ADVANCED METHOD FOR ULTRASONIC PROBE CHARACTERIZATION

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1. INTRODUCTION

It is commonly known that each ultrasonic examination requires specific ultrasonic probes chosen for their intrinsic parameters such as frequency, refracted angle, beam width, focal depth, etc. As an advanced NDT procedure developer and as a probe manufacturer among others, Vinçotte has to handle this problematic from the probe design to the final application.

Ultrasonic beams generated either by a conventional or by a phased array (PA) probe are usually modeled as a simple line segment which is entirely defined using three essential parameters: the refracted angle, the exit point and the probe delay. These are necessary to locate and to size the detected indications in the required examination volume.

These parameters are calculated during the so-called probe characterization process that is achieved using fully or semi-mechanized acquisition system on specific calibration blocks. Given that the inspection performances are based on 100% required volume coverage, on good detection performances and on accurate localization and sizing of the indications, it is crucial to find the best method to calculate these parameters. Thus, in order to automate the entire probe characterization process and to compare the efficiency of several calculation methods, Vinçotte has developed a specific software called APC (Automated Probe Characterization). The first part of this document introduces this process and this new software. The second part presents a comparison between some results given by conventional calculation methods and some results given by the new advanced method.

2. PROBE CHARACTERIZATION PROCESS

In ultrasonic testing, according to our quality system, several forms of characterization or calibration must be achieved:

- The electronic devices must be annually characterized to ensure that the system performs as designed, this will not be discussed in this paper;
- At each inspection, generally before and after, the entire system has to be calibrated in order to guarantee that the required accuracy is achieved. This step is more a verification than a real determination of specific parameters. This will neither be discussed further.
- At the probe manufacturing and then annually, the probe can be fully characterized ideally using the same equipments (cables and electronic devices) than for further use. For every ultrasonic probe, either conventional or phased array, this process results in some intrinsic parameters and curves: the refracted angle (RA), the exit point (EP) and the probe delay (PD), as well as the sensitivity curve, the beam width curve and the spectral analysis (FFT). This will be treated in this paper;

Since innovations and developments are at the heart of our philosophy, and with the constant evolution of ultrasonic acquisition software, a new approach had to be considered to this basic process.

In a first time, in order to improve the representativeness of the main scanning configurations (pipes and planes from the outer side), Vinçotte has developed and manufactured several blocks, each containing specifics reflectors: a half-moon (HM) and a set of side drilled holes (SDH) perpendicular to the scan direction at different depths. An encoded acquisition on such a block will provide the required data to characterize the probe.

In a second time, in order to automate the entire probe characterization process and to optimize the calculation method, the APC software was developed. This processes raw ultrasonic data to calculate the probe parameters. It also computes the average distance between real reflectors positions and relocated ones using the parameters previously calculated. This allowed us to compare the different implemented computation methods and to develop a new advanced method based on results optimization.

2.1. Ultrasonic equipment

2.1.1. Probes

This process can be applied to any kind of conventional probe and to any kind of phased array probe associated to a specific focal law (e.g., single probe, twin side by side, twin tandem).

2.1.2. Mechanical settings

According to the working configuration (axial scanning, circular scanning or planar scanning), there are two different mechanical settings, one fully mechanized for circular configurations (see Figure 1 on the left) and one semi-mechanized for planar and axial configurations (see Figure 1 on the right).

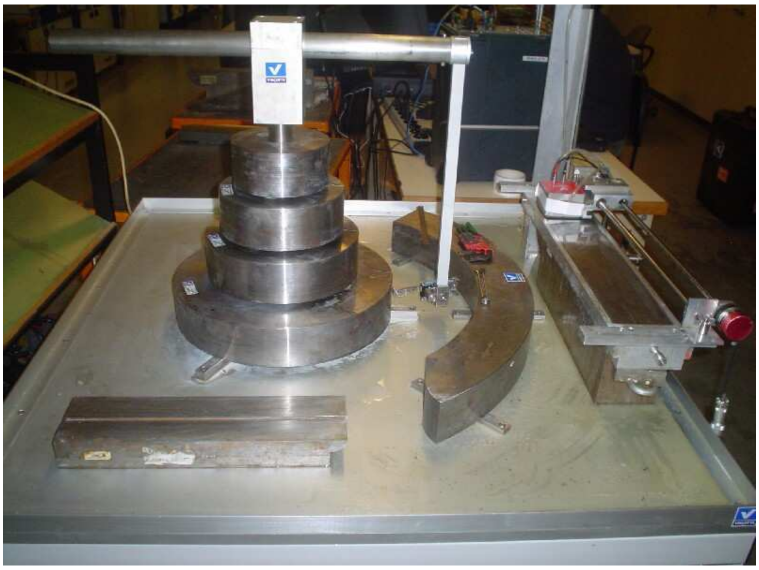


Figure 1: Characterization system

2.1.3. Ultrasonic device

In order to be as close as possible to the real inspection configuration, the same device has to be used to perform ultrasonic acquisition. The same type of cables (e.g., cable length can influence probe delay results) must also be used.

2.1.4. Ultrasonic software

Actually, only a few different versions of Ultravision (from Zetec) or Tomoview (from Olympus) can be used to perform probe characterization.

2.1.5. Characterization blocks

In order to cover the main scanning configurations, Vinçotte has developed and manufactured several blocks containing a HM and a set of SDH (diameter 1 mm) at different depths (see Figure 2). These carbon steel blocks exist for each of the three main working configurations (AX for axial scanning, CIRC for circular scanning and FLAT for planar scanning) from 3” to 36” diameters in order to cover most of the existing pipes configurations.

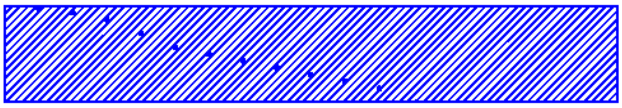


Figure 2: Schema of a flat characterization block with a set of SDH

2.2. APC software

The probe characterization process is achieved using in parallel the ultrasonic testing (UT) chain to perform the acquisitions and the APC software as the main guideline. The APC software is always associated with files: one describing the blocks, one describing the initial software parameters to use, one storing the temporary data and results, others containing the raw data from the acquisitions and others containing the final results.

