PRACTICAL APPLICATION OF THE PHASED-ARRAY TECHNOLOGY WITH PAINT-BRUSH EVALUATION FOR SEAMLESS-TUBE TESTING

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Abstract: Modern testing machines for full-body tube and weld testing are carried out in Phased-Array Technology. To fulfill the extensive testing requirements, a fast and versatile machine adjustment concerning various specifications and defect types is required.

Longitudinal defects including oblique deviations up to ±20° are detected without gaps. To achieve this, the Paint-Brush technique is applied. Up to 32 test-modes are implemented within the software allowing a variable adaptation of the machine parameters for various testing-environments. The testing-process can include more to 400 virtual probes, each in single evaluation-channels and up to 1200 test-functions. Additional optimization features include the variation of virtual-probe size and focal-laws, definition of overlapping test-tracks, different number of Paint-Brush evaluation cycles and individual probe normalization and calibration.

Three Phased-Array probes are packaged in one compact probe-tank performing the complete test task, allowing minimal untested tube ends. The testing-results are presented in strip-charts and various presentations according to the need for the test-task and be transferred into a data-storage network.

Typical tests include transversal and longitudinal defects with oblique components up to 20°, as well as wall-thickness and eccentricity measurement, lamination and Bore Slugs. Practical results for seamless tubes in a diameter range of 88 to 256 mm including defect detection capability and reproducibility will be presented.

Introduction: The testing of seamless tubes in immersion technology with helical tube transport requires in addition to detection capabilities of longitudinal and transversal defects, laminations and wall thickness monitoring the inclusion of oblique variations. For economical reasons, high test-speed and a compact assembly are constraints applied to this type of machine. The Phased-Array technology gives the opportunity to fulfill these specifications. It allows parallel operation of a large number of probes, multiplexing various virtual probes for different positions and different test modes and contributes significantly to the test speed by parallel processing a high number of test channels. The key procedure herein is the implementation of the Paint-Brush method.

It has been realised in the system for automatic testing of seamless tubes. Using the Paint-Brush Method allows to cover an oblique range up to ±20° in addition to the tests for longitudinal defects at advanced speed. Further, one single Phased-Array probe for transversal flaw detection and wall thickness monitoring is included in the same tank. Herein, big advantages can be achieved by variable overlapping of virtual probes and adjustable virtual probes in size, focus and angle. The versatility of Phased-Arrays allows further the testing of laminations, internal wall deformations (Bore Slugs) and coupling checks in a very compact test tank.

The tubes to be tested have diameters from 90 mm to 400 mm and a wall-thickness in the range of 5mm to 30mm. All Phased-Array probes are located within one tank, which is located in 6 o'clock position under the tube, as is illustrated in figure 1.

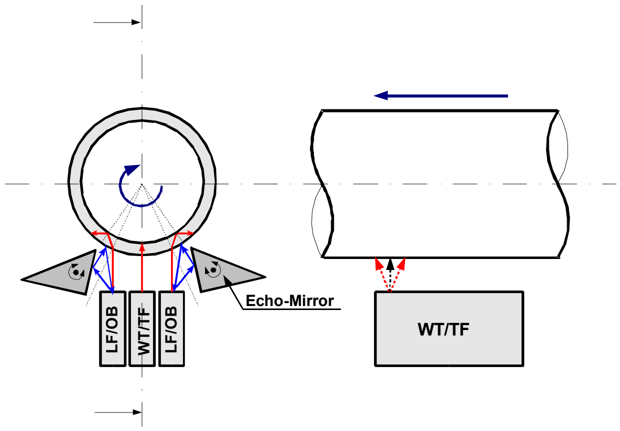


Fig. 1: Sketch of the test tank

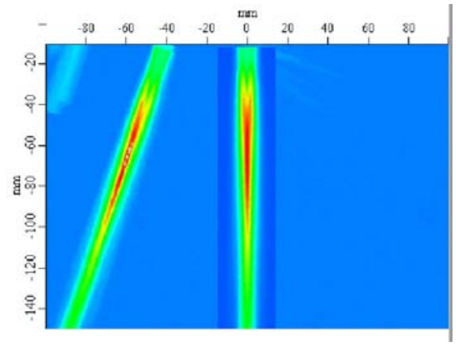
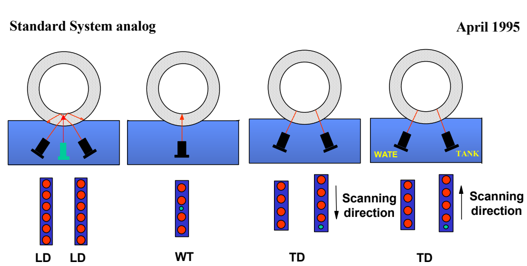


