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Phased Array Equipment Substitution-Practitioner Approach Applied to Large-Scale Turbine Inspections

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Abstract: The paper presents experimental results for equipment substitution (machines and software) when performing large-scale turbine inspections using phased array ultrasonic technology (PAUT). The major concept of equipment substitution is linked with specific tolerances of EDM notches located in reference blocks. The main features such as: detection angle, signal-to-noise ratio, index, depth, orientation and defect height are evaluated based on A- and S-scan. This approach is based on inspection scope requirements and can drastically reduce the number of checked and documented variables of phased array system when performing a substitution. Examples are given for shear- and longitudinal waves on specific blocks of GEC Alstom low-pressure turbine components (L-0 steeple, L-1 steeple and L-1 blade). Tolerances on equipment substitution based on experimental results are also presented.

Problem Statement

Ultrasonic equipment (machines and software) is an integral part of inspection procedure validation. Performance demonstration and equipment substitution process are standardized [1-2] only for pressure vessels and namely for in-service inspection of nuclear components. Qualification of phased array ultrasonic technology (PAUT) for in-service inspection of pressurized components, in aeronautics and in-situ turbine components stressed the importance of equipment checking [3 – 10]. PAUT is a very dynamic technology, with a fast pace development during the last few years. New probes, improved machines and the new software versions, and/or improvements identified during the field execution led to a practical approach of equipment substitution. Our approach is based on defect requirements and the pattern displayed by sectorial scan (S-scan) for a specific set-up, system and piece of software. Similar approaches are found in Zetec technical documents [11 – 12] and in OlympusNDT new book[13]
Qualification process is time-consuming and very costly. PAUT adds new challenges: multiple pulser-receiver system, beam forming, dynamic depth focusing and multiple angles with multiple focal depths. The complexity of the set-up could easily reach 1,000 variables to be checked. The checking procedure is more time-consuming than the inspection itself. A new approach must be taken for checking the system performance, as mentioned above. In-situ inspection qualification of turbine components presents significant differences compared to full performance demonstration for in-service inspection welded joints and other components in nuclear utilities:

- Defects are located only on specific stressed areas (see **Figure 1**)
- Some components could be inspected only by diffracted techniques (side scanning)
- Tolerances on defect features are more stringent than for weld inspection qualification
- There is no blind test and independent qualification body[14]
- Procedure qualification is performed on open trials by the inspection company, namely on EDM notches
- S-scan presents specific pattern for each type of component (see **Figure 2** and **Figure 3**)