This whole characterization process including the software use is fully described in our internal instruction mu12906_Ed. B: "Automated characterization of UT probe on specified blocks with HM and SDH reflectors".

At each process step corresponds a specific APC window. The operator has to fulfill progressively all the software cells with the probe parameters, eventually the associated focal laws parameters, the characterization block chosen, the electronic devices used, and the acquisitions parameters such as the acquisition file name, the gain…

Using dedicated predefined setups for the ultrasonic software according to the probe type and to the chosen block, the APC software will suggest the last parameters to eventually adjust: the mechanical resolution, the time base, the digitizing frequency, the voltage, the pulse width, the wave type and the sound velocity. All the other parameters have to remain unchanged; particularly the scan axis offset, the index axis offset, the refracted angle, the exit point, the probe delay and the skew angle have to remain equal to zero. For PA probes, the focal law has to be correctly introduced respecting the previous recommendations.

The operator can now perform the acquisitions (see Figure 3), and can next export the data in a raw format that will be read by the APC software. The association between the echoes and the real SDH will be automatically made by the APC software. The next steps concern the choice of the calculation method with the associated options, the calculation of the parameters and then the calculation of the SDH repositioning. The last steps allow the operator to display the results through tables and charts in order to verify the coherence of the whole process and then to export these results to several different files allowing finally the generation of the characterization report.

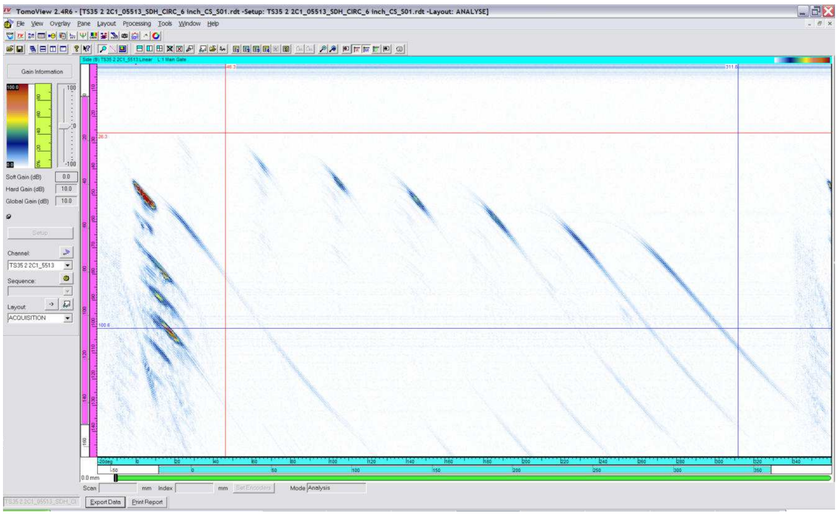


Figure 3: Example of acquisition on SDH reflectors – Ultrasonic software in analysis mode

2.3. APC software: implemented calculation methods

In this section, all the computation methods will be briefly presented. The basic equations behind these methods are described in the annexes.

- **Method 1**: HM acquisition used for EP and PD calculation, SDH acquisition used for RA calculation from TOF measure. If acquisition on the HM reflector is available, this can be used to calculate the probe EP and PD. The RA can be calculated on each SDH using the time of flight (TOF) measure.

- **Method 2**: HM acquisition used for EP and PD calculation, SDH acquisition used for RA calculation from position measure. If acquisition on the HM reflector is available, this can be used to calculate the probe EP and PD. The RA can be calculated on each SDH using the position measure.
- **Method 3**: HM acquisition used for EP calculation, SDH acquisition used for RA calculation from TOF measure with PD fitting. If acquisition on the HM reflector is available, this can be used to calculate the probe EP. Trying all the possible PD values, the RA can be calculated on each SDH using the TOF measure. The PD finally chosen will be the one reducing the difference between the calculated RA's on each SDH.
- **Method 4 or conventional method**: HM acquisition used for PD calculation, SDH acquisition used for RA calculation from position measure with EP fitting. If acquisition on the HM reflector is available, this can be used to calculate the PD. Trying all the probe EP values possible, the RA can be calculated on each SDH using the position measure. The EP finally chosen will be the one reducing the difference between the calculated RA's on each SDH. This method is the most common method and was used during years for probe characterization.
- **Method 5**: SDH acquisition used for EP, PD and RA calculation by SDH pair, TOF measure used for RA calculation. SDH can be used by pair to calculate the parameters. RA calculation will be done using the TOF measure.
- **Method 6**: SDH acquisition used for EP, PD and RA calculation by SDH pair, position measure used for RA calculation. SDH can be used by pair to calculate the parameters. RA calculation will be done using the position measure.
- **Advanced method**: SDH acquisition used for EP, PD and RA calculation fitting EP, PD and RA to minimize SDH repositioning. Here, the APC software will try each possible parameters trio (EP, PD and RA) in order to minimize the relocation of the SDH by comparing them to real positions. The final solution is thus the one that gives the best relocation of the indications in the probe range chosen.

2.4. APC software: advanced features

Some special features have been developed and implemented in the APC software in order to improve the quality of the results:

- Corrections due to the SDH diameter are taken into account during the calculation process;
- From a set of SDH, for the geometrical calculation methods, the RA, EP and PD can be calculated through the simple average of the parameters calculated on each SDH, through the average with a virtual weight depending on the distance between the considered SDH and the reference SDH (the one with the maximum sensitivity), or simply by taking the values calculated on the reference SDH. The option chosen in the examples here below is the simple average.
- A special smoothing algorithm based on Bézier curves has been implemented in order to increase the maximum amplitude position measure precision (see Figure 4).

