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Validation of the simulation of pipeline girth welds PA UT inspections

Fabrice FOUCHER*, Philippe DUBOIS*, Vincent GAFFARD**, Henri GODINOT**, Henri ROMAZZOTTI***, Anne COURBOT***, Erica SCHUMACHER****,
EXTENDE SA*,
15 rue Emile Baudot, 91300 MASSY, France
TOTAL,**
2, place de la Coupole, 92078 PARIS La Défense, France
TOTAL*,**
Avenue Larribau, 64018 PAU, France
www.total.com
EXTENDE Inc. **,**
PO Box 461, Ballston Spa, NY 12020, USA
contactus@extende.com, www.extende.com

Abstract
The technique for automated ultrasonic inspection of pipeline girth welds is based on the so-called zonal discrimination approach, commonly used today in the oil & gas industry.
For each project, qualification of the inspection equipment and procedure according to DNV standards (DNV OS F101, DNV recommended practice: DNV RP F118) and TOTAL internal specifications, is required to ensure inspection performance.

Some of the qualification tests based on the inspection of defective welds are costly and time consuming. Moreover these tests don't provide the opportunity to thoroughly investigate the influence of several parameters such as wall thickness variations, sound properties, beam characteristics, and defect orientation on the probability of detection (PoD) and sizing accuracy. For these reasons, introducing modeling into the qualification work to replace part of the tests currently performed and add other relevant tests that would otherwise be excluded brings added value to the qualification process.

The first stage of the project was to qualify the use of a modeling tool to simulate Phased-Array UT inspections performed with the PipeWizard system. To do so, results of qualification tests performed for a project on pipe welded sections exhibiting both machined (typically notches and flat bottom holes) and real weld defects (typically lack of fusion, lack of penetration, porosities, etc.) were used.

EXTENDE modeled the qualification mock-ups and the UT inspection procedure with CIVA software. Then, calculations were performed to compare simulations and experiments.

The results of this first study are a promising beginning to the use of CIVA calculations in the qualification process of UT inspection of pipeline girth-welds, particularly for PoD and sizing accuracy evaluations.

Keywords: Phased-array UT, zonal discrimination method, pipeline girth welds, simulation, modeling

1. PIPELINE GIRTH WELDS PA UT INSPECTION

For one or two decades, Automated Ultrasound (AUT) techniques have been routinely used for the inspection of pipeline girth welds. The most commonly used method is the so-called zonal discrimination approach. It is based on the division of the weld into different zones of inspection of about 3mm maximum in height (see figure 1).

Basically, the fundamentals of this method are:
- To focus the UT beam so that the beam spot size is the same as the inspected zone
- To set temporal acquisition gates to reduce the volume of data and support interpretation especially in the root area (see figure 2 with the example for the inspection of a fusion line).

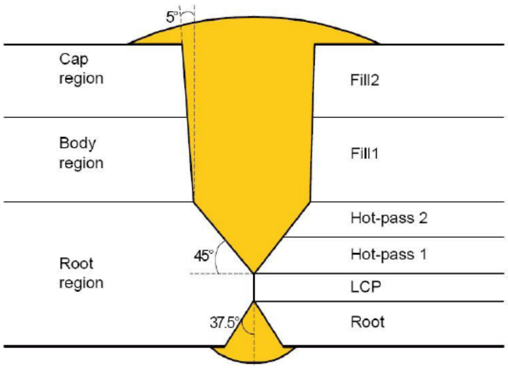


Figure 1: Zonal subdivision of the weld

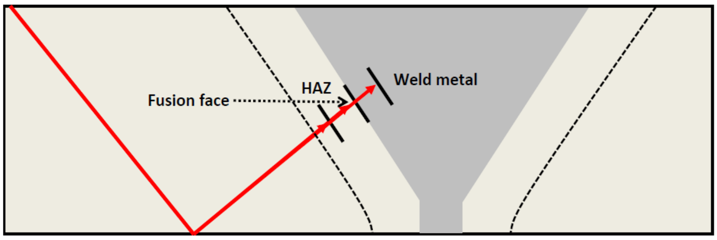


Figure 2: Acquisition gate adapted to fusion line region inspection

To obtain this performance and a good reliability in terms of probe positioning and coupling, most of the current systems rely on Phased-Array UT technologies which strongly reduce the number of probes. The project discussed in this article involves the PipeWizard PA system. Several probes and/or several electronic settings are defined on the inspection system so that different acquisition channels are created, each of these aiming at inspecting a given zone.