Fig. 2: Combined Angular and perpendicular sound beam

Two Phased-Array probes are used for longitudinal defect testing and one Phased-Array probe is used for transversal defect, lamination and Bore-Slug testing, as well as for wall-thickness measuring. All probes can be rotated along the probe axis, allowing on the one hand a perpendicular positioning of the probe for WT/TF measurement and on the other hand an angular incidence of the sound field at approximately 19° for longitudinal flaw detection.
To allow transversal flaw testing with angular incidence and the tests with perpendicular incidence with one probe the classical Phased-Array approach is used: applying delays to the element transmissions and receptions the sound beam is steered within a specified range, as is illustrated in figure 2, which contains the combined plot of two tank measurements with the same Phased-Array probe, one without delays and one with delays for 17° deflection.

Development of full Body pipe tests
Vallourec & Mannesmann of Brazil is improving it's equipment and process of non destructive testing through developments of new technologies in partnership activities in the centre of research of the Vallourec group at CEV – France and with GE Inspection Technologies as equipment manufacturers. Among the diverse implemented technological advances, we detach the improvement of the line of ultrasonic inspection. During the last years, full body pipe testing has undergone a continuous evolution, which is illustrated in Table 1.

1995	**Ultra Sonic US I** 	**4 Tanks** • Transversal and • Longitudinal discontinuities, • Wall-Thickness, • Overlapping at reduced test speed

<table>
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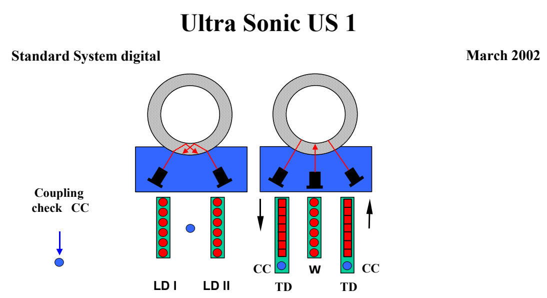
<td>
</td>
<td>2 Tanks

Transversal and
Longitudinal discontinuities,
Wall-Thickness,
Lamination,
Bore Slugs,
Transversal defect: Overlapping 50%
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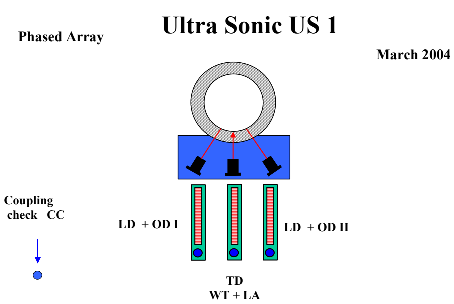
<td>
</td>
<td>1 Tank

Transversal and
Longitudinal discontinuities,
Wall-Thickness,
Bore Slugs,
Overlapping at full test speed (variable)
</td>
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<tr>
<td colspan="3">Tab. 1: Continuous development of test tank</td>
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The unit of seamless pipes inspection used since 1995 had four immersion tanks for the accomplishment of the functions of detection of longitudinal transversal discontinuities, wall thickness measurement and lamination. In 2002 an upgrade of the electronic system and the compacting of the inspection line with the use of only two immersion tanks was carried out, where one was used for detection of longitudinal discontinuities and wall thickness measurements and the other tank for detection of transversal discontinuities.

In March of 2004, the new Phased-Array system with sweeping arrangement in Paint-Brush was installed, which consisted of only one immersion tank with two probes for detection of longitudinal discontinuities and one probe for detection of transversal discontinuities, measurement of wall thickness and detection of laminations.

Through of these developments, VMB increased the inspection capacity and optimized the productive process. For the guarantee of 100% inspection coverage, initially 35 mm pitch was required. Nowadays with the Phased-Array system is possible to inspect pipes with 96 mm pitch keeping the same inspection coverage. No gaps exist between the elements in these new probes arrangements, and the electronic device used allows virtual probe configuration for overlap increments.