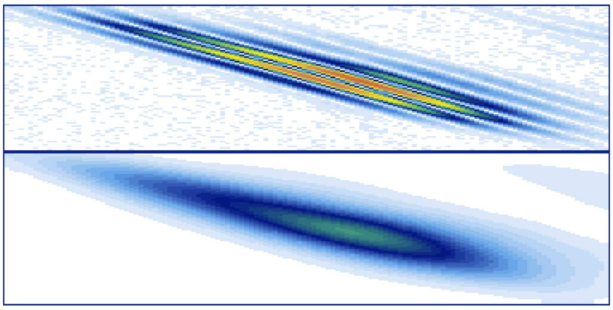


Figure 4: Example of non-smoothed and smoothed reflected signal on HM reflector

3. NUMERICAL RESULTS

3.1. Measurements on carbon steel characterization blocks

This section presents some comparisons between the several calculation methods implemented. These methods are described in the section 2.3 and 5. The most important values are the delta positioning which are the average of the distance between the SDH real position and the SDH calculated position based on characterization parameters. Accuracy increases with a decrease of this delta.

Two different examples are presented here below through:

- A table containing the numerical characterization results for the several calculation methods and for the different focal laws;
- A chart comparing the delta positioning values for the several calculation methods and for the different focal laws;
- A repositioning chart generated by the APC software for the conventional calculation method and for the new advanced calculation method.

Since the focal laws are calculated for stainless steel (V_{SSL} = 5700 m/s) and characterized using a carbon steel block (V_{CSL} = 5920 m/s), an adjustment has to be made for the refracted angle simply by using Snell's law: $\frac{\sin(RA_{SSL})}{V_{SSL}} = \frac{\sin(RA_{CSL})}{V_{CSL}}$. In the advanced method, the EP and the PD are considered equal between different materials.

Description of the focal laws nomenclature using the example **L30HP30**:

- **L** means longitudinal waves (T for transverse waves);
- **30** means a 30° theoretic refracted angle;
- **HP** means half path (TD for true depth, PR for projection, PL for plane), it is the focalization type;
- **30** for a 30 mm focalization distance.

Transmitter-receiver Phased Array 2 MHz probe (type WR2TS45L00_2M4x8A2A) on 6" carbon steel circular characterization block

			Half Moon reflector		SDH reflectors					
Focal Law	Method	RA_{SSL} Theoretic (°)	Sensitivity on HM (dB)	HM Pulser Voltage (V)	BW -6dB (mm)	EP (mm)	Delay (µs)	RA_{CSL} (°)	RA_{SSL} (°)	Delta Positioning (mm)
CIRC L0TD20	Adv	0	29.3	90	2.7	19.2	16.3	1.4	1.3	0.56
	1	0	na	na	na	na	na	na	na	na
	2	0	29.3	90	4.5	22.4	16.1	9.5	9.1	1.61
	3	0	29.3	90	4.2	22.4	15.7	20.6	19.8	5.61
	4	0	29.3	90	4.5	19.0	16.1	1.3	1.3	0.66
	5	0	29.3	90	3.4	26.8	15.8	20.6	19.8	3.44
	6	0	29.3	90	3.7	18.5	16.4	0.5	0.5	0.65
CIRC L30HP30	Adv	30	20.2	90	6.1	14.4	15.3	27.2	26.1	0.48
	1	30	20.2	90	6.8	17.0	14.8	31.9	30.6	1.41
	2	30	20.2	90	6.8	17.0	14.8	31.2	29.9	1.19
	3	30	20.2	90	7.9	17.0	15.6	24.4	23.4	3.54
	4	30	20.2	90	7.4	14.3	14.8	27.0	25.9	1.43
	5	30	20.2	90	4.4	24.3	13.4	39.6	37.9	3.36
	6	30	20.2	90	6.8	11.5	15.6	22.5	21.6	1.25
CIRC L40HP30	Adv	40	19.7	90	9.2	11.3	14.6	35.3	33.8	0.72
	1	40	19.7	90	7.6	16.4	14.6	38.8	37.1	1.77
	2	40	19.7	90	7.4	16.4	14.6	38.9	37.2	1.78
	3	40	19.7	90	9.8	16.4	15.9	34.3	32.9	4.83
	4	40	19.7	90	6.8	9.5	16.0	34.2	32.8	3.07
	5	40	19.7	90	9.4	13.9	14.7	37.2	35.6	1.61
	6	40	19.7	90	10.9	8.5	16.1	34.8	33.3	1.11

