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An overview of validation campaigns of the CIVA simulation software

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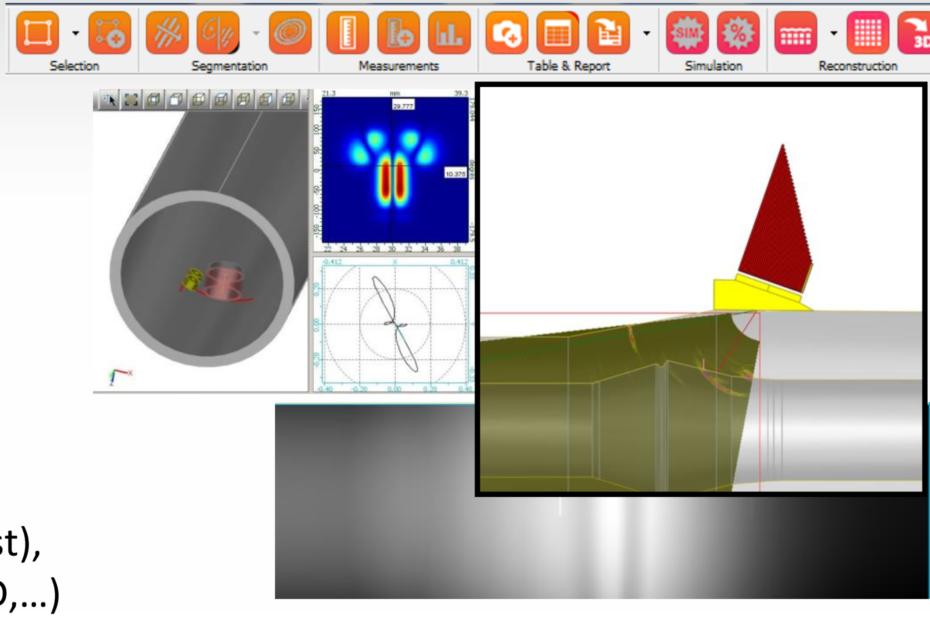
Outline

- Introduction
- Simulation software validation
  - Different strategies and context
  - Conditions to perform fruitful experimental validation works
- Overview of CIVA UT validation campaigns
- One validation campaign:
  Corner echoes & UT angled beam probe
  - Results
  - Models improvement
- Conclusion

What is CIVA software ?

- 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



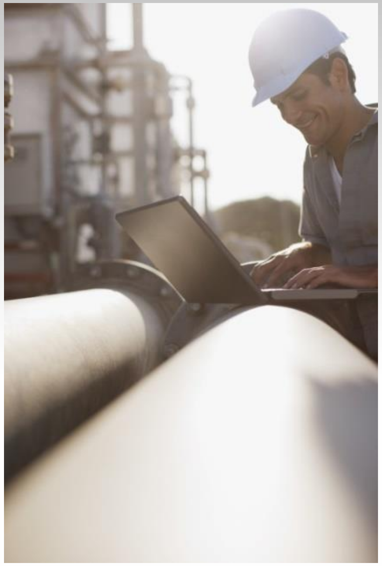
- Mostly based on semi-analytical models (fast), connection with numerical ones (FEM, FDTD,…)

- Developed by CEA (French Atomic Energy commission):
25 years of experience with models & validations

- Distributed by EXTENDE

- CIVA Education: For universities and training centers
  - Help to understand physics behind NDT

Benefits of NDT modeling



DESIGN, OPTIMIZE AND PREPARE INSPECTION:

- Better understanding, easy variation of parameters :
  a wide range of testing scenario to converge
  to the **optimal solution**
- **Better mastering** of a technique and **less iterations**
- Less mock-ups, less trials : **Save time and money**

EXPERTISE:

- Reproduce field results to understand **complex situations**
  and confirm/disprove a diagnosis

QUALIFY: To support performance demonstrations

- Study of **influential parameters** by simulation (and reduce mock-up tests)
- Predict the worst case scenario or compute POD curves
  An **element of technical justification** in qualification stage

DISCUSS AND CONVINCE:

- To **ease** technical discussions between all "players"
  (inspector, manufacturer, end user, etc.) and **convince**

TRAIN AND TEACH

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Simulation software validation

- Sometimes (scan plan preparation, pre-design, help for overall physical understanding, …), qualitative results given by modelling tools are enough.
- But, to be able **to support decision making** (design, optimization, technical justification,…..), quantitative and accurate simulation results are necessary :

  Models reliability becomes then of first importance.

