CONTRIBUTION TO DETECTION AND SIZING LINEAR DEFECTS BY CONVENTIONAL AND PHASED ARRAY ULTRASONIC TECHNIQUES

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Abstract: Crack height measurement using time-of-flight techniques (back-scattering tip echo diffraction and pulse-echo focus beam phased array) was performed on flat bars with fatigue induced cracks, in the laboratory conditions. The thickness ranges from 6 mm to 25 mm. The crack height was between 0.6 mm to 12.7 mm. Frequency range of conventional probes was between 5 MHz to 10 MHz. Linear phased array probes frequency was between 4 MHz to 12 MHz. Ligament measurement of EDM notches was performed on straight blocks of 25 mm and 35 mm using conventional and phased array probes. Conventional probes using tip-echo diffraction technique could detect and size cracks within ± 1.5 mm accuracy. The ligament is reliable measured for values greater than 3 mm. Phased array technique based on volume-corrected sectorial scan measurements could reliable size cracks within ±0.5 mm. The ligament measurement with phased array B-scan for the best detection/display angle range is accurate for values as low as 1.5 mm. The accuracy of ligament sizing is ± 0.6 mm.

Introduction: The previous published results regarding equipment substitution (1), crack sizing using tip-echo diffraction technique (2) and crack sizing using mode-converted techniques (3) led to the development of detection and sizing procedures for pipe welds of primary circuits in CANDU reactors. The paper presents a comparison between the performance of conventional probes of higher frequency (5-10 MHz) and linear phased array probes in shear-waves and longitudinal waves mode with frequency between 4 MHz to 12 MHz. Discussions regarding the application of phased array technique on mock-ups and in the field are also presented.

Results: The lab experiment was performed on straight steel bars with fatigue induced cracks. Ligament evaluation was performed on eight blocks with five EDM notches cut along each block width. The EDM notches were oriented at different angles from 0° to 40° (see Table 1).

Table 1: Samples used in experimental program.

Bars with fatigue cracks			Bars with EDM notches for ligament study	
Block ID	Thickness (mm)	Crack height (mm)	Block ID/thickness [mm]	Ligament height [mm]
#4	6.4	0.6	TED-4A – 25	0
#6	6.4	1.6	Lig-1.5A - 25	1.5
#7	12.7	1.3	TED-4B - 25	3
#8	12.7	5.5	Lig-6A - 25	6
#9	12.7	2.3	MUVE3-2 – 35 mm	0
# 10	12.7	3.2	Lig-1.5B – 35 mm	1.5
#12	19.1	1.2	Lig-3B – 35 mm	3
OHR-20	20	7.8	Lig-6B – 35 mm	6
#18	25.4	0.6 – 12.1		

The crack height was measured on each bar side with optical gauges. The accuracy of measurement was ± 0.05 mm. Ultrasonic equipment consists of Sonatest Masterscan 335 flaw detector, R/D Tech OMNISCAN MX (conventional and phased array) and FOCUS 32/128 for phased array. A hand-driven scanner X-Y was used in combination with OMNISCAN and FOCUS. Sampling on both axes was 0.25 mm. The high-damped conventional and piezo-composite phased array probes are listed in Table 2. The mono-crystal probes were used with 45° and 60° wedges. Linear phased array probes were in two modes: a) with a wedge to generate shear waves (SW) with a sectorial scan between 30° to 85°; b) direct contact hard-face to generate longitudinal waves with a sweep angle between -40° to 40°.

Table 2: Probes characteristics used for the experiment

Probe size [mm]	Center frequency [MHz]	Relative bandwidth [%]	Probe ID	Active area [mm x mm] pitch [mm]	Nr. elements	Frequency [MHz]	Bandwidth [%]
6.4	5.0	85	Shear waves				
9.5	5.0	92	2	6 x 6 / 0.31	20	10	75
6.4	7.5	96	20	5 x 5 /0.31	16	8.8	78
9.5	7.5	92	27 I	6 x 6 /0.5	12	5.4	72
6.4	10.0	94	36 A	13 x 8 / 0.6	16	4.4	76
9.5	10.0	97	43 E	10 x 7 /0.8	16	7.6	95
			Longitudinal waves				
			2F	6 x 6.0.31	20	11.9	73
			21	14 x 10/0.5	28	10.5	84
			47A	13 x 12 / 0.8	16	5.5	76

Each detection was optimized for crack tip and measurement was repeated three times for the same location. The OMNISCAN and FOCUS acquisition files were analyzed with TOMOVIEW 2.2R9 software.

