# Ultrasonic Imaging in Automatic and Manual Testing

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**Abstract.** Owing to the successful use of phased array probes in automatic testing machines, more and more applications can now be found in the field of manual inspections. Miniaturization of electronic components and improvements of processing speed allow the integration of phased array hardware into a small, battery driven instruments for fast ultrasonic imaging. The advantages of the phased array technique are obvious:

- Real time display of the scan sector (sweep area for the sound field)
- Top – Side – End view of the covered volume after a linear scan, when combined with a probe position encoder.
- Ultrasonic images are easily understandable, even for non-experts.
- Ultrasonic images allow a direct flaw location and evaluation, even offline with the captured A-scans .

Applications and their results with automatic and manual testing will be described and this technique will be compared to the conventional technique.

## Introduction

Ultrasonic materials testing today is about 55 years old. Up to now the processing of the A-scan (echo amplitude as a function of distance) is the basis of flaw evaluation, and all further processing up to images. This is also true for medical diagnostics, however, from the beginning here imaging of the scanned volume was the goal, and has been achieved already at a very early stage. In NDT the evaluation of the A-scan is still very common, and is described in many national and international standards. Flaw or volume imaging are most welcome enhancements to the given test results, because they visualize the test results in the work piece or a part of it, and can be understood by non-experts too. Imaging on the other side requires much more sophisticated hard- and software, which is now also available in portable, battery operated instruments. Examples on the use of phased array technology and an analysis of the technology change for the future will be given.

## History

Before the introduction of PCs for signal processing, the signal amplitude and time of flight was monitored by a gate, converted to an analog output voltage, and then used for further processing. Probe position encoders finally allowed to display the echo distance or the echo amplitude as function of the probe position using an XY-plotter: the B- and C-scan was born. This technique was very suitable for all automatic testing applications: plates, pipes, or profiles could be tested automatically by simply moving the object along one or several probes, and plotting the results as a function of the location. At that time (~1965), in medical diagnostics an instrument [1] with “real time” imaging was already available (fig.1): here the probe rotated in water in the center of a mirror, and the echo amplitudes were displayed on a CRT as a function of the probe angle, fig 2. Only 4 years later, the bulky rotating probe was replaced by a linear array probe, which could be manually operated. With the progress in electronics and computer technology, at the beginning of the 80th it was finally possible to manipulate the sound field of an array probe by time controlled excitation of each single element: with a constant delay from element to element we achieve a linear movement of the beam, replacing the mechanical shift of the probe, with more sophisticated phased excitation we can steer the beam and change its focus from shot to shot.

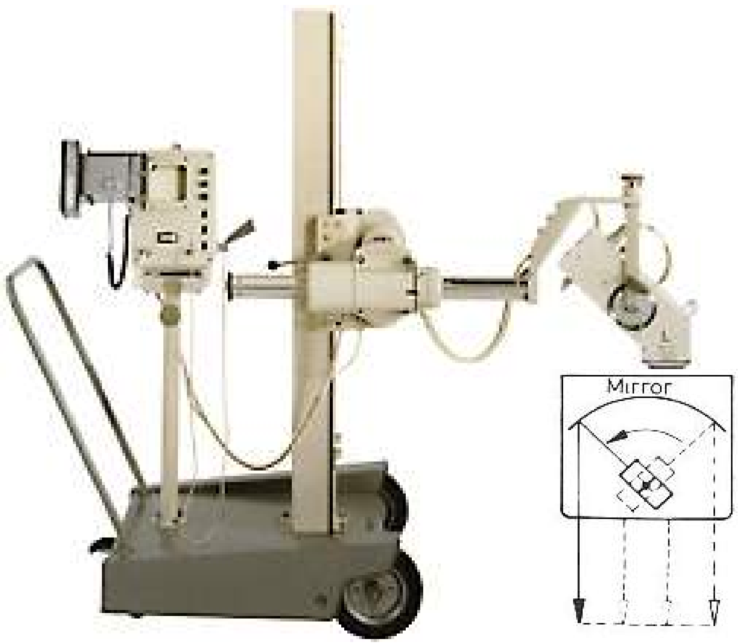


Fig. 1 Visoson (1966)

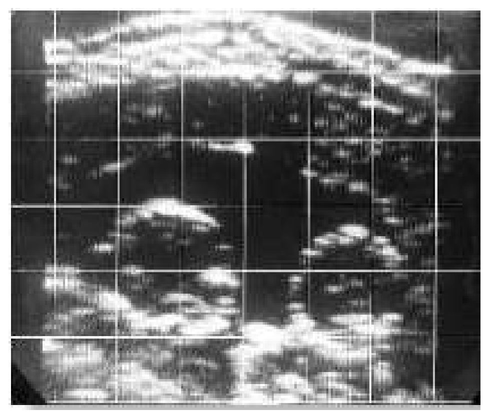

Fig. 2 Twin pregnancy (1966) [2]

## Phased Array probe in Testing Machines

With mechanized, automatic testing the main goal is to maximize the efficiency of testing. The influencing factors are:

- The hardware (investment costs for the machine and its operation)
- Time required for testing the part, for setup after geometrical part change, or for service.

