RESULTS OF THE 2009 UT MODELING BENCHMARK OBTAINED WITH CIVA: RESPONSES OF NOTCHES, SIDE-DRILLED HOLES AND FLAT-BOTTOM HOLES OF VARIOUS SIZES

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ABSTRACT. This communication presents the results obtained on the configurations proposed in the 2009 UT modelling benchmark with the ultrasonic models implemented in the CIVA software platform. The aim, this year, is to study the relative amplitudes and the shapes of specular and corner echoes for different flaws in "2D" and "3D" configurations. Experiments have been performed with contact probes (single element or phased array) radiating transversal or longitudinal waves at 45° incidence angle on planar mock-ups containing flat-bottom hole, side-drilled holes and backwall breaking notches of different heights and widths. The echoes are simulated by applying an integral formulation for the field radiated by the probe (the pencil-model) and different scattering models depending on the kind of defects. Comparison between simulated and experimental results are presented and discussed.

Keywords: Ultrasonic Benchmark, UT Simulation, Semi-Analytical Model, Corner Echoes
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INTRODUCTION

The Center for NDE at Iowa State University proposed two topics for the annual benchmark: a review of the previous benchmarks [1] and a study, presented in this paper, of the relative amplitudes and shapes of corner echoes of backwall breaking notches of different heights and widths, and of direct specular echoes of flat-bottom holes and side-drilled holes. The defects were contained in a steel planar mock up, two flat mono element probes and one phased array probe generating 45° longitudinal or transversal waves were used. Computations of this paper were performed using the CIVA software, a platform for NDT developed at CEA LIST (French Atomic Energy Commission) [2]. The models implemented in Civa for field and echo computations and the benchmark configurations will be briefly described. Then we will present the results of the benchmark studies obtained with Civa.

BRIEF DESCRIPTION OF CIVA ULTRASONIC MODELS

Transducer Beam Model [3]

To calculate the transient wave field radiated inside the specimen, the transducer is

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sampled as a series of source points over its surface. For each point source, elementary contributions are obtained by means of the pencil method (a high frequency approximation). The pencil-matrix formulation allows one to predict wave front radii of curvature along each wave path as well as its time-of-flight; it is combined with the computation of plane wave transmission/reflection coefficients corresponding to each interaction of the pencil with an interface. Impulse responses are then synthesized from these contributions and convolved with the input signal.

Flaw Scattering Models [4]

Different models are available in Civa, depending on the kind of defect or control (pulse echo, TANDEM, TOFD…). All the models are based on one three steps process: calculation of the incident field over the flaw surface, calculation of the flaw scattering using specific approximations (Kirchhoff's approximation [5] or others like Born or GTD…), and calculation of the received signal using the reciprocity principle to avoid the integration over the probe in reception. In echo predictions, the flaw is meshed and the field scattered at each discrete element is obtained from the field incident on this element by applying Kirchhoff's diffraction coefficient (which depends on incident and observation angles for this element and on the polarity of both the incident and the scattered modes). Then, the total scattered field is computed by summing the contributions from all elements. Finally, the reciprocity principle is used to obtain the output signal of the probe acting as a receiver.

A recently developed model is based on the separation of variable [6]: experimental validations carried out in a pulse-echo configuration on side drilled holes highlighted some differences between Kirchhoff simulation and measure for transversal waves [1] These discrepancies are explained by the theoretical principle of Kirchhoff approximation: it takes into account specular reflection on a cavity but not the creeping waves. These waves propagate around the cavity circumference and may have a significant influence especially at low frequency or for small defect radii. Therefore, the development of the exact analytical model for the scattering from a cavity has been integrated in CIVA (next release) for the moment for the cylindrical geometry. This exact model relies on the separation of variables (SOV) method. We consider a plane wave propagating along x direction and incident on a cylindrical cavity embedded in an elastic isotropic solid. Only a 2d configuration can be treated: the incident and scattered waves vectors are included in the plane normal to the cylinder axis. Other models can be used in CIVA like models based on the GTD (Geometrical Theory of Diffraction) for TOFD examination [7] or based on Born approximation [8] for solid inclusions. In this paper, the only models used were that developed under Kirchhoff's approximation for notches and flat bottom-holes and the SOV model for side-drilled holes.