Crack height: Conventional probes could reliable size fatigue cracks if their height is greater than 1.5 mm. The last significant tip for cracks with height less than 1.0 mm is less than 2:1 ratio. High-damped probe of high frequency can't size the crack of 0.6 mm in 6-mm bar. Examples of crack height measurement are presented in Figure 1 to Figure 3.

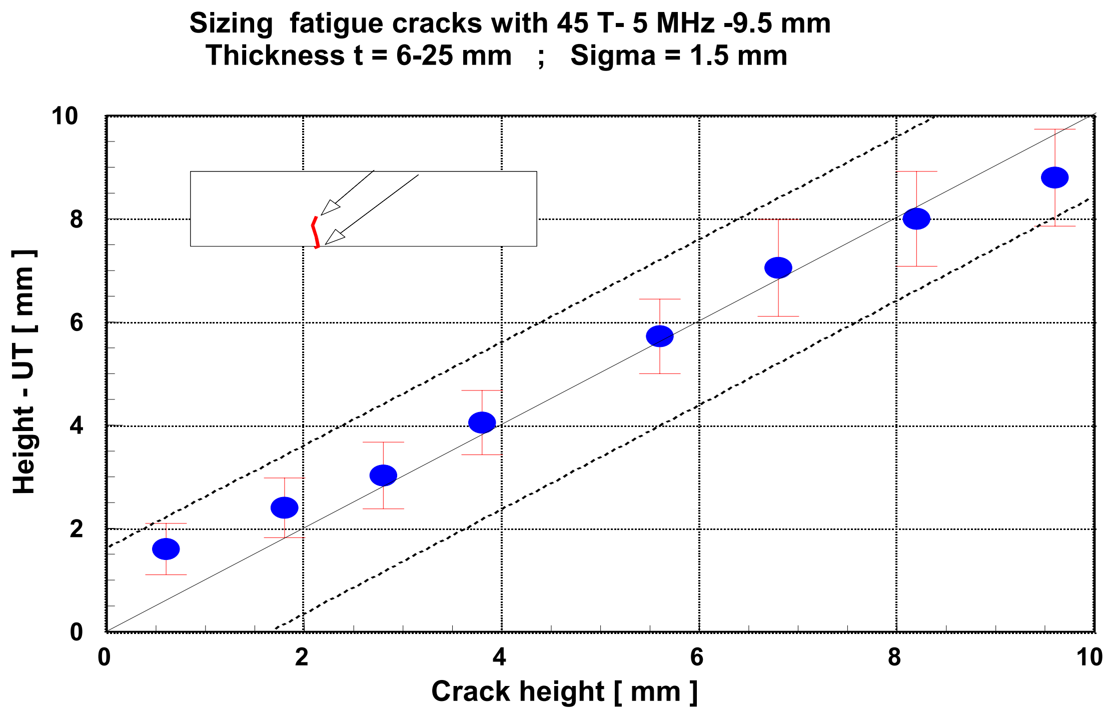

Figure 1: Sizing capability with RATT ($h_{crack} = \Delta CRT / \cos\beta$) for 5MHz, 9.5-mm probe.