Table 1: Numerical results for circular configuration

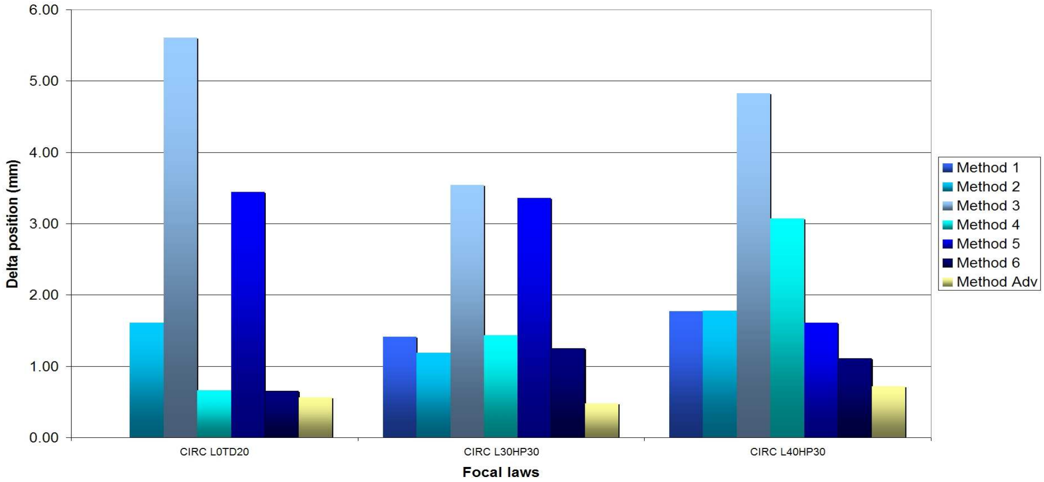


Figure 5: Comparison chart for circular configuration

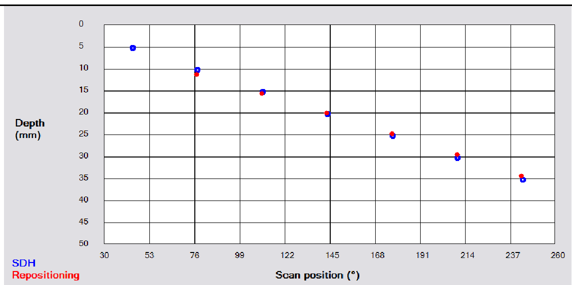
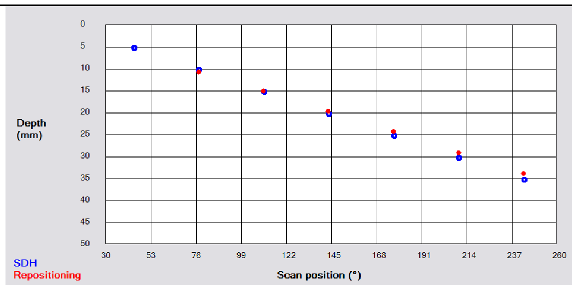
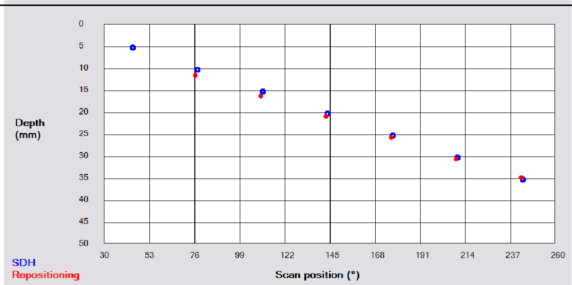
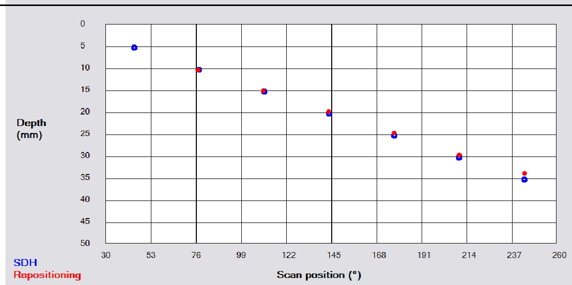
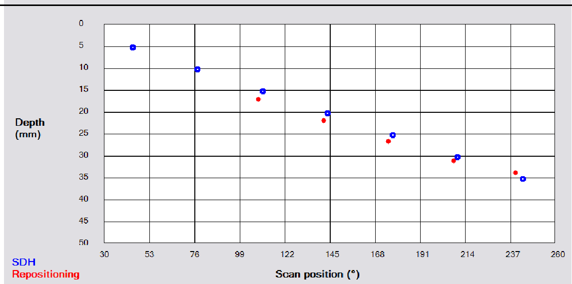
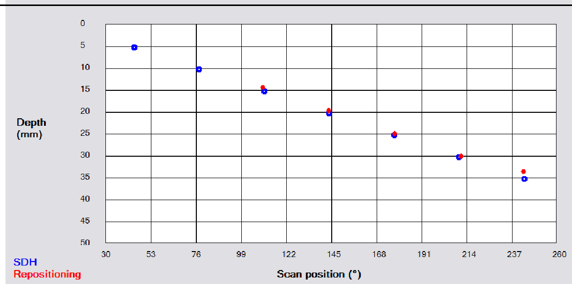
	Conventional method	Advanced method
L0TD 20		
L30HP 30		
L40HP 30		

Table 2: SDH repositioning for circular configuration

Transmitter-Receiver Phased array 2 MHz Probe (type WR5TS45L00_2M3x11A5B) on 14" carbon steel axial characterization block

			Half Moon reflector		SDH reflectors					
Focal Law	Method	RA_{SSL} Theoretic (°)	Sensitivity on HM (dB)	HM Pulser Voltage (V)	BW -6dB (mm)	EP (mm)	Delay (µs)	RA_{CSL} (°)	RA_{SSL} (°)	Delta Positioning (mm)
AX L35HP70	Adv	35	24.3	90	5.0	30.6	18.5	33.3	31.9	0.12
	1	35	24.3	90	6.5	31.2	18.0	36.1	34.6	2.45
	2	35	24.3	90	6.7	31.2	18.0	33.9	32.5	1.24
	3	35	24.3	90	6.8	31.2	18.7	32.3	31.0	1.57
	4	35	24.3	90	6.5	30.5	18.0	36.1	34.6	3.13
	5	35	24.3	90	6.5	30.6	18.6	32.6	31.2	0.62
	6	35	24.3	90	6.5	30.6	18.6	33.2	31.8	0.26
AX L45HP70	Adv	45	24.6	90	7.5	28.7	18.3	44.1	42.1	0.21
	1	45	24.6	90	9.1	30.6	17.7	46.6	44.4	1.45
	2	45	24.6	90	9.2	30.6	17.7	45.9	43.7	0.98
	3	45	24.6	90	9.6	30.6	18.4	43.7	41.7	2.21
	4	45	24.6	90	9.1	28.8	17.7	46.6	44.4	3.07
	5	45	24.6	90	9.2	29.0	18.2	44.0	42.0	0.35
	6	45	24.6	90	9.2	29.0	18.2	44.0	42.0	0.36
AX L55HP70	Adv	55	22.5	90	9.9	25.3	19.8	53.7	50.9	0.36
	1	55	22.5	90	11.4	28.6	18.5	56.9	53.8	2.13
	2	55	22.5	90	11.7	28.6	18.5	56.1	53.1	1.52
	3	55	22.5	90	12.3	28.6	19.9	53.6	50.8	3.78
	4	55	22.5	90	11.4	25.3	18.5	56.9	53.8	5.17
	5	55	22.5	90	11.4	26.9	19.4	53.7	50.9	1.08
	6	55	22.5	90	11.3	26.9	19.4	54.0	51.2	0.77

