A POD approach by simulation of an industrial ultrasonic inspection

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Abstract: The reliability of non-destructive testing is a real industrial issue. To address this need, indicators based on the probability of detection (POD) have been developed [1, 2]. They allow to define the detection performance of a NDT inspection technique by considering the variability of influencing parameters. The interest is to provide a statistical indicator to qualify the operating mode for given structure (geometry, material) and inspection technique.

The aim of this work is to evaluate the relevance of this approach in an industrial context and to identify the necessary resources (human, financial, material, etc.). The realization of POD studies can be carried out either experimentally, numerically, or by combining both. The experimental approach requires a significant number of models with calibrated defects of different dimensions, which is difficult to implement and expensive. The studies performed in this project are based on numerical simulations obtained with the CIVA software. It allows to investigate the variability of many parameters and to classify them according to their influence on the final NDT result. The disadvantage of the latter lies in the lesser consideration of the operator's gestures and human factor.

The mechanical structure of interest is a butt-welded assembly with a lack-of-fusion defect perfectly oriented along the "V" bevel. Two ultrasonic inspection techniques are studied: one using a single-element probe and the other using a phased array transducer. All steps leading to the POD curves are implemented. A metamodel-based approach is used to vary several parameter combinations in real time. The most influential parameters on the test results are determined using Sobol indices. Finally, this approach allows to evaluate many test scenarios using the associated POD curves.

[1] A. Berens, NDE reliability data analysis, 17, 689-701, 1989.
[2] MIL-HDBK-1823A – NDE system reliability assessment, US Dept of Defense, 2009.

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ECNDT 2023, Lisbon

Introduction

Context

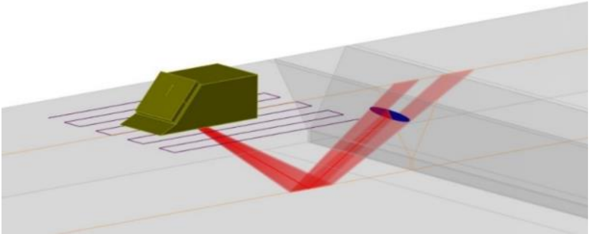
- Reliability required for Non Destructive Testing (NDT)
- Uncertainties during the inspection:
    - Characteristics of the inspected structure (geometry, mechanical parameters, etc.)
    - Defect
    - Probes
    - Performance of the inspection, human factors, etc.
- Need to use statistical indicators such as probability of detection (POD) [1-3]

[1] A. Berens, NDE reliability data analysis, Nondestructive Evaluation and Quality Control, 17, 689-701, 1989.
[2] MIL-HDBK-1823A – Nondestructive evaluation system reliability assessment, US Dept. of Defense, 2009.
[3] B. Chapuis, P. Calmon and F. Jenson, Best Practices for the Use of Simulation in POD Curves Estimation, IIW Collection, 2018.

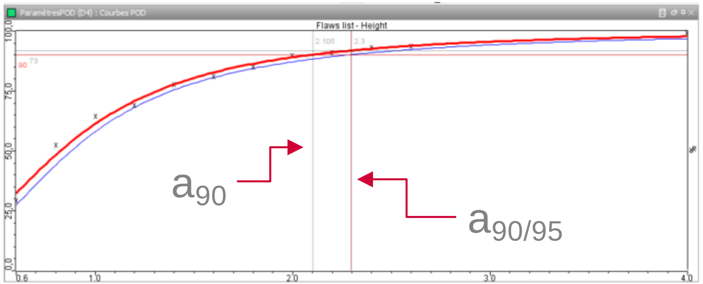
Introduction

Probability of detection (POD)

- POD curves are a statistical indicator that can be used to estimate the maximum size of a defect that may not be detected by NDT.
- The scope of the study must be considered
    - One NDE technique
    - One component (material)
    - One type of defect
    - One test procedure



