets.

Context/Motivation/Methodology

- A well-mastered methodology is necessary to provide useful reliability studies such as MAPOD (Model Asssisted POD) ones :
    1. To build a relevant nominal model of the inspection case
       (collect relevant input data, adjust model fineness and computation efforts to purpose)
    2. Definition of relevant uncertain influential parameters and their variability (sensitivity analysis)
    3. Uncertainties propagation: Data sampling & computations
    4. POD curve generation and analysis, POD model selection
    5. Evaluation of POD curve reliability : Check hypotheses on influential parameters variability



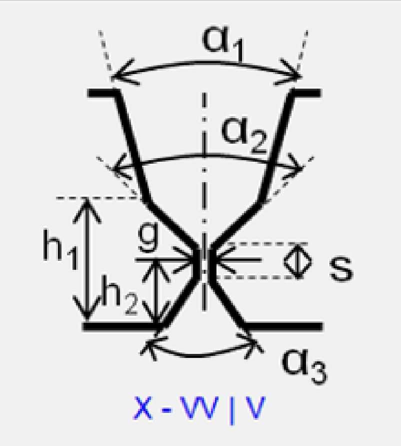


B. Chapuis, P. Calmon and F. Jenson, Best Practices for the Use of Simulation in POD Curves Estimation, IIW Collection, 2018.

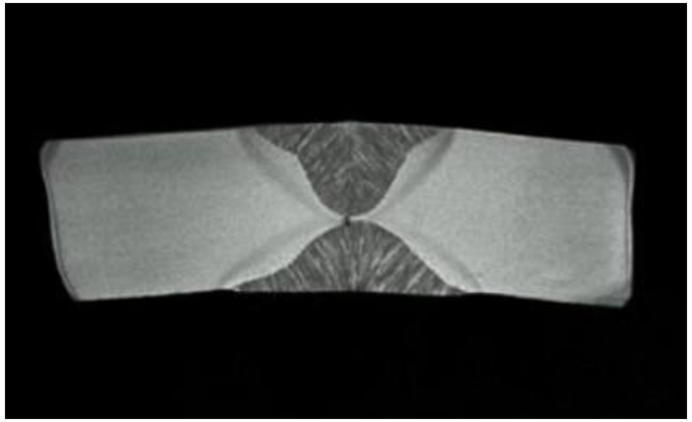
Pipeline Longitudinal Weld Inspection and model

- Illustration case :
  - API 5L X65 pipe with longitudinal weld (X bevel) made by SAW (Submerged Arc Welding)
  - OD: 18’’
  - Wall Thickness 28 mm
  - 99 defects implemented in the test mock-up:

		Sizes of Defects		
Types of Defects	Number of Defects	Heights	Lengths	Depths
Lack Of Fusion	9	0.35-2.10	1.5-12.0	0.5 - 24
Lack Of Penetration	14			
Cracks on HAZ	20			
Transverse cracks Type A	12			
Transverse cracks Type B	24			
Transverse cracks Longitudinal cracks	20			

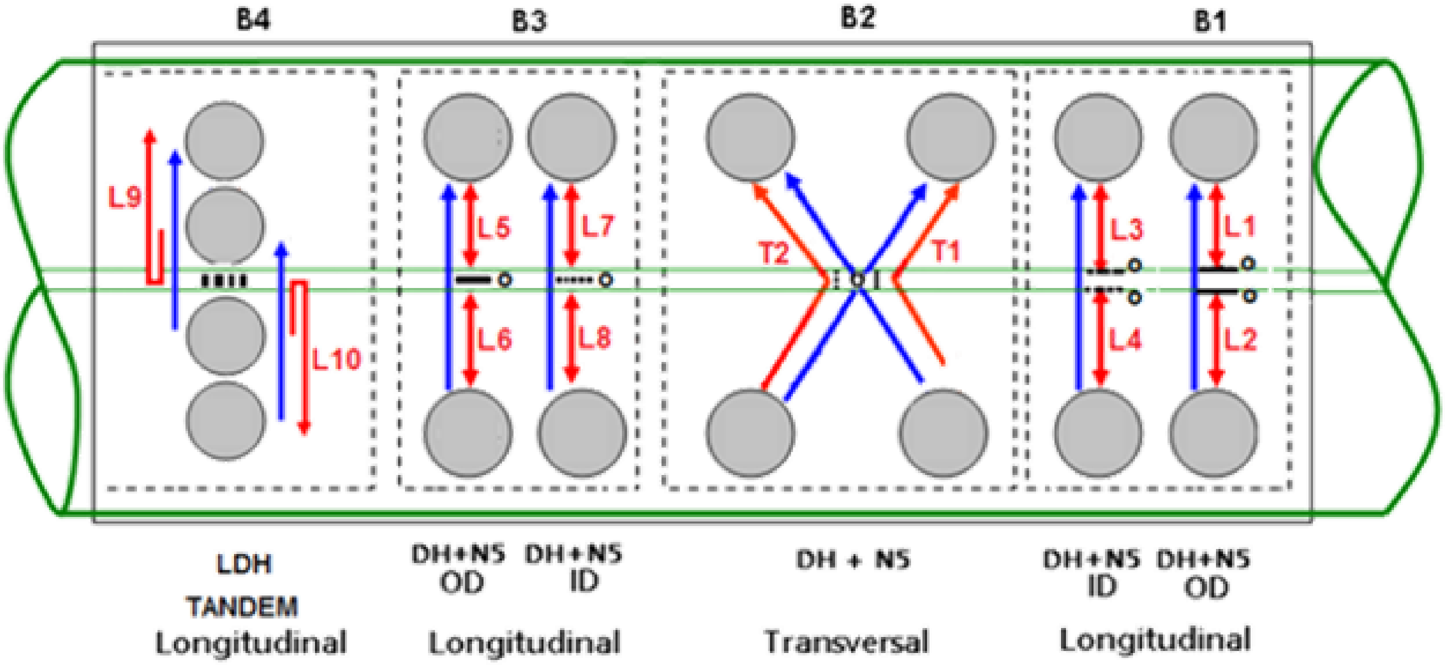


g (gap) = 3mm
s (root face) = 3mm
Angle 1 = 95°
Angle 2 = 78°
Angle 3= 117°
h1 = 22mm
h2 = 11 mm
Weld width on cap ~ 32mm