In order to ensure that required inspection performances are met, oil & gas companies require that the AUT equipment and procedure go through a qualification process before using it for girth weld inspection.

For instance, TOTAL specifications require two main steps to be performed to validate inspection systems and procedures:

- A calibration step: It consists in manufacturing calibration blocks including reference reflectors (Flat Bottomed Holes, Notches, Side Drilled Holes) positioned in the different areas defined by the zonal discrimination procedure. The inspection system is set so that the amplitude of the echo of the target reflector reaches 80% of Full Screen Height (FSH) for each channel. A range of dynamic and repeatability tests are also performed to ensure the reliability of the calibration settings and of the equipment positioning (mechanical parts) and the proper operation of alarm channels (in case of bad coupling for instance).
- A performance evaluation step: For this second step, several welds are created in which realistic flaws are artificially produced by deliberately deviating from optimal welding parameters. AUT is then used to detect and size these flaws. Macrographs are finally performed on salami cuts at different increments of the welds. The macrographs help to verify the performance of the AUT system as well as to determine PoD and sizing accuracy curves.

This qualification process is cost and time consuming (costs of the mock-up, costs of the macrographs, time spent to realize the tests, etc.) and the results obtained for the PoD and sizing accuracy curves are strongly dependent on the size and orientation of the defects that have been created in the weld. Moreover, some of the influential parameters of the inspection cannot really be evaluated. With only few inspections, it is not possible to have flaws covering all possible skew, tilt, position and size. , it is also difficult to evaluate the impact of other parameters such as the variations related to the system positioning on the pipe, the uncertainties on the probe settings, the metallurgical noise of the work piece or the human factor.

That is why TOTAL is interested in introducing modeling to replace at least partially the second step of the qualification procedure. If it is demonstrated that a model could reproduce the results obtained with AUT systems, then simulation could bring significant benefits to this process by increasing the number of tests and the reliability of the results in a cost-effective way.

2. THE CIVA SOFTWARE PACKAGE

In many sectors of industry, simulation plays an increasing role in NDT, helping the design of inspection methods, their qualifications or the analysis of inspection results. The CIVA software package, developed by the CEA (French Atomic Energy Commission), can simulate 5 major NDT techniques: Ultrasonic Testing (UT), Guided Waves Testing (GWT), Eddy Current Testing (ET), Radiographic Testing (RT) and Computed Tomography (CT). All five of these modules are available in the same environment, bringing to the users a unique NDT oriented Graphical User Interface and some dedicated tools, which make its use quite easy.

The mathematical formulations used in the different modules generally rely on semi-analytical models. To summarize the different models, it can be indicated that the UT module relies on a ray theory geometrical approach (but not only ray tracing) to compute beam propagation, the so-called “pencil method”. The interaction with defects is calculated using either “Kirchhoff” approximation or the Geometrical Theory of Diffraction “GTD”, or also SOV and Born models. The Guided Waves module uses a hybrid “SAFE” method (Semi-Analytical and Finite Elements), considering a semi-analytical modal decomposition approach for the propagation along the length of the part, and a FEM approach in the part cross-section.
The Eddy current module involves a Volume Integral Method which only requires a numerical sampling of the flaw, the electromagnetic field induced in the work piece being calculated analytically. The X-ray and Gamma-ray tool uses a “ray” approach associated to the Beer-Lambert straight line attenuation model to compute direct radiation. The scattering radiation is solved thanks to a probabilistic approach (Monte-Carlo method) that reproduces the photons/matter interaction phenomena. The CT module calculations rely on the same model as the RT one, including specific tools linked to the tomographic technique. In the present release, two 3D reconstruction algorithms have been implemented: FDB (Feldkamp, Davis and Kress) and PIXTV.
For interested readers wishing to have more information on the models, the following reference papers are available, [1] for the Ultrasonic tool, [2] for the Guided Waves module [3] for the Eddy Current part, [4] for the radiographic one and [5] for the CT module. Extensive validation works of the different codes are performed, and published on the EXTENDE website www.extende.com/validation-2. This validation activity also includes the participation in international benchmarks [6].