- The result is a POD curve as a function of the size of the defect (more generally the characteristic variable) giving two indicators:
    - POD is greater than 90% (a_{90})
    - POD with a confidence interval ($a_{90/95}$)



Introduction

POD Study

- Several approaches possible

Experimental

- Advantages
  - Consideration of human factors
- Disadvantages
  - Difficulty of implementation
  - Cost

Numerical simulation

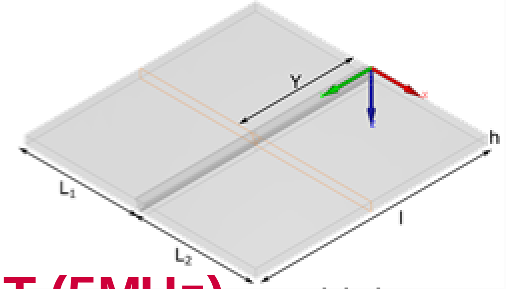
- Advantages
  - Generation of high volumes of data
  - Sensitivity analysis
- Disadvantages
  - Less consideration of human factors

Combination of the two approaches

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

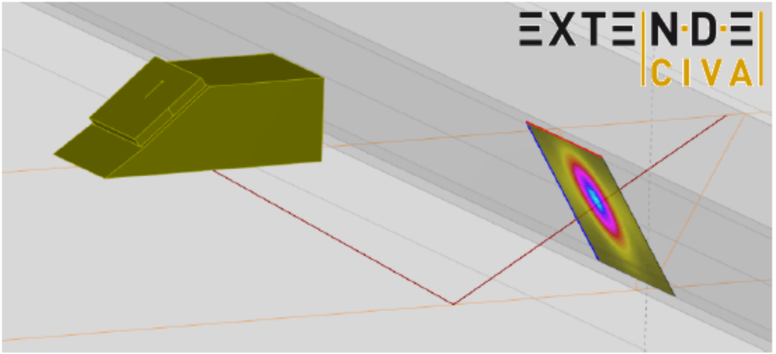
Presentation of the case study

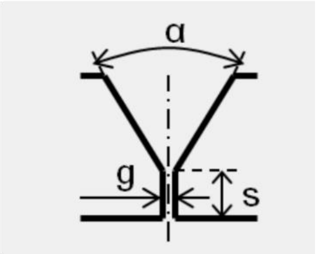
Butt-weld with V-bevel



Thickness
$h = 15\ mm$

Conventional UT (4MHz)



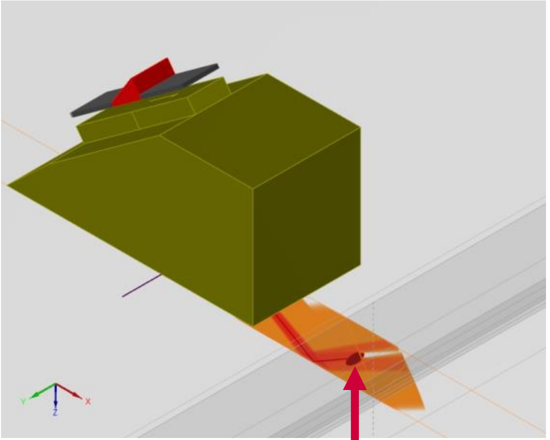


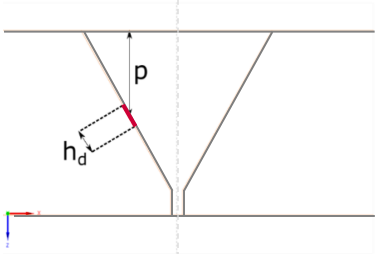
Angle: $\alpha = 60°$

Gap: $g = 1\ mm$

Stub: $s = 2\ mm$

Phased array UT (5MHz)





