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CIVA Modelling Module for Zonal Discrimination Method
Part 1-Calibration Block

Ed Ginzel [1]
[1] University of Waterloo, Waterloo, Ontario, Canada
e-mail: eginzel@mri.on.ca
Dave Stewart[2]
[2]Simply AUT, Edmonton, Alberta, Canada
e-mail: david.stewart@simplyaut.ca

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Abstract

The 2023 edition of CIVA simulation software has incorporated a module specifically designed for pipeline production weld inspections (Automated Ultrasonic Testing or AUT). Both Zonal Discrimination Method (ZDM) and Total Focussing Method (TFM) options have been included. Unlike the standard ultrasonic module, the "AUT" module has provision to run and display the outputs from multiple channels. This allows for the echo-dynamic display to be seen in a view similar to the strip-chart display commonly used with the zonal discrimination method. Having configured the delay laws to generate an acceptable calibration, CIVA tools such as the meta-model and POD modules can then be used to assess the reliability of the setup (including the efficacy of the calibration block design) for a qualification process. This paper illustrates how the calibration block design is executed for the zonal discrimination method. Results are compared to data collected for a field qualification. A subsequent paper is planned to compare the statistical analysis carried out in the field to assess the inspection reliability.

Keywords: CIVA, phased-array, ultrasonic, Zonal Discrimination Method

1. Introduction

Zonal Discrimination Method (ZDM) has been a popular inspection method for construction of pipeline girth welds since the 1980s. With its absence of radiation, rapid data collection and ability to allow flaw sizing, it quickly replaced radiography as the preferred NDT option. In 2011 the authors published a paper [1] to illustrate how CIVA simulation software could be used to simulate the zonal discrimination method. In 2013, Fernadez and Foucher [2] presented another paper that illustrated CIVA being used to simulate ZDM. Both papers took advantage of the fact that CIVA provides a display tool called "Echodynamic increment". Echodynamic increment plots the maximum amplitude from a channel at each position along the scan path. This is the same information that is collected and displayed for the amplitude-gated data in each zonal channel in the ZDM strip-chart. However, in preparing the presentations for strip-charts, these papers required that the individual echodynamic increment plots be pasted next to each other to give the appearance of the traditional strip-chart. The 2023 version of CIVA can collect the amplitude data and prepare the strip-chart from multiple channels.

By limiting the gated time-interval to a small region before and after the position of the weld bevel, the data display of amplitude in the strip-chart can be used to quickly identify the presence of flaws. Incorporating a colour-display in the strip-chart, flaws having amplitude greater than the evaluation level can be identified, evaluated and dispositioned.

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The key to the reliability and effectiveness of any ZDM project is in the design of the calibration block and the configuration of the ultrasonic beams. The beams must be positioned precisely in the zone they are intended to interrogate. Codes [3, 4] are now in place to describe how adjacent zones in the same plane should limit the over-trace to at least 6 dB and not more than 14 dB lower than from the zone for which the beam is calibrated for. DNVGL-ST-F101 - Appendix E - E.2.4.10 states "*Transducers used for zonal discrimination shall give signals from adjacent zones (over-trace), given that there is no shift in weld bevel angle between the zones. For adjacent zones of comparable size and with equal calibration sensitivity, the over-trace shall be within 15% FSH to 50% FSH when the peak signal from the calibration reflector representing the zone of interest is set to 80% FSH*." This separation of zones is critical to the methods used for sizing flaws as the sizing estimates are based on apportioning the amplitude responses in adjacent channels.

CIVA 2023 AUT module provides facility to build a calibration block using specified calibration targets. Surface notches and flat bottom holes (FBHs) can be specified for size, angle and position relative to the theoretical weld bevel. The probe and wedge design can be selected from several manufacturers' options in the library or a custom design can be made.

Upon completing the initial calibration block design, delay laws can be imported for each zonal and volumetric target and a simulated test scan run. The test scan is configured to limit computations to just the main zones plus the zones immediately adjacent to the main zone. After assessing the zonal discrimination by determining if the amplitude differences between zones is in accord with the code and procedure requirements, refinements can be made to the delay laws if required. Additionally, the number and position of the targets can be adjusted if over-traces are excessive or not adequate.

Once the calibration block and delay laws have been optimised, the process of determining if the inspection procedure is reliable can then be carried out using a parametric study and the principles of meta-modelling and POD tools in CIVA.

In this paper the CIVA AUT calibration component is validated by comparing details with the parameters used for a field qualification.

2. Weld and Target Configuration

For the field qualification, a J-bevel was used. The pipe was NPS 6" (168mm outside diameter) with nominal wall thickness of 15.88mm. Weld details are illustrated in Figure 1.