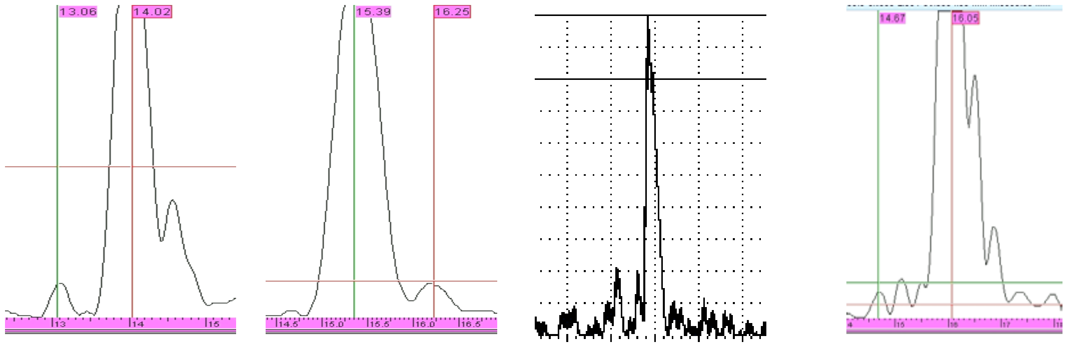

Figure 2: Examples of crack height evaluation using front tip or back tip. Signal-to-noise ratio for the last significant peak is closer to 2:1 (6 dB).

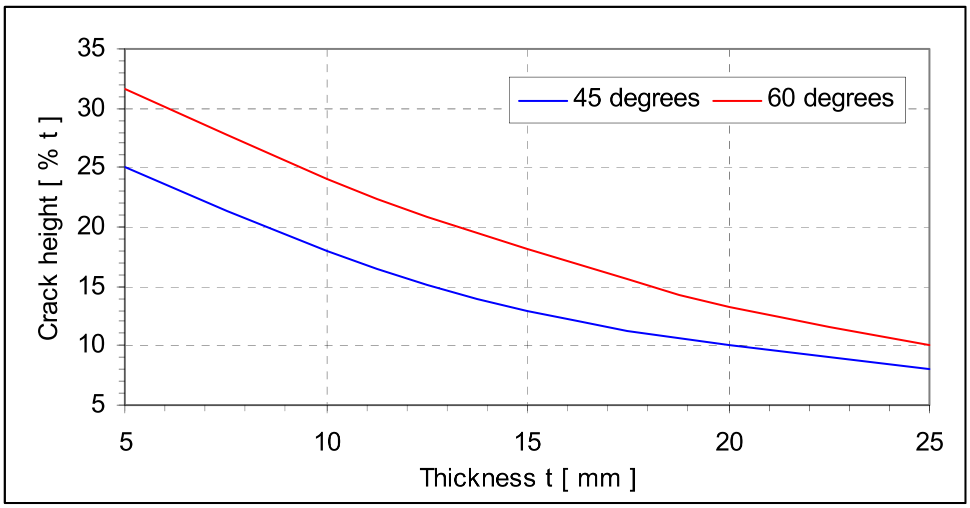

Figure 3: Crack sizing capability for mono-crystal probes.

Phased array results are presented in Figure 4 to Figure 7. The results are better compared to mono-crystal probes due to the following facts:

- Focus beam
- Multiple A-scans
- Combination of views
- Increased signal-to-noise ratio
- Use pattern recognition in volume-corrected sectorial scan
- Use longitudinal waves of higher frequency (> 10 MHz) for crack tip depth sizing.

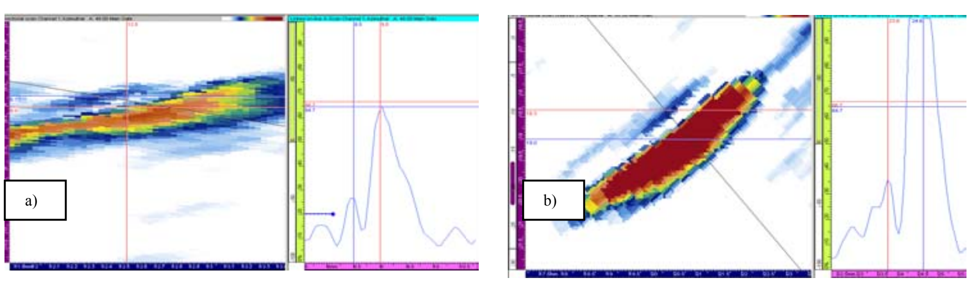

Figure 4:Example of crack height measurement using volume-corrected sectorial scan. a) H_{PA} = 0.8 mm; H_{crack} = 0.6 mm in bar #4; b) H_{PA} = 1.4 mm; H crack =1.2 mm in bar # 12.