One of the main advantages of the semi-analytical approach is to make it possible to solve parametric studies with computation time compatible with industrial use (sensitivity study, tracking of the best design or of the worst case scenario, etc.). By giving quantitative and numerous results in a relatively short time and integrated in an intuitive environment, the simulation can constitute a real benefit to optimize performances and cost efficiency in a NDT process.

3. DESCRIPTION OF THE STUDY

In this study, EXTENDE and TOTAL have simulated with CIVA software, a part of the inspections carried out for a project qualification. The pipelines involved are 48’’ OD ones with a wall thickness of 1.05” (26.8mm). Welds preparations are J-BEVEL type with a bevel angle of 1°. A cross-section schematic view of the weld is displayed below.

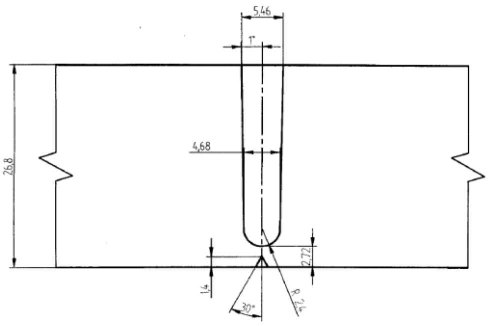


Figure 3: 1° J-Bevel weld cross-section

The PipeWizard Systems is used to perform the inspections. The system mainly includes two linear phased-array probes (one for the upstream side and one for the downstream side) working at 7.5MHz and providing different acquisition channels to focus the beam successively in the different zones of the weld while the mechanical system rotates around the pipeline circumference to cover the full volume of the weld. Each channel is defined by the focal law applied to a specific group of elements, among those available on the whole array.

The calibration mock-up has been defined in the software and the results obtained on 10 representative channels have been analyzed. After that, the second step of the qualification process has been simulated with the modeling of the response from a couple of weld flaws whose geometries were derived from the macrographs available in the project qualification report.

4. INPUT DATA REQUIREMENTS FOR CIVA CALCULATIONS

The following data are required to run accurate CIVA calculations:

	Required data	Comments
Pipe and weld geometry	Detailed drawing	
Pipe material	1. Compression wave speed 2. Shear wave speed 3. Density	
Probes characteristics	1. Frequency 2. Array type, 3. Number of elements 4. Elements width and length 5. Pitch 6. Index point 7. Wedges properties: geometry, material, wedge angle, wedge delay (acoustic path length)	1. Measured central frequency shall be preferred to theoretical frequency.
Focal laws	1. Open elements (active aperture), 2. Delays, 3. If delays not available, specification of the focal laws are required: Angle of deviation and depth of focusing (if any)	Focal laws were calculated back by CIVA for the present study. In addition, it shall be noted that offset of maximum two elements is allowed in the inspection procedure.
Inspection set-up	Position of the probes with respect to the weld centreline. Step	
Calibration block	Detailed drawing of reference, reflectors location and geometry	
Experimental results	Exact amplitude of all defects captured by the same channel.	It is very interesting for the calibration of the calculations to be able to compare calculated and measured amplitudes on all defects seen by a channel.

