Simulation and processing tools for the design and performance evaluation of FMC-TFM techniques

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Abstract. Phased array Imaging techniques such as FMC-TFM and derived methods are of great interest and are increasingly used as they improve performance in a wide range of situations.
In the same way as for conventional Phased Array processes, it is necessary to provide the means to quantify and demonstrate the performance of a control. This involves relying on new criteria, being able to demonstrate their reliability and assessing the sensitivity of the different parameters. In this paper, we present the potential of simulation and post-processing tools to address these issues. Indeed many alternatives are possible, whether in acquisition techniques (FMC, PWI, ATFM), or processing possibilities (artefact filters, imaging modes, signal processing). This communication is based on the use of the CIVA simulation and analysis platform, whose recent advances make it possible to accurately assess the sensitivity of all the parameters of a control based on the FMC-TFM technology either at the level of the control method (probe, positioning, geometry, material characteristics ...) or the data processing which is possible to personalize it through a new python plug-in solution accessible to all.

Keywords : Phased arrays, UT inspection, TFM imaging, Surrogate model, POD, NDT performance assessment, Sobol, FMC, PWI

CONTEXT AND MOTIVATIONS

Simulation tools are increasingly used considering their capabilities for different industry sectors to predict structural reliability and product quality, eg. "Effect of defects" in aeronautics, "Risk Based Inspection", "Continuous improvement of product quality" in the steel industry, "Performance Demonstration" in the nuclear industry.
More precisely, using simulation allows to:

- Perform more virtual tests by varying a wide set of influent parameters and assess the effect of such variations on the performance of the inspection method. Simulate more test configurations will allow to optimize the conception of the method and to demonstrate the performances.
- Easily introduce flaws of various shapes, sizes, and materials into the configuration simulation model, defects which are never or little observed, not being able to be manufactured and for which a detectability must be given.

- Reduce the cost of NDE assessment: the possibility to make some parametric variations on any influent configuration parameter allows anticipating the inspection during the component conception stage, or minimizing the number of mock ups to be manufactured to demonstrate the performance of a given inspection procedure.

A new NDT method can actually become possible and admissible if it is accompanied by NDT standards and tools that will allow to assess, compare and demonstrate its efficiency. This requires taking into account the main variables and uncertainties of a NDE method, but also must to be able to evaluate the variability and the specificity of the method according to its possible sensitivity to its own parameters, both at the stage of detectability and diagnosis.

The principle of the Total Focused Method (TFM) [1] is now well known. TFM and derived methods are more and more recognized as an efficient alternative or valuable complement of classical phased array methods. One of the advantages of TFM is to be able to produce a direct image of the defect that is easily interpretable but also more adapted to an automatic diagnosis. Another benefit is the possibility of applying different imaging modes (direct or over skip imaging) to the same array response matrix, depending on the geometry of the testing specimen or the nature and orientation of the defects.

Although TFM is generally applied on a FMC (Full Matrix Capture), many other acquisition schemes are possible and can be used for different purposes, for example:

- SMC (Sparse Matric Capture) [2] that consists in using only a part of the elements of the probe can be used to speed up the acquisition process.
- PWI (Plane Wave Imaging) [3] that consist to transmit plane ultrasonic wave fronts at different angles (as a sectorial scanning) allows a high image quality obtained with a few ultrasonic shots. Furthermore, this method is less sensitive to attenuation and random noise than the TFM on FMC.
- ATFM (Adaptive TFM) [4] that consists in extracting a first image of the surface in front of the array aperture before focusing inside the specimen through a standard TFM process taking into account the complex surface allows to be robust to unknown surface conditions.

All these methods derived from TFM have their own parameters. In these cases, the simulation and post-processing tools are very useful for evaluating or developing the best acquisition scheme and optimizing the best compromise between speed and image quality with a good level of confidence. In addition, there is a crucial step in the TFM imaging process: the calculation of the flight times for each mode and at each point of the grid, which assumes a good knowledge of the NDE conditions and whose sensitivity in relation to the uncertainties (positioning, materials, geometry etc…) have to be evaluated.