- ENIQ RP#45 mentions « *The availability of validation data is a key aspect for using simulation for technical justification*.»

(European Network for Inspection Qualification, Recommended Practices nr 45 : Use of modelling in Inspection Qualification)

- Different types of validation:
  - Comparison with analytical results
  - Comparison with other codes/software
  - **Comparison with experimental results**
- ENIQ mentions: *« Validation of models is typically performed by comparison of their predictions with the results of experiments.»*

Simulation software validation

- CIVA software development goes along with **extensive tests & validation works**:
  - To demonstrate applicability of new models when they come out ,
  - Quality Assurance and Non regression tests between each release,
  - Annual participation to WFNDEC benchmarks (since more than 10 years for CIVA UT and ET) published at QNDE conferences (see wfndec.org),
  - In the frame of industrial projects and collaborations, or made by users themselves.

- Some of these works lead to communications, **important literature can be found** (see references in this paper).
- But most of results not publicly available and targetted on specific situations.
- Difficult to capitalize all these works & give clear and organized information to users.

Simulation software validation

- EXTENDE and CEA decided to launch a specific action to provide evidence of modeling results validity for a wide scope of NDT configurations:
  - Users can use them in confidence when they simulate similar situations,
  - Users are also informed about the limits of the models.

- Validation campaigns since 2010, funded by EXTENDE, and performed at CEA
- Relies on comparisons between experimental results and available models in CIVA platform.
- A lot of efforts on CIVA UT but works also performed on CIVA ET and RT

- Results published on EXTENDE website: www.extende.com
  - http://www.extende.com/objectives-of-the-experimental-validation-ut
  - http://www.extende.com/objectives-of-the-experimental-validation-et
  - http://www.extende.com/objectives-of-the-experimental-validation-rt

Simulation software validation

- Conditions for fruitful experimental validation works :

Exhaustive and accurate knowledge of input parameters	Reliable reference measurements	Estimation of the measurement uncertainty	Similar simulation and experimental procedures
Choice of relevant output data to establish the validity	Trained and experienced user of the simulation software	Separated investigations of influent parameters	Well-documented report for every steps

- Many potential sources of uncertainties :
  - Presence of inhomogeneities in the specimen, unknown transducers parameters, mock-up defects parameters, conditions of mechanical positioning/coupling/scanning, etc.
  - Requires sometimes **reverse engineering** to get these parameters
- Measurement uncertainty evaluation (through repeatability and reproducibility tests):
  - Reached uncertainty: +/-2 or 3dB **even in good lab conditions**
  - In UT, less variability in immersion testing than in contact testing
- Similar procedure applied for experiments and simulation (same calibration, analysis based on same output data, etc.).

Overview of CIVA UT validation cases

- Different UT techniques, different types of reflectors and different phenomena investigated:

Inspection mode / Reflectors	Pulse echo mode	Tandem mode	ToFD
(Reference reflectors) Side Drilled Hole Flat Bottomed Hole	(Mostly) specular echoes L, T modes	Specular or corner echoes	Specular echoes
Notches	(Mostly) corner echoes in L, T, including mode conversion. Single element and phased array settings	(Mostly) Corner echoes with pair of probes or Phased arrays settings (Zonal Discrimination Method)	(Mostly) tip diffraction echoes in L mode
Geometry (specimen boundaries)	(Mostly) specular echoes (surface or backwall echoes)	Corner echoes (side wall echoes)	Backwall echo Lateral wave echo

- A lot of cases on calibration reflectors (FBH, SDH): Important to rely on accurate calibration defects results in modelling studies
- Straight beam or angled beam
- Both conventional and PA probes
- Majority of Immersion testing cases (less uncertainty) but also contact ones

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Overview of CIVA UT validation cases

- Extensive study of model results evolution when **varying parameters**:
  - Defect dimensions & orientations (vertical, horizontal, tilted)
  - Different transducers dimensions, frequencies, focusing
  - Different component geometries and material properties (e.g. attenuation)
  - ….

Example of parametric variations and phenomena influence on	
Relative to the :	**Parameter:**
Defect	Height
	Length
	Aperture
	Tilt angle
	Depth position (--> for instance DAC and DGS curves)
Probe or system set-up	Frequency range (generally from 2 and 5, also from 1 to 10 MHz)
	Crystal size
	Refraction angle
	Focused or Flat
	With/Without focal laws for PA probes (focal depth, sectorial scanning)
	Influence of the tilt of the probe (immersion testing)
	Varying PCS for TOFD
Component	Flat, cylindrical , irregular surface
	Attenuation effect due to microstructure (sensitive often for probe frequencies >=5MHz)
Other	Impact of mode conversions if any (particularly with L waves angle beam probe)
	Comparison between several models available in CIVA (semi-analytical ones or numerical methods)
	Impact of creeping waves if any

A validation campaign: Corner echoes

- **Corner echoes**: A UT Technique commonly used to detect vertical or tilted planar indications with angled beam probes.