Changing to phased array probes in testing machines leads to a drastic reduction in the mechanical complexity by reducing the number of probes and time for testing, because one phased array probe covers a bigger volume form one single position, and the overall sensitivity increases due to the variable focusing and sound field steering, thus leading to an additional probability of detection (PoD).

## Pipe inspection with ROWA

Six phased array probes with 5 MHz, fig.3, each subdivided into 4 groups with 32 elements (= 768 elements in total) are completely surrounding the pipe, fig. 4. The minimum distance to the pipe surface is 23 mm, far enough to prevent probe wear by possible contact with the moving pipe. The standard technique would require much more single element or EMUS probes in contact with the pipe surface, subject to a high wear [3].

Fig. 3  ROWA probe (4x32 elements)

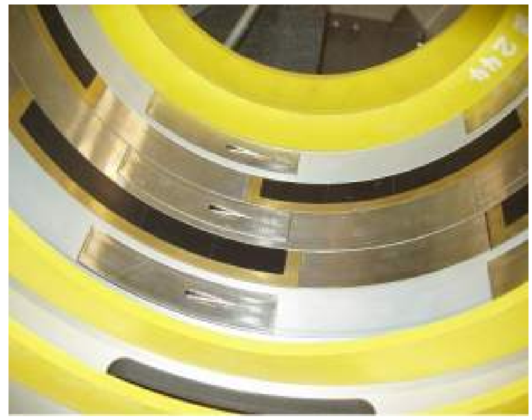

Fig. 4  ROWA probe chamber

A circulating water jacket in the test block allows a constant coupling, with very short untested ends and a change in pipe diameter only requires an exchange of the rubber seals on both sides of the test block, which can be done within a few minutes. Pipe diameters from 177 mm to 250 mm can be tested with block 1. In order to extend the diameter range of pipes a second test block can be moved into the test line, for diameters from 240 mm to 339 mm, fig 5. The subdivision of the probe into 32 element arrays also simplifies the service, because it allows a fast and economical exchange of just the one array, if necessary.

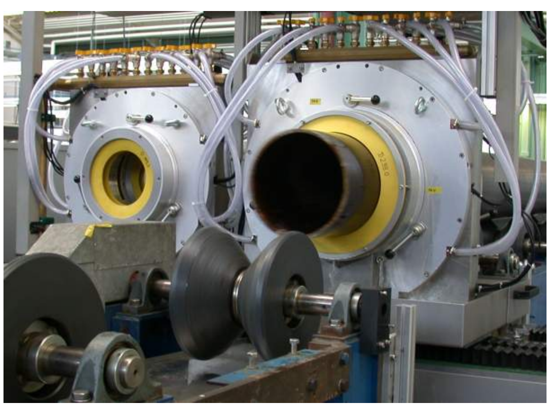

Fig. 5  ROWA test blocks

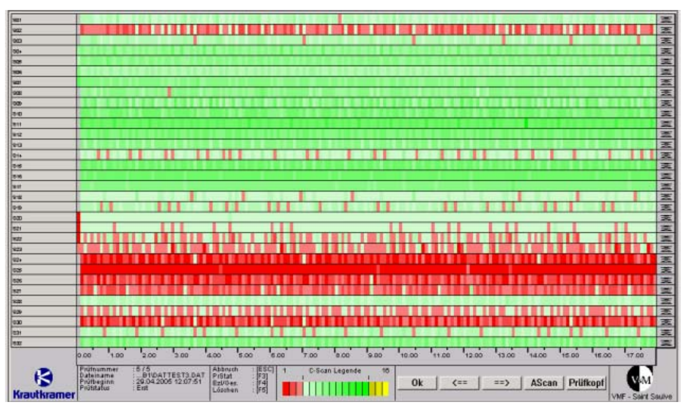


Fig. 6  ROWA test report

The virtual probe size (aperture) used for testing may be 1 – 32 elements, in practical application we use 5 – 8 elements, with an aperture of 9 mm to 14.4 mm. The element pitch is 1.31 mm in block 1 and 1.8 mm in block 2, giving a minimum near field length of 67 mm (in water). For testing the complete circumference 42 cycles are necessary.
After a diameter change a new set of delay laws needs to be recalled, and using a test pipe, a sensitivity normalization is performed, separately for each of the 6 probes. For this procedure

