Practical Experiences in Manual Ultrasonic Phased Array Inspection

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Abstract

As with the transition from analog to digital Flaw Detectors in the 80th of the last century, manual phased array technique can again be understood as an important milestone in today’s ultrasonic testing. Owing to the successful use of ultrasonic phased array technology in medical diagnostics (~1970) and in automatic testing machines (~1995), more and more applications can now be found in the field of manual inspection. 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: B-scan, C-scan and S-scan in real time, easy understandable images with direct evaluation. New applications and their results will be described and images will be discussed including a comparison to the conventional technique.

1. Introduction

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. As opposed to medical ultrasonic in NDT the evaluation of the A-scan is still very common, and is described in many national and international standards. Imaging like B- and C-scans 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 have already been realized using time consuming mechanical scanning systems. Real time 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.

2. History

Using ultrasonic instruments having a monitor gate, and having outputs for analog voltages proportional to the echo amplitude and the time of flight with simultaneous probe position recording, it was already possible to visualize the results in B- and C-scans at very early stage. However, at that time only used in automatic testing machines for the inspection of plates, pipes, or profiles, or in a laboratory. 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. 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 from 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).

### 3. 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 economically be 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 codes,
- 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 medical ultrasound and automatic testing machines, phased array is now migrating into the field of manual inspection, especially in those cases, where flaw/volume imaging is demanded (e.g. by the customer) or if the use of this technique is requested by a future standard.

### 4. 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. With a 16 element probe on a wedge we have the following options:

- The usable focal depth can vary from [image of phased array weld inspection]

![Fig. 1 Phased array weld inspection](image)
100% down to 10% of the maximum possible near field length.

- The refraction angle can electronically be swept through the whole range, if needed from 0° to almost 90°.

A probe position relative to the weld can be found, from which the complete cross section of the weld is scanned at once. With conventional UT an angle beam probe needs to be moved transverse to the weld in order to completely scan the weld. Alternatively a linear array on a wedge may scan the weld at a fixed angle, fig. 1.

The advantage of phased array is clearly the (object related) image of the tested volume including the detected flaws. This is available in real time including the probe position. For a wider use in typical standard applications it is essential to have as well:

- a simple and intuitive instrument operation (performed by a Level 2 operator with minimum additional training).
- a conventional ultrasonic channel for direct integration of amplitude evaluation acc. given standards.

5. Understanding the image

As with the conventional test always a sound beam with its typical characteristics were used: Near field (Fresnel zone) – focus – far field with beam divergence. Scanning over a defect means: Collecting the amplitudes of a target (flaw, reference reflector) with all parts of the sound beam, as it gets scanned, fig. 2. The image produced always reflects the reflector size loaded with the sound beam diameter at the distance of the reflector. This is why the 1mm side drilled holes in the scans show up as ellipses having a lateral width of more than 6 mm, fig. 3 and 4. This “blur” may be minimized, when the sound field can be focused to the depth of the reflector. Knowing the geometry of the sound field, it would be possible to derive the real size of the reflector by substracting the HWW (half value width) from the measured size of the indication. However, this is only true in case of no focusing. As the smallest reflector image is achieved, when the focus is at the depth of the defect, it is desirable to use a large aperture.
6. Weld inspection with sectorial scan

As welds are typically inspected with probe angles of $45^\circ$ to $70^\circ$ beam steering with a phased array probe can be set $35^\circ - 75^\circ$. Knowing the weld geometry (type, width and thickness) the optimum probe distance can be calculated to the weld. Start with a distance, at which the minimum angle ($35^\circ$) hits the edge of the HAZ (heat affected zone) at one skip, fig. 5. Now looking at all larger angles, the whole cross section of the weld plus the HAZ will be covered, fig. 6. Of course, each depth in the weld will be hit by an angle, which might not be ideal to the orientation of flat defect, e.g. a lack of side wall fusion. With scanning the weld at this constant distance therefore the gain should be increased, so that echoes will be received even under these circumstances. In order to increase the probability of detection, a second scan at a larger distance may be performed in order to optimize the scan angle with respect to the weld preparation.

The huge advantage of sectorial weld inspection is the test speed, and the easy differentiation of real defects and geometrical echoes, e.g. from the root and the weld cap: At a typical test speed of 100 mm/s the scan of 1m weld (one side) is performed in $\sim$10 seconds! A magnetic guiding strip or ruler supports the scan. Whenever a defect echo occurs, the operator has to locate and evaluate the defect.

