EVALUATION OF CIVA FOR ULTRASONIC APPLICATIONS

M. Dennis, T. Seuaciuc-Osorio, G. Connolly, F. Yu, EPRI, United States,
C. Greener, Rolls-Royce, United Kingdom

ABSTRACT
The importance of mathematical models to assist in predicting inspection results has increased with the
need to properly demonstrate nondestructive evaluation (NDE) procedures prior to field use. One of the
most commonly used programs to aid in this task is the CIVA software, developed by CEA. CIVA allows
users to perform simulations for ultrasonic, eddy current, and radiographic inspection methods.

This paper provides an independent assessment regarding the accuracy of this software using a
series of practical examples. The CIVA simulation results are taken from a pair of simple test blocks with
a variety of prepared geometrical defects and an austenitic stainless steel piping sample. The results are
compared directly against experimental data. It is demonstrated here that CIVA simulation can reproduce
basic phenomena of reflection from prepared defects; though the comparison is strongly dependent on
choice of user input by way of modelling parameters. In conclusion, the strengths and weaknesses of the
comparison are highlighted and discussed.

INTRODUCTION
In general, the modelling approach is being used for the demonstration of a range of NDE methods, be
they UT, RT or ET, in the nuclear industry to a greater extent [1-3]. Over time, simulation is starting to fill
a more prominent role within NDE for a variety of reasons: performance demonstration, qualification of
techniques, scan planning and even for educational, training and illustrational purposes [4].

The modelling approach is executed by way of a variety of potential modelling tools and thus it is
important that confidence is placed in the abilities of these modelling tools. This is typically done through
validation, by either potentially exhaustive analytical study of the model and its applicability, or through
quantitative comparison against experimentally-derived results in a series of carefully-chosen cases [5].
Even in cases where the comparison is revealed to be unfavourable, the latter case also is important for
determining the range of capabilities of the model and its limitations.

The simulation software in this paper is CIVA v10.1 [6,7] (the latest version at time of writing),
developed by CEA. It performs beam-computation using a semi-analytical model in order to predict the
response of arbitrary simulation flaws within a component when interrogated in pulse-echo or TOFD
mode. These responses have to be quantitatively predicted with the help of experimental calibration and
sizing reference.

In this context, this paper presents three quantitative comparisons, using the UT module, that aim to
investigate a range of CIVA's capabilities. The first is a study upon CIVA's abilities to predict the
detection of reflectors away from the central axis of the beam. The second is a comparison of CIVA's
response predictions against experimental results for reflections received from a notched block and the
third is a similar comparison for reflections received from an austenitic stainless steel piping sample.

OFF-AXIS DETECTION

Experimental procedure
For this axis, EPRI has had constructed and delivered a reference block composed of 304 stainless steel.
The block measures 76.2mm×304.8mm×101.6mm tall. One end of the block is flat and the other has two
radii of 50.8mm and 101.6mm. The block also incorporates nine Side-Drilled Holes (SDH) of diameter
1.5875mm at depths varying from 6.35mm to 88.90mm. They are numbered, arbitrarily, from one through nine with the first hole closest to the top of the block and the ninth hole closest to the bottom of the block, as viewed in Figure 1. The first four holes are spaced at 6.35mm intervals and the bottom six holes are spaced at 12.70mm intervals.

For the experimental acquisition, data were collected using Zetec’s Omniscan MX 16-128, controlled by Ultravision 1.2R7. The automated scans were performed using an ATCO LPS-1000 dual-axis encoder with a resolution of approximately 600 steps for each mm in either axis. Motion control was provided by Zetec’s MCDU-02. The probe used was General Electric’s SE1057, a 2.25MHz conventional round probe of 0.5” (12.7mm) diameter. A plexiglass wedge was used to generate transverse waves at 45º in the stainless steel sample.

The first steps were to use the probe transmitter transducer in pulse/echo mode to obtain a back wall reflection which was to serve as a reference signal for the CIVA simulation and also to obtain the longitudinal wave velocity in the specimen. Then a stainless steel calibration block was used to measure the exit point of the wedge and the wedge delay. Finally, the transverse wave velocity in the specimen was estimated using the 50.8mm and the 101.6mm radii at the curved end of the specimen.