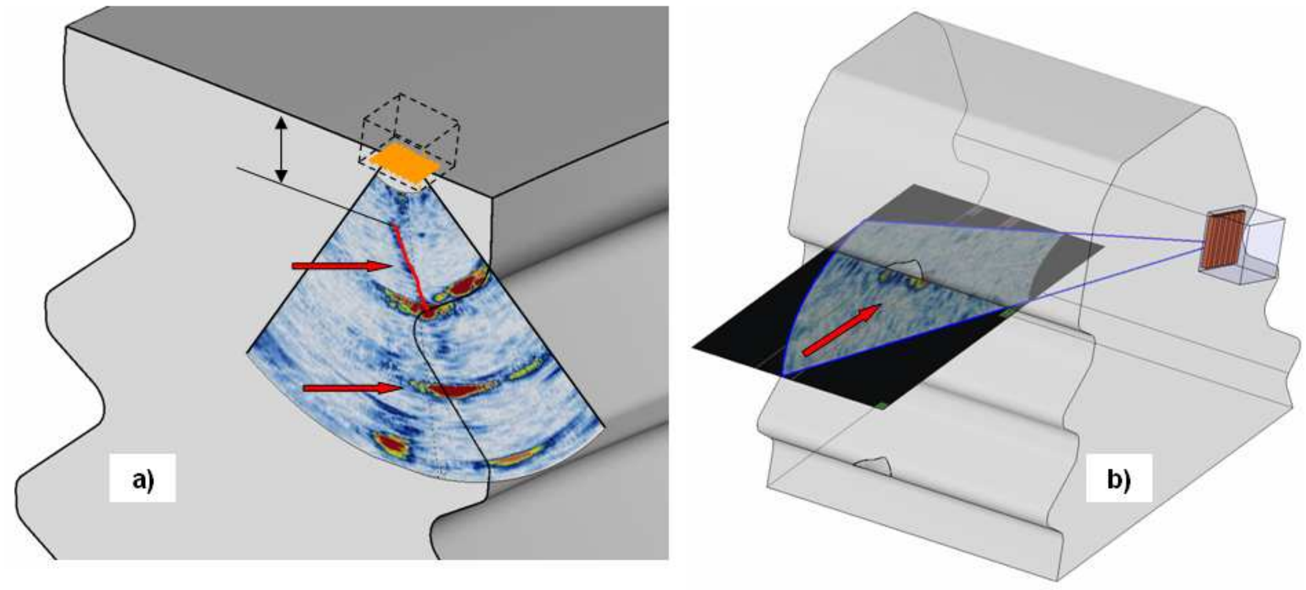

Figure 1: Example of data plotting for GEC ALSTOM components: a) L-0 steeple and b) L-1 steeple.

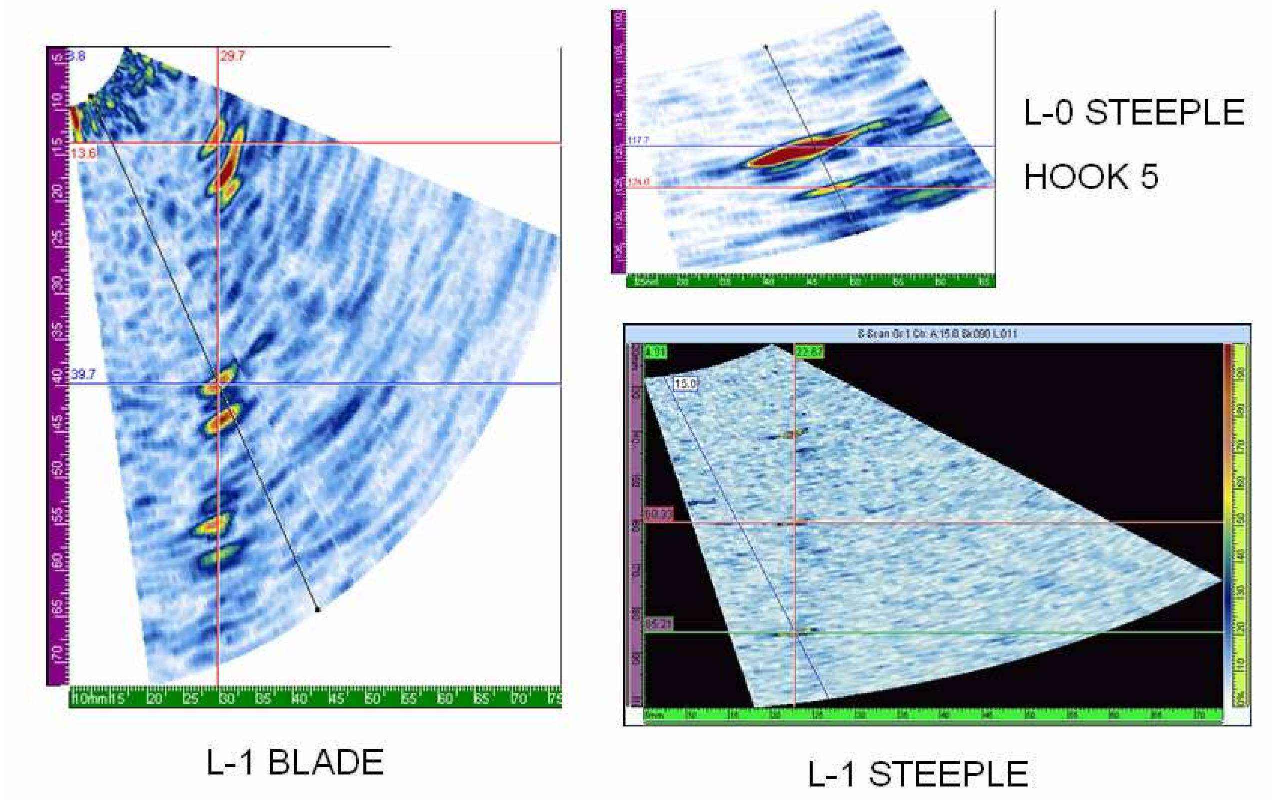

Figure 2: Example of S-scan display for L-1 blade, L-0 steeple-hook 5 and L-1 steeple.