The test for transversal defects and Wall-Thickness is carried out in conventional Phased-Array technology. Up to 6 virtual probes are formed on one Phased-Array probe with 224 elements. This allows calculational overlapping of virtual probes of 75%. In cycle sequences, the shots are installed and sequentially executed. The probe has a frequency of 3 MHz, which allows good resolution for wall thickness measurement and at the same time good Phased-Array operation. To do all tests with one probe allows keeping the tank compact, since in opposite to conventional testing technologies, no separated tilted probes are needed. Figure 3 illustrates one example, how this probe can be setup. Due to the Phased-Array Nature, the setup is fully configurable. In particular, this means, that one is enabled, to adjust it to the necessities of the test. If, for example, one needs to detect small pittings, the overlapping for the lamination could be increased.

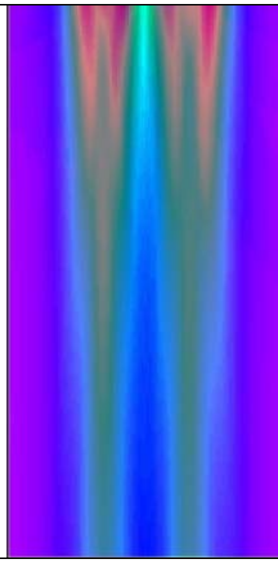
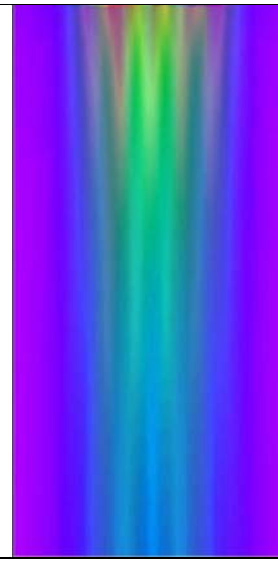
	
No overlapping	66% overlapping

Fig. 3: Effect of virtual probe overlapping

Principles of the Paint-Brush testing method

This method is applied in the tests for longitudinal with and without oblique components. A realistic testing scenario can be described in the following way: if defects from –12° to 12° in steps of 2° are to be tested, there results a total number of 13 shots including the 0° shot for longitudinal defects. Assume the following parameters:

1	Shot distance:	1mm
2	Tube surface speed:	1.5m/s
3	Water path:	40mm -> 54µs
4	Wall Thickness	20mm -> 35µs

With assumptions 1 and 2, a pulse repetition frequency of **1.5Khz** needs to be realised.
With assumptions 3 and 4 a total time for 13 measurements results to:

13*(54µs + 35µs) = 1157µs = **0.864kHz**

The discrepancy is obvious: it is not possible to perform these tests with a conventional technology.
The Paint-Brush method resolves this discrepancy. It works in the following way:

1. Parallel transmission of all elements without delays
2. Parallel Reception of all elements without delay
3. Digitization of all elements' signals in time and amplitude
4. Evaluation regarding longitudinal defects
5. Storage of all signals in a RAM
6. Evaluation of stored data regarding obliquities in electronic evaluation cycles with reduced cycle time

The key to higher processing speed is in the cycle time: the full physical path is needed only one time and the evaluation for oblique signals is performed in an electronic cycle, which is very fast.
Assuming an electronic cycle time of 35µs, one finds:

1*54µs +35µs + 12*35µs = 509µs -> 1.965kHz,

which over specifies the required PRF in the example. Thus, using the Paint-Brush principle allows a much faster processing, or equivalently, allows a deeper evaluation of data at the same throughput.
The principles can be best understood looking at the B-Scan build by all elements. Figure 4 shows two B-Scans from a lab experiment. The same defect was tilted from 0° to 15°. On the one hand, the position moves and on the other hand the signal front rotates relative to the general incidence, what is clear from the reflection characteristics

of the defect. This effect is used in the evaluation, where in certain channels a test for one direction is made and compression to an A-Scan channel is carried out.
The machine uses a Phased-Array probe with 52 elements + 16 overlap elements. The signals of these 52 elements are compressed to sections of 8 elements with a general overlap of 50%, hence there are 12 virtual probes. Each of these virtual probes undergoes the evaluation cycles, resulting in 156 Channels for the above example.

