RECONSTRUCTION OF DEFECTS BY ULTRASONIC TESTING USING SYNTHETIC APERTURE PROCEDURES

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INTRODUCTION

The three methods ALOK (Amplitude Time Locus Curves), PHASED ARRAY and LSAPT (Line-Synthetic-Aperture-Focussing-Technique) use the method of synthesizing a large aperture by moving a probe. The result is a high lateral resolution and the capability to focus into the farfield of the probe. As pointed out in Fig.1, a focal probe focusses only in one depth within the nearfield length. The PHASED ARRAY probe allows to change this focal distance within the nearfield length electronically. The SAFT-method allows to focus in all depths simultaneously within the nearfield length which is given not by the probe diameter D but by the synthetic aperture D'.

Synthesizing an aperture using a remote controlled automatic inspection system has no special demands on the manipulators. Probe position and ultrasonic data have to be acquired according to the specifications of the different methods.

All methods are primarily based upon the time-of-flight or phase information which is related to the flaw geometry and not or with less importance on the amplitude of the backscattered or reflected signals.

In general, the reconstruction performed with data obtained within a synthesized aperture is a phase corrected averaging method which allows a significant improvement of the signal-to-noise ratio. In addition, ALOK uses pattern recognition methods to eliminate unwanted signals which are not related to reflectors.

ALOK, HOLOGRAPHY and SAFT use probes with a divergent beam. Using PHASED ARRAY probes the divergent beam can be synthesized by steering a focussed beam within the angle limits. Applying the phased array probes together with the compound scan technique all four methods insonify a reflector from many different probe positions and therefore from different insonification directions. This means that there is a high redundancy in the data and therefore the reliability of the testing method is strongly improved.

The methods differ in the state of development, in the complexity of data acquisition and reconstruction during the inspection or off-line.
The ALOK-method is closest to those ultrasonic testing and evaluation methods used today in inservice inspection of nuclear pressure vessels.

PHASED ARRAY implies first an electronically steerable probe which can be used like any other plane or focal probe. In addition, using the beam forming capability, new methods like sector scan or compound scan allow to characterize and to reconstruct.

A combination of ALOK and PHASED ARRAY probes is not only possible but is one of the basic activities of the IzfP to improve practical applications. Implementing arrays in the ALOK system, data which have to be stored at each probe position are maximum amplitudes with the time of flight values for all reflected pulses within one angle and for all angles the sound beam has been steered. Using the feature that the main axis of the soundfield points always to the reflector, the directivity pattern of the reflector can be derived without a deconvolution technique and can be classified into globular or planar. The so-called "Synthetic Aperture Focussing Technique", SAFT, due to its physical properties is the most perfect imaging method. Its disadvantage is the high amount of data - the complete RF-signal - which have to be stored during data acquisition and the long reconstruction time. Currently work is going on to optimize the reconstruction procedure by parallel processing or by introducing the Fast Fourier Transformation.

EVALUATION WITH THE ALOK METHOD

The ALOK system (amplitude-time-locus curves) has been designed for automated ultrasonic inspection of thick-walled components. The basic features like extracting out of the RF-signals amplitude and time-of-flight of all detected signals in realtime or the noise elimination procedure by forming time-of-flight curves or the flaw border reconstruction by an iterative procedure have been described earlier /1,2/.

In the following the on-line presentation of the data during the inspection will be described. This information is desirable to have a direct overview on the state of the inspected volume and to decide very
early what inspection mode should be evaluated with highest priority. In the ALOK-system this is given by an on-line C-scan presentation on a coloured display. One can select within one presentation up to four inspection techniques like pulse-echo in different angles or tandem technique. Up to 50 scanning paths with selectable scan length can be combined within one C-scan. The intensity is colour coded and can be adjusted to different dynamic ranges.

Figure 2 demonstrates this capability during the inspection of a 90 mm thick specimen containing simulated cracks. It shows three C-scan presentations, that is from left to right: tandem zone in the depth from 10 mm to 50 mm, tandem zone in the depth of 40 mm to 80 mm and pulse-echo 45 degree. The area covered is in scan direction 270 mm and in increment direction 82 mm. The probes have been moved parallel to the weld, the insonification direction was perpendicular to the weld. In Fig. 2 in addition on the right side the scan direction and insonification direction was perpendicular to the weld with a scan length of 240 mm and in increment direction of 290 mm. All four indications can be seen with different intensity due to the inspection mode and due to their different positions inside the inspected volume.

APPLICATION OF PHASED ARRAYS

Since 1977 electronically steerable ultrasonic probes have been developed systematically at the IzfP. The research and development activities on defect reconstruction and classification by sector or compound scan imaging have been reported in /3,4/. Here two special applications should be mentioned, the aspherical focussing and the threedimensional beam steering of a point focus.