SIMULATION AND PROCESSING TOOLS FOR TFM EVALUATION IN CIVA SOFTWARE

CIVA software allows simulating the TFM by post-processing or by directly setting the reconstruction parameters in the NDT configuration as illustrated in Figure 1. Several preset acquisition schemes are available such as the classical FMC, PWI or Adaptive TFM but it is also possible to program any transmission-reception schemes as SMC or others, before proceeding a TFM. CIVA also allows the evaluation of the contributions of the different types of waves and imaging modes with the possibility to merge them together. Finally, several filters are available, especially to avoid some typical TFM artifacts [5].

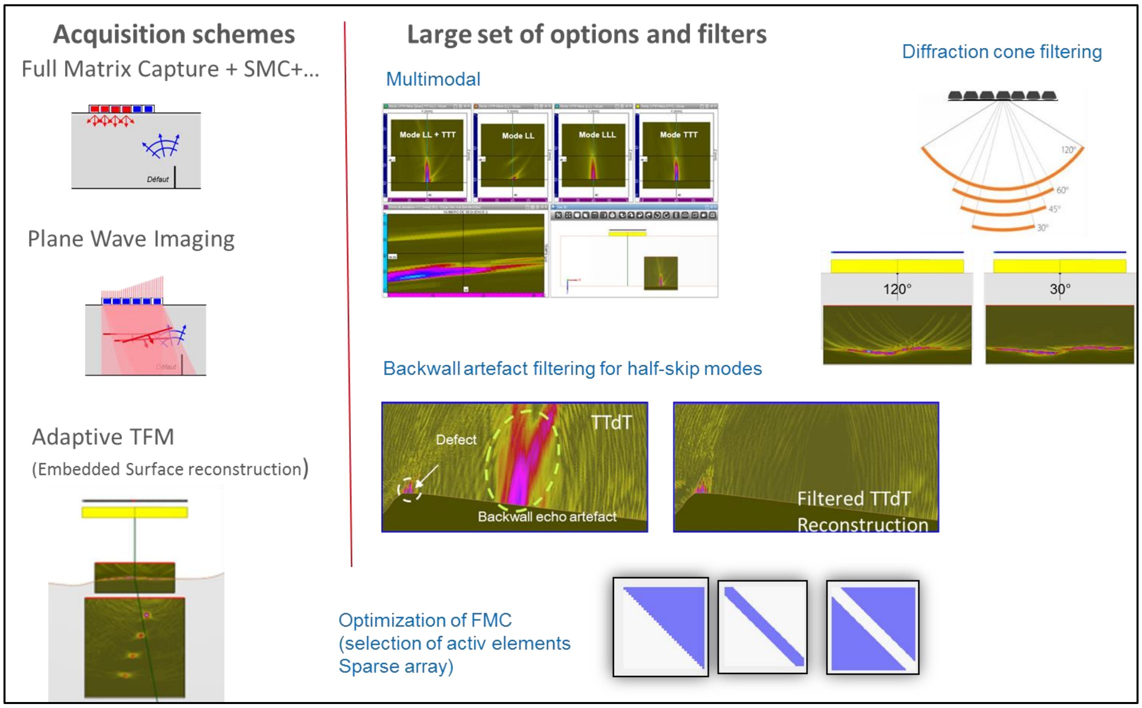

Figure 1: examples of TFM features available on CIVA simulation software

NDT demonstration of performance means multi-parameter studies, taking into account the propagation of uncertainty and statistical analysis, which involves intensive calculations.
To meet this need, the CEA has developed a strategy based on metamodels. A metamodel (or surrogate model) consists of calculating a first set of simulation results for a given range of multi-parameter variations and taking advantage of them through a smart interpolator that will allow the user to access real-time performance . This strategy opens up great possibilities for sensitivity studies and POD. [6]

The use of simulation requires confidence in the models that need to be validated.
Every year CIVA is confronted with validation campaigns or benchmarks. Some results are available on the Extende website (http://www.extende.com/objectives-of-the-experimental-validation-ut). We can also mention here the WFNDEC benchmark of 2014 dedicated to the TFM [7]

PERFORMANCE EVALUATION OF A TFM TESTINGPROCEDURE USING SIMULATION

To illustrate the tools and methodology that can be used for NDT TFM assessment, we followed the steps of a NDT performance demonstration through a case study of a V-bevel pipe welding inspection.