Lack of fusion

Presentation of the approach

MAPOD Study (« Model Assisted POD ») - 5 steps

1) Definition and verification of the nominal configuration

2) Choice of influencing parameters and preliminary studies

3) Parametric studies

4) Sensitivity analysis

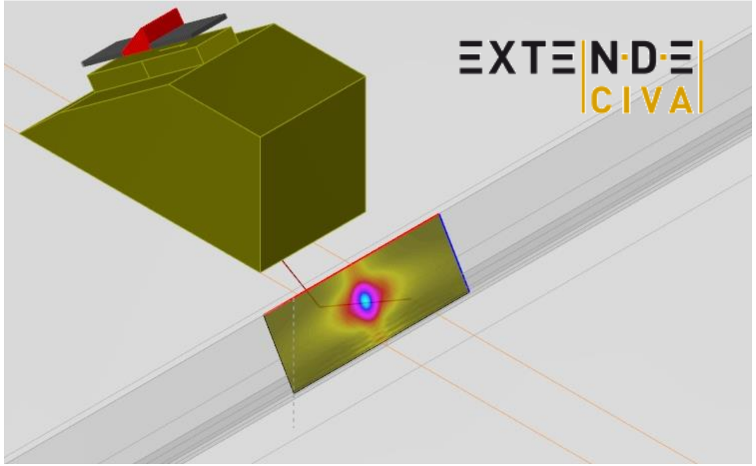
5) POD curves calculation

- Two different studies: conventional UT and PAUT
- Presentation of the approach considering PAUT
- Comparison of PAUT results with conventional UT

Results of MAPOD for PAUT

1) Definition and verification of the nominal configuration

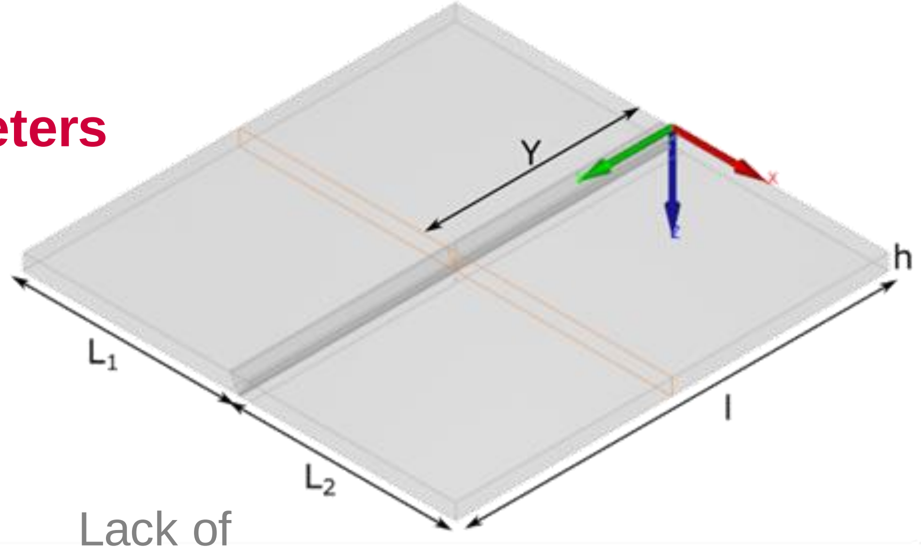
- Procedure
  - Array probe: 5L64-A2, 64 elements
  - Wedge: SA2-N55S
  - Frequency: 5 MHz
  - Electronic linear scanning (unfocused): angle of refraction 60°
  - Calibration: Time Corrected Gain (TCG), SDH $\Phi = 3$ mm
    - Depth 15 mm, 20 mm and 30 mm