The first example refers to a situation occurring frequently at the testing of longitudinally welded pipes. A longitudinal or shear wave is generated in the curved surface and shall be focussed to a point as small as possible. Given the centre frequency, this can only be realized with an aperture length of a certain minimal size which can be calculated.
Because of the different surface curvatures the immersion technique is used causing a two-media problem. Therefore the time-delivering of the array elements has to be chosen in such a way that the differences in time of flight of the ultrasonic pulses between the i-th transducer element and the focal point inside the pipe wall is minimal. Here the Fermat principle is used.

Figure 3 shows as an example the difference in time of flight relative to the centre element as a function of element position for the special case that the array probe has been arranged under an angle of 22 degree relative to the surface of the specimen. Obviously, the time delay curve is no longer symmetrically and shows a deviation of up to 600 nsec compared with a symmetrically focussing unit. Part b) of the figure shows the increase of amplitude compared to the unfocussed case.

At present, a phased array prototype has been built and used with 24 channels which allows to steer the beam in one plane. Perpendicular to the scanning plane the sound field can be influenced only by attaching fixed lenses in front of the array. The future development in the array technology would be the use of a two-dimensional array which allows:

- to create a point focus instead of a line focus
- to focus electronically into different depths
- to minimize the resolution cell and therefore to increase the flaw characterization capability
- to steer the beam three-dimensionally
- to improve the SNR.

The straight forwad solution would be a matrix array. But as can be seen immediately starting from a 24 element linear array, the number of independent channels would increase to 576 which is too expensive.

A first step in the reduction of the number of channels would be to use symmetric properties and to steer the point focus in the center plane only which would save 50 % of the channels.
A second step would be to use a ring array. A ring array is easier to manufacture, has no grating lobes if the distance of the rings is more than 1 wavelength and has symmetrical pressure distribution. A segmented ring array would add the capability of beam steering.

A first ring array with 2 MHz center frequency and 30 mm diameter has been calculated and built for NDT. To allow a beam steering, the rings have been segmented where the number of elements has been minimized as a function of the quotient mainlobe/sidelobe. The total number of elements is 48. Two of the characteristic pressure fields are shown in Fig. 4 on the left hand side steered at 0 and on the right hand side steered at 30.

This configuration allows to steer the beam in arbitrary directions, to work with a point focus and to focus the beam in different depths. Again if it is sufficient to steer the point focus not three-dimensionally but only twodimensionally the number of elements could be reduced by a factor of 2.

**DEFECT ANALYSIS BY LSAFT**

SAFT (Synthetic Aperture Focussing Technique) has been developed in USA /5,6,7/ where a probe is moved two-dimensionally and a volume is processed to allow B-scan or C-scan image presentation or an isometric view. Here a simpler version will be discussed where the probe is moved only in one line (Line-SAFT = LSAFT) and the image plane is the B-scan plane.

The basic mechanism of SAFT will be explained in Fig. 5. A probe, in this case pulse-echo 45 degree receives signals at different time-of-flight values. By digitizing the complete RF-signal the time-of-flight to all sample points is known exactly. Unknown is the direction within the sound beam the signal may have been received. SAFT uses no pre-knowledge of the actual insonification angle. At a first step all the different amplitudes are projected at their measured time-of-flight on an arc within the beam divergency angle. The intensity level is colour coded down to -48 dB.
Fig. 5. LSAFT-image of a crack.

Image formation as a function of the number of probe positions

Now the probe will be moved to create a synthetic aperture. The next probe position would show a similar behaviour like the one shown, but this radar like image will be superimposed to the first one but shifted by the step size of the probe. Superimposing 32 of these images - the probe has been moved by about 10 mm - allows us to recognize some structures in the image which gets more clear by superimposing 64 images. Finally after an aperture of 77 mm, 256 different probe positions have been used to form the image. The result is

- a B-scan image
- a maximal lateral resolution of 1/2 wavelength
- an axial resolution due to the pulse length
- exact positioning of the reflector with the theoretical limit of the sample distance (better than 1/5 wavelength)
- possibility to measure the depth extension of a flaw
- measurement of the flaw inclination
- recognition of form echoes
- high image quality with 512 x 512 image points
- scaling 1:1.

In Fig. 5 a crack has been imaged, vertically orientated, with the depth extension of 23 mm, starting at a depth of 130 mm and as a form echo the cladding can be seen in a depth of 205 mm.

The reconstruction time for each probe position was 5 sec which taking 60 probe positions is a total reconstruction time of 5 minutes. Each signal has been digitized by 2 kbyte therefore after 60 probe positions, 120 kbyte had to be stored. The advantage of the method is, that the reconstruction time is independent of the number of defects
In Fig. 6 the synthetic aperture length has been held constant to 150 mm and the number of probe positions has been varied by decreasing the probe step size from 4.8 mm down to 0.3 mm. As can be seen at the side lobe structure of the crack and of the interface, 32 probe positions with a step size of 4.8 mm are not sufficient. An optimal value seems to lie within 64 and 128 different probe positions that is a step size of 2.4 mm or 1.2 mm. Certainly this is a function of the beam directivity pattern and the flaw depth. Therefore a more thorough investigation is necessary to derive quantitative results.