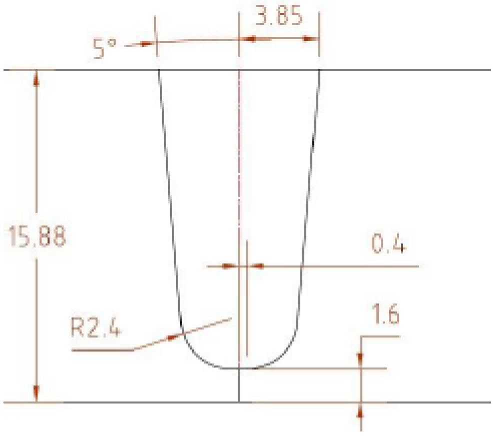

Figure 1 Qualification weld parameters

The inspection procedure included transverse targets and extra targets were used to extend the detection capabilities into the Heat Affected Zone (HAZ) in the root and cap regions. An extra target is also incorporated to verify that the fusion zone channels are extended sufficiently to detect flaws that might be at the centreline. This is typically a through-wall hole or slot. In addition to the more common lack of sidewall fusion flaws, flaws can also occur inside the weld volume. These would include porosity clusters and interpass lack of fusion or "stop-start" flaws. Separate B-scan data collection with pulse-echo channels is used to detect and characterise these flaws and they would not be sized using the same zonal discrimination technique as is used for the sidewall nonfusion.

Details of some of the targets used in the field qualification are illustrated in Figure 2. The Fill targets in the field calibration block were made using electrode discharge machining (EDM) with a specially prepared electrode that had an angled cut to allow the tip of the target to align with the weld bevel when the electrode was angled at 20° from the horizontal.

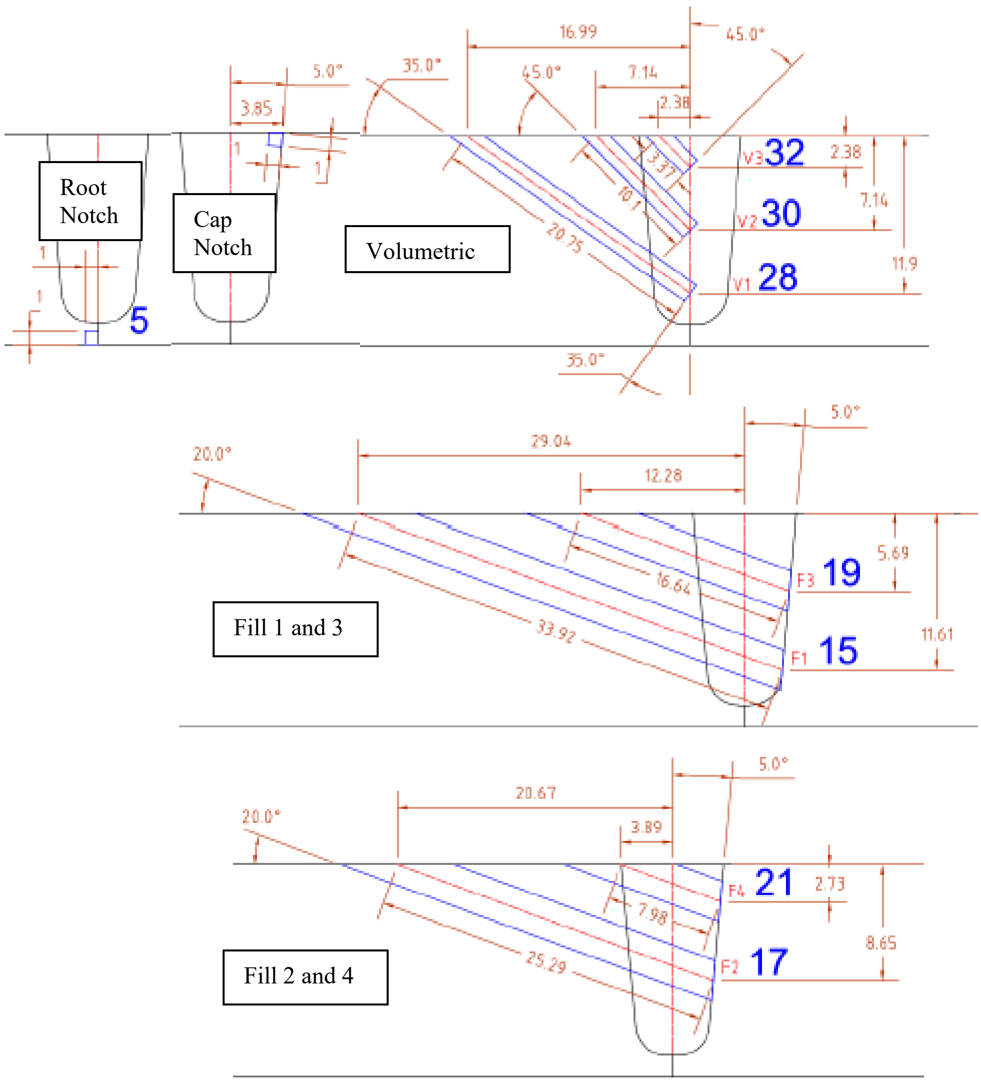

Figure 2 Field qualification calibration targets

3. CIVA AUT Calibration Block Construction

The field data used in this paper is from a successful qualification of a ZDM procedure. This procedure obtained acceptable zonal discrimination with the targets in the positions indicated in Figure 2. Therefore, in order to validate the simulation, the same target layout was used. A simple user-interface allows the positioning of the probe and targets. When the complete set of targets is input, the resulting 3D image provides a view of layout as seen in Figure 3.