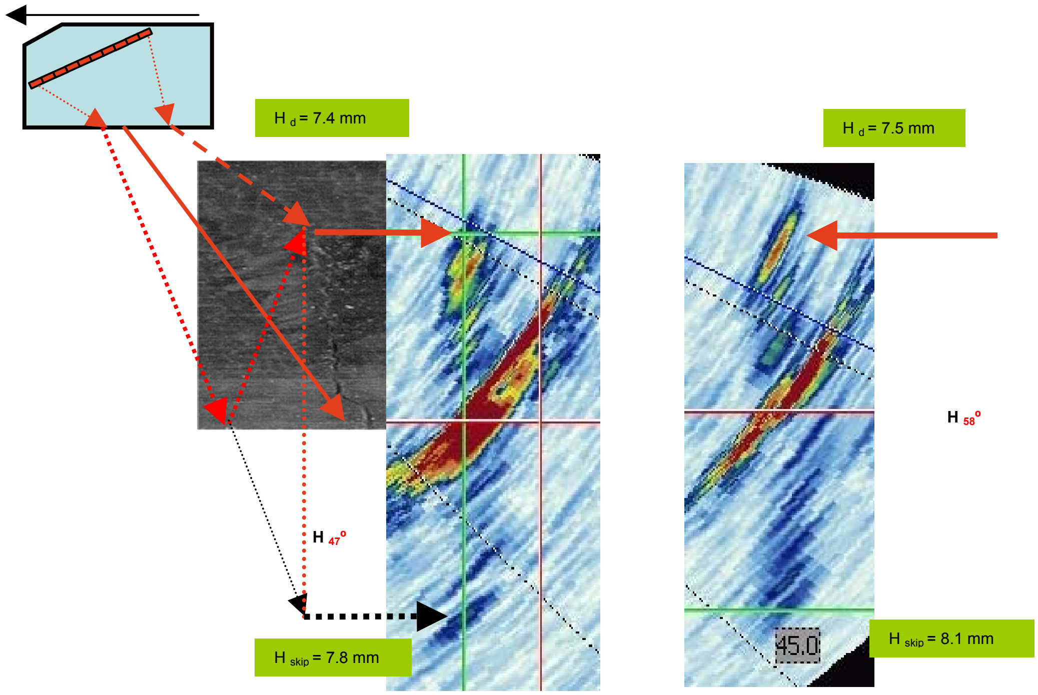

Figure 5: Example of crack height sizing in sample OHR-20 with OMNISCAN at different angles and different scan values. The values are within ± 0.4 mm versus the actual crack height.

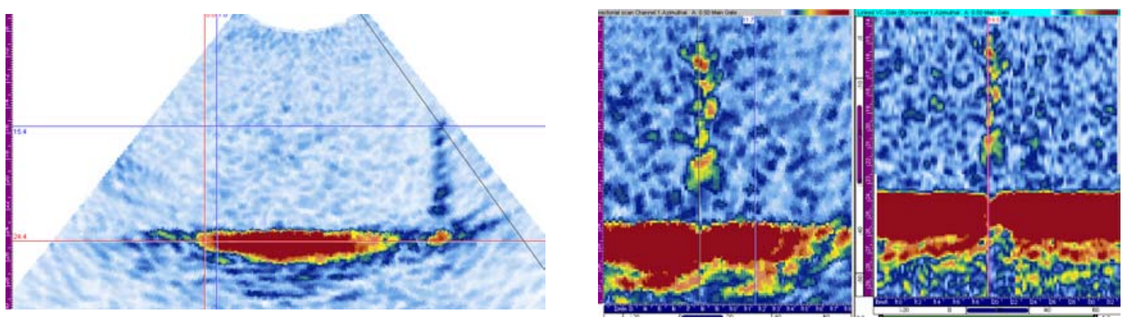

Figure 6: Example of crack sizing using P21 in L-waves mode (left). Crack branches are displayed in S-scan and VC B-scan (right).