- A wide scope of configurations investigated:
  - Immersion and contact testing
  - Various refraction angles
  - Longitudinal and shear waves
  - Various probe size and frequencies
  - Various defect sizes

- See full description at: http://www.extende.com/ultrasound-corner-echoes

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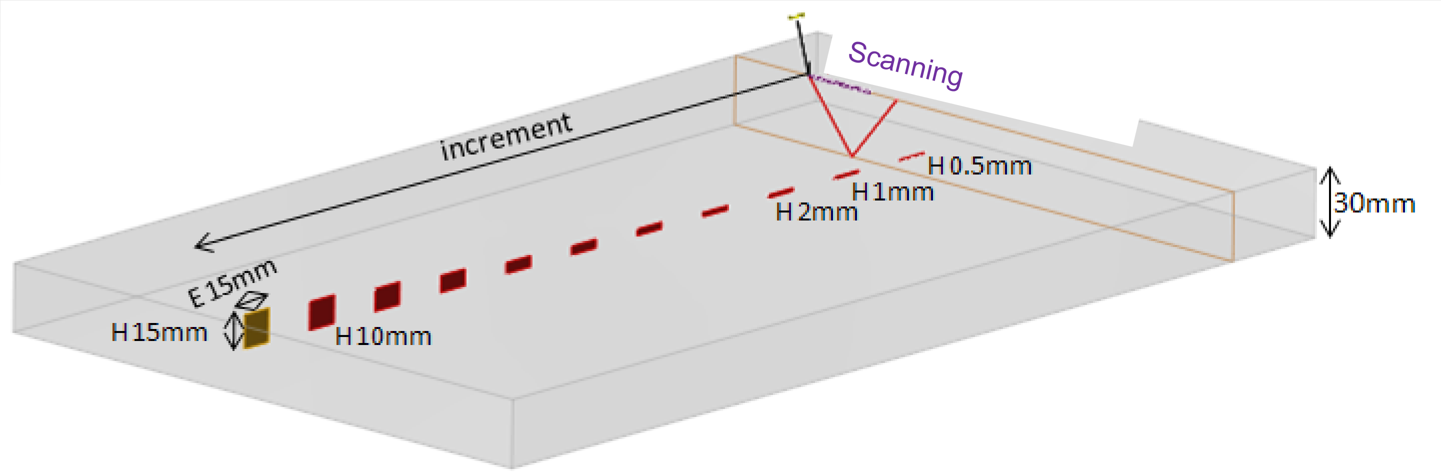
A validation campaign: Corner echoes

- Example: Study of notch height variation impact:
  - Ferritic steel mock-up :