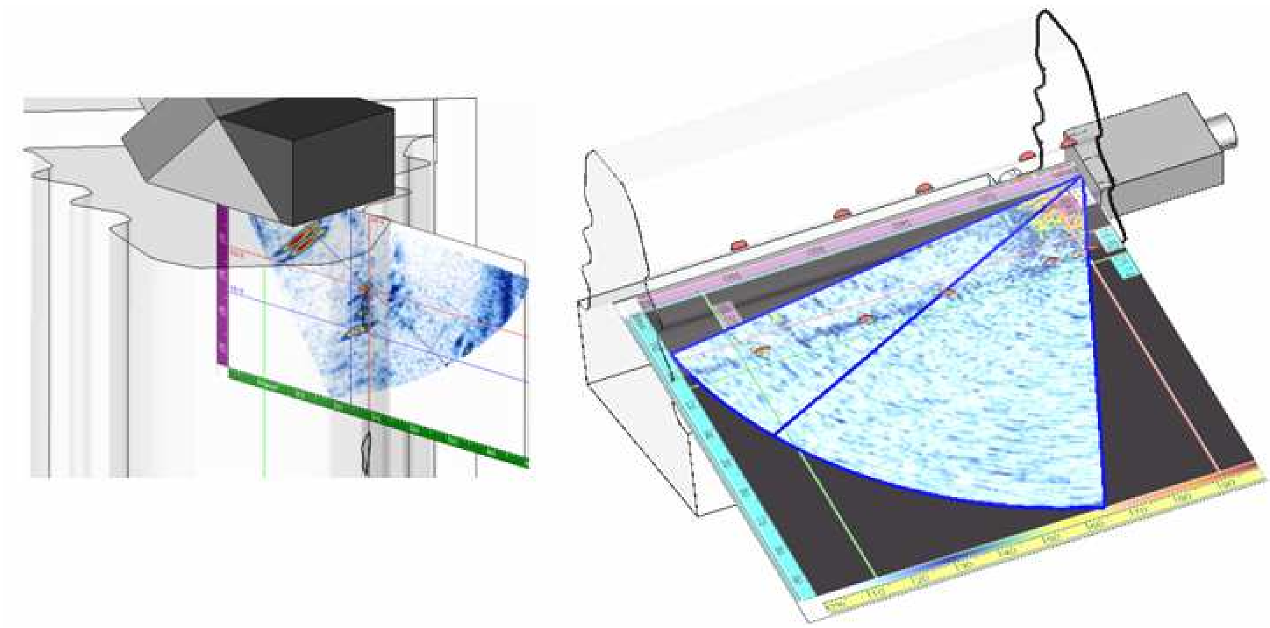

Figure 3: Example of S-scan display and data plotting for L-1 steeple-side technique.

The main idea behind equipment substitution is based on repeatability and reliability of scanning pattern, data acquisition, reproducibility of defect parameters (depth, location, orientation, height, signal-to-noise ratio-(SNR), detection angle, sizing angle), regardless of the type of machine and software version used for set-up, acquisition and analysis. Probe variability within the same family or different types with similar performance was not taken into account for this evaluation.

Experimental Program

Table 1 details the diversity of equipment required for inspection of specific components.

Table 1: PAUT equipment used for GEC Alstom in-situ inspection.

Component	Machine	Scanning type	Software	Remarks
L-0 Steeple	FOCUS	automatic	Tomoview 2.2R9	If automatic scanning is not possible, manual inspection using templates is mandatory for the whole length of the steeple
	FOCUS LT	automatic	Ultravision 1.0R5	
	OMNISCAN 16	manual	Omniscan 1.4R3	
L-1 Steeple L-1 blade	FOCUS	manual	Tomoview 2.2R9	PA probes identical for each system;
	FOCUS LT		Ultravision 1.0R5	
	OMNISCAN 32		Omniscan 1.4R3	
	TOMO III PA		Ultravision 1.1Q4	

The features presented in Table 2 were used to assess the PA system compatibility.