Table 3: Numerical results for axial configuration

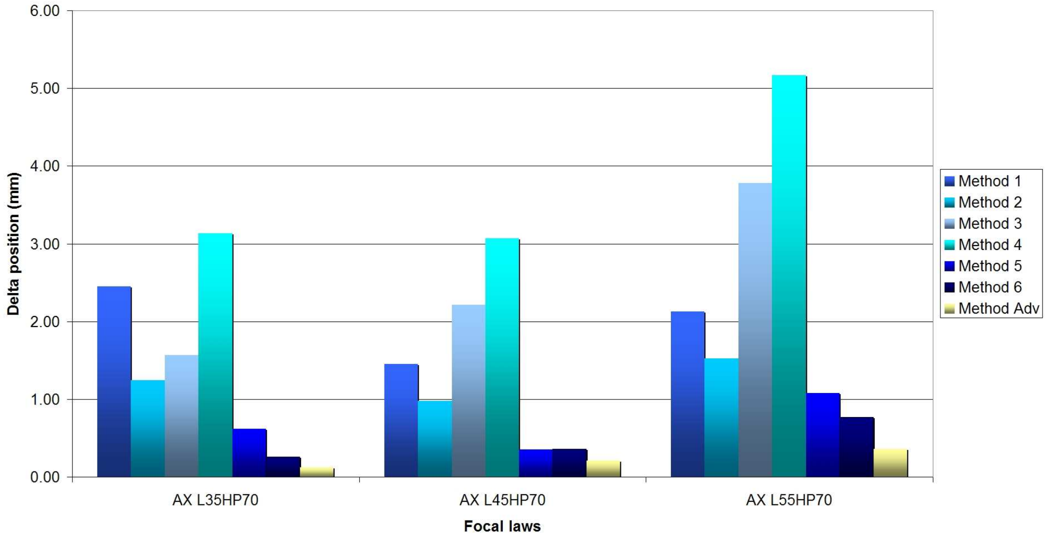


Figure 6: Comparison chart for axial configuration

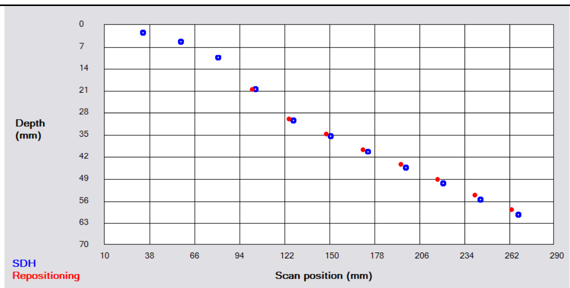
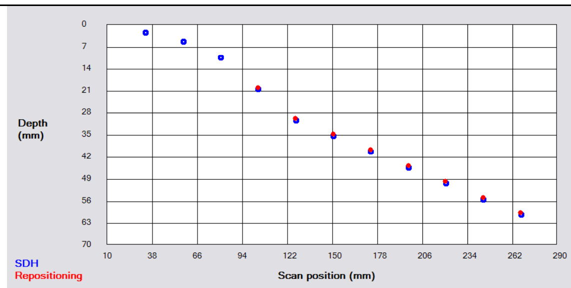
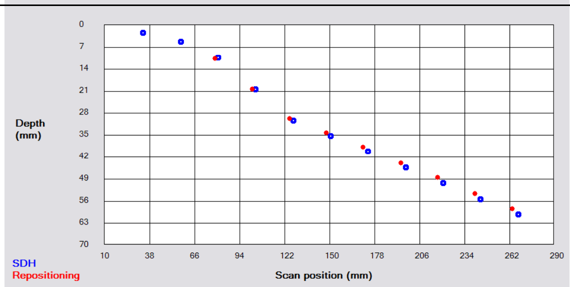
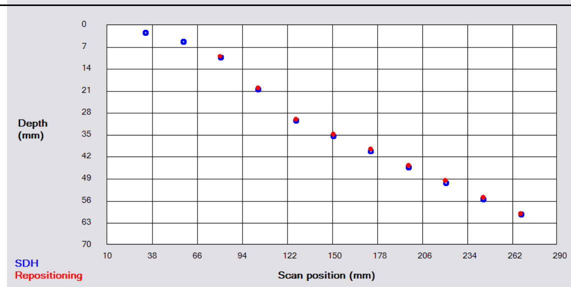
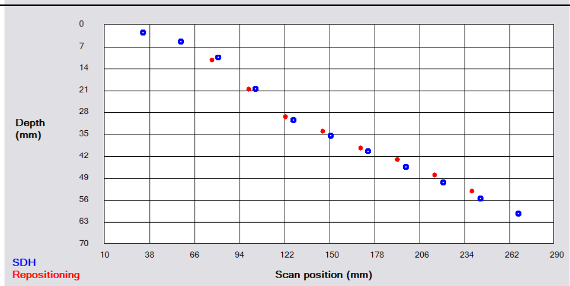
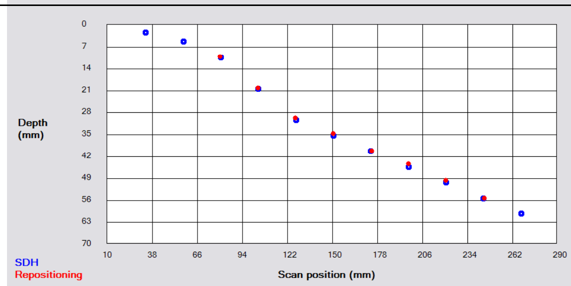
	Conventional method	Advanced method
L35HP 70		
L45HP 70		
L55HP 70		

Table 4: SDH repositioning for axial configuration

3.2. Measurements on dissimilar metal weld

The main problem associated with the characterization process concerns the material transfer. Indeed, most of the time, representative characterization blocks (i.e. made in the same material type, with the same structure, thermal treatment and shape as the material to inspect) are not available. Thus the probe parameters are calculated using acquisition data on a specific material (generally carbon steel) and are used on another material (generally stainless steel) that has different ultrasonic properties. For example, a very difficult case is the inspection of dissimilar metal weld that presents particularly unknown ultrasonic properties with an anisotropic structure. The simplest way to handle this problematic is to assume that the RA has to be recalculated using both material velocities applying Snell’s law, and that the EP and the PD have to stay equal.

Considering the previous points, some experimental tests were done on a “real” stainless steel block with a dissimilar metal weld containing some SDH reflectors. This section presents some comparisons between the conventional method, the advanced method and a customized advanced method used to relocate the SDH of this block. This last method can be achieved adjusting “manually” the material velocity in order to improve the accuracy of the SDH repositioning. This is possible only if a representative block is available.