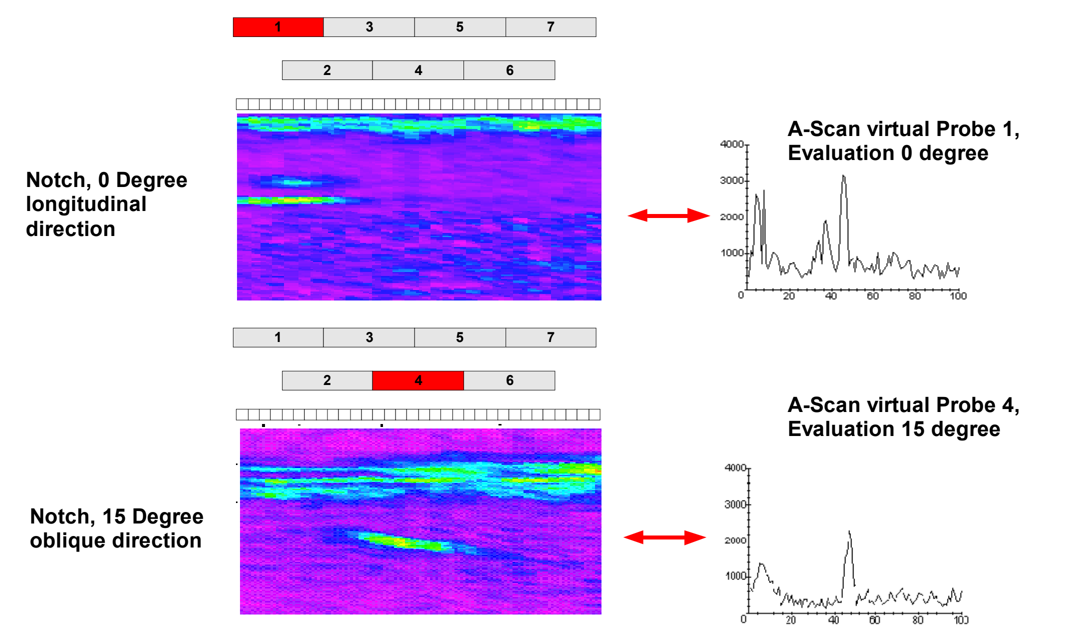


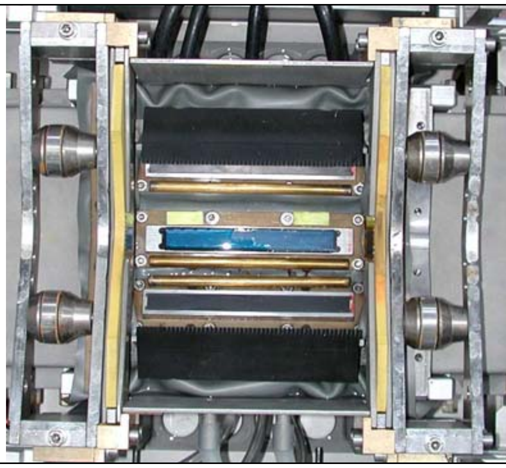
Fig. 4: Data Reduction to A-Scan Channel

Due to the changes in angle incidence for increasing obliquities, the relative signal in case of oblique contributions is smaller than that of the longitudinal defects. Experiments have been carried out in the Laboratory investigating this effect. Table 2 shows a typical result of these measurements. It demonstrates in particular one important feature: An obliquity can not only be detected, if the evaluation law is chosen accurately, but has a certain bandwidth, thus is usually seen in the adjacent evaluation channels. Choosing the evaluation channels carefully, allows not only to cover the accurate exact values, such as 5°, 10° but also the values in between. Figure 8 shows oblique A-Scan signals recorded during the commissioning runs.

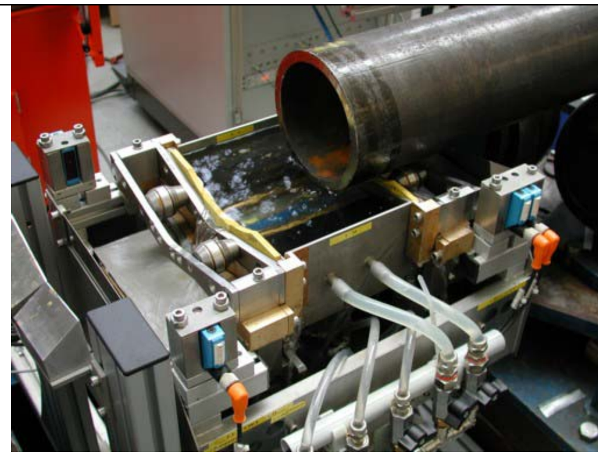
Evaluation Angle / ° oblique defect / °	0	1	2	3	4	5	6	7
0	**90**	77	56	45	20			
2,5	90	**95**	85	67	58	45	35	
5	45	62	81	**90**	85	74	48	
7,5	52	80	94	**96**	86	75	31	
10				40	54	65	**70**	56
12,5			25	35	43	60	**85**	50
15					27	34	42	**46**
20							20	21