DESCRIPTION OF THE 2009 ULTRASONIC BENCHMARK

For a complete description of the configurations studied, see [9]. Experimental measurements were made at CEA LIST and it was proposed to simulate the corresponding cases and then compare measured and simulated amplitudes of the echoes.

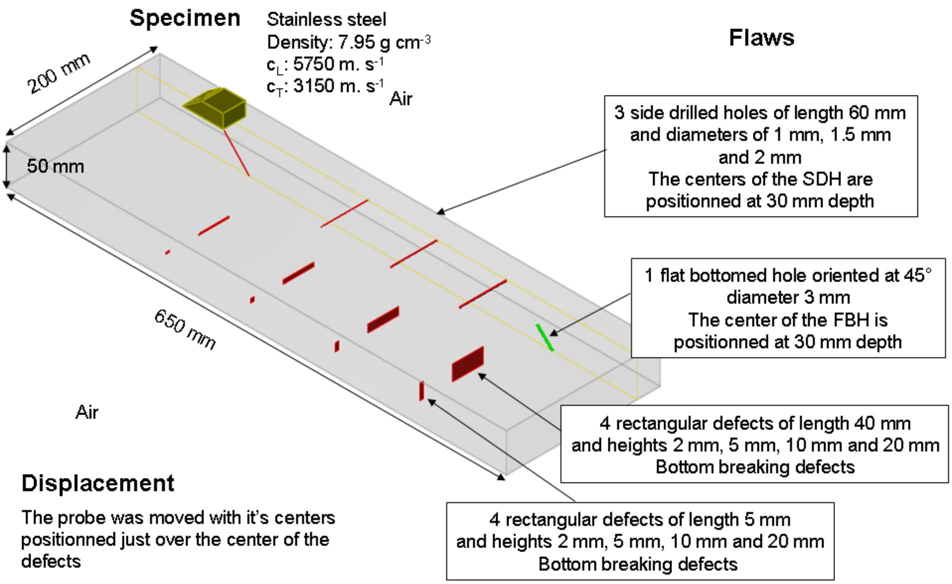

FIGURE 1. Description of mock-up.

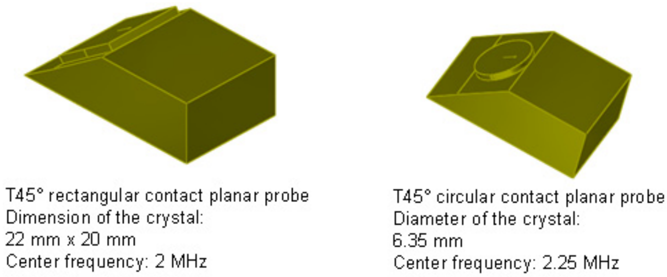

FIGURE 2. Description of the two mono element probes.

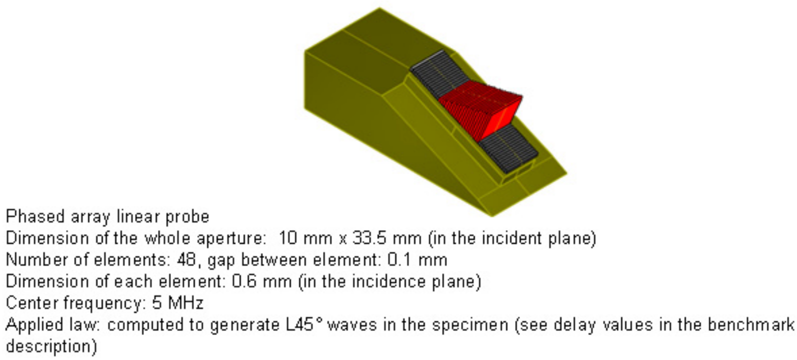

FIGURE 3. Description of the phased array probe.