approximately 5 minutes are required. The ROWA machine allows a maximum testing speed of 1 m/s. It detects defects from 6.3 mm equivalent reflector size onwards, and measures the wall thickness with a precision of ± 0.05 mm, fig 6.

## Rail wheel set (Deutsche Bahn)

This is another good example where phased array technology is the optimal solution, because here the coupling area for the probes is very much restricted (2 mounted wheels and 3 brake disks). Only phased array probes allow an economical inspection of the volume of interest. The testing machine has 4 phased array probes with 2.7 MHz, each having 14 composite elements mounted on a plexiglass wedge [4]. The steering angle lies between 25° and 75°. The two middle probes can be turned by 180° in order to scan the volume of the center part, fig. 7. Delay law calculation, testing and result imaging is performed by the 64-channel COMPAS system. The final image from 2 phased array probes, which is displayed after one revolution is called TD-scan, and it represents the volume corrected C-scan in circumferential direction. Continuous vertical lines are related to the diameter changes (corners), single indications to flaws or drilled holes, fig. 8.

Fig. 7  Wheel set test system (DB)

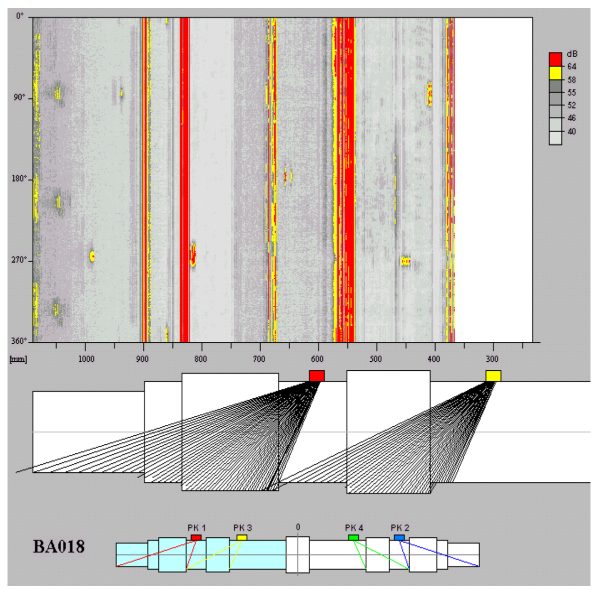


Fig. 8  Test result of the wheel set (left side)

## Phased array in manual testing

Compared to automatic testing machines, the use of phased array in manual application grows slower. The reasons for this are not only related to the higher investment costs for phased array equipment, but also, because

- many standard application can be economically solved with standard technique,
- all qualified operators are familiar with most of these standard applications, and know how to interpret an A-scan,
- the performance of these applications are clearly described in standards and test instructions, and finally

- phased array technique in solid material is more complex than in human tissue (the experiences from medical Ultrasound cannot directly be transferred to NDT).

With the established successes in automatic testing machines, phased array will also migrate into the field of manual inspections, especially in those cases, where flaw/volume imaging is demanded (e.g. by the client), or if the use of this technique is requested by a future standard.

## Comparison of the two techniques

In order to understand today's differences between standard technique and phased array a simple weld inspection as an example is shown. The question is: What can I do with a given phased array probe (no. of elements, pitch, frequency on a wedge)?

- The usable focal depth can vary from 100% down to 10% of the maximum possible near field length, where the minimum value also depends on the maximum available time delay between two adjacent elements.
- If a large focal range is required, the aperture must be large, and the frequency should be high.
- In case a large steering range is needed, we would need to reduce the frequency and the pitch.
- For weld inspection a wedge is necessary to produce shear waves.
- Proper selection of the wedge angle optimizes the usable steering range.