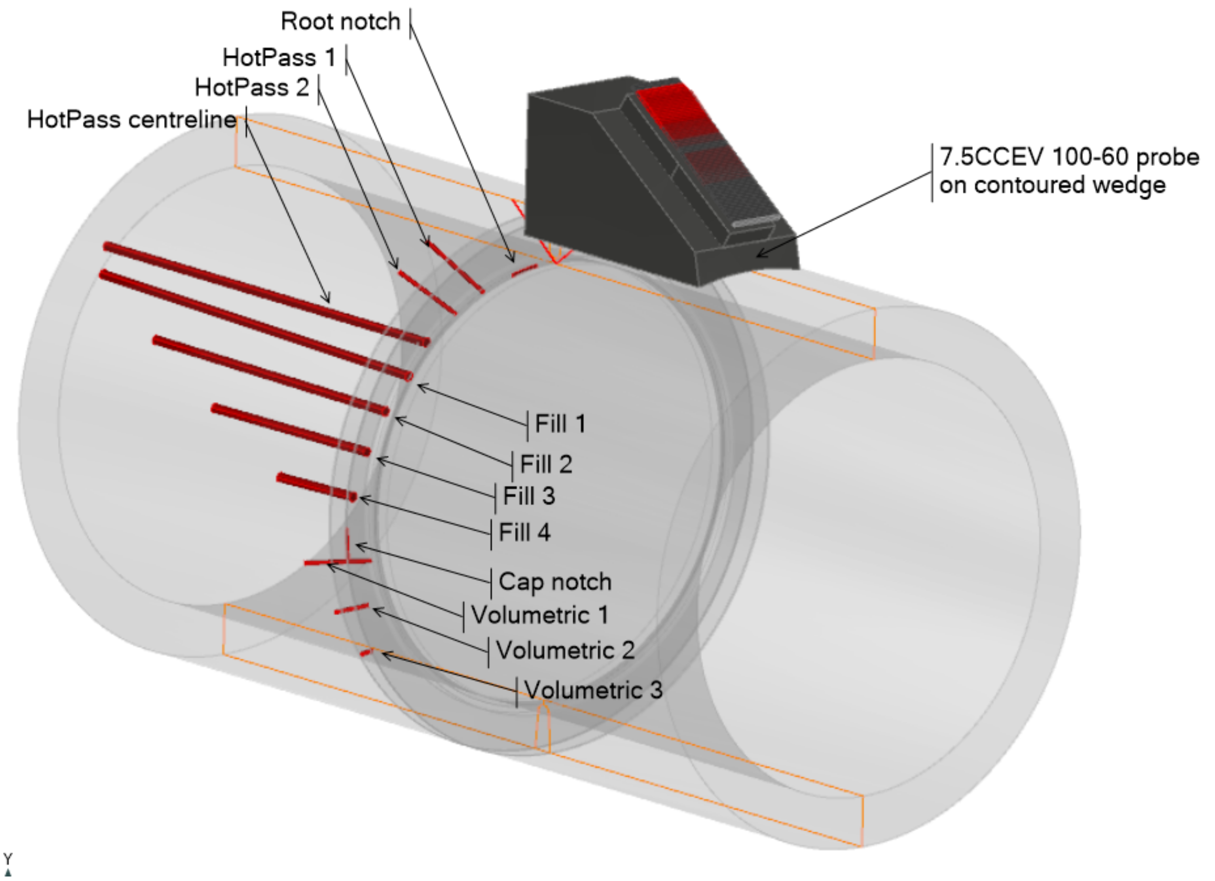

Figure 3 CIVA AUT calibration targets

Phased-array delay laws are imported for each zone and volumetric target. Apertures from the qualified procedure were used as a starting point to locate the beams at the centre of each target. At the time of writing, the CIVA AUT module assumes that the pipe is an isotropic steel, so the acoustic velocities are constant for each delay law. The field qualification was done an a TMCP steel which is anisotropic. As a result, the CIVA AUT delay laws had to be altered slightly compared to those in the field; however, the refracted angles used in the field were the same as those used in the simulation. With the narrow gap J-bevel, the Fill zones all used a tandem arrangement of the apertures so the UT module in CIVA was used to visualise the ray paths of the Tx and Rx components to ensure they intersected at the centre of the zones. Figure 4 shows how the tandem paths were optimised.