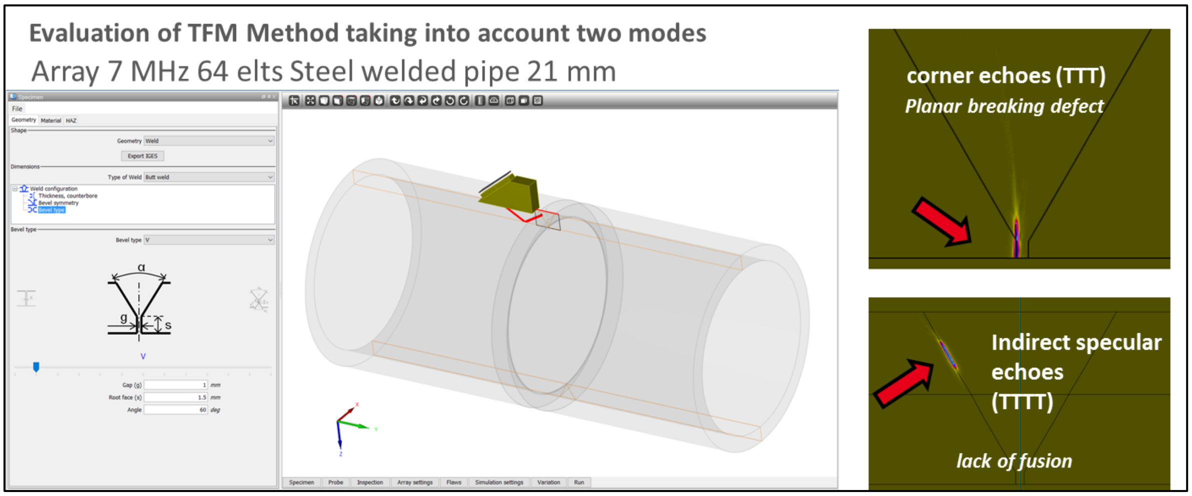

Figure 2 : Simulation of V-Bevel inspection with TFM

In this example (Figure 2), a 64 elements probe with a frequency of 7MHz is used, to inspect a steel welded pipe with a thickness of 21mm. We are focusing here on the control of lack of fusion flaws along the bevel and planar breaking defect. This type of configuration is usually handled by the zonal discrimination method (AUT ZDM) which ensures complete coverage of the weld using several channels with specific aperture and delay laws. The idea here is to show how an alternative method with a single TFM channel can be assessed. Please note that this “school case” has been chosen only for illustration purposes, and does not be considered as a validated proposition of a new NDT method. The objective of the study is to show how simulation tools can be used for estimating the coverage of the control, the sensitivity of the parameters, establishing a POD and evaluating the sizing accuracy for a TFM use case.

Sensitivity MAP: the verification of the coverage of the region of interest can be evaluated through the computation of a sensitivity maps according to the disorientation and the positioning of the flaw [8]. The Sensitivity map can be computed in CIVA with the “Parametric Study” and “Metamodel” tools, which allow to select any parameter as “variable” or not.

To evaluate the region of interest at each possible position of the flaws, with a disorientation range between -20 and 20 degrees around the 30° bevel orientation a metamodel can be computed covering this area of variability. We have considered in this example a standard defect of 3mm height.
For each acquisition scheme, a common calibration procedure has been done, based on the response of a 2mm side drilled hole situated at the middle of the thickness of the specimen
The Figure 3 shows the sensitivity maps obtained for the two acquisition schemes FMC and PWI, on different angles of disorientation. The areas in dark red correspond to an optimal sensitivity (0dB or + compared to the reference). The dark blue areas correspond to a critical sensitivity for a good detection and characterization of the defect (under -6dB).
On our example, we can see that for a tilt aligned on the bevel, the coverage of region of interest is excellent, for a disoriented tilt of -7 ° there is a lack of sensitivity near the external surface, for a tilt of 10 ° the cover is again sufficient with a fall of sensitivity near the back wall. This type of

representation is very interesting to optimize its acquisition scheme and to ensure the good coverage of the method.
We can also note that the FMC scheme requires 4096 signals (64x64) while a PWI scheme, which requires sweeping the area over a range of 45-70 ° with a 1.6 ° step requiring only 960 signals with a similar coverage.