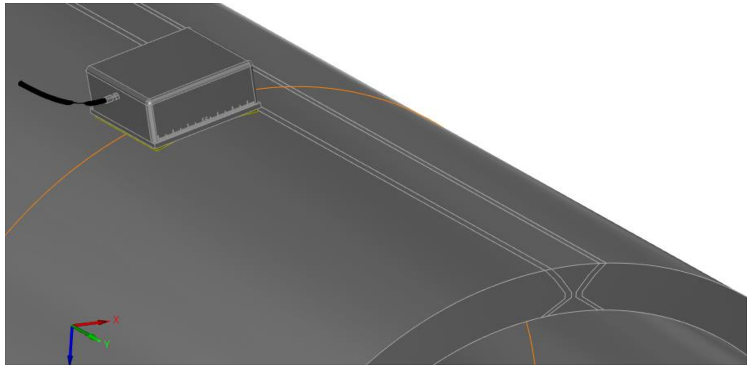
Pipeline Longitudinal Weld Inspection and model

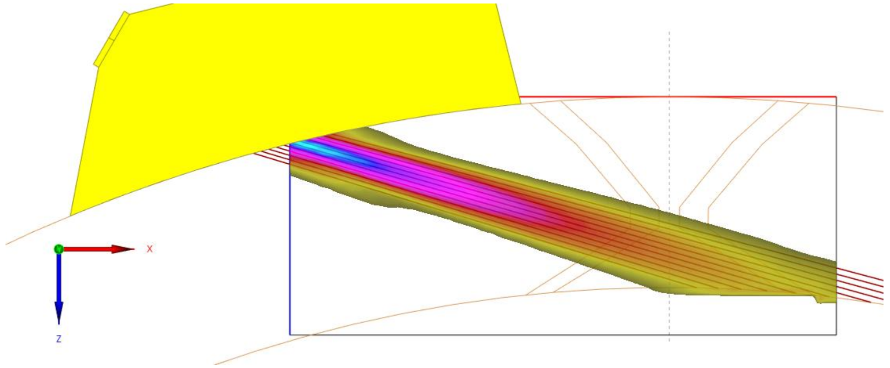
- UT Inspection System:
  - Set of 12 channels using 12 mono-element probes (different angles, different distances to weld centreline)
  - Each channel inspect a certain area of the weld
  - Mechanized scanner allows to inspect the full weld length



Pipeline Longitudinal Weld Inspection and model

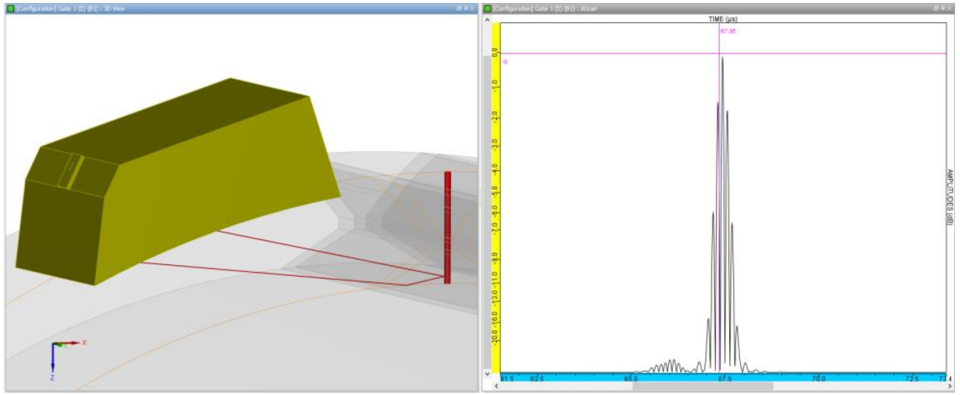
- Building the nominal model in CIVA: Channel L7 (60° Shear Waves) → Weld lower volume area
  - Sound beam simulation to verify (and maybe optimize ?) relevance of channels' parameters :





  - Calibration : <u>To be performed in the model following the same procedure as the experimental process to give meaningful and quantitative results.</u>