PRESENTATION OF THE RESULTS

For a given probe, the amplitude reference A_{REF} for all the amplitudes given in dB is the maximum amplitude of the specular T45° or L45° direct echo obtained from the side drilled hole of 2 mm diameter at 30 mm depth. The measured relative amplitude is given in dB: $20 \log(A / A_{REF}) - (G - G_{REF})$, where G and G_{REF} are the gains in dB. The amplitude reference for the simulation was obtained with the SOV model. For each graph the gap between 2 lines is always 1 dB. All the echoes computations were performed with Civa release 9.2, except for the side drilled holes echoes: Civa9.2 was used to compute these echoes with the Kirchhoff approximation and the next release of Civa (Civa10) was used to compute the same echoes with the Separation Of Variable model.

T45° RECTANGULAR CONTACT PROBE, 2 MHZ

Results for the Side Drilled Holes (SDH): the graph (Figure 4) represents the amplitudes (dB) of the T45° direct echo from the SDH versus the SDH diameters. As we told before, the amplitude reference for the simulation was obtained with the SOV model (Civa10). But, for information, we also plot on this figure the results obtained with the Kirchhoff model (Civa9.2). In this case, the difference between Kirchhoff and SOV predictions is about 1 dB for the reference's SDH. We compare the normalized experimental and simulated wave form of echoes from the SDH (Figure 5). The simulated waveforms are in good agreement with the experimental one (the shape, amplitude and time of flight of both the specular and the creeping wave are well simulated).

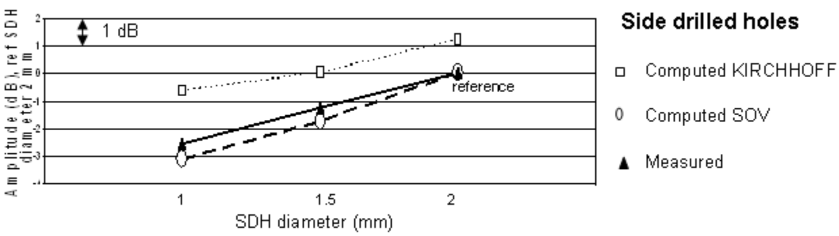

FIGURE 4. T45° rectangular probe, comparison of measured and simulated CIVA amplitudes of the T 45° direct echoes of the side drilled holes of different diameters (reference: echo 2 mm diameter SDH, SOV model for the computed reference). Computed SOV and Kirchhoff results are presented.

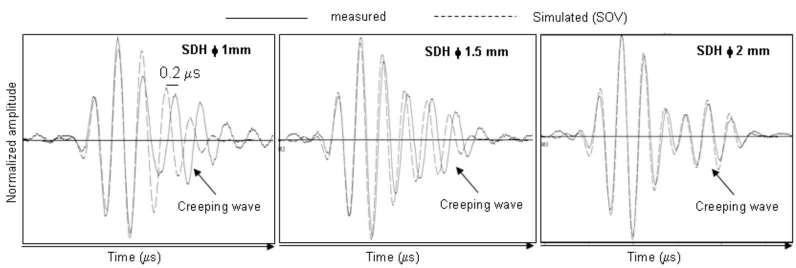

FIGURE 5. T45° rectangular probe, comparison of experimental and simulated waveforms of the T45° direct echoes of side drilled holes of different diameters (normalized amplitudes). Computed SOV results are presented.