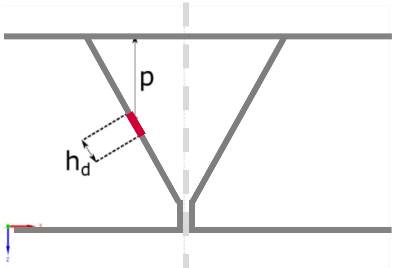
Results of MAPOD for PAUT

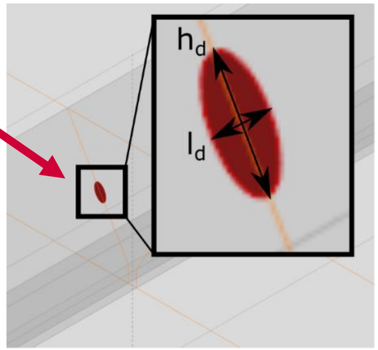
2) Choice of influencing parameters and preliminary studies

Considered influencing parameters	
Geometry	Part thickness Bevel angle Shear wave celerity (T)
Defect	Defect height Defect length Defect depth
Probe	Central frequency of the array probe Wedge height Wedge angle of incidence Compression wave celerity in the wedge
Testing	Probe rotation around the z-axis Initial position of the probe along the y-axis Probe increment resolution along the y-axis



Lack of fusion





Results of MAPOD for PAUT

3) Parametric studies

▶ Objective: first parameters selection

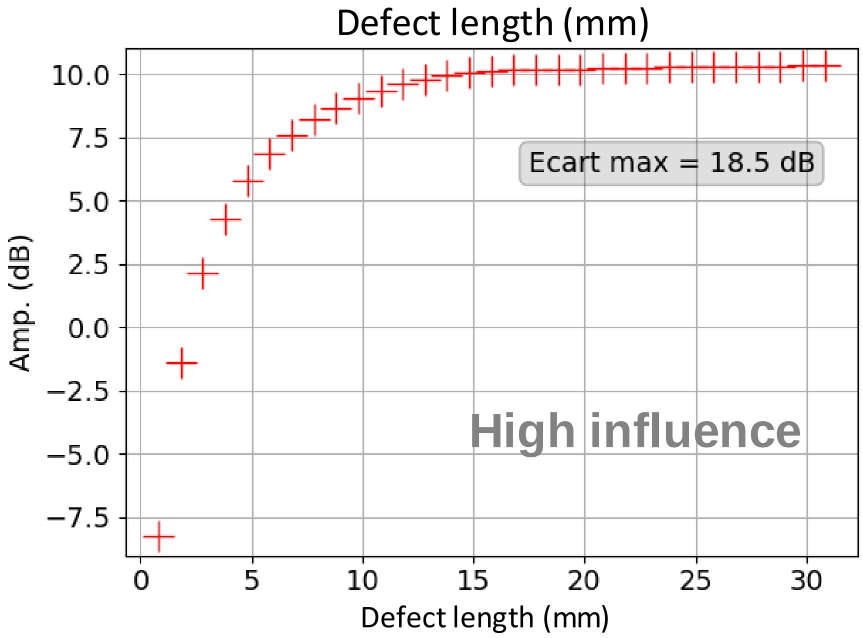
	Considered influencing parameters	Nominal value	Variation range [min ; max]
Geometry	Part thickness	15 mm	[13,5 mm ; 16,5 mm]
	Bevel angle	60°	[57° ; 63°]
	Shear wave Celerity (T)	3255 m/s	[3155 m/s ; 3355 m/s]
Defect	Defect height	2 mm	[0,6 mm ; 4 mm]
	Defect length	5 mm	[0,8 mm ; 30,8 mm]
	Defect depth	7 mm	[4,5 mm ; 9,5 mm]
Probe	Central frequency of the array probe	5 MHz	[4,5 MHz ; 5,5 MHz][1]
	Wedge height	27,4 mm	[25,8 mm ; 27,4 mm]
	Wedge angle of incidence	36°	[35° ; 37°]
	Compression wave celerity in the wedge	2330 m/s	[2280 m/s ; 2380 m/s]
Testing	Probe rotation around the z-axis	0°	[-10° ; 10°]
	Initial position of the probe along the y-axis	174,5 mm	[173,5 mm ; 175,5 mm]
	Probe increment resolution along the y-axis	2 mm	[0,5 mm ; 4 mm]