Table 2: System main features tested on specific reference blocks.

Feature	**Reference block**	**Remarks**
L-1 Blade and L-1 Steeple		
Machines: OMNI 32, FOCUS, FOCUS LT, TOMO III PA Software: Omniscan 1.4R3, Tomoview 2.2R9 and Ultravision 1.0R5		
depth	L-1 BLADE CAL BLK #5 L-1 STEEPLE CAL BLK #1-MAN	For each target
SNR		For each target
defect length		For each target
index		Aligned targets
Focus LT to replace Focus [Ultravision vs Tomoview]		
Time base calibration	R25, R50, R75, R100	1% Cr forging (v=5,898 m/s)
Vertical linearity	IOW-MOD,	V=5,912 m/s
Angular resolution	L-0 STEEPLE NDE PDI BLK #1	Lateral scanning H1
Saturation effect	L-0 NDE STEEPLE MIDDLE #1	Large EDM notch, starts at 10 mm from surface
Soft palette	IOW-MOD 3	V = 5,912 m/s
Defect depth	IOW-MOD 3 L-0 DE Steeple Block#2B	IOW-MOD 3: V = 5,912 m/s; SDH z=60 to 90 mm L-0 DE Steeple Block#2B-target 2, H1-H5
Detection angle	L-0 DE Steeple Block#2B	
Defect height	L-0 DE Steeple Block#2B	

Minimum three measurements were taken for the same event, for each system.

Data Evaluation

The PA machines and the software are equivalent if the following conditions are met:

- SNR (specular) > 30 dB
- SNR (diffracted) > 10 dB
- Sensitivity = ± 2 dB
- Depth = ± 2 mm
- Index (manual) = ± 2 mm
- Index (automatic) = ± 5 mm
- Defect height = ± 1 mm
- Detection angle = ± 2°
- Time base = ±1 mm / 100 mm UT path
- Vertical linearity (FSH): ± 1 dB [from 10% - 100 % FSH]
- Saturation effect: depth > 10 mm
- Angular resolution: < 0.5 mm/0.5°

Examples of data comparison for L-1 components are presented in **Table 3** and in **Figure 4** to **Figure 7.**

Table 3: Data comparison for Omniscan 32 and Focus LT in target location, SNR and index.

Target # / Location	OMNISCAN 32			FOCUS			Accept/reject
L-1 Blade Cal Blk #5; probe 3D							
	Depth	SNR	Index	Depth	SNR	Index	
1 / 15	15.8	18					accept
2 / 40	40.2	24	21.8			22.7	accept
3 / 55	55.6	16					accept
L-1 STEEPLE CAL BLK #1-MAN; probe 22							
2 (7) / 15	15.5	16	29.1	15	21	28.6	accept
3 (8) / 40	40.2	22		40	24		accept
4 (9) / 60	59.8	18		60	20		accept
5 (10) / 85	84.8	17		85	18		accept