    Amplitude normalized versus
    a Through Drilled Hole of 1.6 mm diameter



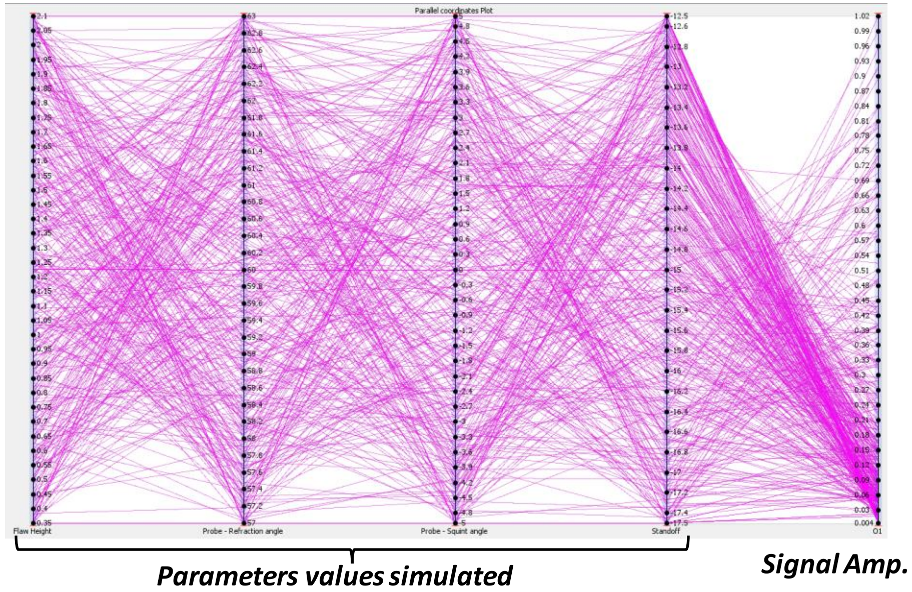
Sensitivity Analysis

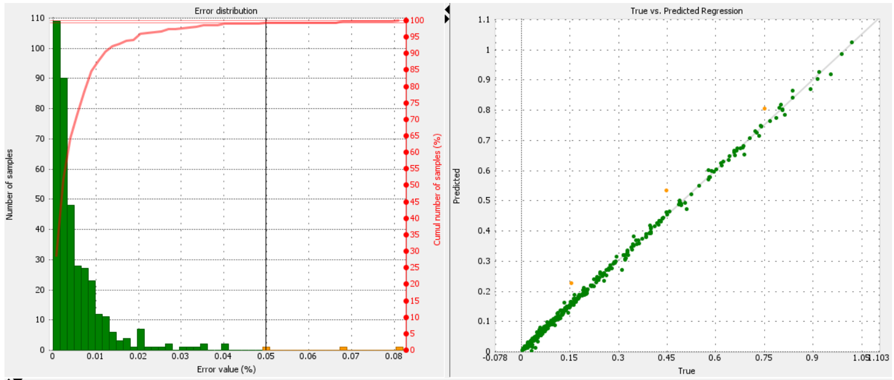
- Target flaw : Longitudinal planar defect in the weld area covered by channel L7
- Criterion : Signal maximum amplitude
- First, a quite long list of potentially influential parameters is established:
  - Defect parameters: Height, Length, Position in the weld (axial and ligament), orientations (3 angles)
  - Specimen parameters: Wall thickness, Outer Diameter, Shear Waves velocity
  - Inspection parameters: Probe position « Stand Off », Refraction angle, Squint angle
- Multi-parametric studies are performed rather than single variations in order **to account for interactions between parameters**
- First stage : Evaluate the most influential ones through 3 multi-parametric Designs Of Experiments (DOE) and try to reduce the list for the final analysis and avoid prohibitive DOE.

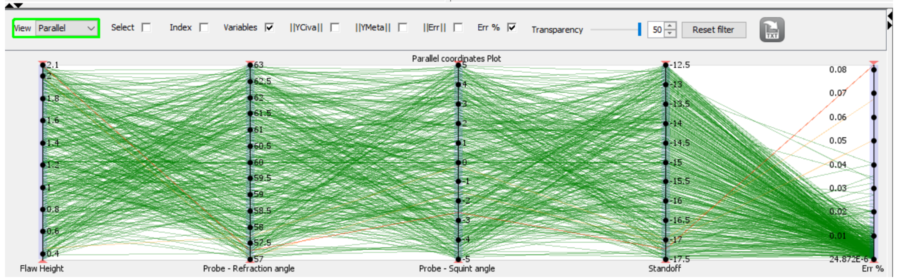
Sensitivity Analysis

- Parametric study example with 4 parameters: 400 Simulations
  - Flaw height: from 0.35 mm to 2.1mm,
  - Probe refraction angle: from 57° to 63°,
  - Probe squint angle: from -5° to +5°,
  - Probe standoff: from 50mm to 70 mm from the weld centreline.
- Metamodel can be generated from this simulated database to oversample the data and access to any parameters combination
- Metamodel « error » shall be assessed :
  - Cross validation technique
  - « True » vs predicted diagrams