The block was raster scanned at 1mm increments along the scan axis (x-axis) and the index axis (y-axis). The scans were performed at 50mm/s, unidirectional i.e., the data were taken with the probe moving only in the positive scan direction. Care was taken to ensure that no signal was saturated. Coupling between the transducer and the wedge was achieved using mineral oil and coupling between the wedge and the specimen was achieved using running water.

Five different skew angles were used; three positive, one neutral and one negative. The angles were 135º, 150º, 165º, 180º and 195º. One important thing to note is that the side-drilled holes do not extend throughout the entire thickness of the block; they are only drilled two thirds of the way through to the other side; this potentially means that the results of the positive and negative scans would be fundamentally different.

**Simulation procedure**

From the calibration method described above, the longitudinal and transverse wave velocities were estimated as 5661.56ms⁻¹ and 3129.90ms⁻¹ respectively. These values were employed for the CIVA simulation procedure.

The probe was modelled as a single element, circular and flat transducer with a diameter of 12.7mm. The signal used in the simulation was from the first experimental backwall reflection obtained with this probe on the specimen. The physical wedge parameters were obtained from a CAD drawing of the wedge and the refraction angle was determined experimentally using a calibration block.

![Figure 1 – Stainless steel specimen with numbered SDHs, used for off-axis detection](image-url)
The beam was calculated in the beam simulation with a resolution of 0.8mm in all three spatial dimensions along the length of the theoretical direction of the transverse wave. Only direct modes of propagation and reflection were included in the simulation to limit computation time. Additionally, only transverse waves with back wall echoes were considered. The flaws were inserted as side-drilled holes.

Five different skews were simulated, in similar fashion to the experiment: 135°, 150°, 165°, 180° and 195°, which correspond to probe skews of -45°, -30°, -15°, 0° and 15° respectively.

The inspection parameters were set to match those of the experiment as closely as possible. As such, the simulated scanning was set to be performed at 1mm steps in both scan and index directions. In every scan, the simulated wedge was to be initially flush against the origin corner (i.e., where $x=y=0$ of axes as illustrated in Figure 1) and the number of steps was chosen so that the scan ended with the impact point approximately at 203mm (atop the center of the radii at the opposite end of the specimen) and with the wedge approximately flush against the opposite side of the specimen at the last index position. Here the results for three cases are presented: 150° (positive skew), 180° (no skew) and 195° case (negative skew). These three cases are illustrated in Figure 2.

**Experimental and Simulated Comparison**

The experimental cumulated corrected side views and their corresponding simulated cumulated corrected side views for each case are shown in Figure 3. Here it is again noted that in CIVA's direct mode, only the direct responses from the flaws are computed and that no bounce, not even from the back wall, is computed. This is the principle cause of difference between the experimental results and the simulation in the no skew case.

The side views in Figure 3(a) and Figure 3(b) show a good qualitative, visual agreement between experiment and simulation. The relative amplitudes of the responses appear to be comparable, with the first four side-drilled holes having the strongest responses. Although the simulation seemed to underestimate the response of the first holes, there is a good quantitative agreement between simulation and experiment.

![Figure 2 – CIVA schematics, showing the side and top views respectively, for: (a) and (b), the 180° neutral skew case; (c) and (d), the 150° positive skew case; and (e) and (f), the 195° negative skew case](image-url)
The results of comparison at 150° skew are shown in Figure 3(c) and Figure 3(d). A principal reason for the different is that the simulation shows a response along the length of the side drilled-holes while the experiment only shows a response of the corner at which the side-drilled hole meets the side surface of the specimen. This may explain why the first two holes are observed in the simulated side view but cannot be seen experimentally.

Had CIVA not predicted response along the length of the hole, the first two holes might have gone undetected in the simulation as well as they would also lack the corner reflection. The only similarity in the simulation and experiment lies in the presence of the reflections of the corner of the side-drilled holes and the side surface of the specimen.

The results of comparison at 195° skew are shown in Figure 3(e) and Figure 3(f). With the probe skewed the other way (towards the side that does not contain the holes), no hole is detected experimentally though the simulated views clearly indicate the presence of side-drilled holes, to the great disagreement of the experimental data. In summary, it is noted that while performed well at 180° skew, its performance at different skews was quite poor.