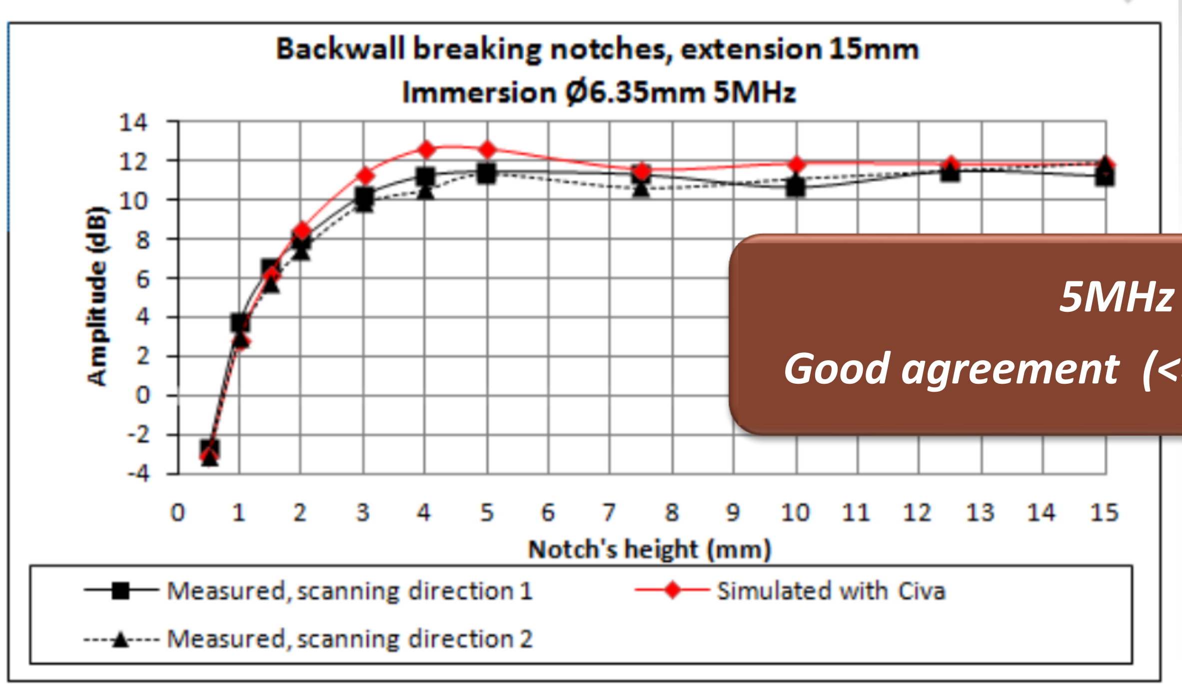


  - Parameters:
    - Planar notch 15mm long and varying height from 0.5mm to 15mm
    - 3 different immersion angled beam probes refracting shear waves at 45°
    - Water path : 25mm

Central Frequency (MHz)	Crystal size
5MHz	Ø6,35 mm
2.25MHz	Ø12.7 mm
2.25MHz	Ø6,35 mm

A validation campaign: Corner echoes

- Results :

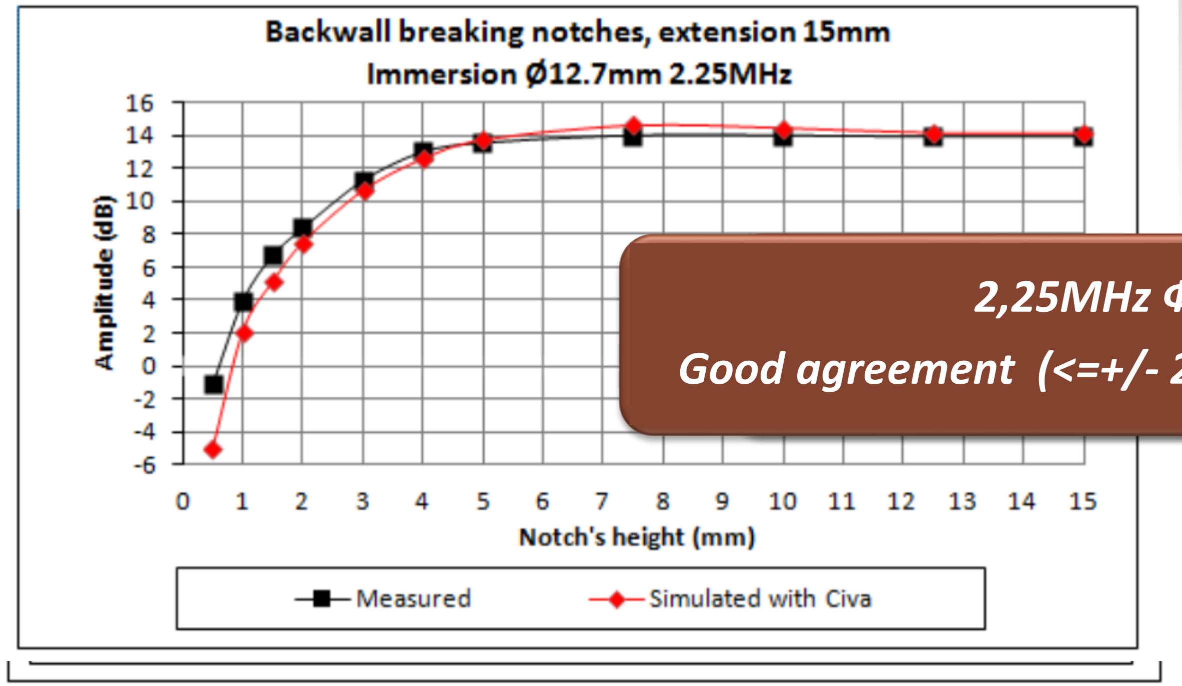


5MHz Φ6,35mm probe

Good agreement (<=+/- 2dB) for all defect heights

A validation campaign: Corner echoes

- Results :