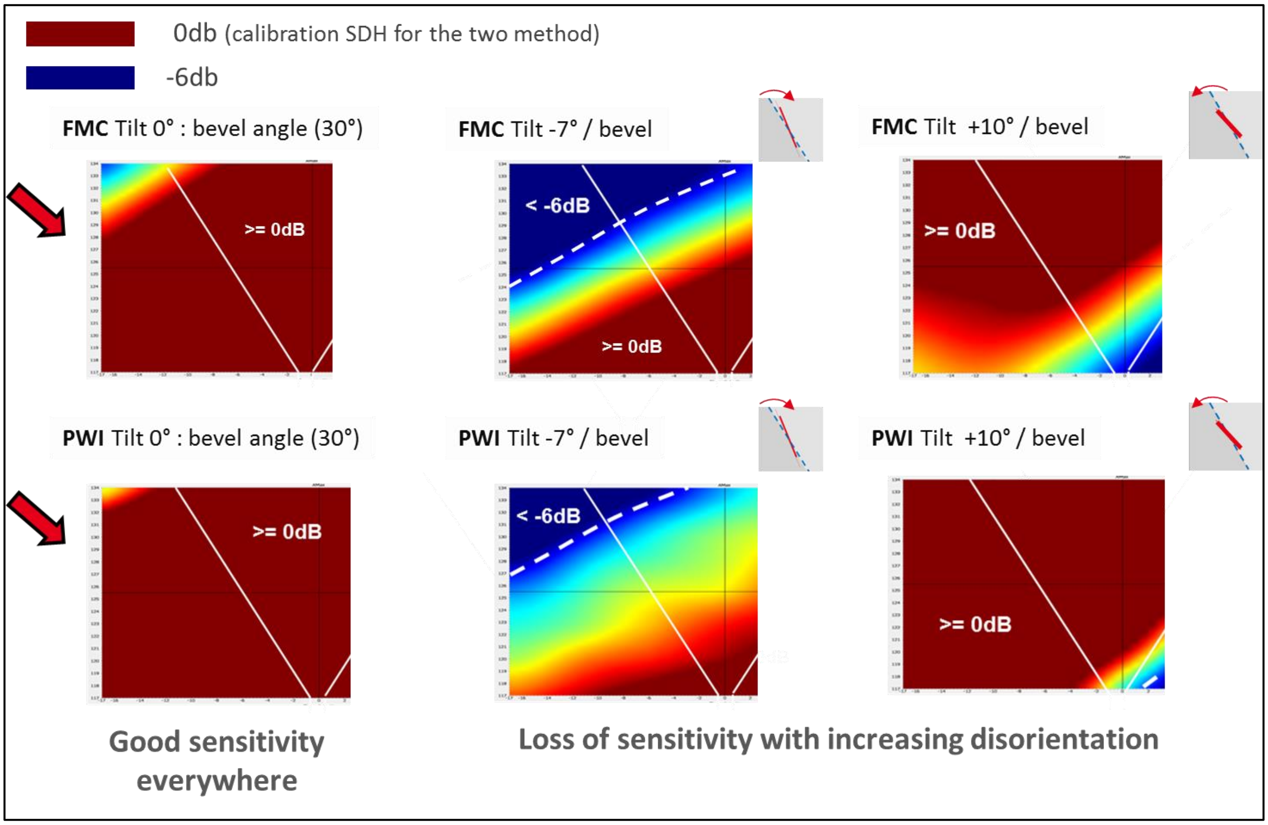

Figure 3: Sensitivity Map for several angles and acquisition schemes

Metamodel for performance evaluation: A metamodel based on maximum of amplitude of the TFM result can be compute to evaluate the performance of the method taking into account the characteristic parameters of the defect and uncertain parameters. We are focusing here in the case of breaking flaw. Six parameters are considered with uncertainty: height of the breaking flaw (from 0.01 to 4mm), tilt (from -10 to 10° along the bevel), skew (from 0 to 3°), thickness of the part (from 19 to 23mm), materials properties (T wave velocity from 3190 to 3390), and offset of positioning. The database required 1500 calculations and took about 24 hours to be generated on a standard PC (3D computation).Once completed, validation of the resulting metamodel is necessary. Cross validation tools make it possible to ensure the maximum of error generated by the metamodel versus the physical simulation. The evaluation is based on using a part of the samples to build the metamodel and comparing these results to the other part of the samples. In our case, the fit is good with 95% of the samples below 4% error. (Figure 4)