NOTCHED BLOCK CIVA COMPARISON

Experimental Procedure

In this section, a comparison is made between the simulated CIVA data and experimental data collected from a flat steel block with two large parallel notches cut into its volume from the bottom face. The geometry of the block is planar, measuring 255.6mm×152.4mm×25.298mm tall. The two notches are each 40mm away from their respective ends of the block, and parallel to the end face. Each notch is cut such that its depth was stepped in five steps and thus there are a total of ten steps in the entire block. The depths of the cuts of one notch steps ranges from 1.27mm to 10.03mm and the depth of the cuts in the second
notch varies from 12.78mm to 22.86mm in increments of approximately 0.1" (2.54mm). In all, the notches are varying from 5% Through Wall Thickness/Through Wall Extent (TWT/TWE) to 90% TWT/TWE. The schematic is shown in Figure 4.

The terminology employed in this report treats the shallower-cut notches as the deeper notches, since their tips appear to be deeper when viewed from the probe in contact with the top surface and vice versa for the deeper-cut notches. The notches are arbitrarily numbered from one to ten with one being the shallowest notch (tip at 2.44mm from the upper surface) and ten being the deepest notch (24.03mm from the upper surface).

Before experimentation began, a calibration, of a similar nature to that described in the previous section for the off-axis detection, was performed in order to find the wave velocities, the wedge exit point and the wedge delay.

The data were collected using an R/D Tech Tomoscan III/PA instrument. A circular probe of centre frequency 1.5MHz and of 0.5in (12.7mm) diameter was used to scan the block via a plexiglass wedge so as to introduce a transverse wave into the stainless steel specimen at an angle of 45°. The probe assembly was moved across the top surface of the block in nine parallel rows of 456 linear steps at 0.5mm increments (i.e., in each row, 457 data were collected). There was a gap of 15mm between each pair of rows, so chosen since the notch steps were 30mm wide and thus a row was positioned such that it would lie directly atop the transition in notch depth and the two either side of it would lie atop the middle of the step. As before, care was taken to ensure that no signal was saturated. Coupling between the transducer and the wedge was achieved using mineral oil and coupling between the wedge and the specimen was achieved using running water.

**Simulation Procedure**

The material properties used in this CIVA simulation were 5772.72ms⁻¹, 3086ms⁻¹ and 7900kgm⁻³ for the two wave velocities and the density respectively. The steel of the specimen was modelled as isotropic, homogeneous and with an exponential attenuation law of 0.004dbmm⁻¹ of the fourth power of attenuation at 2MHz centre frequency. The plexiglass specimen was assigned the properties 2669.54ms⁻¹, 1320ms⁻¹ and 1180kgm⁻³ for its wave velocities and density respectively. No wave attenuation was applied to the wedge.

In order to facilitate reflections from the ends of the specimen, the CIVA model of the specimen is around 50mm longer than its real experimental equivalent, and two flaws that cover the entire cross-section of the experiment acts as reflectors for simplicity of simulation. The notches are constructed and inserted directly into the CIVA model.

The first clean backwall reflection that was obtained from the experimental calibration was used as the CIVA input signal. As before, the coupling medium was modelled as water and the bottom medium as air. The CIVA computation was performed in 3D with active backwall echoes for accurate computation. Up to three reflections of the transverse wave mode were permitted and simulated i.e., mode conversion was completely ignored. Surface waves, shadowing and creeping waves were also ignored by the simulation.

The simulations were performed once with the probe facing towards the end with the deeper notches and once with the probe facing towards the end with the shallower notches. For brevity of presentation, only the results corresponding to the former case are shown in this report.

**Experimental and Simulated Comparison**

The cumulated top views and the cumulated side views are shown in Figure 5 from both the experimental and simulated results. The notches, where observable, are numbered in each figure subpart. In the experimental data, the first and last several notches were not discernible due to interference from the
wedge or from the specimen backwall. In CIVA, only the last several notches were not observable due to the effect of the backwall. However, all of the shallower notches were discernible since CIVA was not set to model the effects of wedge interference. In general, the experimental and simulated results compare well where a corner echo is predicted. The principal differences are that CIVA produces stronger edge diffraction and a weaker echo from the upper corners. It is also possible that the experimental edge diffraction is too weak to be observed above the background noise level.

A more quantitative comparison is offered from the echodynamic curves shown in Figure 6(a). The relative strengths of the responses from each notch is extracted from both the experimental and simulated data, then placed side by side and overlaid for a direct comparison. The data are normalised according to the magnitude of the first reflection that was observable in both sets of data (i.e., the second notch). It is seen that the simulation tends to overestimate amplitudes of subsequent notches though the resolution of the experimental data is rather coarse.