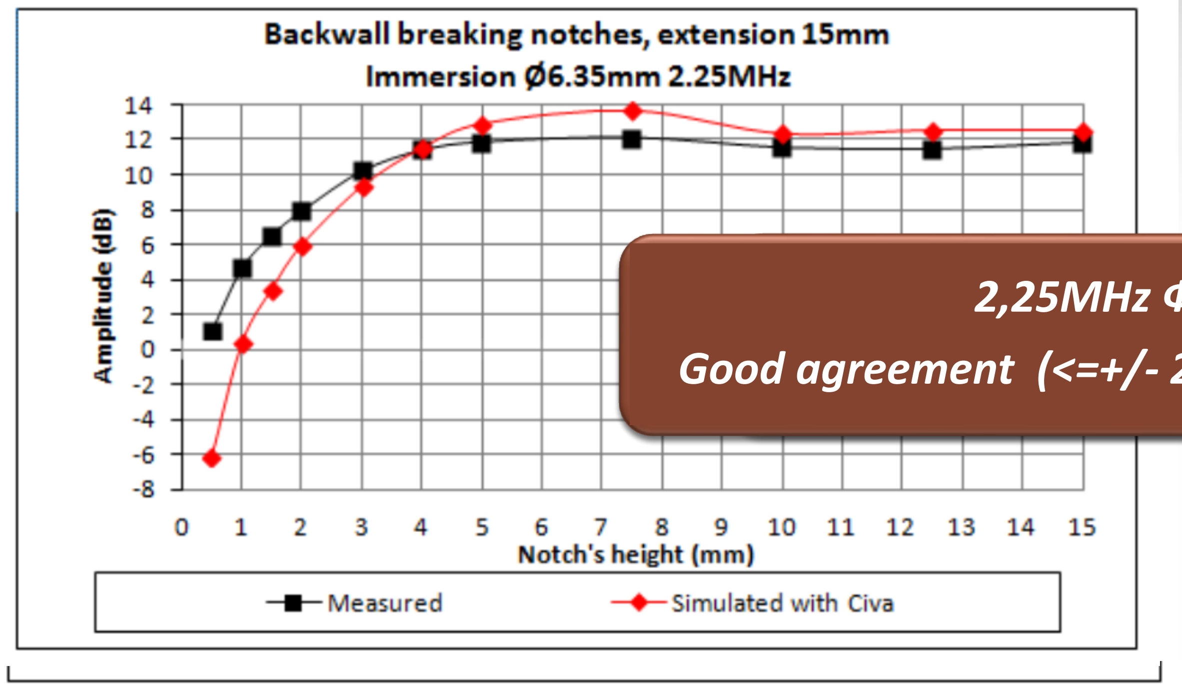


2,25MHz Φ12,7mm probe

Good agreement (<=+/- 2dB) for defect heights >=1mm

A validation campaign: Corner echoes

- Results :



2,25MHz Φ6,35mm probe

Good agreement (<=+/- 2dB) for defect heights >=2mm

- Overall very satisfying results … but highlight 2 « limitations »:
  - Kirchhoff semi-analytical models less or not accurate when defect size gets smaller than wavelength
  - At similar wavelength and for the smallest defects:
    Less good agreement for smaller crystal (i.e. divergent probe)

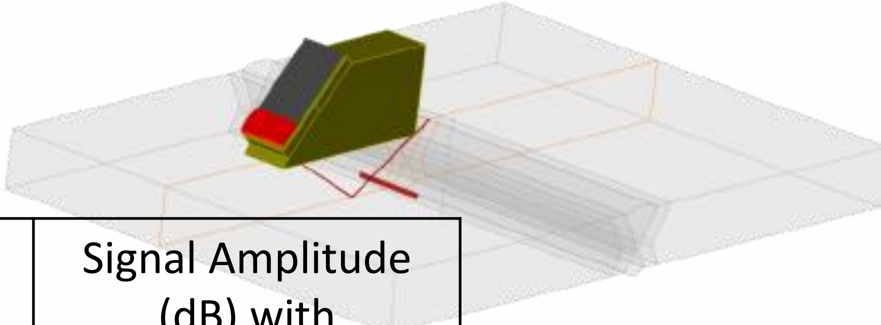
A validation campaign: Corner echoes

- Models improvement since this validation campaign was performed:
  - **FEM inside CIVA**:
    - For planar rectangular defects, Transient Finite Element Model can now be selected instead of semi-analytical ones (e.g. Kirchhoff GTD),
    - More accurate for smaller defects or at angles when surface waves can be generated on the defect,
    - Hybrid technique : FEM computation is restricted to a box around the defect and SA method is used to compute the incident beam → Much less time consuming than doing a full FEM simulation.