Tab. 2: Signal Amplitudes for oblique reference notches with different evaluation angles

Results: Figure 5 shows the test-mechanics. The tube transport is helical and as the tube passes, the tank is pressed from below to the tube. Because of the fact, that only one tank is needed, not much space in the line is needed. Further, for the operator, only 4 components need to be altered in case of a dimension change.



Test tank, top view

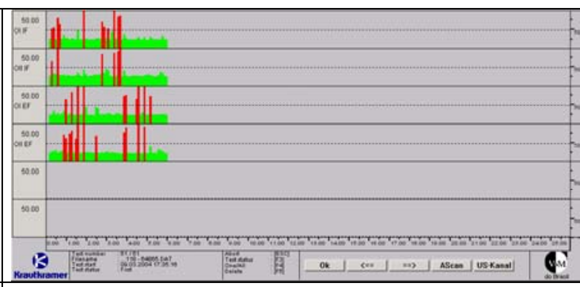


Test tank with tube

Fig. 5: Testing mechanics

Several dimensions have been successfully tested since the machine has been set into operation. In online operation, the specifications could be matched with reference pieces containing oblique notches, longitudinal notches and flat bottom holes. Figure 6 shows the analog results strip as one example for the defect detection capabilities, together with the longitudinal analog strip. One can see, that the oblique reference notches, which are clearly detectable with the oblique evaluation, do not lead to an alarm in the longitudinal evaluation line.
In comparison with the classic system of ultrasonic inspection, the Phased-Array system detaches the signals of detection of natural discontinuities from those of the lamination process, such as folds of irregular geometry.
It is observed that the noise to signal ratio of the Phased-Array system is outstanding, offering a bigger inspection-sensitivity than conventional systems with single element probes.
In addition to the analog strips for flaw evaluation signals, analog signals for the monitored wall-thickness and eccentricity are part of the standard result presentation. These are accompanied by a digital event display for all Tests and several pages of statistics. Examples are illustrated in figure 7

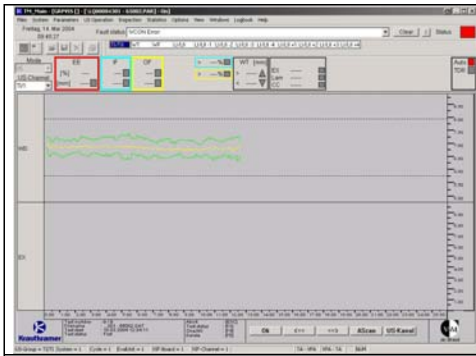
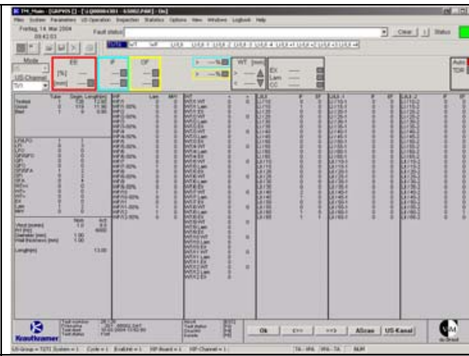
Longitudinal evaluation



Oblique evaluation, ±5° up to ±20°

Fig. 6: Comparison of longitudinal and oblique evaluation

Within the commissioning phase, it turned out, that obliquities higher than 20° were actually detected, though on reference defect level 20° was the limit. Figure 8 illustrates the signal of a natural defect. It is detected in the 15° evaluation channel and thus releases an Alarm. Checking the longitudinal evaluation of this defect, one finds, that no alarm would be generated. Figure 9 shows two defects with oblique evaluation response together with the correspondent analog signal strip and the standard longitudinal test strips. One observes, that the defact signal is existent in longitudinal evaluation, but the signal-to noise is small, which is not the case in oblique measurements, hence these defects can only be detected at very high gain level, which is generally not advantageous concerning the test integrity.