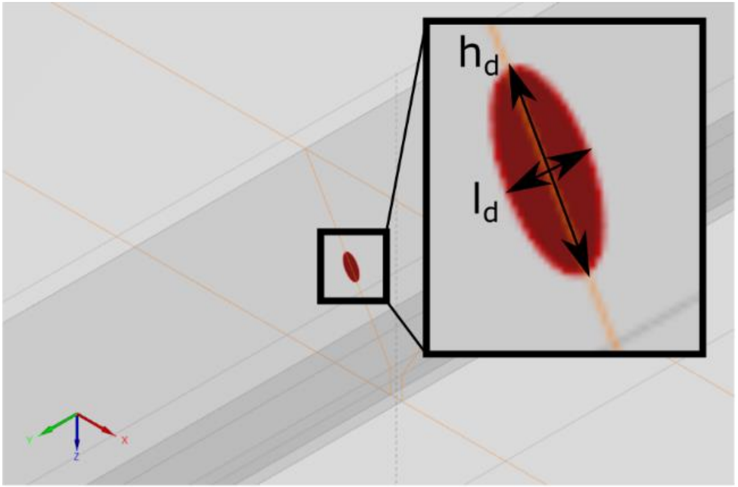
[1] *Range from ISO 18563-2 (Chapter 8, Section 8.4.3): central frequency shall vary between ±10%.*

Results of MAPOD for PAUT

3) Parametric studies - examples

Defect length (mm)