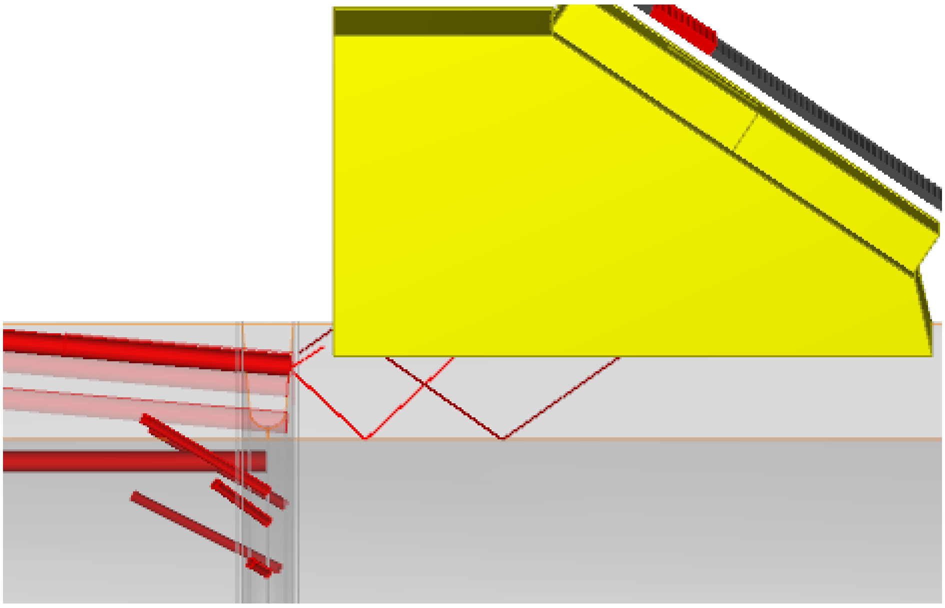

Figure 4 Tx-Rx tandem ray paths for Fill 3 set to intersect on calibration targets

4. Calibration Scan

Having configured the calibration block targets and the appropriate delay laws for each zone and volumetric target, the scan of the calibration block can be made. This uses the Batch-File manager in CIVA to organise the computation of the responses from multiple channels. Upon completion the overall results can be seen on a Strip-chart, or the individual channels can be evaluated using the B-scans, C-scans and echodynamic plots.

Figure 5 shows the strip-chart generated by the validation scan compared to the responses from the field qualification. The field calibration block included extra targets including Time of Flight Diffraction (TOFD) cap and root notches, Heat Affected Zone (HAZ) notches, a centreline slot and transverse notches. These were not used in the CIVA AUT setup.

As well, the field qualification used a separate analysis view for volumetric data.