Good fitting for this metamodel



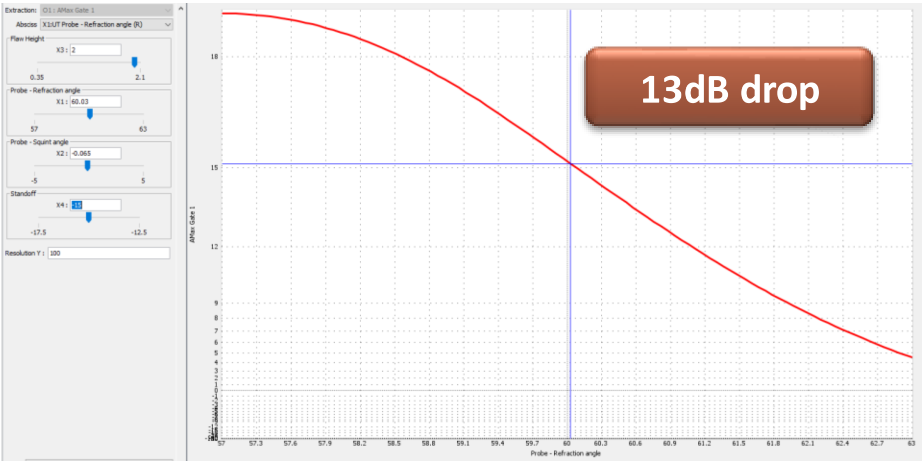




Sensitivity Analysis : Use the metamodel

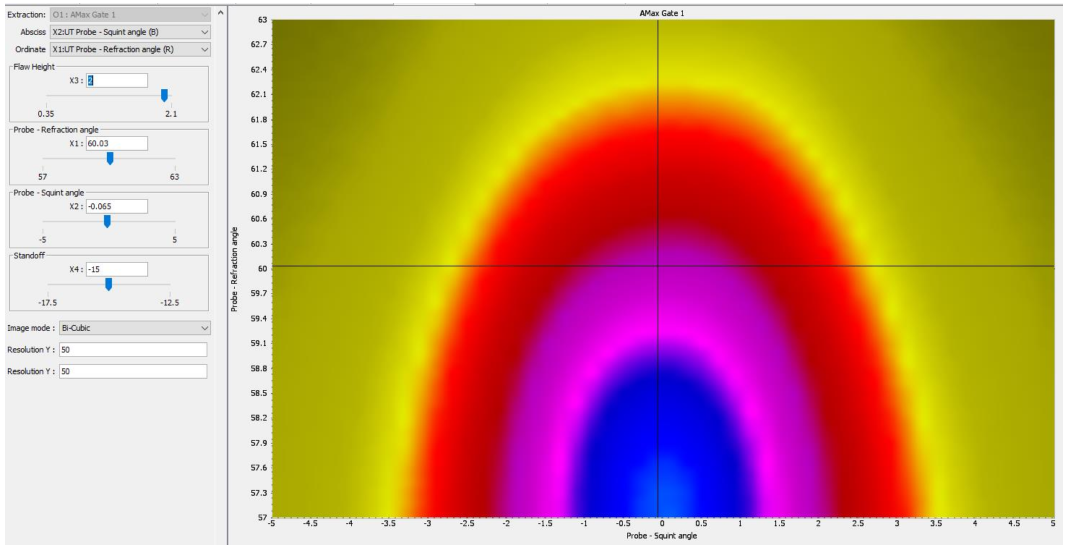
You can explore any combination of parameters' values

- Impact of one parameter on signal amplitude

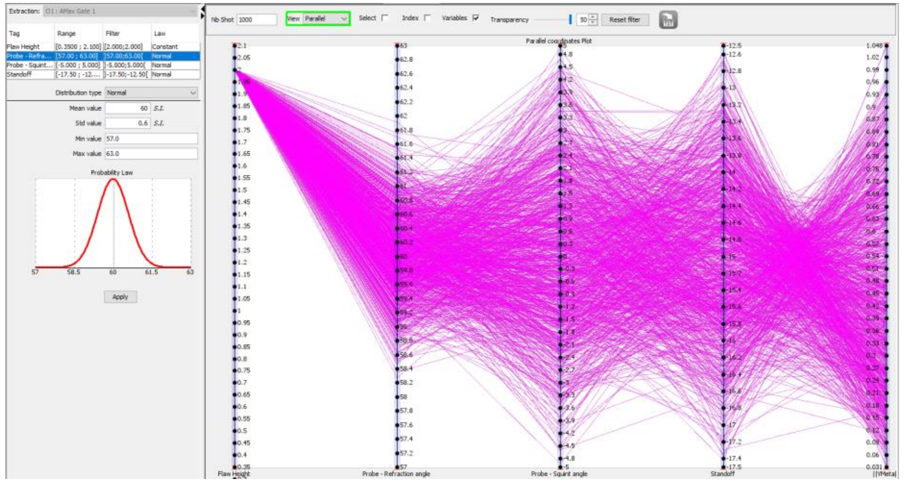


Refraction angle variation from 57° to 63° for a flaw height of 2mm, probe squint of -2° and probe standoff of 60mm.

- Impact of two parameters on signal amplitude



Refraction angle variation from 57° to 63° and squint angle variation from - 5° to +5° for a flaw height of 2mm, and probe standoff of 60mm.