The direct comparison of the estimated depths of the notches (shown in Figure 6(b)) is rather more favourable. In order to acquire the depth experimental and the simulated estimates, the echodynamic curve was scanned for the pair of -6dB drop points either side of the peak; then the midpoint of these values was returned as the depth of the notch tip. Figure 6(c) shows the deviation of the depth estimates from the true notch depths. It is observed that this deviation tends to increase as the actual notch depth is increased, perhaps to be expected.

Figure 4 – Schematic of the notched block showing detailed dimensions and the numbering system of the two notches

Figure 5 – Experimental and simulated results respectively, with numbered notches, for: (a) and (b), cumulated top view; and (c) and (d), cumulated side view
Figure 6 – Compared experimental and simulated results with numbered notches, showing: (a) index position versus normalised amplitude; (b) actual notch depth versus measured notch depth; and (c) actual notch depth versus measurement error.

Figure 7 – Schematic of the austenitic stainless steel piping sample

AUSTENITIC STAINLESS STEEL PIPING SAMPLE CIVA COMPARISON

Experimental Procedure

Lastly, a comparison is made between simulated CIVA data and experimental data collected from an austenitic stainless steel piping sample. The piping sample (schematic shown in Figure 7) has an internal diameter of approximately 9.5” (241.3mm); an external diameter of approximately 10.8” (274.3mm) and contains two circumferential flaws of interest. One flaw is on the side of the weld and the other is ID-
connected and offset from the base of the weld. The flaws are set about 50° apart from one another; one is centred at 30° and is 0.9" (22.9mm) in length; the other is centred at 78.1° and is 1.2" (30.5mm) in length. In this report, the flaw at 30° is referred to as the first flaw and that at 78.1° is referred to as the second flaw.

The experimental apparatus used to acquire the data is a Zetec Omniscan MX 16-128, controlled by Zetec UltraVision 1.2R7. The ATCO LPS-1000 dual axis automated scanner is used as an encoder, with the R/D Tech MCDU-02 acting as a motion controller. Scanning is performed only along one axis, however.

After having performed the calibration procedure described earlier, this piping sample is interrogated using a 0.25" (6.35mm) circular conventional probe of centre frequency 3.5MHz. The probe is mounted upon a plexiglass wedge so as to facilitate the introduction of transverse waves into the steel at 45°. As before, coupling between the transducer and the wedge was achieved using mineral oil and coupling between the wedge and the specimen was achieved using running water.

The block was scanned around the circumference in increments of 0.8°, with the probe facing towards the weld; the objective was to capture the first flaw in a half-skip ray and the second flaw in a direct ray. The total scanning range of the probe was 120° in the circumferential direction and 35mm in the axial direction.

**Simulation Procedure**

The specimen geometry was imported directly into CIVA as a 2D CAD geometry, and then revolved 120° at a radius of 137.185mm. The flaws were imported separately into the model and carefully positioned using the CIVA GUI. The exact shapes of the flaws were taken from the original CAD drawing provided by the manufacturers and since the flaws are largely internal, there is a chance that they are not entirely faithful to the actual shape and size of the flaws. The critical material properties used for the CIVA simulation were 5766.537ms^{-1}, 3120ms^{-1} and 8030kgm^{-3} for the two wave velocities and the density respectively. The longitudinal wave velocity figure was taken from the calibration performed during the experimental procedure. The corresponding figures for the plexiglass wedge were taken from the comparison involving the notched block.

![Figure 8 – Experimental and simulated results respectively, with numbered flaws, for: (a) and (b), cumulated top view; and (c) and (d), cumulated side view](image)
The CIVA computation was set to 3D and wave attenuation was ignored. Backwall echoes were taken into account but surface echoes and shadowing were ignored, as before. Transverse waves of up to three reflections were included in the simulation and all longitudinal waves were ignored i.e., mode conversion was also neglected to increase computation speed.

To match the experimental data acquisition, the simulated scans were performed in 89 rows (aligned in the axial direction), separated by 0.8°. In each row, 35 data were collected at intervals of 1mm.