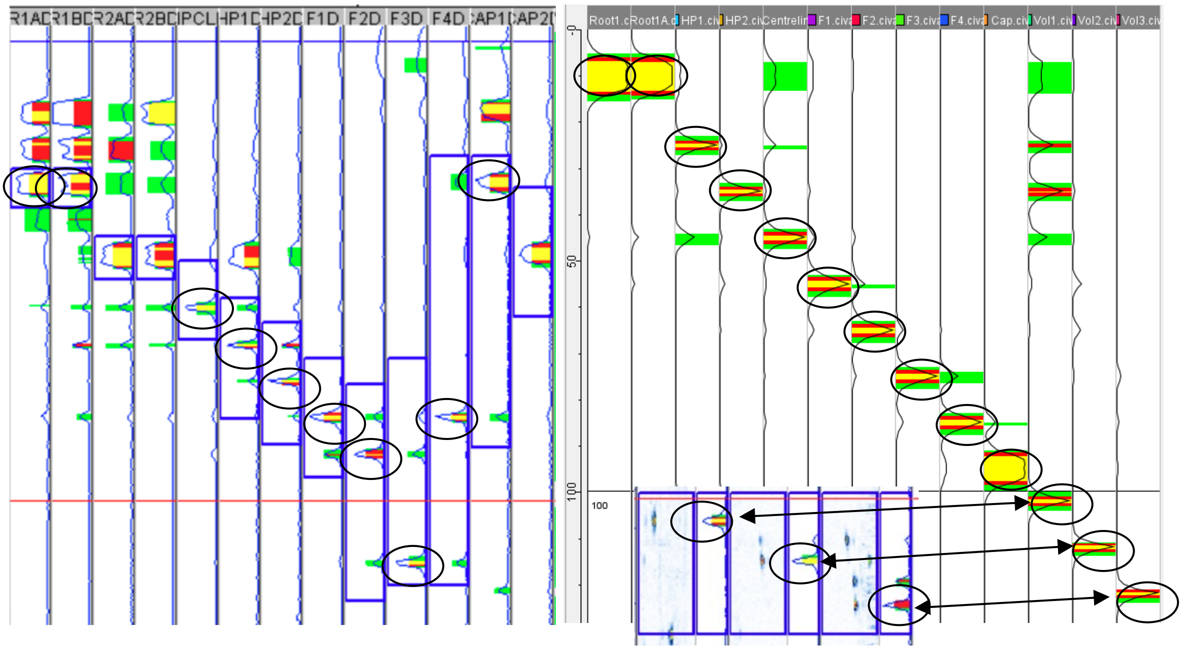

Figure 5 Strip-chart validation scan of calibration block (PWZ left CIVA right)

Figure 6 illustrates the options for individual views available for each channel or zone. Since the strip-chart display does not indicate time in the amplitude gate, these other views can be helpful to assess arrival times to help characterise the source of signals.

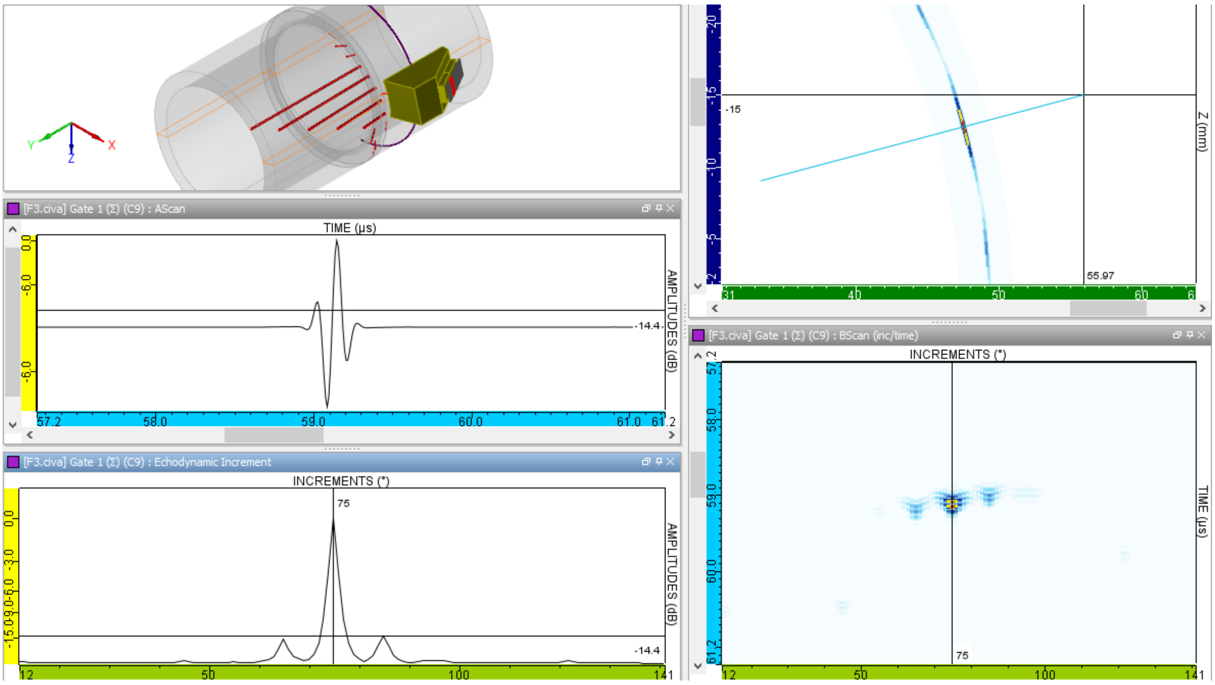

Figure 6 Views available for each zonal channel

In addition to the strip chart, echodynamic curves, A and B scan displays, the AUT module allows the calculation of the relative sensitivity of the individual beams being used in the scan. For example, in Figure 7 the relative sensitivity coverage provided by tandem paths used for the Fill Zones is indicated on the left side. When all Fill channels are considered as a group, the CIVA plots for each beam is normalised to the beam having the maximum sensitivity. On the right side of Figure 7 the colour palette is adjusted so all Fill zones (and the cap) have their maximum sensitivities equalised as would be the case in a calibration and the -6dB regions are outlined.