Table 1: Summary of main input parameters to enable simulation

5. MODELING OF THE CALIBRATION MOCK-UP

The first part of the study aimed at reproducing the calibration process. The calibration mock-up is represented hereafter. It includes various reference reflectors such as Flat Bottom Holes (with different diameters, positions and orientations) and notches (different sizes, shapes and locations):

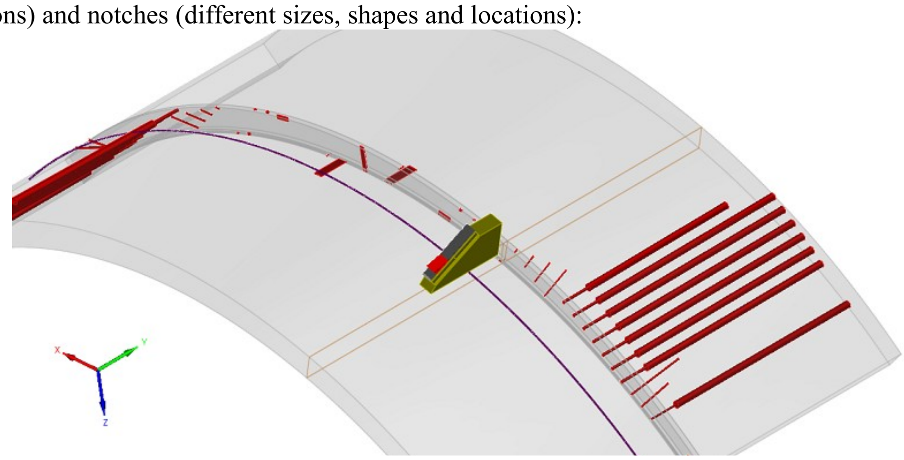


Figure 4: View of the calibration mock-up model in CIVA

10 channels were simulated. They have been selected in order to cover pipe wall thickness:

- Channels dedicated to the root and the Hot Pass zone: R1U, R2U, H1U
- Channels dedicated to the fusion line or “Fill” zone: F1U, F2U and F7U
- Channels dedicated to the cap zone: FC1U and FC2U
- Channels dedicated to the volume of the weld: V3U, V3D

These channels operate either in the pulse-echo or in the tandem mode. As each channel is highly focused, it can be pointed out that this method is really sensitive to the actual location of the transducer and the actual group of active elements. The main features of the different channels are summarized in the following table:

Channel name	Type	Number of active elements in the group	1st active element (system set up procedure)	1st active element (CIVA)	Angular deviation (°)
R1U	T/R	17	19	23	60
R2U	T/R	16	23	23	60
H1U	T/R	17	34	36	50
	T	8	36	38	50
F1U	R	8	43	45	52
	T	16	29	32	50
F2U	R	17	41	44	52
	T	16	20	22	45
F7U	R	17	15	14	47
FC2U	T/R	16	8	8	50
FC1U	T/R	16	9	8	50
VOL3U	T/R	17	28	28	45
VOL3D	T/R	17	30	28	45

Table 2: Channels set-up

As an example, the image below corresponds to the F2U channel settings represented in CIVA. It shows the beam path (6dB envelope) and the reference reflector (in this case a FBH). The beam calculated by CIVA is displayed both in the incident plane of the transducer and in the orthogonal plane (weld plane). It can be noticed that the beam spot size corresponds to the expected requirement of the zonal discrimination method (i.e. around 3mm spot height):