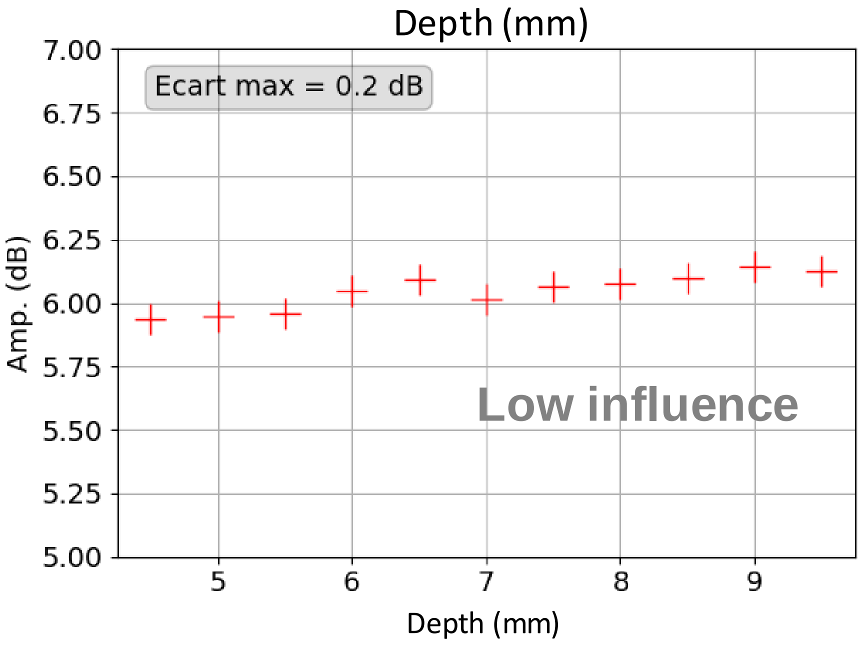


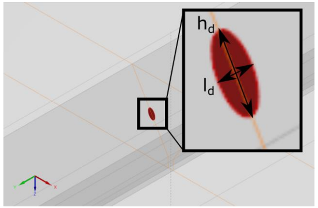


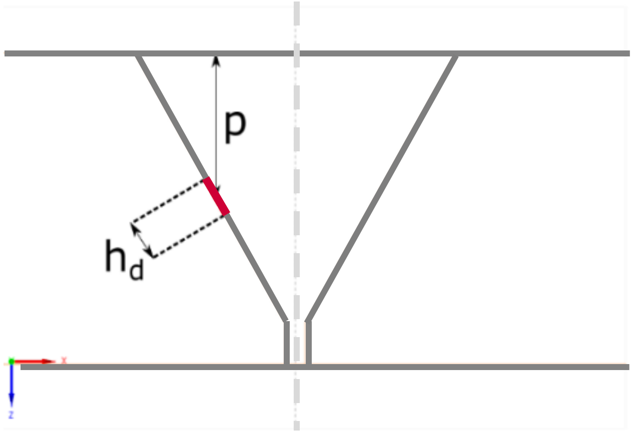
Results of MAPOD for PAUT

3) Parametric studies - examples

Defect depth (mm)





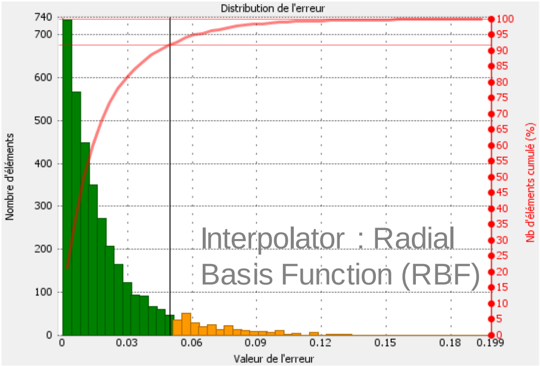


Results of MAPOD for PAUT

4) Sensitivity analysis

- Objectives:
  - Study the impact of parameters on signal amplitude
  - Rank parameters from most to least influential for a given test scenario
- Parameters used for the final metamodel – 3510 random draws

Influential parameters used	Nominal values	Variation ranges [min ; max]
Shear wave celerity (T)	3255 m/s	[3155 m/s ; 3355 m/s]
Defect height	2 mm	[0,6 mm ; 4 mm]
Defect length	5 mm	[0,8 mm ; 30,8 mm]
Probe rotation around the z-axis	0°	[-10° ; 10°]
Initial position of the probe along the y-axis	174,5 mm	[173,5 mm ; 175,5 mm]
Probe increment resolution along the y-axis	2 mm	[0,5 mm ; 4 mm]



Results of MAPOD for PAUT

4) Sensitivity analysis – 3 test scenarios

Scenario 1: uniform distributions : assumes few knowledge nor control of uncertainties

Influential parameters used	Variation ranges	Distribution	Mean, standard deviation
Shear wave celerity (T)	[3155 m/s ; 3355 m/s]	Uniform	-
Defect height	[0,6 mm ; 4 mm]	Arithmetic list	-
Defect length	[0,8 mm ; 30,8 mm]	Uniform	-
Probe rotation around the z-axis	[-10° ; 10°]	Uniform	-
Initial position of the probe along the y-axis	[173,5 mm ; 175,5 mm]	Uniform	-
Probe increment resolution along the y-axis	[0,5 mm ; 4 mm]	Uniform	-

Scenario 2: "optimal" inspections

Influential parameters used	Distribution	Mean, std. deviation
Shear wave celerity	**Normal**	3255 ± 30 m/s
Defect height	Arithmetic list	-
Defect length	Uniform	-
Probe rotation	**Normal**	0° ± **3°**
Probe initial position	Uniform	-
Probe increment resolution	**Normal**	**0,5 ± 1 mm**

Scenario 3: "poor" inspections

Distribution	Mean, std. deviation
Normal	3255 ± 30 m/s
Arithmetic list	-
Uniform	-
Normal	0° ± **7,5°**
Uniform	-
Normal	**4 ± 2,5 mm**