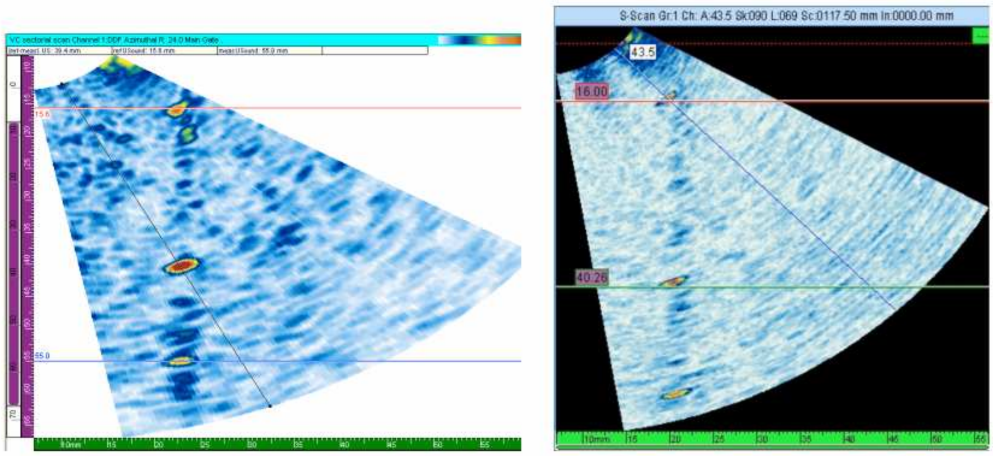

Figure 4: Example of calibration targets S-scan display (depth and index) for FOCUS LT (left) and Omniscan 32 (right).

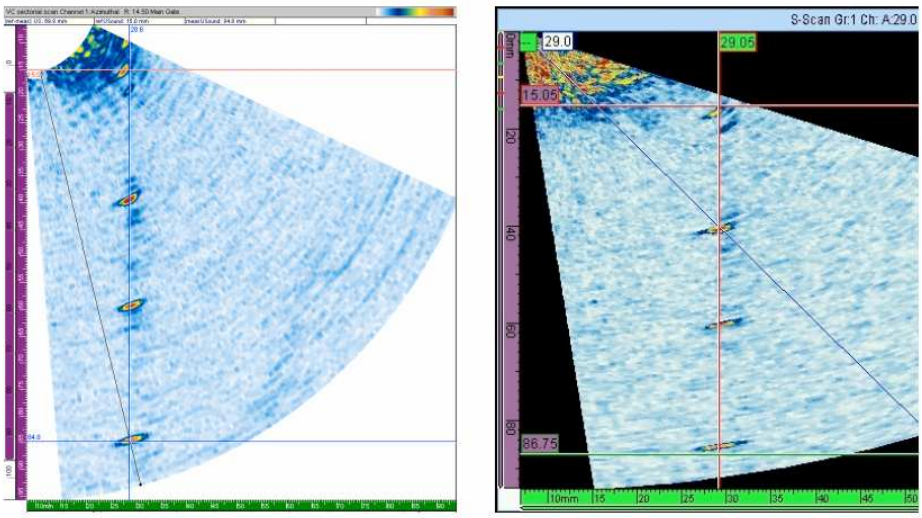

Figure 5: Example of calibration targets S-scan display (depth and index) for FOCUS LT (left) and Omniscan 32 (right).

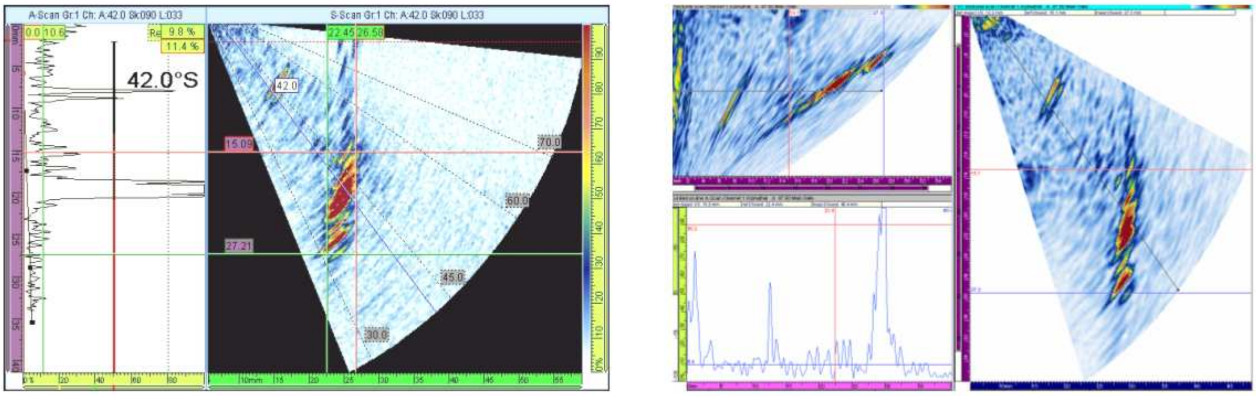

Figure 6: Examples of S-scan display for: *left*) OMNISCAN 32 and *right*) FOCUS LT; for detecting and sizing with shear waves probe two complex notches in L-1 blade.