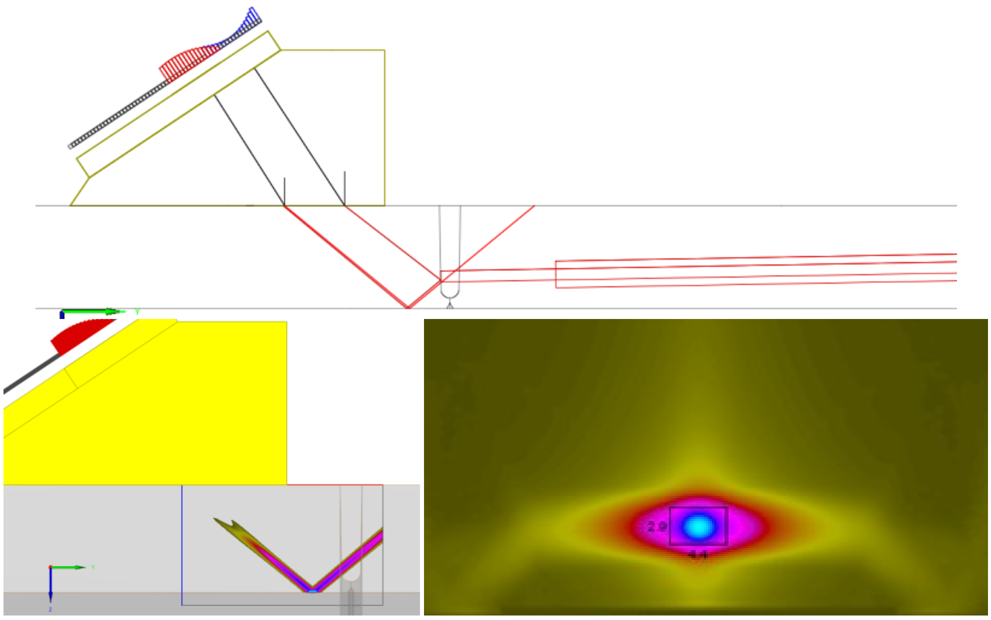


Figure 5: F2U channel views: a) Ray tracing,
*b) Transmitted beam calculated in the incident plane, c) spot sizing in the weld plane (2.9mm*4.4mm at -6dB)*

The results chart of the calibration mock-up is presented below (experiments on the left and CIVA calculations on the right). The signals of reference reflectors set at 80% Full Screen Height are highlighted with a yellow frame. A good agreement can be noticed between experiments and calculations. However, two discrepancies can be mentioned: With the channels R1U and R2U, the first group of signals on the left of the chart seems to be overestimated by the simulation. With the channels F7U, FC2U and FC1U, the last signal on the right of the chart is slightly out of the time acquisition gate of the simulation and therefore is excluded from the simulation chart. In both cases, these reflectors are not the main target of the respective channels. The uncertainties on the focal laws actual settings or on the system position can easily explain these differences.