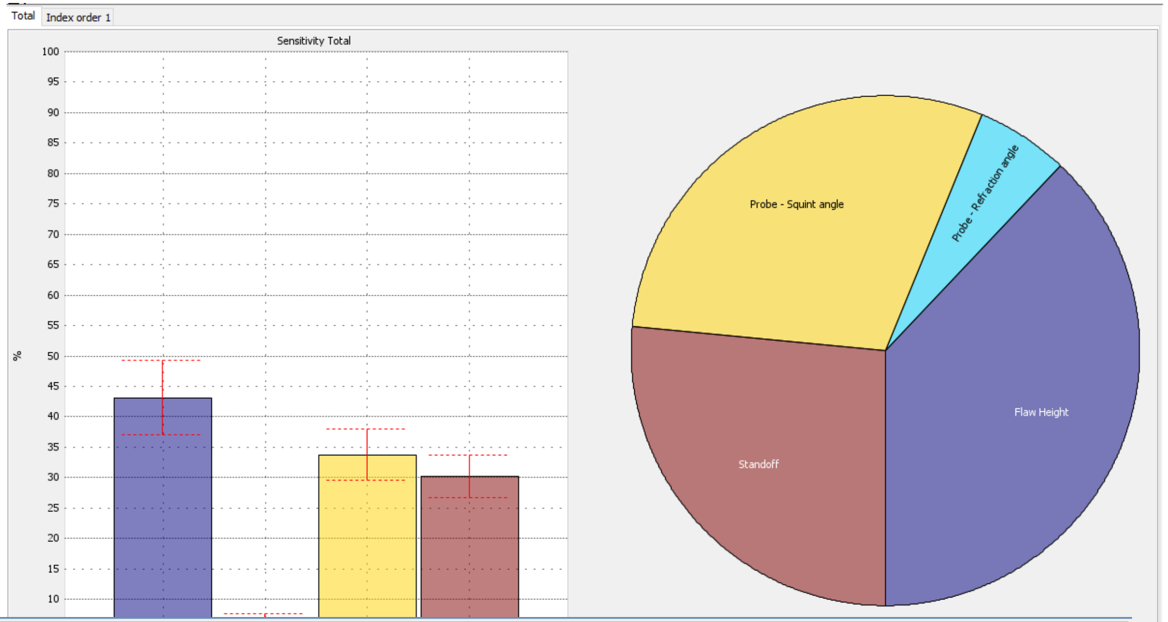


- Parallel plot : Track worst and best cases
Impact of the 4 parameters on signal amplitude for N trials (here 1000) assuming different probability of occurrences (here a constant flaw height of 2mm and normal (gaussian) laws for the 3 other parameters).

From sensitivity analysis to POD Analysis

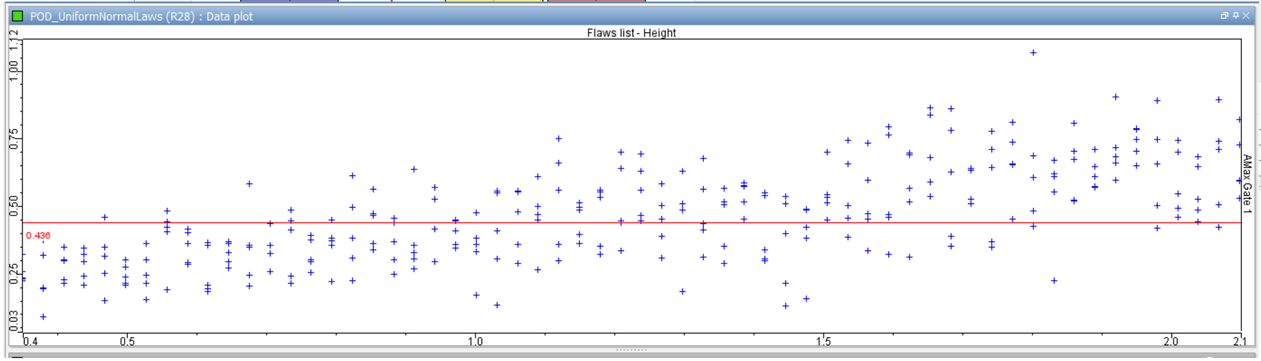
- Metamodels also give access to Sobol indices ranking the influential parameters:

Example: Refraction angle less influential
than squint angle, flaw height and standoff
for the defined probability of occurrences



- A final metamodel is built with the 6 most influential parameters:
  - Flaw height
  - Flaw axial position and ligament
  - Probe squint
  - Refraction angle
  - Probe standoff

- Samples are extracted from the metamodel to build the « POD » dataset :
  - Signal amplitude vs flaw size, assuming variability (uncertainties) on other parameters



POD Analysis

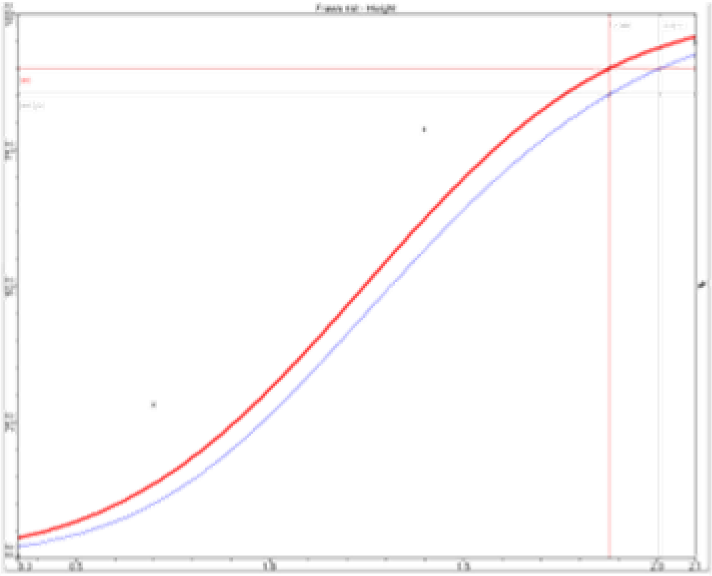
- Case 1: Comparison between simulated POD et experimental POD :