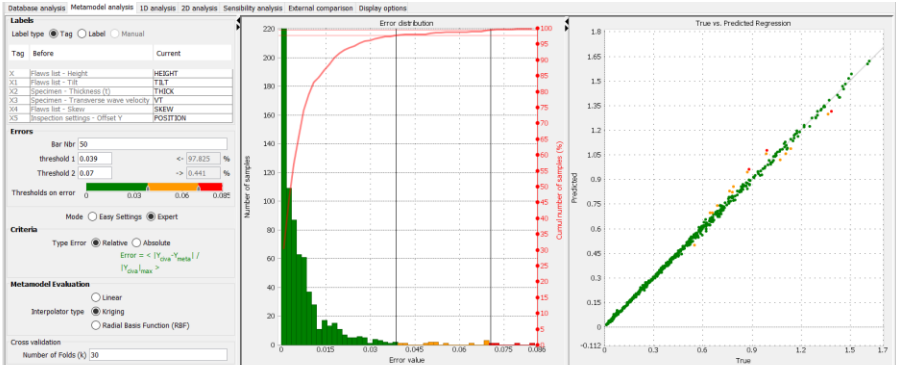

Figure 4: Metamodel cross validation

Statistical analysis of the parameters sensitivity using metamodel:

The objective here is to evaluate the level of influence of the parameters to the maximum of amplitude. The user defines assumed statistical distributions for variables and the Sobol Index gives the relative influence of each parameters to the output. We see here that the height of the defect is predominant, then the tilt, the material characteristics, the skew, and finally the thickness of the part and the position. (Figure 5)

It is also possible to evaluate this sensitivity according to the parameter ranges. For example, we can observe the variation of the sensitivity of the parameters according to the size of the defect. We see here that from 2mm the method is no longer sensitive to the size, and the tilt then becomes predominant. As in conventional UT the amplitude of the corner echo does not vary with Height for large defects.

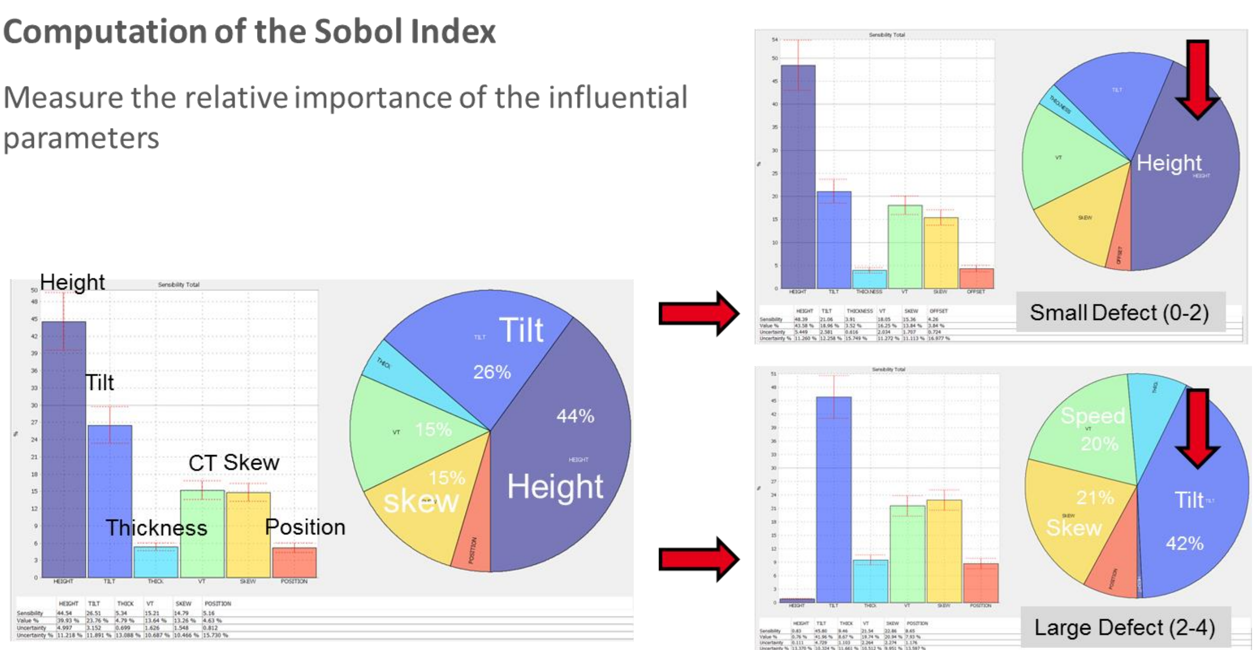

Figure 5: Sobol indices computed with metamodel

Using parallel coordinate plots is another way to evaluate the influence of parameters