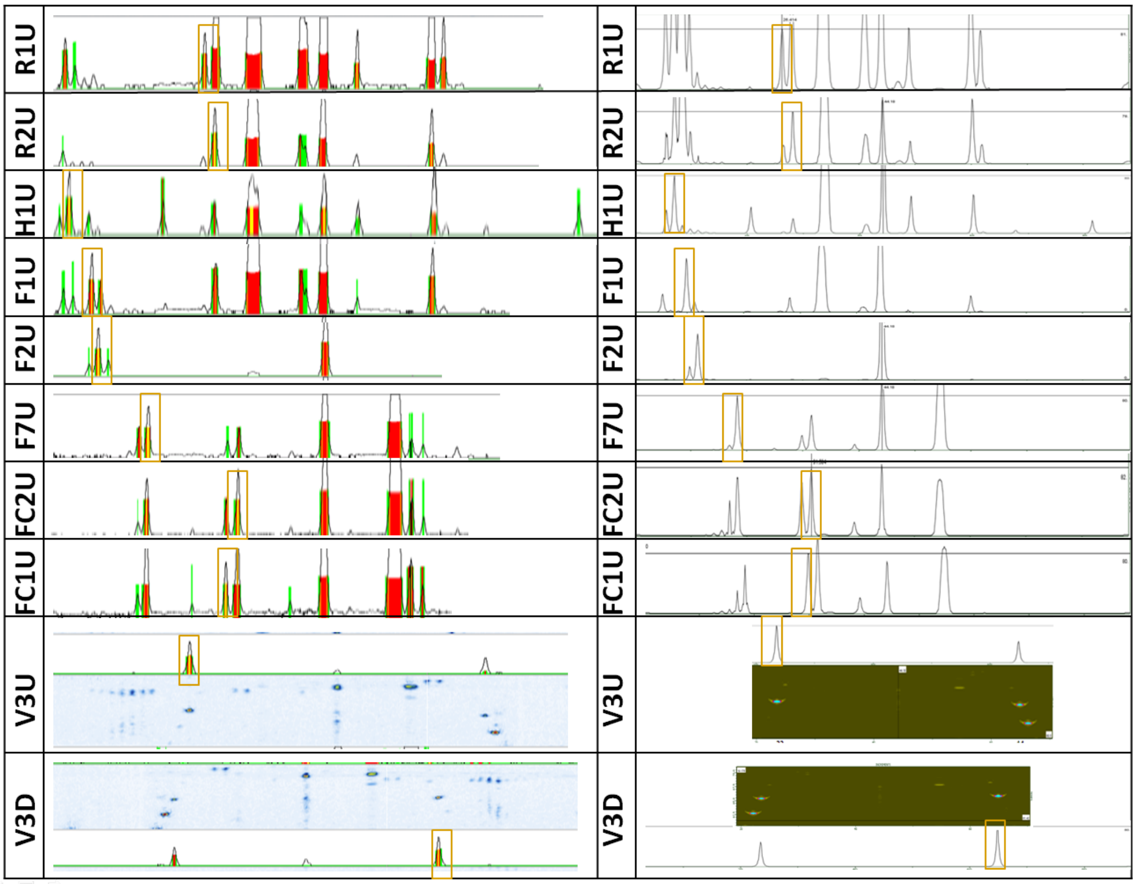
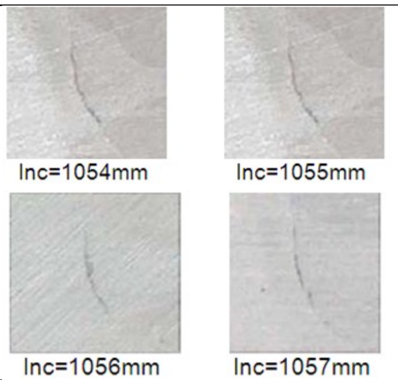
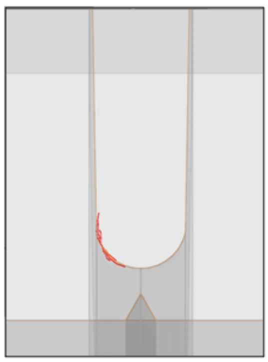
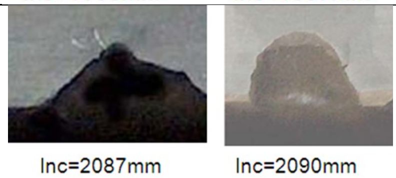
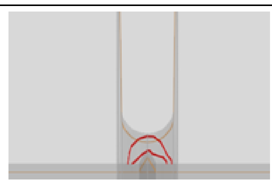


Figure 6: Calibration results: PipeWizard on the left, CIVA results on the right

6. MODELING OF REAL DEFECTS IN QUALIFICATION WELDS

The second step of the qualification process was to compare CIVA calculations with AUT inspection results on defective welds. Various types of flaws among the different qualification welds available have been selected
The macrographs of five typical flaws are shown below as well as their representation in CIVA software.

Weld 1 – Flaw 1: Lack Of Fusion (LoF)		
Weld 1 – Flaw 2: Burn Through (BT)		