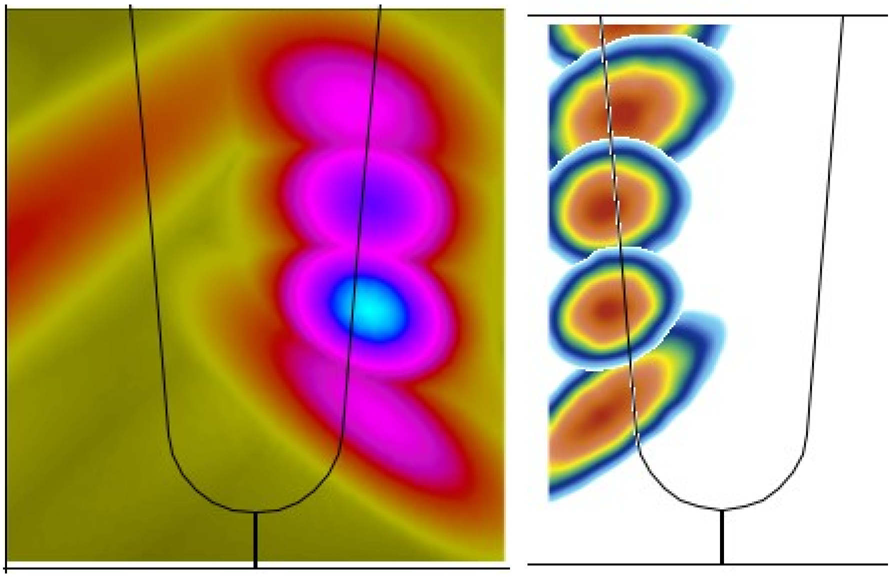

Figure 7 Sensitivity Coverage in 4 Fill Zones relative to maximum (left). Equalised and indicating to -6dB on overlays (right)

The Sensitivity Coverage feature is a fast convenient way of assessing the number of tandem fill zones that should be used to ensure good detection of flaws of concern. Too often, companies try to use zones that are too big for adequate coverage. As an example, using 3 fill zones instead of 4 fill zones in the same weld as in Figure 7, large areas of missed coverage are apparent, as seen in Figure 8. Nearly 1mm of vertical extent is not being covered between the --6dB portions of the beams for the Fill 1 and Fill 2 zones and between Fill 3 and the Cap zones. Centres of the fills in the 4-Fill zone option are separated by 2.96mm whereas in the 3-Fill zone option it is 3.27mm. Note, this is just a 0.3mm difference in zone separations; however, the ultrasonic coverage difference is significant. Apertures could be reduced to increase the spot sizes of each beam, but this would compromise the accuracy of sizing using apportioned amplitude.

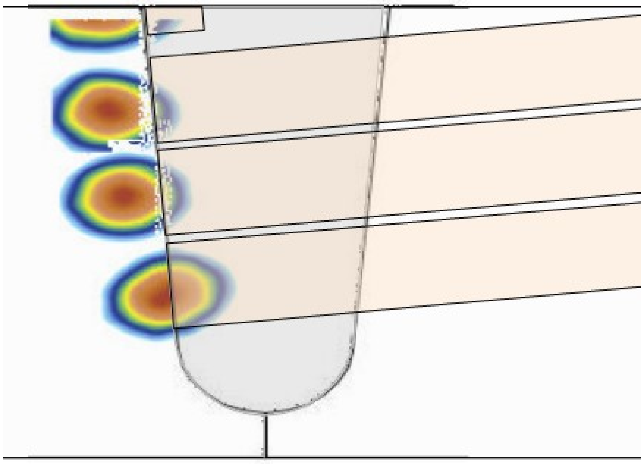

Figure 8 Sensitivity Coverage in 3 Fill Zones equalised including cap

5. Evaluation

Upon completion of the Calibration scan, CIVA provides a summary of amplitude results in tabular form (Table 1), rating the normalised zone amplitude for the primary zones target to the other channels.

Table 1 Table of zone amplitudes

	Root1	Root2	HP1	HP2	HPC...	F1	F2	F3	F4	Vol1	Vol2	Vol3	Cap
Root1	0.0	0.0	0.0	-25.2	-10.6	-21.5	-32.5	-37.4	-46.0	2.8	-49.0	-39.7	-54.2
Root2	0.0	0.0	0.0	-25.2	-10.6	-21.5	-32.5	-37.4	-46.0	2.8	-49.0	-39.7	-54.2
HP	22.5	-35.4	0.0	-25.2	-10.9	-47.8	-60.9	-55.5	-76.7	-2.6	-49.0	-39.7	-70.0
HP2	-35.6	-48.9	-24.3	0.0	-24.3	-37.6	-54.1	-53.1	-74.5	1.3	-42.8	-42.9	-65.2
HPCe...	-14.0	-15.4	-7.0	-24.2	0.0	-22.5	-21.4	-31.5	-42.4	-17.6	-63.4	-64.2	-55.4
F1	-41.0	-23.0	-34.2	-18.6	-23.6	0.0	-16.1	-35.6	-50.6	-15.9	-35.3	-57.7	-58.9
F2	-46.5	-32.7	-46.5	-29.0	-24.1	-7.6	0.0	-14.1	-34.7	-16.9	-35.5	-44.8	-49.6
F3	-42.2	-43.4	-39.7	-38.5	-30.3	-24.1	-11.6	0.0	-9.0	-16.5	-37.3	-17.4	-38.1
F4	-59.4	-58.3	-36.8	-38.1	-25.7	-37.4	-31.9	-10.6	0.0	-13.2	-62.8	-15.4	-12.4
Vol1	-40.6	-40.0	-6.3	-7.8	-15.6	-44.9	-52.0	-54.8	-44.0	0.0	-46.4	-40.8	-54.1
Vol2	-56.1	-46.0	-42.2	-22.9	-29.8	-47.5	-50.2	-46.8	-59.7	-8.1	0.0	-24.0	-63.6
Vol3	-57.4	-57.7	-56.4	-46.3	-38.5	-65.0	-54.4	-34.5	-25.3	-0.3	-28.1	0.0	-9.2
Cap	-72.0	-69.2	-48.1	-46.1	-40.0	-55.3	-45.0	-34.9	-15.8	5.6	0.0	0.0	0.0