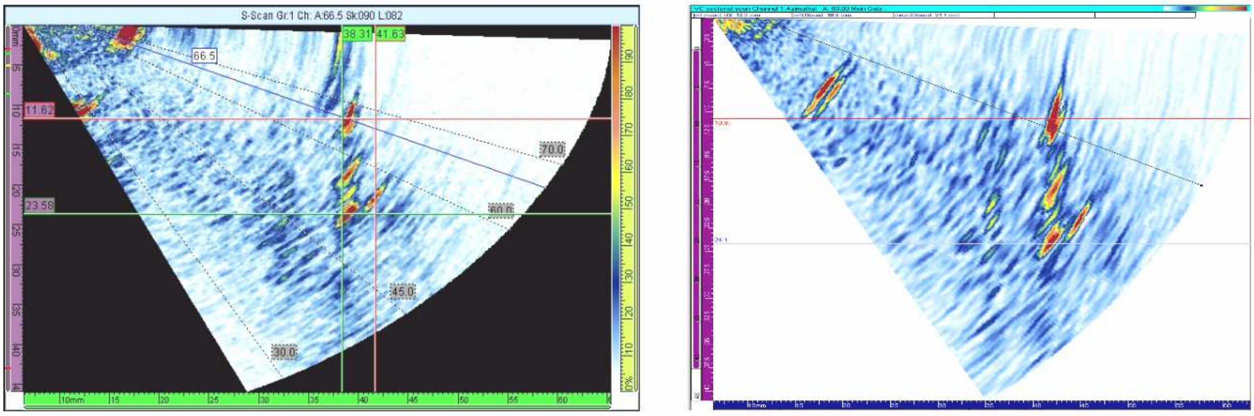

Figure 7: Examples of S-scan display for: *left*) OMNISCAN 32 and *right*) FOCUS LT in detecting and sizing with shear waves probe a complex notch in L-1 steeple.

Examples of data comparison between FOCUS [Tomoview 2.2R9] and three machines FOCUS LT [Ultravision 1.0R5] used for automatic scanning are presented in **Table 4** and **Figures 8** and **Figure 9**.

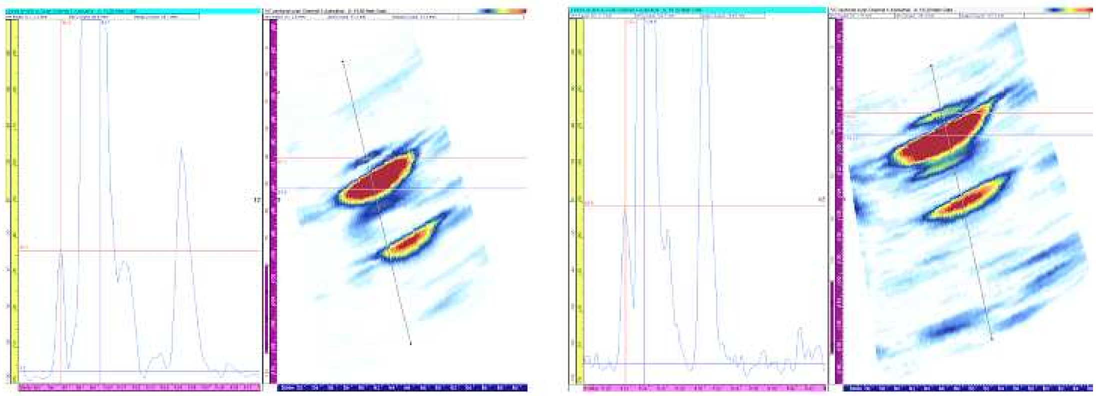

Figure 8: Examples of SNR evaluation for notch tip on H4 using Tomoview 2.2R9 + FOCUS 32/128. (left) and FOCUS LT + Ultravision 1.0R5.