To tackle the « small defect inaccuracy »

A validation campaign: Corner echoes

- Models improvement since this validation campaign was performed:
  - **FEM inside CIVA**:
    - Example on one case: PA Inspection – S60 – 2MHz*
    - Corner echo on a rectangular defect of 20mm long and different heights in a ferritic steel piece
    - Comparison "Transient FEM" and "Kirchhoff-GTD":

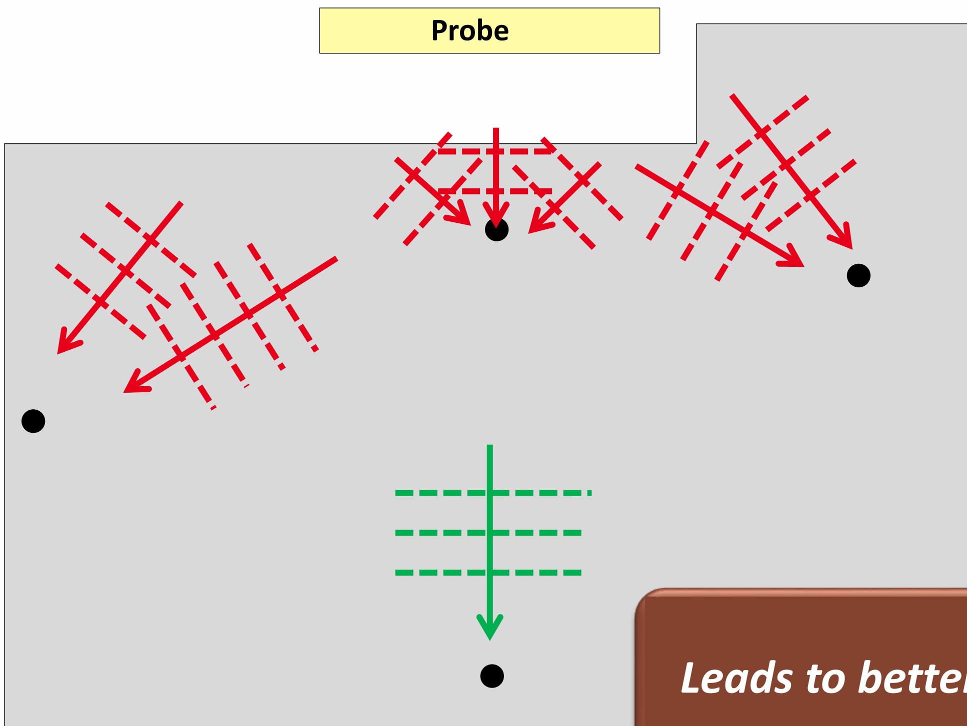


Defect Height (mm)	Signals Amplitude (dB) with **K-GTD**	Signal Amplitude (dB) with **Transient FEM**
0.1	-11.6	-34.5
0.5	-9.6	-13.2
2	-3.4	-3.9
5	0	0

** Shear wave wavelength in carbon steel ~ 1,5mm at this frequency*

A validation campaign: Corner echoes

- Models improvement since this validation campaign was performed:
  - **A "Full Incident Beam" model** replaces a previous planar wave approximation performed when computing beam/defect interaction.
  - More accurate in various situations:



Favorable case for PW approximation

- Focal axis, far from probe

Unfavorable cases → more accurate with "full beam" modelling

- Near the probe
- Out of the focal axis
- Irregular geometry

Leads to better accuracy with divergent or focused probe

Conclusion

- Accurate & reliable simulation tools are necessary to be fully accepted and useful to support NDT methods development & qualification.
- Variety of validation works have been carried aroung the CIVA simulation software (see references in this paper) but need for a specific action to provide users experimental validation evidences in an organized way.
- Large scale validation campaigns were conducted by CEA and EXTENDE, leading to a considerable amount of data published on EXTENDE website.
- An overview were given here even if of course the goal was not to show « all results ».
- Well predicted cases are shown giving confidence to users wishing to simulate comparable configurations, but model limitations are also discussed and analysed on the website.
- Lead to model improvements such as illustrated in the « corner echoes » validation works where 2 major developments went to overcome some « weak points » of the initial model .

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