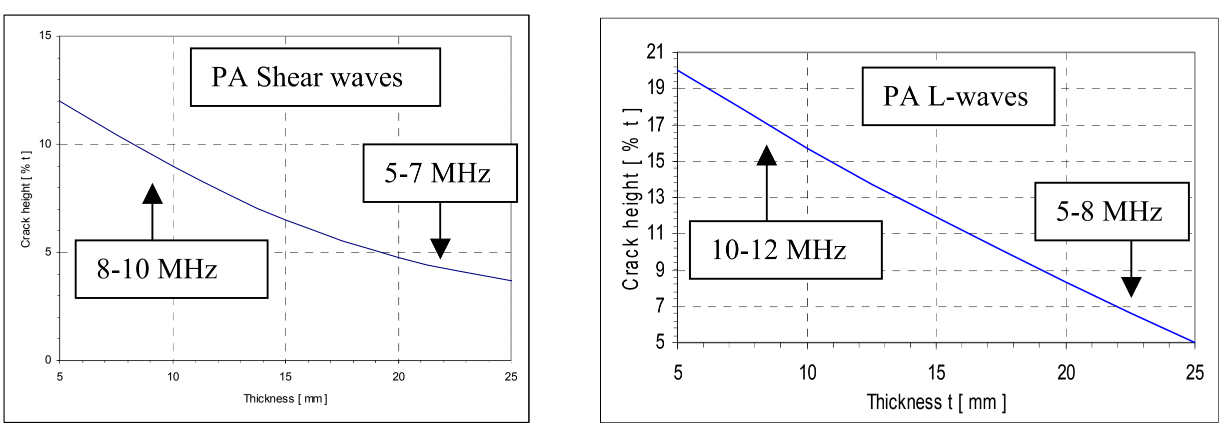

Figure 7: Crack sizing capability for phased array techniques: a) shear waves; b) L-waves.

<u>*Ligament measurement*</u>: Conventional probes cannot size the inner ligament for height < 3 mm. Accuracy in sizing is about ± 1.5 mm. The evaluation depends on ligament angle and beam orientation. The average results for 2-sigma distribution of the most common used probe (5 MHz-45°) are presented in Figure 8. The 60°-probe leads to errors larger than ± 3 mm and is unacceptable for ligament sizing. Phased array techniques could reliable size the ligament starting with 1.5 mm. The sizing accuracy is about ± 0.4 mm. The LW technique is the most accurate and straightforward technique. Representative results for 25 mm and 35 mm is presented in Figure 9 and Figure 10. The average results for 2-sigma distribution are presented in Figure 11.

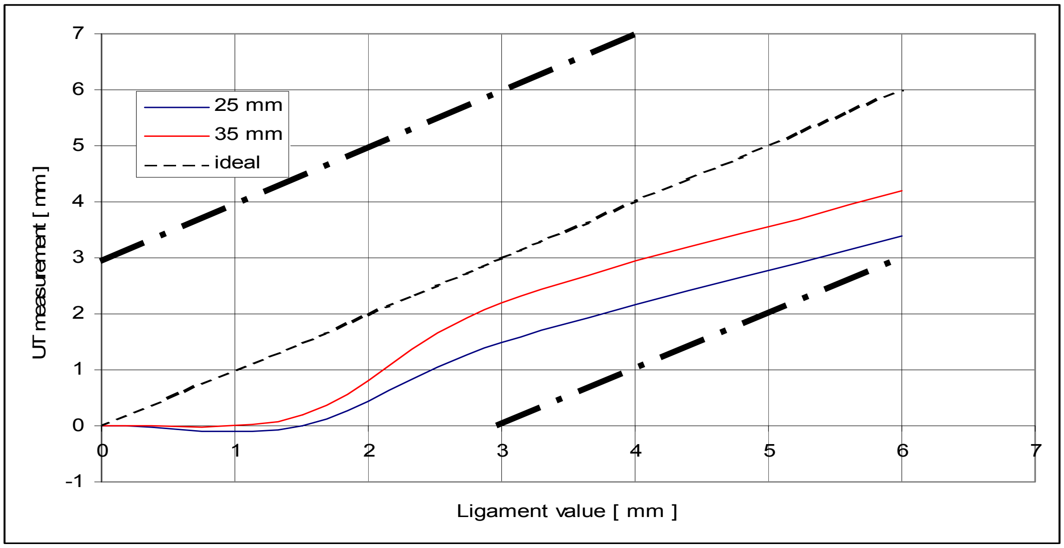

Figure 8: Ligament measurement by mono-crystal probe of 5 MHz-45° of 9.5-mm active diameter.