The example here after presents acquisition results in analysis mode (B-Scan) including an overlay representing the dissimilar weld within some SDH. The presented comparison is only visual and has been done by changing the focal law parameters and the material velocity in the ultrasonic software.

Transmitter-receiver Phased Array 2 MHz probe (type WR2TS60L00_2M4x8A2A) on 6” calibration block ASME III dissimilar weld for focal law L40HP30

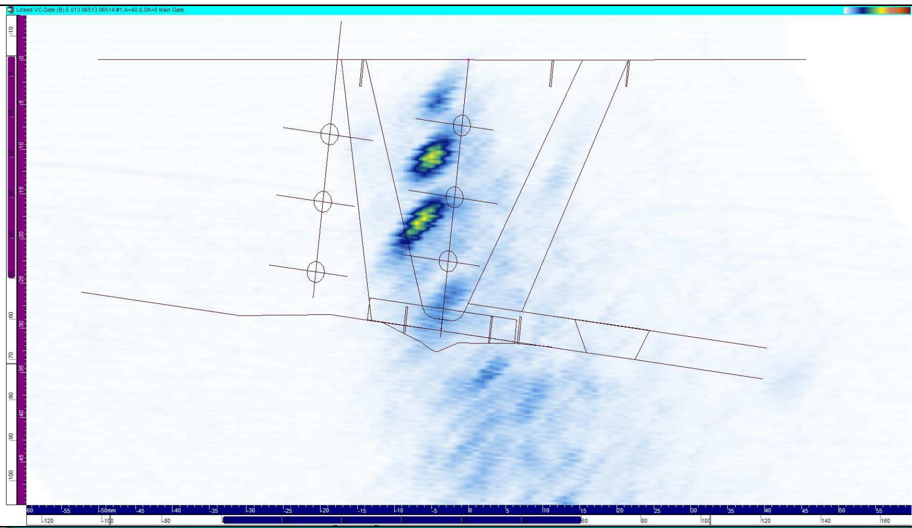
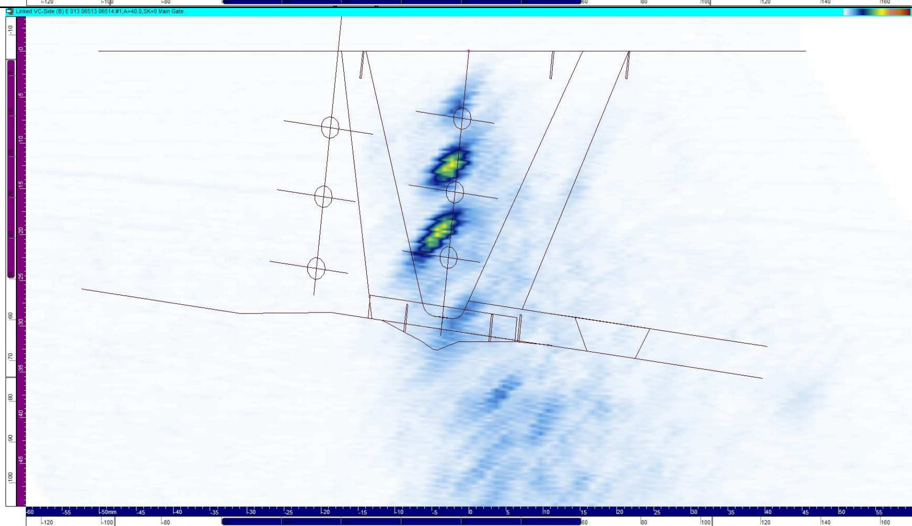
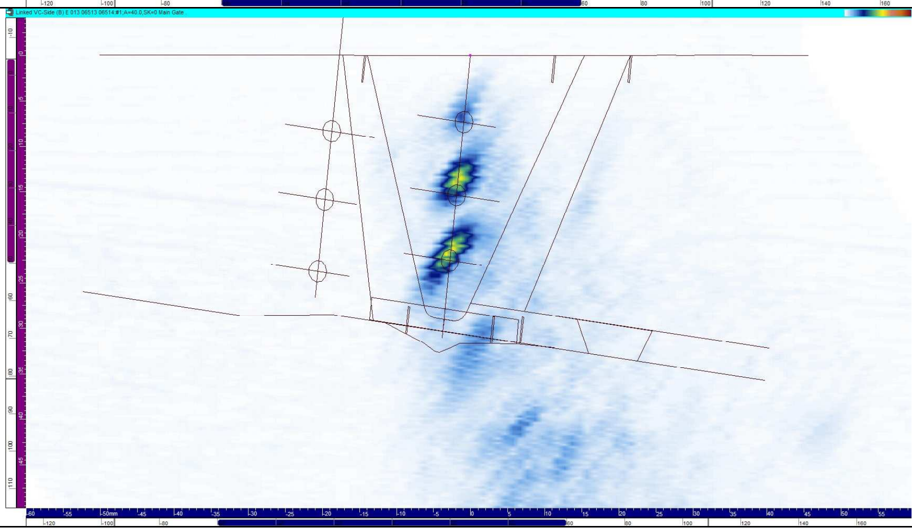
Conventional method: V_{SSL} = 5700 m/s RA = 40.02° EP = 17 mm PD = 17.3 µs	
Advanced method: V_{SSL} = 5700 m/s RA =38.33° EP = 15.3 mm PD = 16.7 µs	
Customized advanced method: V_{SSL} = 6200 m/s RA =38.33° EP = 15.3 mm PD = 16.7 µs	

Table 5: Comparison in analysis mode for focal law L40HP30

4. CONCLUSION

In this paper, we presented an innovative characterization method with the new associated software. This new approach underlined the limitations of the conventional methods based on geometrical theory and showed the necessity to find another method. This new method is born by developing a way to compare the efficiency of all the conventional methods. Indeed, the advanced calculation method is based on the optimization of the reflectors repositioning.