When the CIVA AUT calibration scan is compared to the qualified field calibration scan, we can see that the zonal discrimination predicted by CIVA is very similar to the actual results. Table 2 provides a summary of the zonal discrimination by indicating the screen height differences of adjacent channels in the Fill Zones.

Table 2 Table of overtrace amplitude differences in Fill Zones

Zone	Field			CIVA		
	Zone above	Main Zone	Zone below	Zone above	Main Zone	Zone below
F1	-7.1	0	NA	-7.6	0	NA
F2	-9.2	0	-10.2	-11.6	0	-16.1
F3	-10.6	0	-8	-10.6	0	-14.1
F4	NC	0	-9.3	-12.4	0	-9
Cap	NA	0	NC	NA	0	-12.4

NA=not applicable NC=not calculated

Table 2 indicates that the simulated calibration and field qualification calibration are comparable. This would provide assurance that the number and positions of the targets could be planned for the project using the CIVA AUT simulation prior to the fabrication of the calibration block. Identical overtrace cannot be expected. Even in the field, small variations can occur in a calibration from one calibration scan to the next. A significant factor resulting in variation between field and simulation results can be attributed to the fact that the field material was TMCP steel (anisotropic) and the simulation assumed isotropic steel.

Having established an acceptable calibration block design and delay laws, the project could proceed to the field. In the field, a qualification of reliability would have amplitude responses compared to flaw sizes determined by salami sectioning and macro photos. This would be the foundation of the Probability of Detection (POD) used to establish the 90|95 (i.e., the flaw size that would be detected 90% of the time with a 95% confidence). A further process can be carried out to qualify the sizing capability of the procedure such that there is more than 85% probability of rejecting a defect which is not acceptable according to the ECA-determined criteria. This shall be shown at 95% confidence level. This is the so-called POR criterion and requires that an accurate sizing procedure be used in the analysis process.

In order for the confidence level to be reliable, both the POD and POR require relatively large numbers of samples be assessed. The CIVA AUT simulation software incorporates provisions to assess both of these items and will be the topic of a future paper.

6. Sensitivity Experimentation

In the year 2000, the authors participated in the first AUT qualification in accordance with DNV OS-F101. This was the first time that a probabilistic approach had been used to assess an AUT system. The calibration block designed for that qualification was based on Canadian AUT experiences from the 1990s. To ensure a conservative approach, the Canadian standard required use of a 2mm diameter FBH for the zonal targets. In the DNV qualification it was seen that although sensitivity set using the 2mm diameter FBH provided excellent probability of detection (POD), the overtrace was excessive and reduced the accuracy of the sizing estimates.

With the introduction of the CIVA AUT calibration module, we can now examine what the effects would be when varying the diameter of the FBHs in the fill zones.

Having completed the setup for a good calibration, as evidenced in Figure 5, the setup was modified by just changing the Fill targets from 3mm diameter to 2mm diameter. The Fill Zones appeared to look identical as seen in Figure 9.

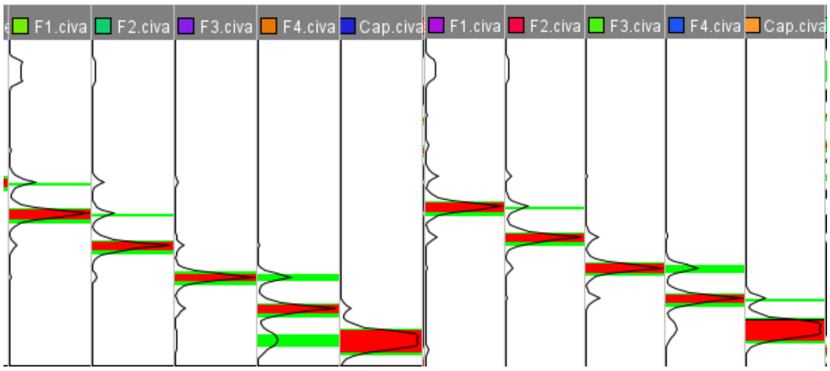

Figure 9 Comparing sensitivity in fills. 2mm FBH (left) and 3mm FBH (right)

In all cases, CIVA has normalised the main target to 0dB. From the strip charts they appear to be "equal". However, upon a more detailed comparison significant differences can be seen.