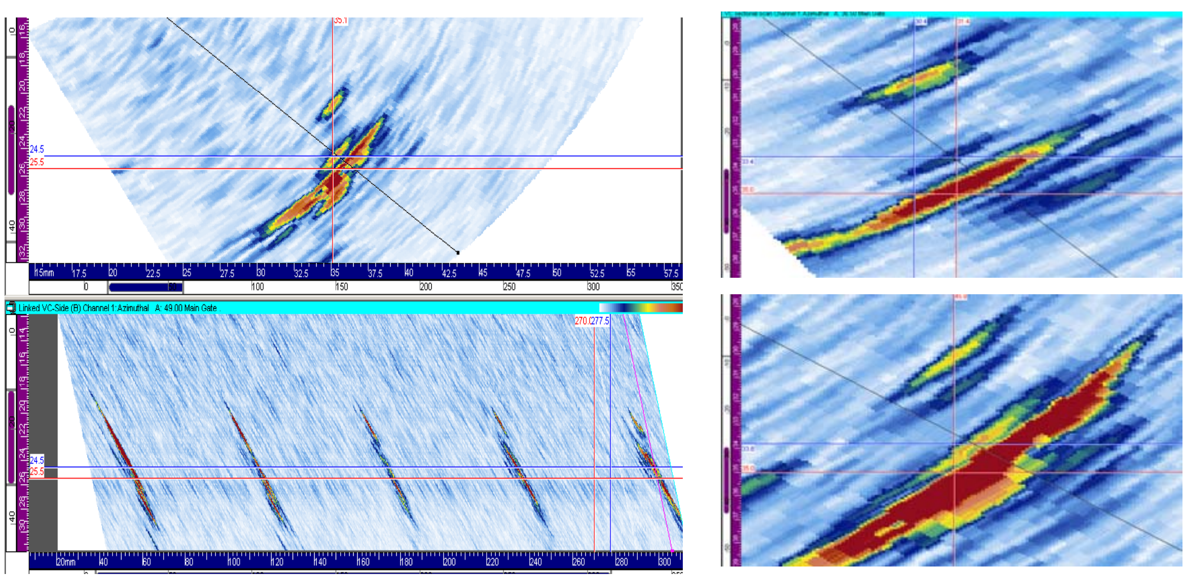

Figure 9: Example of ligament measurement with SW phased array probe at different angles.

Discussions: The experimental setup is the first phase of capability demonstration of phased array techniques in comparison with conventional ultrasonic method. The data were collected and analyzed with *a-priori knowledge* about defect nature, location and size. The data presented in this paper were acquired in ideal conditions on flat bars.

Next phase is to apply ultrasonic phased array to welded pipes with implanted defects. A similar experiment was performed for turbine components (4).

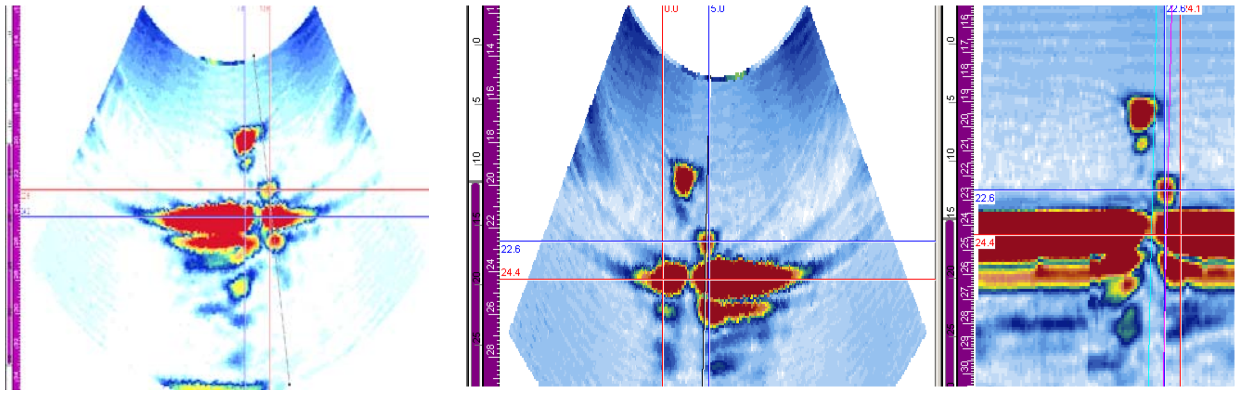

Figure 10: Example of ligament measurement with LW phased array probe at different angles.