Measurements on carbon steel characterization blocks presented here demonstrate that the new method provides an important improvement compared to the conventional method on carbon steel block. Another striking observation is that the new RA calculated can be far from its theoretical/nominal value. Regarding all the codes, norms (e.g. EN12668) and standards, this casts doubts on the necessity to limit the acceptable variation on the probes parameters to a certain value linked to a nominal value. For example, a probe is generally accepted when $RA = \left[RA_{Nominal} \pm 2°\right]$ where *nominal* means the theoretical RA. Yet the old conventional method was generally able to respect that condition but regarding results presented in Table 1 and Table 3, using the new advanced method, it is obvious that it will not be possible anymore. This condition should rather be adapted to $RA = \left[RA_{Initial} \pm 2°\right]$ where *initial* means the first calculated characterization value.

Measurements on dissimilar metal weld presented here demonstrate that the new method provides an important improvement compared to the conventional method but that we still are limited by the problematic of material transfer. It is a well-known fact that ultrasonic propagation into anisotropic material is quite difficult to foresee. For example, the mechanical vibration direction stays generally constant when the energy propagation direction can vary. Ultrasonic velocity can also fluctuate according to the beam direction. Thus, it will always be better if a representative block with some known reflectors could be available, so the ultrasonic velocity could be eventually adjusted. Otherwise, the new method already provides a good appreciation compared to older methods.

5. ANNEXES

5.1. Axial or planar scanning: general coordinate system, notations and equations on HM

The zero position for HM acquisition is set when the probe front is at the HM beginning. Figure 7 below shows the notations used in the associated equations.

$$HP = USound - \frac{PD \times Vel_{Block}}{2}$$ **Equation 5-1**

$$HP = HM\_R$$ **Equation 5-2**

$$PD = \frac{2}{Vel_{Block}} \times \left(USound - HM\_R\right)$$ **Equation 5-3**

$$EP = HM\_R - Scan$$ **Equation 5-4**

Where *USound* is the ultrasonic path measured (mm), *Scan* is the scan position measured (mm) , Vel_{Block} is the block ultrasound velocity (mm/µs) and *HM_R* is the half-moon radius (mm).

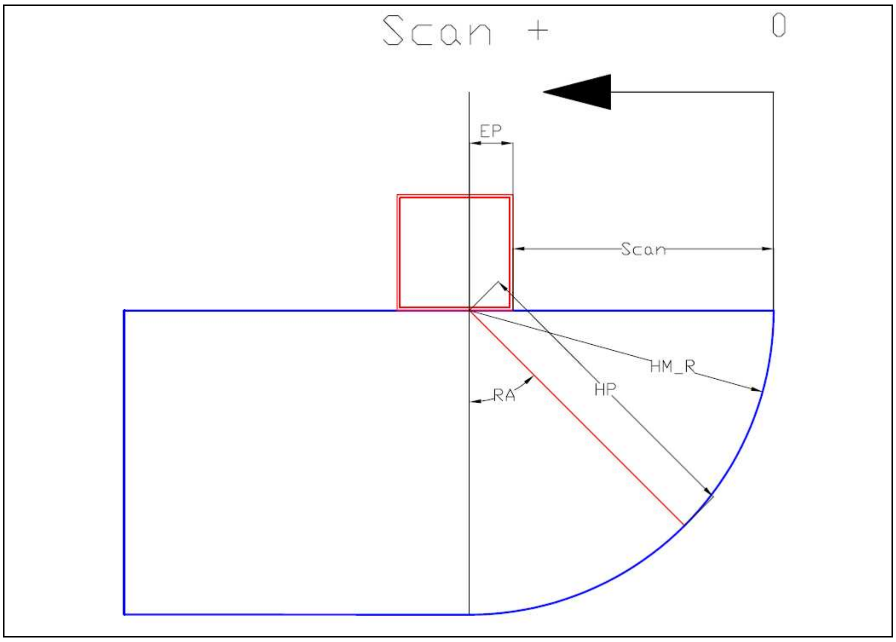


Figure 7: General coordinate system and notations on HM

5.2. Axial or planar scanning: general coordinate system, notations and equations on SDH

The zero position for SDH acquisition is set when the probe front is at the block beginning. Figure 8 below shows the notations used in the associated equations. On one SDH, 2 equations are available ($RA = f(EP)$ and $RA = f(PD)$) with 3 unknown values (EP, PD and RA).

$$Tang(RA) = \frac{Scan + EP - Scan\_real}{Depth\_real}$$ **Equation 5-5**

$$HP = USound - \frac{PD \times Vel_{Block}}{2}$$ **Equation 5-6**

$$Cos(RA) = \frac{Depth\_real}{HP}$$ **Equation 5-7**

Where *Scan_real* is the center SDH real scan position (mm) and *Depth_real* is the center SDH real depth position (mm).

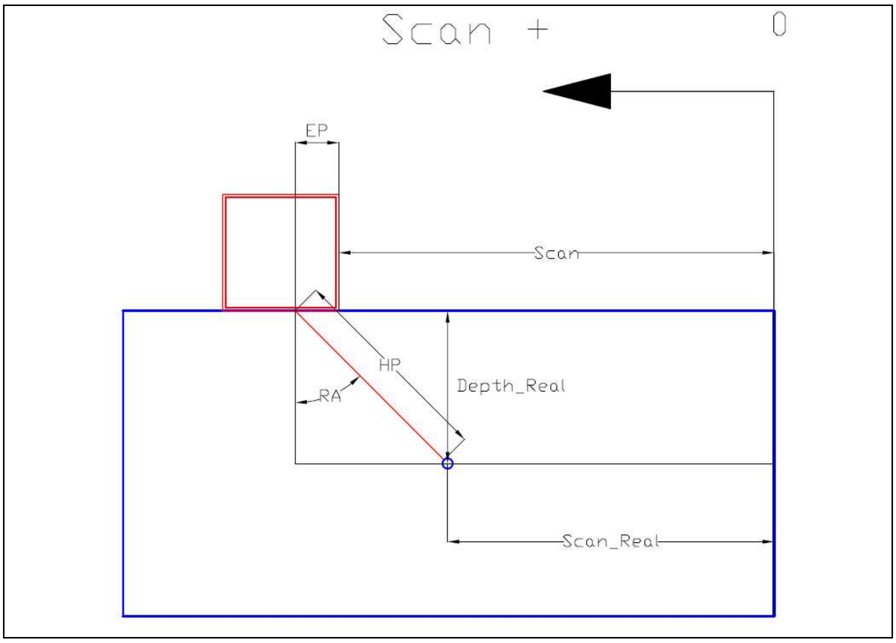


Figure 8: General coordinate system and notations on SDH

5.3. Circular scanning: general coordinate system, notations and equations on HM

The zero position for HM acquisition is set when the probe front is at the HM beginning. Figure 9 below shows the notations used in the associated equations.