**Experimental and Simulated Comparison**

The cumulated top views and the cumulated side views are shown in Figure 8 from both the experimental and simulated results. In all the figure subparts, both flaws are visible, and are numbered according to the number scheme described above. CIVA's backwall reflection shows some differences to the experimental data, probably due to the fact that the real sample does not have such a smooth geometry. There is a reasonable visual qualitative comparison between the two sets of data.

For a more quantitative comparison, the data are processed further. An echodynamic scan is extracted from the both the simulated and experimental data in the circumferential and axial directions. These scans are overlaid and shown in Figure 9. Of the greater practical use is the circumferential echodynamic of Figure 9(a). It shows that the simulation and experimental data agree quite closely in both locating and sizing the two flaws.

The estimated flaw lengths and centre positions are listed in Table 1. It is interesting to note that the simulation overestimates the length of the first flaw whereas the experiment undersized this flaw. Both methods, however, underestimate the length of the second flaw. It is possible that this flaw tapers sharply near its ends and it is not easily detectible and hence has been undersized. Secondly, it is noted that CIVA underestimates the strength of reflection from the first flaw relative to the second flaw. Since the first flaw was detected by half-skip, it may indicate a deficiency (or indeed, a lack of calibration from the user) in CIVA's handling of reflection amplitudes.

<table>
<thead>
<tr>
<th></th>
<th>flaw 1 centre</th>
<th>flaw 1 extent</th>
<th>flaw 2 centre</th>
<th>flaw 2 extent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual</td>
<td>30.0°</td>
<td>10.6°</td>
<td>78.1°</td>
<td>14.8°</td>
</tr>
<tr>
<td>Experimental</td>
<td>30.1°</td>
<td>8.9°</td>
<td>77.4°</td>
<td>12.2°</td>
</tr>
<tr>
<td>Simulated</td>
<td>30.0°</td>
<td>11.8°</td>
<td>78.4°</td>
<td>12.9°</td>
</tr>
</tbody>
</table>

Figure 9 – Echodynamic scans from experiment and simulation when the unwrapped piping sample is viewed from: (a) the end and (b) the top

Table 1 – Estimated centre position and flaw extents from experiment and simulation
CONCLUSIONS
This report has presented three comparisons to study the quality of CIVA-predicted responses of side-drilled holes off the main axis, the relative reflection strength and depth estimations from notches cut into a steel block and the quality of experimental and CIVA-estimated location and sizing of circumferential flaws in an austenitic stainless steel piping sample.

As far as the off-axis detection is concerned, for the negative skews CIVA was capable of predicting the response from the corner formed between the side-drilled holes and the side surface of the specimen. However, it also predicted responses along the length of the holes, which are not present in the experimental data and lead to very different results. For positive skews, predicted relatively high responses while experimentally the side-drilled holes went undetected even at high gains.

In general, there was a good qualitative and visual agreement between simulation and experiment as long as two main limitations are considered: that there is no noise present in the simulations; and that the number of modes and reflections handled by CIVA are to be predefined by the user, who must be aware of the significance of his selected options.

It needs to be mentioned that CIVA does have options to account for structural noise and that any number of modes and reflections and bounces can be included; however, these options greatly increase computational time. It is observed that CIVA can produce reasonable results even without these time-consuming features if one is mindful of these limitations and their consequences on the results, and they may not be need for most applications.

In spite of the differences observed in this report, the CIVA modelling tool is still potentially powerful when used correctly. These can help facilitate understanding of ultrasonic phenomena within the specimen. Another advantage provided by simulation software in general, and by CIVA, is that every simulation of a set of given parameters will give the same result, though there are many factors, some controllable and other uncontrollable, that will affect the outcome of an experiment. If a small change is made to the input parameters of a set of parameters for a simulation, the change in outcome, no matter how small, must have been as a result of that change in input. This is another learning aid and may help the user to understand a very complex system of interaction between ultrasonic rays and the component.

REFERENCES
1) Schmerr LW "Modeling and Simulation of NDE Inspections" Rev. Prog. Quant. NDE 18(A) 679-686, 1999
5) "ENIQ Recommended Practice 6 – The Use of Modelling in Inspection Qualification", ENIQ Report Issue 1, EUR 19017 EN, 1999
6) CIVA, www-civa.cea.fr, viewed 2012
7) Calmon P, Mahaut S, Chatillon S and Raillon R "CIVA: An expertise platform for simulation and processing NDT data", Ultrasonics 44(2) 975-979, 2006