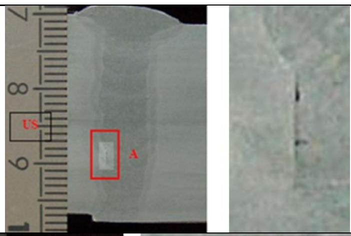
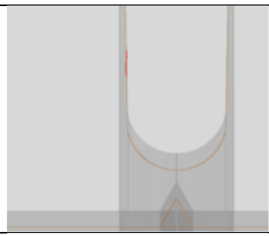
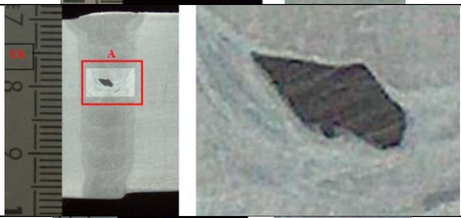
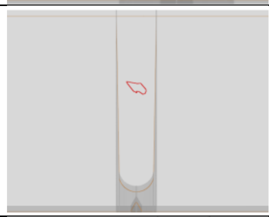
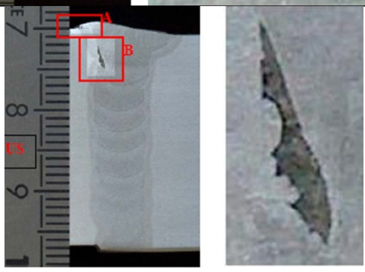
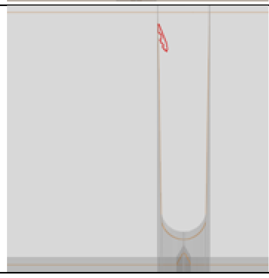
Weld 2: Lack of Fusion (LoF)		
Weld3: Porosity (Por)		
Weld 4: Lack of Fusion (LoF)		

Figure 7: Macrographs of real flaws and their representation in CIVA

The response of these flaws with the different channels involved around the inspected area has been simulated. For instance, the D-Scan and the corresponding echodynamic curve obtained for the 1st flaw of the 1st weld (Lack of Fusion) with the channel H1U (Hot Pas) and the associated calibrated reflector is provided hereafter:

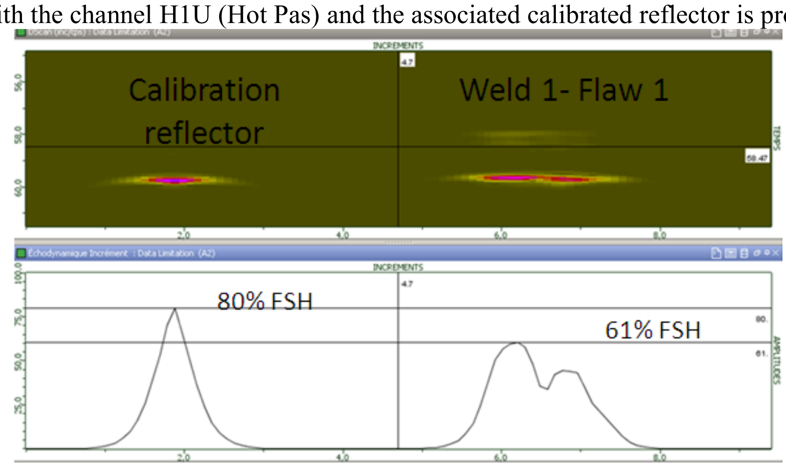


Figure 8: Simulated CIVA D-Scan and echodynamic charts for Weld1-Flaw1 with Channel H1U

From these results, the maximum amplitudes were extracted and compared to the examination reports of the qualification. These results are summarized in the table 3. A good agreement is obtained between the model and PipeWizard results. The amplitude difference is below 2dB for the majority of the studied cases. These results are promising and provide confidence in the ability of CIVA to reproduce acquisition results. On the fourteen amplitudes presented above, only 2 or 3 results show less good agreement. For flaw 2 of weld 1 (Burn Through), the discrepancy on the channel F1U probably comes from a lack of information on the real profile of the flaw. Indeed, considering the macro provided, it seems this flaw is really located at the root, and it is unlikely that this flaw generates such a strong signal on a Fill channel like F1U. An additional macro on another increment would probably give more information on the real profile of this flaw. For the R2U channel, the difference is more probably due to wrong settings in the model as some doubts were emitted regarding the calibration for Root channels (see before), due to uncertainties on the real phased-array settings (active elements of the group, focal law). For the flaw of the second weld (Lack of Fusion), two simulations have been performed with a shift of 1mm on the index point. Actually, as the simulation of the real cracks relies on the hypothesis that the probe to weld distance is the same as in the calibration, some discrepancies may appear on this parameter due to the tack welding performed on the real weld. In this case, it can be noticed that a change of 1mm slightly changes the result on channel F1U while it strongly improves the amplitude received on channel F2U. Such large changes demonstrate the strong sensitivity of this technique to the actual transducer location. It also shows that a scenario can be easily defined in order to evaluate the impact of changing some parameters compared to the “nominal” situation. Not only the location of the transducer, but also the flaw characteristics (location, size, and orientation), the focal laws or the transducer properties are examples of parameters where scenarios of variations can be investigated.