In the following some practical applications shall be demonstrated.

**Tube Sheet Plate**

A tube sheet plate, weight 86 tons, has been analyzed in the depth range of 200 mm to 700 mm. A 2 MHz probe has been moved in step sizes of 1 mm up to 1 m within 100 sec. Figure 7 shows the original LSAFT-
reconstruction scaled 1:2. The direction of the probe movement goes from left to right, the depth from top to bottom. The image size of 1 m x 0.5 m has been divided into 330 000 resolution cells. Both lateral and axial resolution are equal to 6 mm independent of depth. The following informations are obtained:

- overview upon number of defects and their distribution
- exact localization, demonstrated on two examples: x,z = 310 mm, 340 mm and x,z = 632 mm, 555 mm
- flaw size in x-direction: dx = 10 mm and dx = 40 mm
- flaw orientation: x-direction
- flaw characterization: the 40 mm flaw can be resolved into a couple of smaller indications distributed in a depth range of 8 mm.

The image has been calculated within 400 sec.

**Turbine Shaft Inspection**

This is an example where the curvature of the surface has to be corrected in the SAFT reconstruction algorithm. The turbine shown in Fig. 8 has a diameter of 1.70 m and a bore hole. Due to scanner restrictions the surface of the turbine could only be scanned along 200 mm. In this experiment the region of interest was the depth range between 630 mm and 785 mm indicated in the figure by the small rectangle and on the right side scaled 1:1. Four side drilled holes had to be imaged, separated 15 mm, 30 mm and 60 mm and arranged on a circle in the depth of 680 mm. The 640 different probe positions allowed to form the TOF-curves of the four holes and of the bore hole. The inclined TOF-curve is caused by the left bore hole. Then the LSAFT-reconstruction procedure has been performed and the image obtained can now be compared to the drawing. Position and size of the side drilled holes and the inner bore hole have been imaged correctly and confirmed the validity of the curvature correction in the SAFT algorithm.
Of course this correction influences the reconstruction time. The program had to be rewritten to take care of:
- a linear scanner was used, therefore the sample distance was constant in rectangular coordinates and not on the surface of the turbine. Therefore the actual coordinates of the probe position at the surface had to be calculated from the original coordinates.
- the vertical movement of the probe holding device was measured and was used in the program.
- compared to the plane surface, by moving the probe along the surface, the angle of incidence measured in the rectangular coordinate system changed from probe to probe position and had to be calculated.

Due to these points, for each probe position the position of all pixel elements had to be calculated and no "look up table" like in the case of plane surfaces could be used. Therefore the reconstruction time increased from 2 sec for 1 probe position to 25 sec for 1 probe position that is by a factor of 10.

A solution to reduce this factor is obviously the use of a pipe scanner and the implementation of the LSAFT - algorithm in polar coordinates.

**Underwater Imaging**

The last example demonstrates either the capability of form echo imaging or the application of LSAFT to increase the image quality in underwater imaging. The imaging capability of form echoes like weld crown, bore hole or interface have been shown earlier. Therefore a special experiment was made where the surface curvature of the specimen to be imaged changes gradually. This allows to demonstrate the capability of the system. A champagne glass at a distance of 50 mm has been imaged with 2 MHz probe - Fig. 9.
In the lower part those parts of the glass have been completed by hand which could not be imaged due to those cases where the angle of total reflection was exceeded. But it should be pointed out that the curvature has been imaged precisely. With the sound velocity of 1.48 mm/sec in water and the sample rate of 20 nsec the RF-signal has been digitized, an upper limit of the accuracy is given by 3/100 mm.

CONCLUSION

The three methods ALOK, PHASED ARRAY and HOLOSAFT use the principle of synthesizing a large aperture by moving a probe. All methods are primarily based upon the time-of-flight or phase information and less to amplitude information. They differ in the state of development, in the complexity of data acquisition and reconstruction. The ALOK method is closest to those ultrasonic inspection methods used today in in-service inspection of nuclear pressure vessels. PHASED ARRAY combined with the compound scan synthesizes the divergent beam too and insonifies a reflector from many different insonification directions with high energy. LSAFT like the other ones reconstructs a B-scan image. For all three methods examples have been shown which should demonstrate the state of the development of these systems. If the complete RF-scan is stored for all probe positions, at a later date it is possible to derive those data needed for the ALOK or the TIM (partial volume integration method) evaluation. In the meantime a "specification for the digital recording of ultrasonic signals" exists which describes precisely the format for the recording of both digitized ultrasonic signals and the documentation necessary for their interpretation. Therefore signals are available for further analysis to different institutes.

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