This graphic shows the parametric values path linked to the worst cases results avoiding small defects and Illustrates the importance of the tilt and skew (as in conventional UT) and of precise knowledge on velocity (input of the TFM algorithm for time of flight computation)

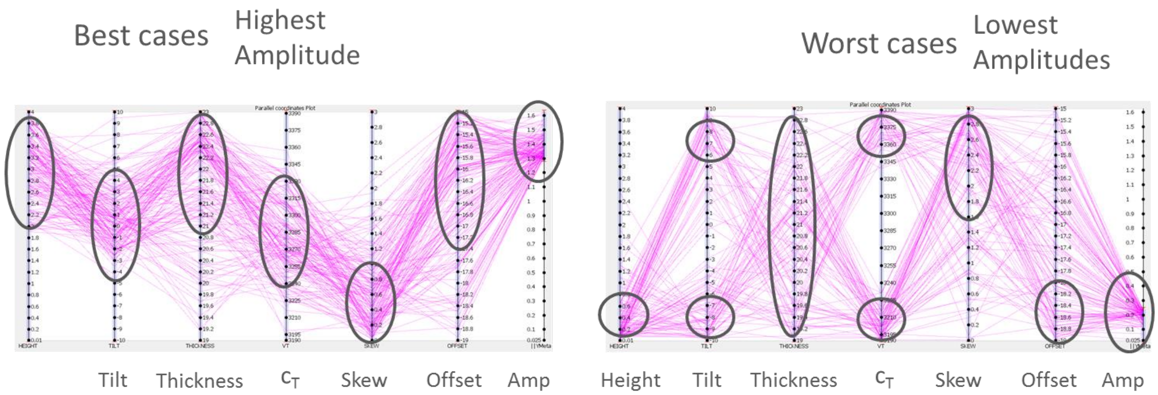

Figure 6: Parallel plot of the parametric evaluation

Probability of detection:

Thanks to metamodel, it is possible to consider a very large amount of draws for statistical evaluation. For example, a computation taking into account 50 sizes of defects, and for each size of defects, 1000 samples of uncertain values. (Equivalent to 50000 simulations) is performed in few seconds.
In our example, we obtained a POD curve with a probability of detection at 90% for fault heights of 1.25 mm. The POD also depends a lot on the choice of drawing laws. We chose to consider here normal drawing laws for uncertain parameters. It is then possible to compute a beam of POD corresponding to different parameters of distributions to increase its confidence in the result.