<table>
<tr><th>Weld- Flaw</th><th>Channel</th><th>PipeWizard Result</th><th colspan="2">CIVA Results</th></tr>
<tr><td rowspan="3">Weld1 - Flaw1 (LoF)</td><td>F1U</td><td>73%</td><td colspan="2">48%</td></tr>
<tr><td>H1U</td><td>58%</td><td colspan="2">61%</td></tr>
<tr><td>R1U</td><td>SAT</td><td colspan="2">SAT</td></tr>
<tr><td rowspan="4">Weld1 - Flaw 2 (BT)</td><td>F1U</td><td>74%</td><td colspan="2">10%</td></tr>
<tr><td>H1U</td><td>66%</td><td colspan="2">57%</td></tr>
<tr><td>R1U</td><td>SAT</td><td colspan="2">SAT</td></tr>
<tr><td>R2U</td><td>27%</td><td colspan="2">SAT</td></tr>
<tr><td rowspan="2">Weld2- Flaw 1 (LoF)</td><td>F1U</td><td>37%</td><td>45%</td><td>41%*</td></tr>
<tr><td>F2U</td><td>24%</td><td>119%</td><td>28%*</td></tr>
<tr><td rowspan="2">Weld3 - Flaw 1 (Por)</td><td>V3U</td><td>SAT</td><td colspan="2">SAT</td></tr>
<tr><td>V3D</td><td>27%</td><td colspan="2">32%</td></tr>
<tr><td rowspan="3">Weld4- Flaw 1 (LoF)</td><td>F7U</td><td>86%</td><td colspan="2">90%</td></tr>
<tr><td>FC2U</td><td>75%</td><td colspan="2">SAT</td></tr>
<tr><td>FC1U</td><td>SAT</td><td colspan="2">SAT</td></tr>
</table>

Table 3: Comparison of PipeWizard and CIVA Results
*(*for this flaw, 2 simulations have been performed, see previous comments)*

7. CONCLUSIONS

For the inspection of pipeline girth welds, the zonal discrimination method based on automated UT systems is the most commonly used NDT technique today in the oil & gas industry. Each new project requires a qualification of the inspection equipment according to DNV standards and companies internal specifications.
EXTENDE have performed a simulation study for TOTAL in order to qualify the ability of modeling tools to reproduce results provided by AUT inspection systems, such as PipeWizard, for pipeline Girth Welds inspection. Inspection set-up and procedure from a project were reproduced in the NDT software CIVA in which all steps of the qualification process were simulated (the calibration mock-up and the response from real flaws embedded in qualification welds). The results of this study show that there is good agreement between the model and the experimental acquisition results. This is promising as it means that simulation can replace part of the extensive qualification tests and allow saving both cost and time as it is done in other industrial sectors such as the power generation industry. In addition, it allows increasing the number of tests thereby helping to improve the qualification process itself. For instance, more reliable PoD or sizing accuracy curves could be built with the assistance of modeling results as the simulation could help to enlarge the population of flaws used to compute the PoD curve which today is strongly dependent on the defects that have been actually created in the qualification welds. The ability to better understand the impact of influential parameters of the inspection can also provide additional benefits such as the possibility to improve the performance and the reliability of inspection methods or also to train and qualify NDT operators.

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