Taking a 25 mm thick butt weld with 30° weld preparation as an example to explain the differences:

Table 1. Application flow

| **Single element probe** | **Phased Array** |
|---|---|
| Two probes SWB 45°-5, SWB 60-5 | 32 elements, 0,58 mm Pitch, 5 MHz, 36° plexiglass wedge |
| Range calibration | Enter probe data (for non-dialog probes only) |
| | Ray tracing:<br>- determination of steering range, probe offset from weld, focal<br>range, and number and position of the elements used |
| Sensitivity setup, if applicable with DAC recording or DGS reference | Sensitivity setup, if applicable with DAC recording |
| Testing: | Testing: |
| - scan both sides with 45° | - scan from left |
| - scan both sides with 60° | - scan from right |
| - Flaw evaluation acc. to instruction / standard | - Flaw evaluation acc. to instruction (offline) |
| - Store the results | - Store all results |
| Report (offline) | Report (offline) |

Table 2. Advantages

| | |
|---|---|
| Use any available Flaw Detector | Fast instrument setup, if application data are stored in the instrument |
| Operator with Level II qualification | Fast linear scan of the weld with simultaneous automatic storage of all data incl. A-scans |
| Always applicable due to available instructions / standards | Imaging: Sector, B- and C-scan in real time |
| | Direct flaw imaging: location and size |
| | Increased PoD (probability of detection) due to variable focusing and steering |

Table 3. Disadvantages

| | |
|---|---|
| Time required for scanning the weld (4 scans) | Higher investment costs |
| Time required for flaw evaluation | Additional training for operator |
| No (sector) image | Time required for 1st setup |
| No B- and C-scans | Sometimes additional software required for further data processing (e.g. sophisticated imaging, volume correction, adding work piece contour, …) |
| | Additional amplitude evaluation in the A-scan, in order to fulfil the given standard |
| | Reduced near resolution (in test mode) and possible false indications, e.g. by grating lobes or mode converted waves |
| | Image: blur caused by minimum sound field diameter (increases for s>N) |
| | Higher surface quality required (phased array probe has a bigger contact area, and unevenness impedes phasing) |

The advantage of phased array is clearly the (object related) **image** of the tested volume including the detected flaws, which is available in real time, and all captured A-scans, only using a probe position encoder – a result, which is significantly easier to recognize to “see” what’s in the work piece. This is the main reason, why phased array will in future penetrate the field of manual inspection plus mechanized scanning. Today it is mainly used in special applications (complex geometry, expensive and/or security relevant parts). For a wider use in typical standard applications, like weld inspection, it is essential to have:

- a simple and intuitive instrument operation (performed by a Level 2 operator with minimum additional training)
- a standard ultrasonic channel for direct integration of amplitude evaluation acc. given standards
- an attractive price for instrument and probes
- the integration of phased array technology in future standards

## Phasor XS


Fig. 9  Phasor XS

The Phasor XS, fig. 9, is the new universal Ultrasonic Flaw Detector from GE Inspection Technologies for manual inspection combining the standard single/dual element use with 16/64 phased array technology: Aperture 1-16 elements, supporting probes with up to 64 elements. Housing and operation are coming from the well known USN 60. In phased array operation you may display a B-scan or a sector scan in real time, if needed combined with the RF A-scan of a selected cycle. Typical applications are: All for the use of the standard technique, and for phased array: plates, forgings and castings using linear probes and B-scan display, fig. 10 (3 side drilled holes in aluminium, 1mm diameter), and welds using phased array wedge probes combined with the sector display, fig. 11. Here the volume of the welding is scanned typically with angles from 35° to 75°simultaneously from one fixed probe position, leading to an increased PoD with a fast and simple linear scan of the weld. The sector scan is true to scale and allows a direct defect location and sizing.

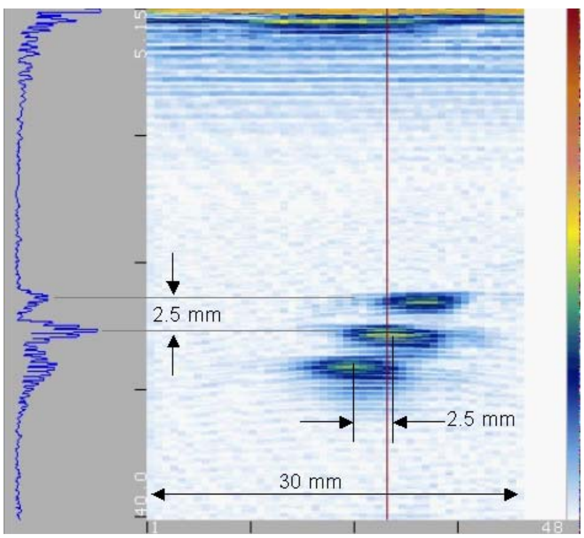


Fig. 10  B-scan of 3 SDH (1mm diameter)