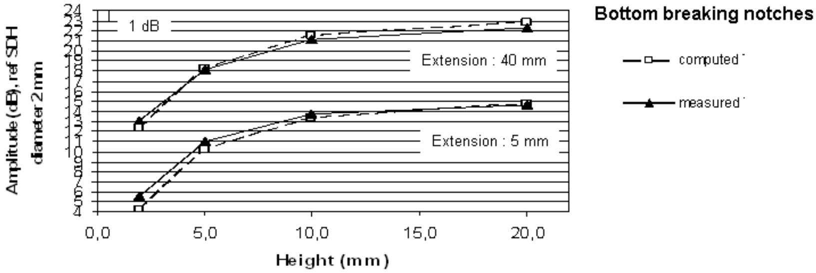

FIGURE 6. T45° rectangular probe, comparison of measured and simulated CIVA amplitudes of the T 45° corner echo of the bottom breaking rectangular flaws of different heights and of 40 mm and 5 mm extensions (reference: echo 2 mm diameter SDH)

Flat bottom Hole (FBH): a good agreement between the measured and the simulated T 45° specular echo is also obtained for the FBH oriented at 45°, for both the amplitude (-6 dB measured and -4.8 dB simulated) and for the waveform (not presented in this paper).

Rectangular defects: the graph (Figure 6) represents the amplitudes of the T corner echo from the rectangular bottomed breaking flaw versus the flaw's height. The echoes increases as expected with the height of the defect, the predictions are in good agreement with experimental measurements. The shapes of the echoes are also very well predicted.

T45° CIRCULAR CONTACT PROBE, 2.25 MHZ

Side drilled Holes: the simulated results are in good agreement with experimental measurements (Figure 7). In this case, the difference between Kirchhoff and SOV predictions is about 1 dB for the 2mm diameter SDH and about 2.5dB for the smallest SDH. This is in accordance with Kirchhoff and SOV comparisons in literature (higher difference for low ka with T mode).

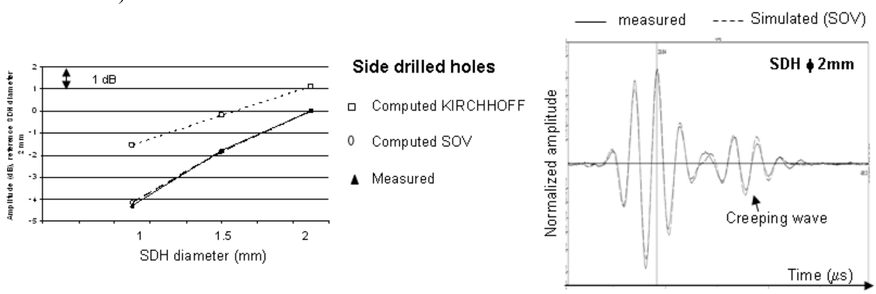

FIGURE 7. T45° circular probe. Left: comparison of measured and simulated CIVA amplitudes of the T 45° direct echoes of the side drilled holes of different diameters (reference: echo 2 mm diameter SDH). Computed SOV and Kirchhoff results are presented. Right: comparison of measured and simulated waveforms of the T45° direct echoes of the 2 mm diameter side drilled hole (normalized amplitudes).

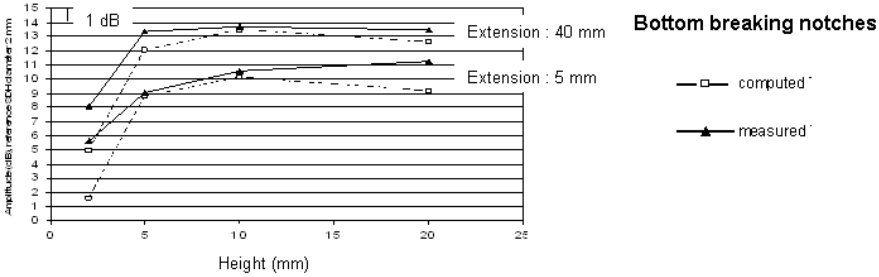

FIGURE 8. T45° circular probe, comparison of measured and simulated CIVA amplitudes of the T45° corner echoes of the bottom breaking rectangular flaws of different heights and of 40 mm and 5 mm extensions (reference: echo 2 mm diameter SDH).