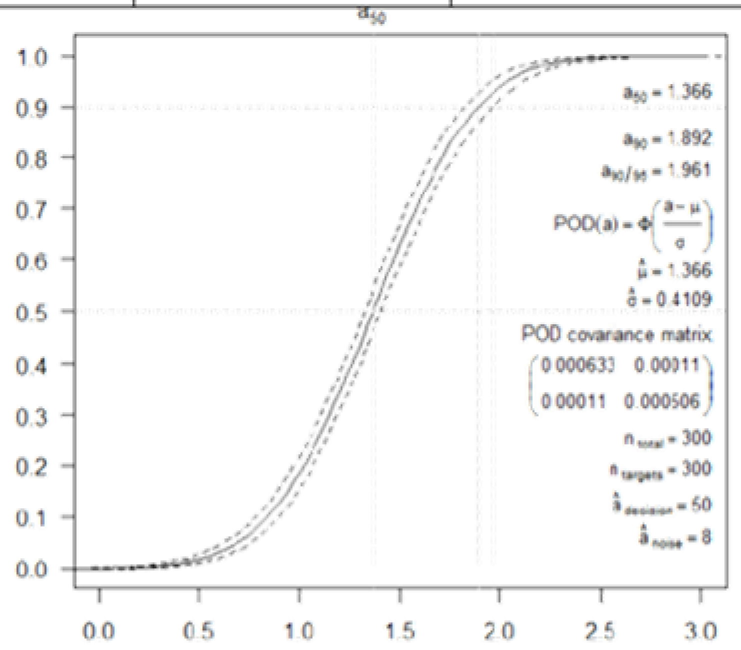
Hypotheses: Signal Response POD curve

- 4 defect sizes (0.35 mm to 2.1mm) and 300 total points
 (Similar for experimental data and model)
- Assumed variability for uncertain parameters:
  - Standoff : $\mathcal{N}(60\text{mm}, std\ 2\text{mm})$
  - Refraction angle: $\mathcal{N}(60°, std\ 0.6°)$
  - Squint angle: $\mathcal{N}(0°, std\ 1°)$
  - Flaw axial position: Uniform law [-10mm; + 10mm]
  - Flaw ligament: Uniform law [0.5mm;1.5mm]

Good agreement

Type of Data	POD indicators		
	a50 (mm)	a90 (mm)	a90/95 (mm)
Simulated data (300 points with 4 defect sizes)	1.248	1.88	2.011
Experimental data (300 points with 4 defect sizes	1.366	1.892	1.961





- But only 4 different flaw sizes and 3 in the rising part of the POD curve: **Quite poor POD curve accuracy**

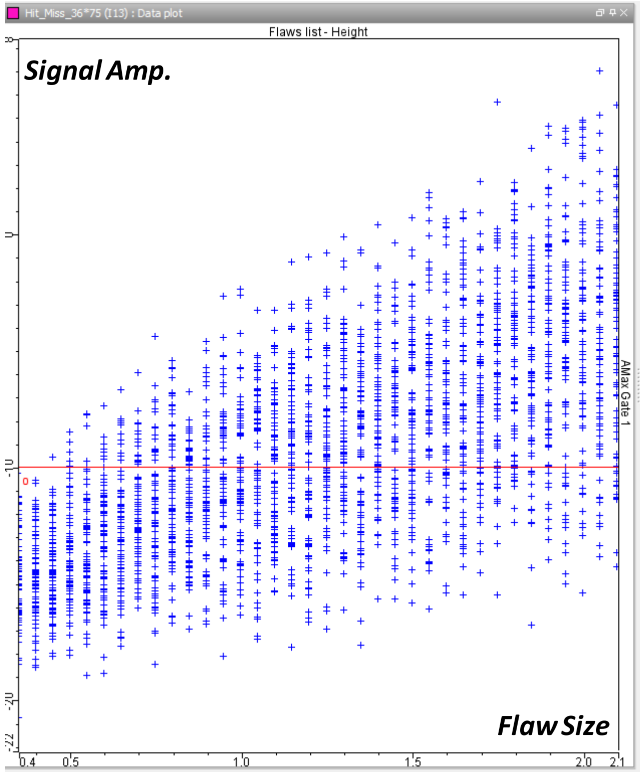
POD Analysis

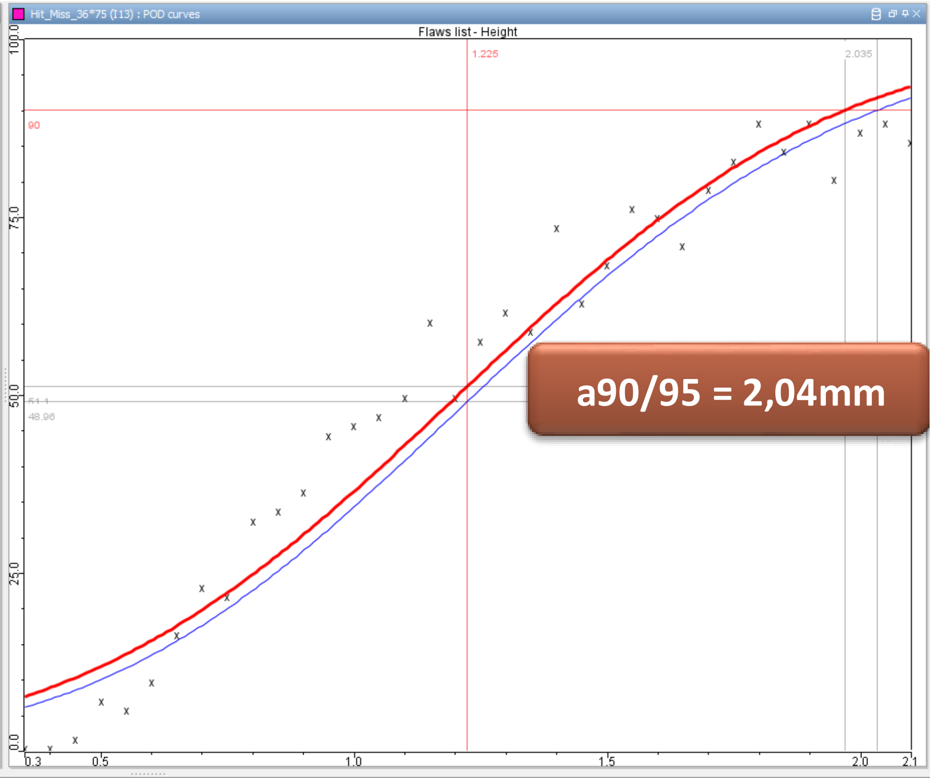
New results in real time : Don't need new simulations !