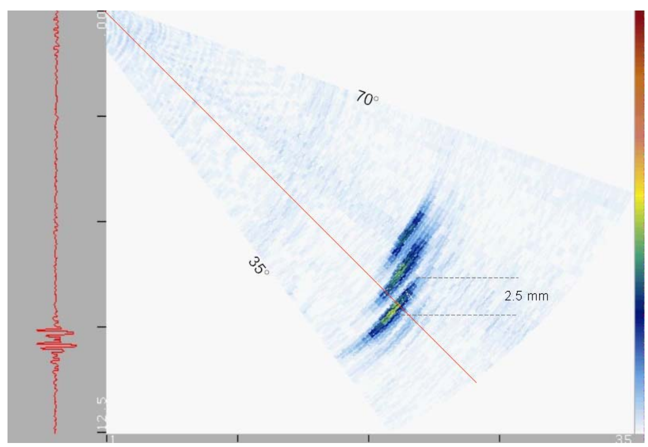


Fig. 11  Sector scan of 3 SDH (1mm diameter)

## Defect size in the image, lateral resolution

Flaw imaging in ultrasonics is complicated by the fact that echoes are reflected back to the probe from all positions within in the sound field, whereby the maximum echo amplitude will be achieved, in case it is hit by the acoustical axis. The result is that defects are never displayed with their real dimensions, but more extended, depending on the diameter of the sound field at the defect’s location. This reduces the lateral resolution drastically.

Example: With an aperture of 10mm, for a 4 MHz probe in steel a divergence angle of 4.5°(-6dB) will result. A 1mm FBH at a distance of 65 mm will get a –6 dB amplitude width of 10.2mm. In other words: If you would display the size of the 1 mm FBH with its –6dB amplitudes, you will receive an image of 10.2 mm = 10 time larger than the real size of the

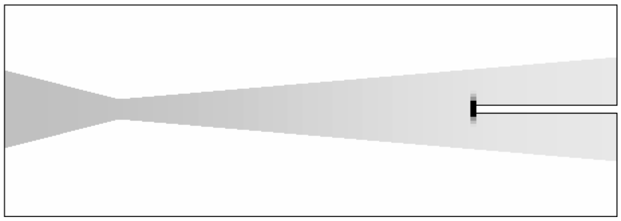

Fig. 12a  Lateral resolution (–1 dB)

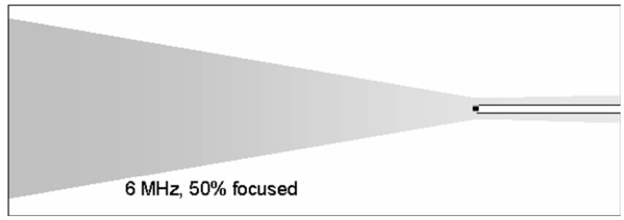


Fig. 12b  Lateral resolution in the focus (-1 dB)

reflector! Even going down to only 1dB down from the maximum echo amplitude still results in a display width of ~3 mm, fig. 12a. The image of defects is always affected by a blur proportional to the width of the sound beam, and one solution for a the optimum image is to focus the beam to the defect depth. Since the focal diameter can be reduced to less than 1 mm, also the defect image can thus be optimised, fig. 12b.

## Summary

For many years GE Inspection Technologies (previously Krautkramer) replaces standard Ultrasonics by phased array technology in the automatic testing machines. The higher investment in phased array electronics here is clearly compensated by the savings in mechanical complexity (less probes, less moving parts, less wear, less downtime). Already today phased array techniques are also used in manual testing, resulting in the visualization of the test results. For the use in standard applications, like weld inspection, the user is asking for an easy instrument operation. And finally this new technology needs also a consideration in the ultrasonic inspection standards.

## References


[1] http://www.deutsches-museum-bonn.de/exponate/echtzeit-ultraschall/exponat.html

[2] H.-J. Holländer 1966, Zwillinge in der 17. Schwangerschaftswoche, http://www.medical.siemens.com/siemens/de_DE/gg_us_FBAs/files/Aktionen/Ultraschall/Historie/Sie_40_Jahre_Prod_END.pdf

[3] Heiner Lompe et al.: Wall Thickness Measurements of Large Tube Diameter using Phased Array Technology, WCNDT 2004

[4] Wolfgang Hansen: Erfahrungen bei der Entwicklung von Radsatzvollwellenprüfständen, Wittenberge 2004