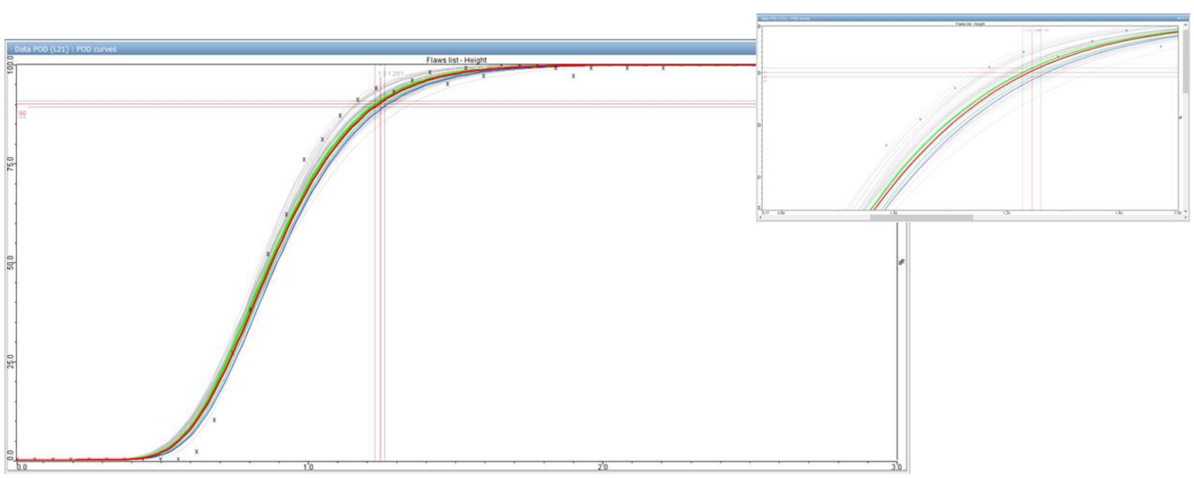

Figure 7: Beam of POD for several parameters of statistical distribution

Sizing Accuracy:
The objective is to evaluate the accuracy of an automatic sizing method for TFM.
We have chosen here to evaluate a contour measurement method at -6dB. A metamodel has been exploited to take into account the propagation of uncertainties and to evaluate the distribution of the error of the sizing measurement. The principle of the study is to compare the size of the simulated defect with the size measured by the 6dB method.
A first baseline study has been computed with evaluation for multiple defect sizes and positions, without further variability. Without uncertainty propagation, defects from 1 to 5 mm have their maximum probability of error at 0.2 mm, with a variance of 0.8 mm. Small defects (under 1mm) have their maximum probability of error value around 1 mm. That can be explained by the insensitivity of the sizing method for defects smaller than the wavelength.

When taking into account the uncertainties (here on the tilt of the defect and on the speed of the T wave), we observe a spread out of the probabilities of sizing error, with a loss of accuracy and a more possible underestimation of the defect.

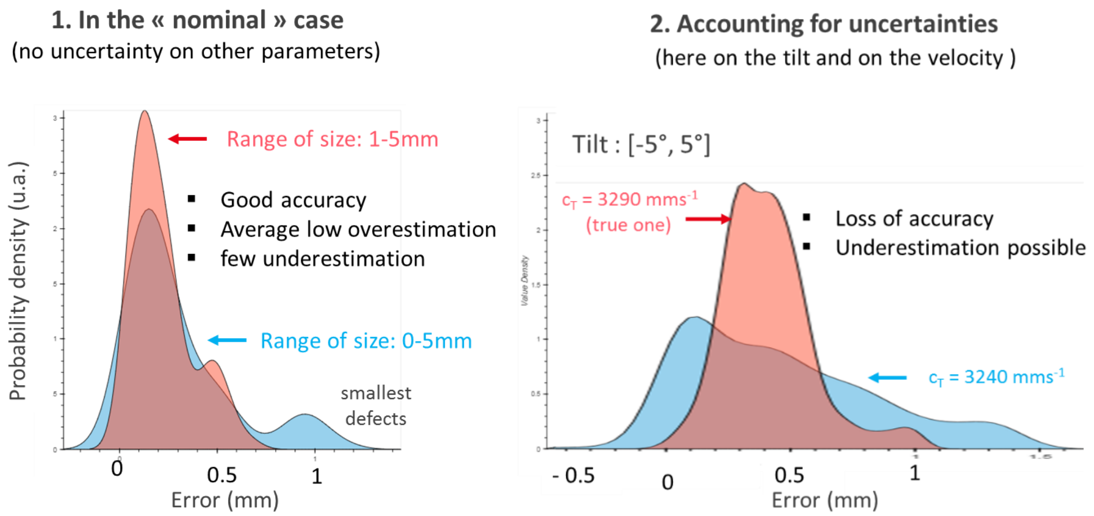

Figure 8: Error probability of sizing

CONCLUSION AND PERSPECTIVES

- We have shown how simulation can be used to optimize or assess the performances of TFM (as other UT techniques).
- In particular, we have illustrated the possibility to carry out sensitivity analysis and POD study on TFM technique.
- The influence of parameters can be quantitatively estimated.
- We have shown how the accuracy of a sizing procedure can also be estimated from simulation.
- This kind of study may request specific processing to fit the NDT process and standards which has to be evaluated (detection, sizing ….)
  For this issue, CIVA will propose the capability for the user to customize some

processing steps through a simple plug-in solution based on Python Scripts (ongoing European project - ADVISE).

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