Flat bottom Hole: as for the previous probe, a good agreement between the measured and the simulated T 45° specular echo is also obtained for the FBH oriented at 45°, both for the amplitude (-4 dB measured and -3.5 dB simulated) and for the waveform.

Rectangular defects: the graph (Figure 8) represents the amplitudes of the T corner echo from the rectangular bottomed breaking flaw versus the flaw's height. Some discrepancies observed between the measured and computed results (up to 4 dB) for the smallest defects (Figure 8) and also, but less important, for the 5mm x 20 mm height defect have to be studied.

L45° PHASED ARRAY CONTACT PROBE, 5 MHZ

The computed L and T fields radiated in the specimen by the phased array probe when delays laws are applied to generate L45° field in the specimen (see [9] for the value of the delays) are presented Figure 9, left.

Rectangular defects: a strong mode conversion of the T beam occurs at the backwall of the specimen (Figure 9, middle) and explains the strong amplitudes obtained for the mixed corner echoes in the case of the two 20 mm height planar defects (see Table 1: the measured amplitudes of the mixed corner echoes are very weak except for the two notches of 20 mm height: +6.5dB and +2.5dB): the converted TL beam is intercepted by the top of the defect where after reflection it returns directly to the probe (Figure 9, right). Most of the discrepancies

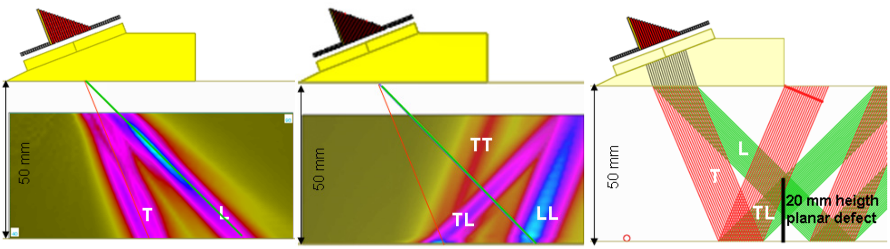

FIGURE 9. L45° phased probe. Left: simulated radiated field in the specimen, L and T modes. Middle: simulated reflected fields at the bottom of the specimen. Right: display of the ray path between the probe, the defect and return corresponding to the applied delay law. The top of the flaw intercepts the TL beam and reflects it directly to the probe, generating a strong TLL echo. A smallest defect doesn't intercept the TL mode and the TLL echo is weak for this defect.

TABLE 1. L45° phased array probe, comparison of measured and simulated CIVA amplitudes of the L, T direct echoes of the SDH and FBH and L, T and mixed corner echoes of the bottom breaking rectangular flaws of different heights and of 40 mm and 5 mm extensions (reference: L direct echo of the 2 mm diameter SDH).