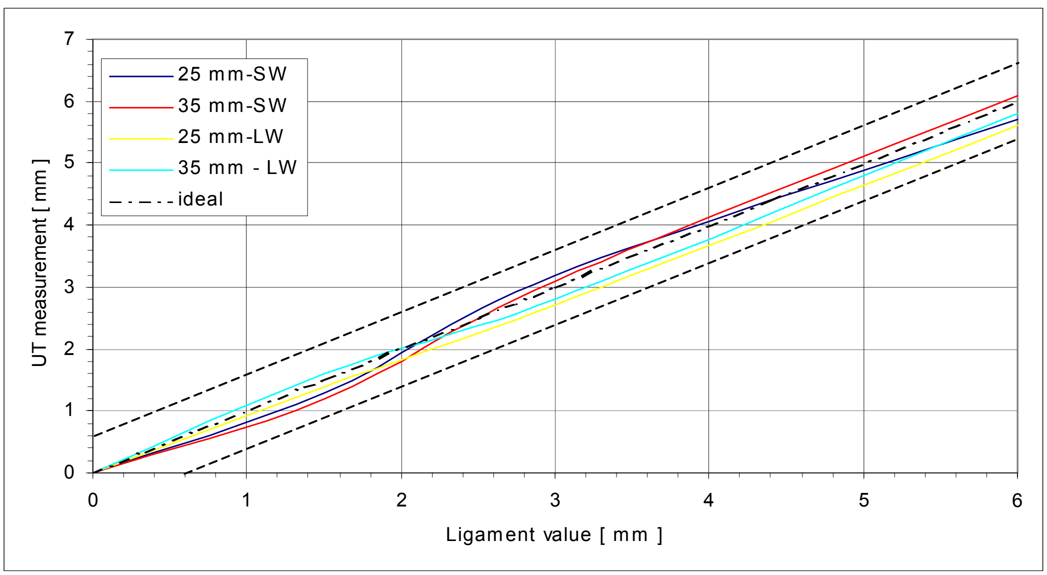

Figure 11: Ligament measurement by phased array probes in SW and LW mode.

Conclusions: The experimental results for crack height and ligament measurements based on time-of-flight and sectorial scan readings concluded the followings:

- Tip-echo diffraction technique using back-scattering and piezo-composite mono-crystal probes could size the crack height within ± 1.5 mm accuracy; for 2-sigma distribution;
- Time of flight measurements with data plotting for back-scattering and specular reflection of the ends of the EDM notch closer to the inner wall *undersize* the ligament;
- A reliable measurement within RMS = ± 3 mm is achievable only for ligament height > 3 mm;
- Phased array techniques in L-waves and S-waves are more accurate;
- Crack height could be accurate within ± 0.5 mm
- Crack pattern is easy to be recognized
- Crack tips are easy to be measured; crack branches are well displayed with focus beam in LW mode

- Ligament measurement is within ± 0.6 mm;
- Ligament height of 1.5 mm from inner surface can be reliable sized;
- Notch angle and notch height is correct plotted within ±5° and ± 0.5 mm;
- Sectorial scan in combination with VC-B-scan could produce a range of reliable data, all within ± 0.5-mm readings;
- The data were obtained on flat bars, in the lab conditions;
- These data must not be generalized for real-field applications;
- A capability demonstration must be performed on welded pipes with implanted cracks.

References: 1. Ciorau, P., Blackney, J., Scott, M. : The influence of ultrasonic equipment on amplitude response of linear reflectors, in *CSNDT Journal, vol.17 , no. 2 (March/April 1996), pp.13 -18*

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