Maintaining the high scanning speed for weld inspection, the test results of a weld inspection with an additional encoder fixed to the probe will generate an uncorrected scan image only. However, all important information on detected defects are contained in this image: The image shows the maximum echo amplitudes or the related sound paths within the two monitor gates in an image with probe position on one, and the beam angle on the other axis, fig. 7. Offline evaluation will allow to calculate the real defect location in the weld, and evaluate the echo amplitudes.
7. Evaluation of defects

The sectorial image directly allows flaw location and sizing in depth direction, fig. 8. From this image it can be differentiated between the geometrical indications and the real defect (lack of side wall fusion), and from the dynamic behaviour of the flaw echo it can easily be found that the defect is open to surface and has a total depth of 6mm. However, the influence of the beam divergence has to be put into consideration, in order not to over evaluate the defect. Since no standard is available today that describes such a technique, the operator has to use the given amplitude evaluation methods, such as DAC or DGS with the conventional technique, as described in various standards. Having a phased array flaw detector that allows a hot switch from phased array to conventional mode, the operator can easily perform a classical amplitude evaluation, using the nearest probe angle that gave the highest defect response.

8. Corner and T-joints

In case the surface opposite to the weld is accessible, testing of these welds is extremely simple and effective using a linear array, since the weld width and any possible defect can directly be displayed in the B-scan. A fast inspection of the weld can be performed, fig. 9, always showing the full cross section of the weld or – using a probe with an encoder – a C-scan image can be recorded and stored in the memory of the instrument. Full offline evaluation with evaluation of defect sizes is possible with the stored data and for documentation all reports are provided directly as graphical jpeg-files on an exchangeable SD-card.
9. Narrow gap laser beam weld

Typically these welds may contain defects that are almost vertically oriented and therefore the standard pulse echo technique will not detect these defects. Therefore, with conventional
technique two 45° angle beam probes at a constant distance to each other in tandem technique will be applied, however, this technique can easily be transferred to a linear array on a wedge, fig. 10. The first shot uses element 1 – 10 for sending and element 55 – 64 for receiving, and then cycling until the last shot using element 28 – 37 for sending and receiving. Without moving the probe a cross section of 36 mm will be tested for vertical defects. To cover the complete weld of a thickness of 95 mm the probe need to be redesigned with a pitch of 1.75 mm, which then will allow the whole weld to be inspected with scanning from both sides. Again, the inspection will be very fast, since the probe only needs to be moved along a guiding strip (magnetic ruler). Typically a scanning speed of up to 100 mm/s can be achieved without loosing information. For any defect found, the sound path is always the same, and only depends on the thickness of the weld (here 134 mm). The depth of a defect will be determined with the corresponding cycle (beam no.). Fig.11 shows two 2 mm FBHs drilled from the side into the weld area. The screen shows the sound path from top to bottom and the depth from left to right. Connecting a position encoder to this probe will allow to easily scan a thick weld, and record all defects in an uncorrected C-scan, displaying all echo amplitudes or sound paths in an image showing the probe position in one, and the defect depth in the other direction, whereby amplitudes or sound paths can be individually color coded, fig 12.

10. Bolt inspection

Using a 16 element probe and scanning into a threaded bolt at angles from 0° to 20° (sector scan) will again demonstrate the ease of use of phased array technique compared to conventional, fig 13: The sector image displays the threads, and a possible crack, growing from the root of a thread (here a 1mm notch), fig. 14. A full bolt inspection requires a 360° turn of the array probe, and location and size of the defect can easily be evaluated in the image.
11. Summary

For many years GE Inspection Technologies (previously Krautkramer) replaces standard Ultrasonics by phased array technology. 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

- a fast scanning speed,
- a higher probability of detection,
- the visualization of the test results, easily understandable by even non-experts, and
- the direct documentation of the results in standardized graphic files.
For the use of the phased array technique including position encoding in standard applications, like weld inspection, the user asks for an instrument which is easy to operate and has a hot switch to the conventional technique for the performance of the classical echo amplitude evaluation according the given standards. With the further development of the manual phased array technique, the evaluation of defects in the image need to become a part of future ultrasonic inspection standards.