		MEASURED	SIMULATED	DIFFERENCE
			(SOV model for SDH)	
Defect	**Echo type**	**Amp (dB)**	**Amp (dB)**	**Δ (dB)**
SDH ϕ1 mm	L direct	-2,6	-2,7	0,2
	T direct	-16,5	-17,8	1,3
SDH ϕ1,5 mm	L direct	-1,3	-1,2	0,0
	T direct	-16,3	-15,4	-0,9
SDH ϕ 2 mm (reference)	**L direct**	**0,0**	**0,0**	**0,0**
	T direct	-14,8	-14,0	-0,8
FBH ϕ3 mm	L direct	2,8	3,0	-0,2
notch 40 mm x 2 mm	L corner	-10,5	-8,8	-1,8
	corner mixed	-23,9	-21,6	-2,3
	corner T	-16,2	-13,4	**-2,7**
notch 40 mm x 5 mm	corner L	-3,6	-2,6	-0,9
	corner mixed	-21,7	-18,3	**-3,4**
	corner T	-7,3	-6,0	-1,3
notch 40 mm x 10 mm	corner L	-1,4	-1,1	-0,3
	corner mixed	-10,8	-8,8	-2,0
	corner T	-3,7	-1,3	-2,4
notch 40 mm x 20 mm	corner L	-1,3	-1,2	-0,1
	corner mixed	6,5	8,7	-2,2
	corner T	-0,5	1,7	-2,1
notch 5 mm x 2 mm	corner L	-13,7	-12,1	-1,6
	corner mixed	too low		
	corner T	-20,5	-16,1	**-4,4**
notch 5 mmx 5 mm	corner L	-6,8	-6,1	-0,7
	corner mixed	-24,2	-21,6	**-2,6**
	corner T	-9,8	-9,3	-0,4
notch 5 mm x 10 mm	corner L	-4,5	-4,5	0,0
	corner mixed	-12,5	-11,3	-1,2
	corner T	-5,2	-4,2	-1,0
notch 5 mm x 20 mm	corner L	-3,9	-4,7	0,7
	corner mixed	2,4	5,8	**-3,3**
	corner T	-3,0	-1,3	-1,8

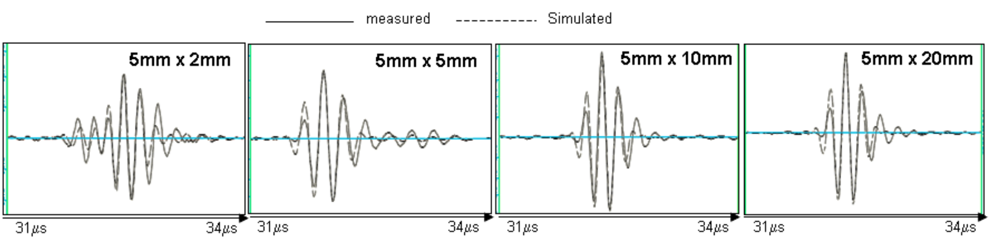

FIGURE 10. L45° phased array probe, comparison of experimental and simulated waveforms of the L45° corner echoes of the 5 mm extension rectangular flaws (normalized amplitudes).

between measured and simulated amplitudes are less than 2 dB. The main discrepancies (up to 4 dB) are observed for the planar defects in the case of T or mixed corner echoes, but the general tendency of the amplitude evolution versus the defect's size is well simulated. For example, the measured amplitudes of the mixed corner echoes show a strong dependence of this echo on the height of the defect: for the 40 mm extension defects, it's relative amplitude varies from about -22dB for those of 2 mm height, -18dB for those of 5 mm height and -11dB for those of 10 mm height up to 6.5 dB for the 20mm height defect. This tendency is well simulated. A good agreement between the measured and simulated waveforms of the corner echoes is obtained (Figure 10 shows an example of comparison for the L corner echoes).

Side drilled Holes and flat bottom hole: a very good agreement is obtained (Table 1). As expected, the amplitudes of the SDH of 2 mm diameter is not different with the Kirchhoff and the SOV model for longitudinal mode.

CONCLUSION

The comparisons between experiment and CIVA codes show a general good agreement for amplitudes and waveform of the various echoes. The improvement in the simulation of T direct echoes of side drilled holes du to the implementation of the SOV model in the next release of Civa is shown when we compare the experimental and simulated waveforms of these echoes: the creeping wave is calculated with SOV model when it is not with the Kirchhoff approximation. But the difference of amplitudes of the T direct echo is not very important in the cases presented in this paper (about 1 dB for the reference). Concerning the backwall breaking notches, the difference between measured and simulated amplitudes of the various (L, T or mixed) corner echoes are most of the time less than 2 dB. The discrepencies observed in some isolated cases (up to 4 dB) have to be studied. Further benchmarks shall be carried out, we will try to give an estimation of experiments uncertainities.

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