	
Analog WT measurement strip	Statistics page
Fig. 7: Evaluation	

In particular, the mechanical setup allows very short untested ends without additional test equipment. This is achieved by a special test method: the tank is in a pre-elevated position and the tube is transported slowly into the direction of the tank. When the tube enters the tank environment, it imposes a small pressure on the tank; hence the coupling can be guaranteed in a very early stage, before the tube fully covers the tank area. Because the speed is kept low, interactions are small. When the tube finally covers the tank, the tank is fully elevated, the coupling water supply is opened fully and the tube is accelerated to its full velocity.

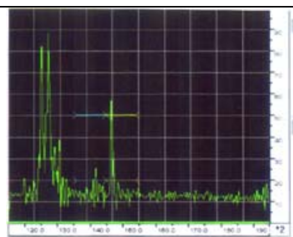
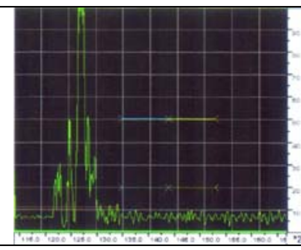
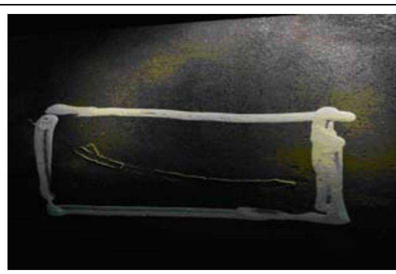
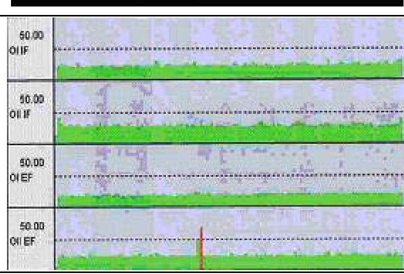
	
15° evaluation channel with natural oblique signal	0° evaluation channel with natural oblique signal
Fig. 8: Typical A-Scans	

Image		
Oblique evaluation> defect in full range		

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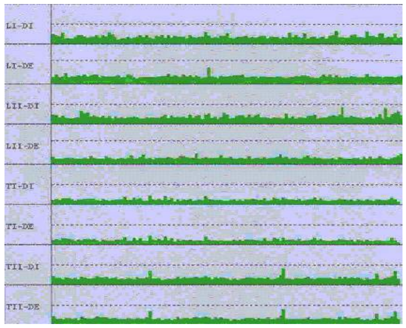
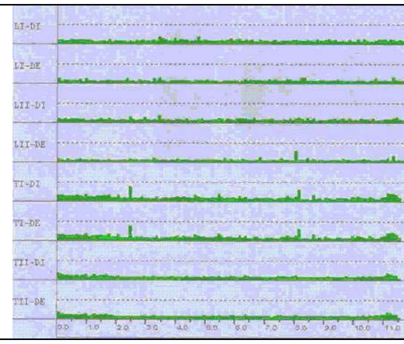
<tr><td>Classical evaluation: defect signals lower than thresh-hold</td><td>
</td><td>
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<tr><td></td><td>Signal in oblique channel, external discontinuity</td><td>Signal in oblique channel, internal discontinuity</td></tr>
<tr><td colspan="3">Fig. 9: Defects with oblique characteristics</td></tr>
</table>

Conclusion: The Phased-Array Technology offers many significant advantages for online testing of tubes. Due to the high versatility of the Phased-Array probes, it is possible to execute test functions with one probe, which formerly needed to be performed with several single element probes and thus allows it, due concentrate all tests in one tank. The variable overlapping, apertures and delay-laws for deflection and focusing permit the accurate optimization of the UT-operation to the test requirements.

Applying the Paint-Brush Method extends the longitudinal testing in a way, that without any reduction of test speed, obliquities in the range of –20° to +20° can be detected. Practical tests in the production line excellently verify the results obtained in the laboratory. Measurements have been carried out with reference tubes comprising reference defects with suitable test defects, among them longitudinal, transversal, oblique reference notches and laminations. On this basis, a significant enhancement of the test quality could be achieved.

Defect detection proved to be very reliable under production conditions. During the test runs, obliquities could be detected, which were not found with conventional methods or pure longitudinal evaluation. These defects could be safely verified after tube reversion and retesting, partly even exceeding the specified range of ±20°

The easy operation and adjustment means integrated in mechanics, software and hardware allow fast and versatile operation and dimensional changes, and thus together with the compact mechanical dimensions characterizing the Phased-Array testing machine as a highly productive tool for online tube testing facilities.