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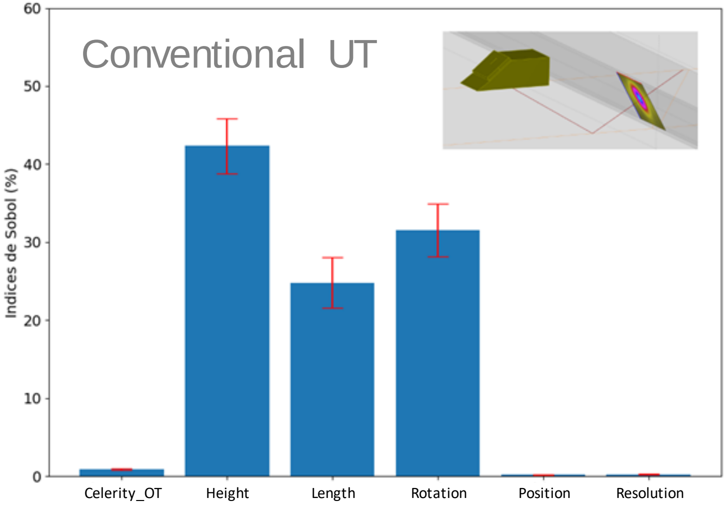
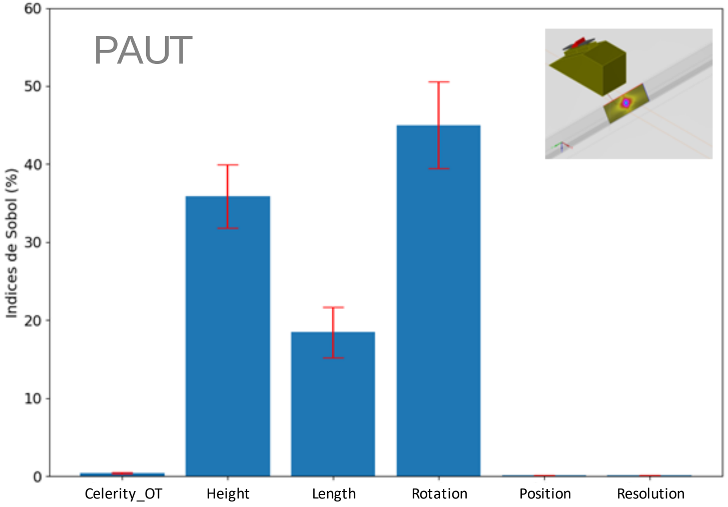
Conventional UT / PAUT comparison

Sensitivity analysis – Scenario 2 ("optimal" inspections)

- Sobol indices
- 3 most influencing parameters:
  - Defect height, defect length and probe rotation around z-axis

Probe Skew has not the same effect for the 2 probes





Conventional UT / PAUT comparison

POD curves

- Conventional UT and PAUT results
  - $a_{90/95}$ – Defect height
  - "Hit/Miss" data

		Scenario 2 "Optimal" inspections	Scenario 3 "Poor" inspections
Conv. UT	$a_{90/95}$ -6 dB	**1,40 mm**	3,92 mm
	$a_{90/95}$ -12 dB	0,69 mm	1,79 mm
PAUT	$a_{90/95}$ -6 dB	**1,72 mm**	-
	$a_{90/95}$ -12 dB	0,87 mm	2,54 mm

Scenario 2 : "optimal" inspections

Influential parameters	Distribution	Mean, Std. Dev.
Shear wave Celerity	**Normal**	3255 ± 30 m/s
Defect height	Arithmetic list	-
Defect length	Uniform	-
Probe rotation	**Normal**	0° ± **3°**
Probe initial position	Uniform	-
Probe increment resolution	**Normal**	**0,5 ± 1 mm**

Scenario 3 : "poor" inspections

Distribution	Mean, Std. Dev.
Normal	3255 ± 30 m/s
Arithmetic list	-
Uniform	-
Normal	0° ± **7,5°**
Uniform	-
Normal	**4 ± 2,5 mm**