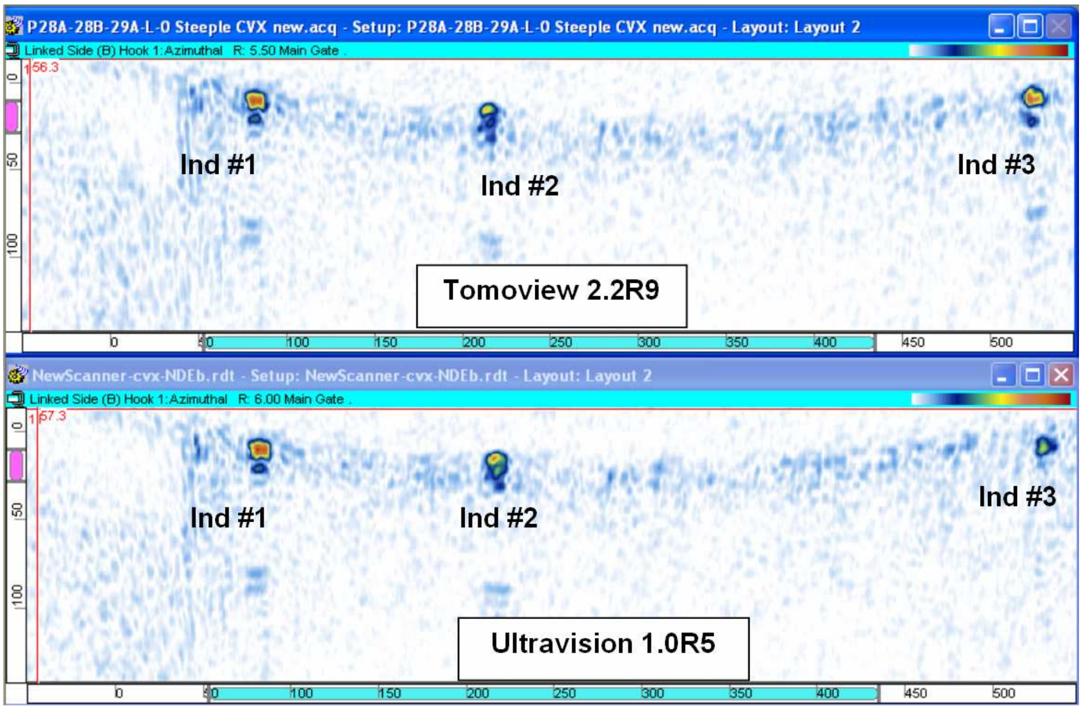

Figure 9: Data comparison between Tomoview 2.2R9 and Ultravision 1.0R5 for automatic scanning of L-0 steeple – hook 2.

Table 4: Data comparison between FOCUS LT and FOCUS for L-0 steeple inspection [Ultravision 1.0R5 vs Tomoview 2.2R9]-automatic scanning.

Feature	Actual	FOCUS	LT s.n.5100	FLT s.n.1088	FLT s.n.1089	Accept/Reject
Time base	25	25.2	25.3	24.9	25.3	accept
	50	50.1	50.2	50.1	50.2	accept
[mm]	75	75.2	75.3	74.9	75.2	accept
	100	100.1	100.0	99.8	100.1	accept
Vertical	100 / +2	101	102	102	103	accept
Linearity	**80 / 0**	80	80	80	80	accept
[% FSH / dB]	40 / -6	40.1	39.9	40.2	40	accept
hard gain	20 / -12	19.8	20.2	19.9	20.1	accept
	10 / -18	9.7	10.1	9.8	10	accept
Vertical	100 / +2	100	103	102	104	accept
Linearity	**80 / 0**	80	80	80	80	accept
[% FSH / dB]	40 / -6	40.4	40	39.5	40.1	accept
soft palette	20 / -12	20.3	20	19.2	20	accept
	10 / -18	N/A	9.8	9.8	9.9	accept
	20	19.5	20.2	19.5	19.6	accept
Depth – SDH	25	24.5	25.1	24.2	24.8	accept
IOW mod	30	29.6	29.4	31.5	30.7	accept
[mm]	40	39.1	38.8	38.4	39.5	accept
	45	45.6	45.7	46	45.8	accept
Depth	68.1	67.3	67.3	67.6	67.5	accept
SDH IOW mod	75.4	74.4	74.4	74.7	74.5	accept
3	82.7	81.7	81.7	82	81.8	accept
[mm]	90	88.8	88.9	89.3	89.1	accept
Target depth	H1 CVX-16.2	16.7	17.3	16.9	16.4	accept
EDM notch	H2 CVX-39.5	41	40.7	40.3	40.2	accept