- Case 2: Larger data set generated with the metamodels :
  - New samples obtained without needing new simulations
  - 36 flaw sizes
  - 75 tests per flaw size
    → data set of 2700 points
  - Same density functions assumed for uncertain parameters

- Hit/Miss POD curve as Signal Response hypotheses are not fulfilled any more
  (data variance around the linear regression is not constant for all flaw sizes)

- a90/95 pretty close to the previous one but much better confidence in the results





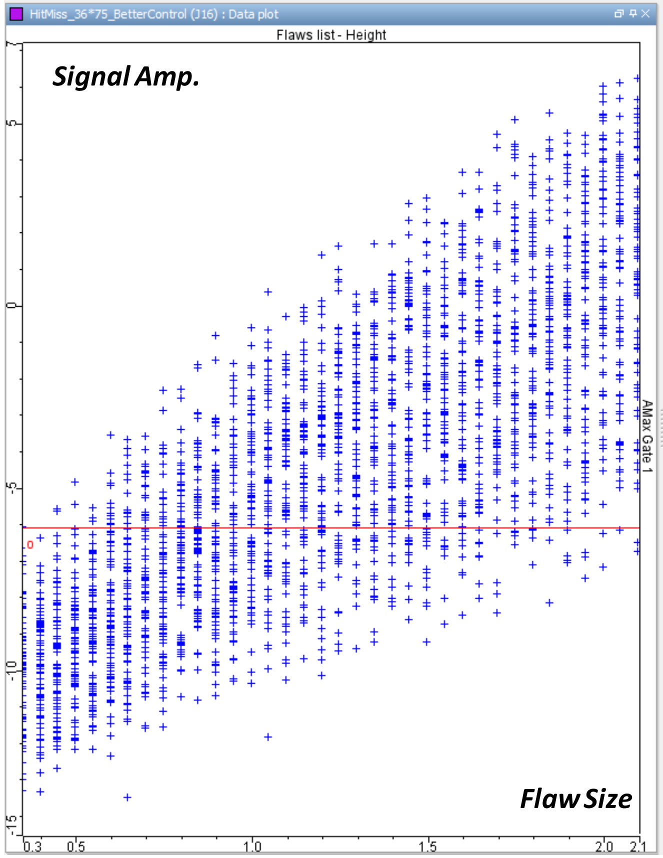
POD Analysis

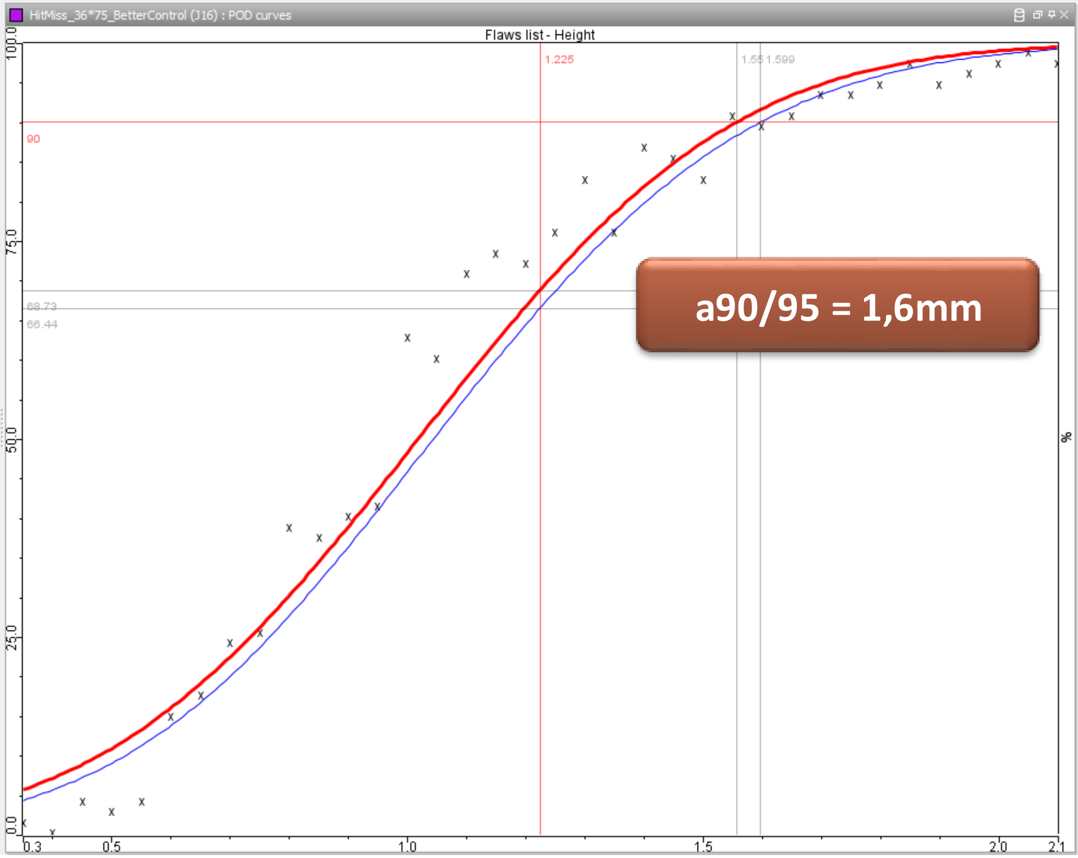
New results in real time : Don't need new simulations !