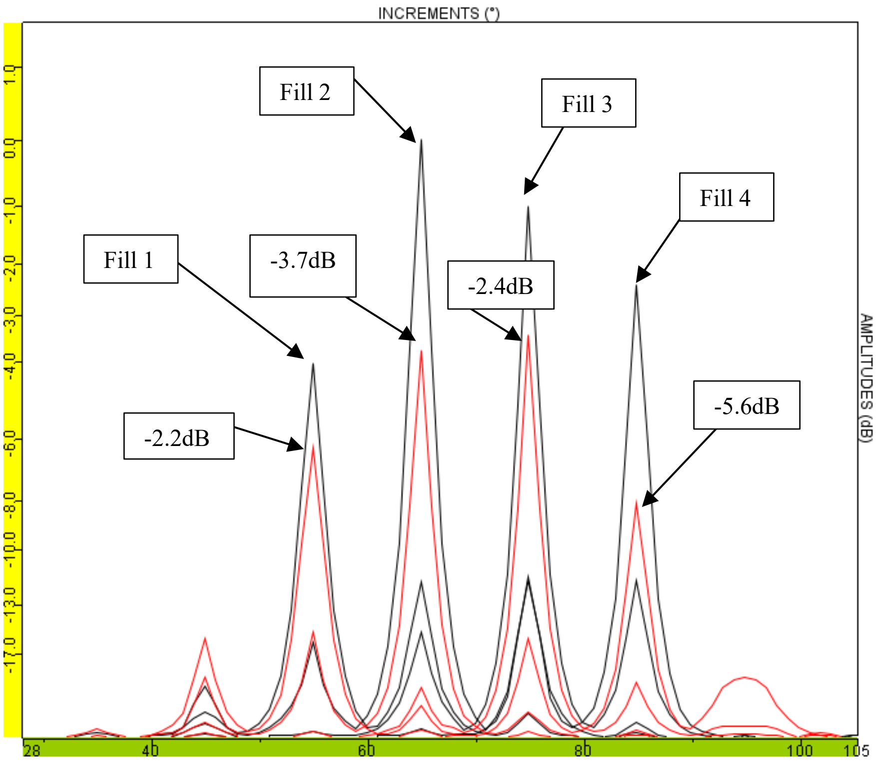

Figure 9 Comparing echo-dynamics in fills. 2mm FBH (red) and 3mm FBH (black)

Figure 9 is a plot of the superposition of the fills from the 3mm and 2mm diameter targets. The Black lines indicate responses from the 3mm diameter targets and the red lines from the 2mm diameter targets. Although the targets have a 1mm diameter difference in all cases, the amplitude variation is not a constant! In the 2000 qualification, the Ermolov equations were used to estimate that a constant 7.2dB difference would account for the decreased sensitivity using 3mm diameter FBHs instead of 2mm diameter FBHs. This assumption is however, based on flat unfocussed probes and although it might be reasonable for pulse-echo configurations where the beam impinges perpendicular to the FBH surface, CIVA demonstrates that it is not valid for tandem paths with focussed beams. In addition to the differences between the primary zonal targets when using 3mm and 2mm FBHs, the overtrace values for each fill zone do not remain constant.

7. Conclusions

Use of CIVA AUT simulation module has proven to provide evidence that the simulation closely matches the field results.

Compared to the process required with just the UT simulation module in 2011, results were obtained much faster and were easier to assess for overtrace between channels as a result of the strip chart display built into the module.

Ability to predict the effects of the target positions (depth), size and angle, allows for optimisation of the calibration block design prior to sending the drawings to the machine shop for fabrication. This could be a cost and time saving if the design targets proved to be inadequate in number or excessive in size.

The AUT Calibration module provides an easy assessment of varying the diameter zone targets when using tandem paths in the narrow gap weld preparations.

The Hot Pass zone of a J-bevel weld preparation can be particularly troublesome to configure targets with suitable size and angles. Having to ability to evaluate these parameters helps to ensure good probability of detection on the curved surface of the bevel.

Having developed a setup with a specific probe and wedge, experimentation with different probes and wedges is possible to assess if a different pitch or frequency of probe could be advantageous.

Sensitivity Coverage is a new feature that provides visual images of the effective region of the beam in each zone. Results can be generated in seconds. It is especially useful for tandem paths and allows the user to identify if the apertures need to be increased or decreased and helps to identify if the zonal targets are adequately spaced to avoid missing flaws.

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