[mm]	H3 CVX-66	67	67.8	66.8	66.9	accept
	H4 CVX-91	92	92	91.7	91.8	accept
	H5 CVX-115	116.1	116.3	115.7	115.4	accept
Target height EDM notch [mm]	0.5	0.5	0.4	0.4	0.6	accept
	2.0	1.9	1.8	1.8	1.9	accept
	2.0	1.7	1.8	1.7	1.8	accept
	2.0	1.8	1.9	1.8	1.7	accept
	2.0	1.8	1.9	2.1	1.9	accept
Detection angle [°]	-4	-3.5	-4	-4.5	-3	accept
	12	12.5	13	11.5	12.5	accept
	22	22.5	23	22.5	22	accept
	20	20.5	19.5	19	19.5	accept
	18	17.5	18	18.5	17.5	accept
SNR corner EDM notch [dB]	>30	42	38	39.5	40	accept
		38	37	36.5	37	accept
		40	38	39	39	accept
		39	40	39	38	accept
		36	35	34.5	35	accept
S N R tip EDM notch [dB]	> 10	14	13	13.5	14	accept
		16	15.5	17	15.5	accept
		17	18	16.5	18.5	accept
		15	16	15.5	16.5	accept
		18	16.5	17.5	18.5	accept

Lateral resolution for detection of 10 artificial pits of 0.5 mm diameter and spaced apart by 0.5 mm is presented in **Figure 10**.

FOCUS + Tomoview 2.2R9 **Tomo III PA + Ultravision 1.0R5** **OMNI MX 16 + Omniscan 1.4R3**

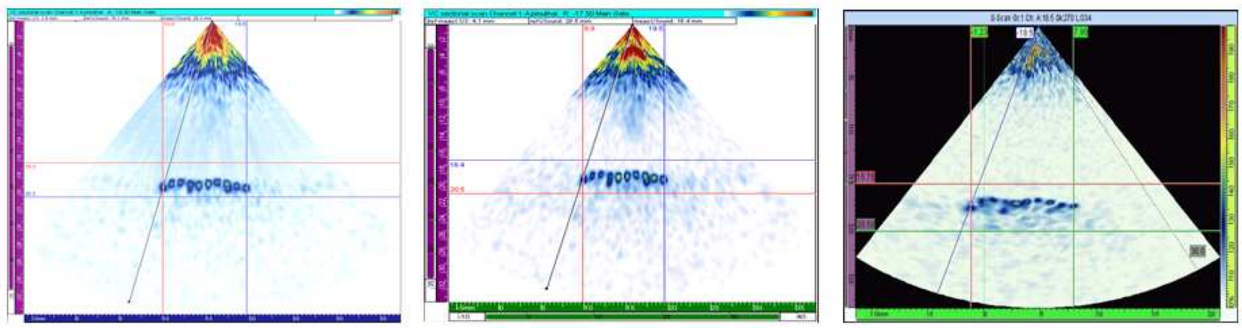

Figure 10: Example of lateral resolution S-scan display for FOCUS + Tomoview 2.2R9, TOMO III PA + Ultravision 1.0R5 and OMNI 16+Omniscan 1.4R3 for detecting 10 artificial pits on hook 1, L-0 steeple.

Concluded Remarks

The results for equipment substitution concluded:

1. OMNISCAN 32:32 can be used for inspecting L-1 blade and L-1 steeple.
2. FOCUS LT + Ultravision can be used for automatic inspection of L-0 steeple.
3. Defect detection, sizing and resolution is almost identical displayed by Ultravision 1.0R5, Tomoview 2.2R9 and Omniscan 1.4R3. All three pieces of software could be used to acquire data on L-0 steeple, L-1 steeple and L-1 blade.

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