Conventional UT / PAUT comparison

Discussion concerning probe rotation around the z-axis

- Higher influence of probe rotation around the z-axis for PAUT than for conventional UT
- New scenario 2*: std. dev. **±1°**
- Different probes characteristics

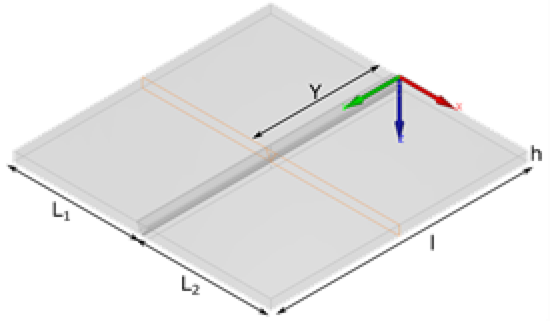
	Conventional UT [MWB60-4 (GE)]	**PAUT** [5L64-A2 (Olympus)]
Central frequency	4 MHz	5 MHz
Aperture	8x9 mm²	9,5x10 mm² (16 active elements)

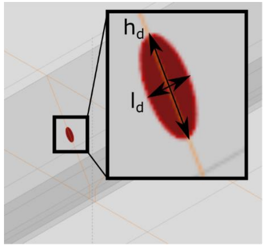
Conventional probe intrinsically more « robust » but PA technique should lead to much less variability

		Scenario 2 "Optimal" inspections Std. Dev. ±3°	**Scenario 2*** "Optimal" inspections Std. Dev. ±1°
UT mono.	$A_{90/95}$ -6 dB	1,40 mm	**1,02 mm**
	$A_{90/95}$ -12 dB	0,69 mm	0,61 mm
UT multi.	$A_{90/95}$ -6 dB	1,72 mm	**0,96 mm**
	$A_{90/95}$ -12 dB	0,87 mm	0,66 mm

- Scenario 2* seems more realistic for PAUT
  - Scanning mechanical system
  - Imaging

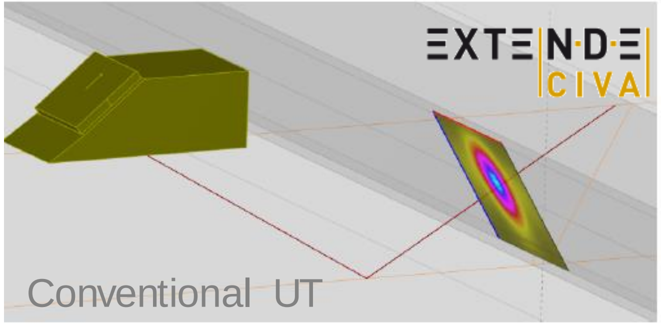
Conclusion and outlook





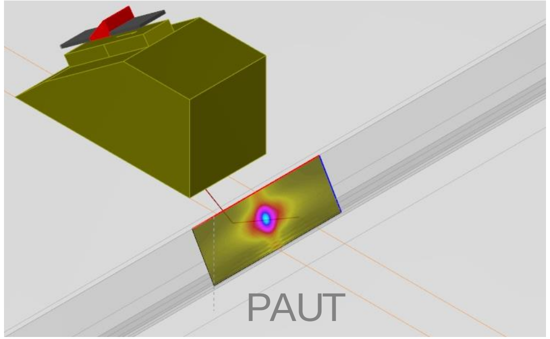
Conclusion

- Two MAPOD studies (5 steps)
- For each study, the 3 most influential parameters are:
  - Defect height
  - Defect length
  - Probe rotation around the z-axis
- Different test scenarios evaluated
- Discussion of the results obtained



Outlook

- Better consideration of human factors
- Enrich this numerical approach with experimental data from NDT inspections



Going for the future