- New « inspection scenario »: Optimized →Standard deviation divided by 2 for inspection parameters

Hypotheses: Hit/Miss POD curve

- 36 defect sizes
- 75 tests per flaw size
- Assumed variability for uncertain parameters:
    - Standoff : $\mathcal{N}(60mm, std\ 1mm)$
    - Refraction angle: $\mathcal{N}(60°, std\ 0.3°)$
    - Squint angle: $\mathcal{N}(0°, std\ 0.5°)$
    - Flaw axial position: Uniform law [-10mm; + 10mm]
    - Flaw ligament: Uniform law [0.5mm;1.5mm]





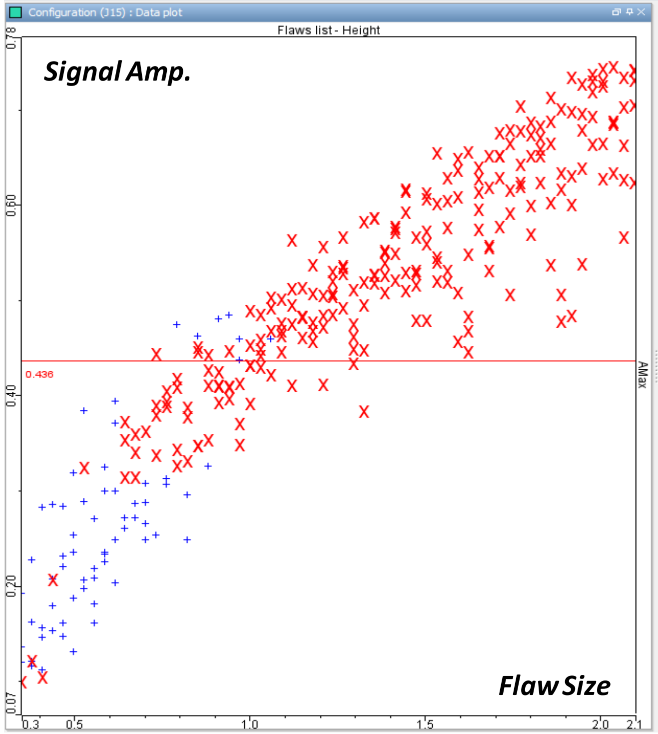
POD Analysis

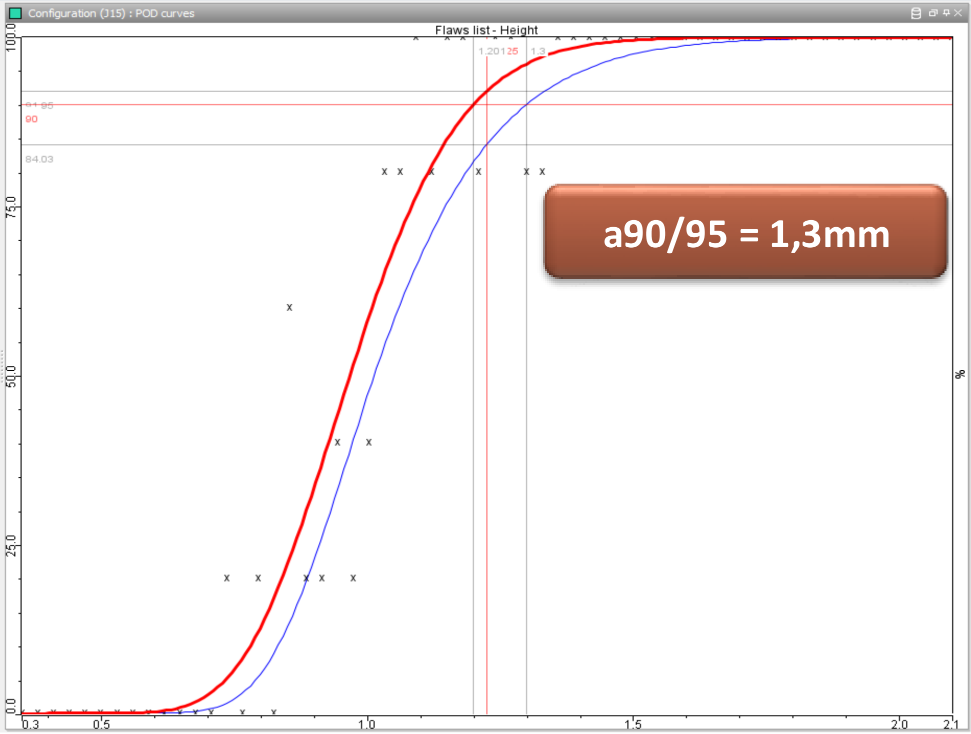
- Case 4 : New analysis accounting for « adjacent channels » :

- Multi-channels system:
  One channel might detect a flaw better than the dedicated one

- Example : L7 data augmented with L3 ones
- Same hypotheses as for case 2
- Red crosses show defects of the L7 zone better detected by L3 channel

A lot of L3 hits ! Not a sign of a well-suited and optimized inspection system but it improves the POD (lower a90/95) !





CONCLUSION

- Reliability studies shall show that NDE meets its requirements … which is useful !
- Sensitivity and POD studies require large data sets to explore the impact of influential parameters
- Often difficult to generate enough relevant data with a pure experimental approach
- Simulation can help ! Even more if metamodels are available to increase sampling and to analyse multiple scenarios without running new simulations each time !
- This presentation has illustrated the POD study of a pipe longitudinal weld inspection with multichannels UT system
- Simulated POD could be compared to experimental one with a good agreement
- Different scenarios could be investigated

THANK YOU FOR YOUR ATTENTION

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