$$HP = USound - \frac{PD \times Vel_{Block}}{2}$$ **Equation 5-8**

$$HP = HM\_R$$ **Equation 5-9**

$$PD = \frac{2}{Vel_{Block}} \times (USound - HM\_R)$$ **Equation 5-10**

$$EP\_Deg = HM\_R\_Deg - Scan$$ **Equation 5-11**

$$EP = R \times Sin(EP\_Deg)$$ **Equation 5-12**

Where *R* is the block radius (mm), *Scan* is the scan position measured (°), *EP_Deg* is the exit point in polar reference (°) and *HM_R_Deg* is the half-moon radius in polar reference (°).

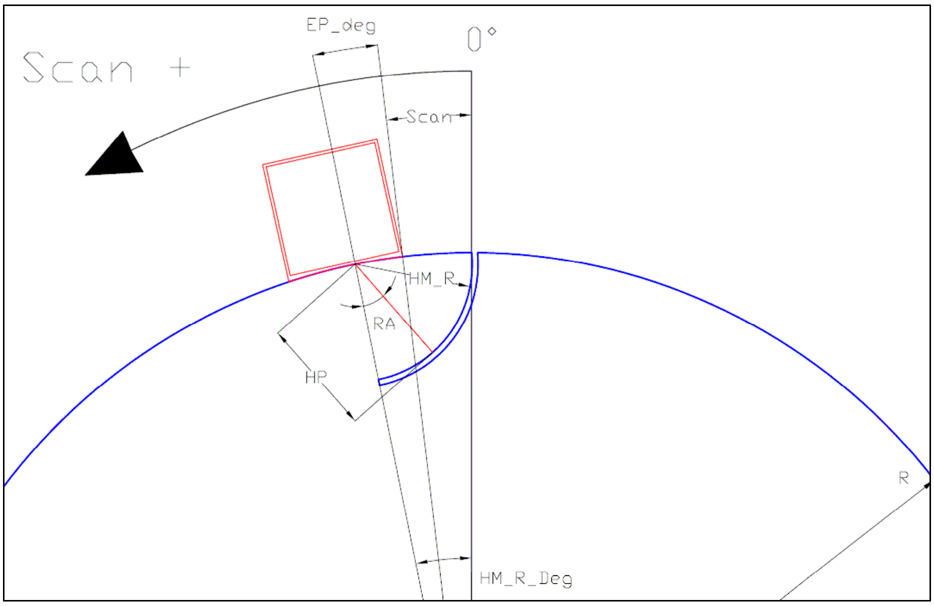


Figure 9: General coordinate system and notations on HM

5.4. Circular scanning: general coordinate system, notations and equations on SDH

The zero position for SDH acquisition is set when the probe front is at the block beginning. Figure 10 below shows the notations used in the associated equations. On one SDH, 2 equations ($RA = f(EP)$ and $RA = f(PD)$) are available with 3 unknown values (EP, PD and RA).

$$EP = R \times Sin(EP\_Deg) \quad \textbf{Equation 5-13}$$

$$Alpha = EP\_Deg + Scan - Scan\_real \quad \textbf{Equation 5-14}$$

$$HP = \sqrt{R^2 + (R - Depth\_real)^2 - 2 \times R \times (R - Depth\_real) \times Cos(Alpha)} \quad \textbf{Equation 5-15}$$

$$Cos(RA) = \frac{R^2 + HP^2 - (R - Depth\_real)^2}{2 \times R \times HP} \quad \textbf{Equation 5-16}$$

$$HP = USound - \frac{PD \times Vel_{Block}}{2} \quad \textbf{Equation 5-17}$$

Where *Scan_real* is the center SDH real scan position (°) and *Depth_real* is the center SDH real depth position (mm).

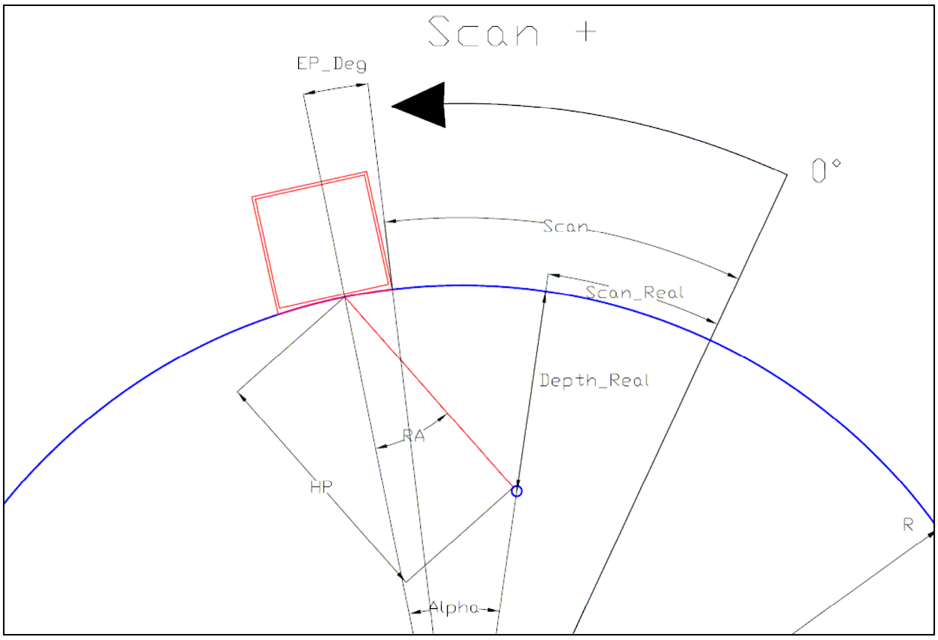


Figure 10: General coordinate system and notations on SDH