SAFT FOR CRACK SURFACE ANALYSIS – COMPARISON OF MODELING AND PHASED ARRAY MEASUREMENTS

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ABSTRACT. The spatial resolution in Ultrasonic Testing as a wave phenomenon in nature is limited to a certain fraction of the wavelength, usually defined to be close to the rayleigh criterion. In case of complicated reflector surfaces – such as stress corrosion cracking - this limitation prevents an exact visualization of the defect shape. There exist a few approaches to improve the spatial resolution, whose reconstruction quality all in common also depend on the achieved signal-to-noise ratio of the raw data. In this work we present a specific SAFT analysis, in which a high number of different angles of incidence produce a sufficiently high number of different reflections at the crack edges resulting in an improved SNR. In doing so, we reconstruct a coherent crack structure. First investigations were made at artificially simulated crack configurations with different contours and curvatures in flat and cylindrical test blocks. The measurements results – visualized by representative scans – show details of crack design and crack orientation. We also will present a comparison of the SAFT analysis between modelling and phased array measurements.

Keywords: Ultrasonic Testing, SAFT, Phased Array

INTRODUCTION

Ultrasonic testing uses disturbances in the spread of the irradiated wave in order to discover possible material flaws. Material interfaces become acoustic sources fed by the incident wave due to the change in wave impedance. Most search techniques used evaluate the time of flight and echo height. Lateral local information is limited to the width and direction of the sound beam. Considerably more precise information on location, extension, surface inclination and defect form or reflectors can be obtained using so-called analysis techniques where sound is emitted and received at as wide an angle as possible. The width of the angle from which the reflector can be ‘seen’, i.e. the aperture, is important for two reasons. On the one hand, the size of the aperture and the wavelength determine the possible spatial resolution while on the other, larger reflectors can only be ‘seen’ properly if the range of their narrow emitted beam angle falls in the observable width of angle. Focusing, which is necessary for a greater spatial resolution, can be achieved using real focusing probes. Although focusing probes function well in many cases, they are unwieldy for use in analysis because they are comparatively large, the resolution becomes worse with increasing distance and another probe and scan process is necessary for different depth zones and acoustic irradiation angles.

SAFT, i.e. Synthetic Aperture Focusing Technique offers an alternative. Here the probe should be able to send and receive sound across a wide angle. However, only small probes, about the size of the wavelength, are capable of doing that. Both focusing techniques require sensors other than those used for search techniques. Both SAFT and phased array were developed to improve RADAR technology. The principles for using acoustic waves were suggested many years ago and used to some extent. Phased array technology has experienced a rapid development in the last few years. SAFT, however, has been used very hesitantly. In the future, this will change for the following reasons:
1. Increasing computer performance has realistically shortened calculation times for SAFT reconstruction, even for PC systems.
2. Automatic ultrasonic test systems are being increasingly used. The advantage here is that the probe position is detected for each A-scan by displacement transducers - a pre-requisite for SAFT reconstruction.
3. SAFT can be implemented superbly using the phased array technique and thus easily combined with other common test techniques. Thus a substantial hurdle is overcome for SAFT, i.e. where another test system using probes unsuitable for conventional testing is needed.

1 SAFT USING PHASED ARRAYS, MODEL CALCULATIONS

1.1 SAFT, notes on the principle

The aperture is the angular range in which an echo from the reflector can be measured. The synthesis of the aperture takes place via numerical combination of measurement data from different probe positions. For each pixel, the measured HF echo signals from all probe positions are superimposed in such a time-shifted way that their (numerical) interference will be optimally constructive if the echo actually comes from the particular pixel. This requires knowledge of the sound flight times for potential echoes which could come from the pixels. For genuine reflective positions, the amplitude in the picture increases with the number of echoes from different probe positions. For all other pixels the phase changes and the complex sum approaches zero. Fig. 2 shows the growth of the signal at the position of a point reflector with an increasing number of HF echo signals from equidistant probe positions within the selected aperture.

FIGURE 1. Possible reflector placement seen from different probe positions

FIGURE 2. Reconstruction of the reflector position with an increasing number of probe positions
The lateral resolution of the point image grows qualitatively as shown in Fig. 3 with increasing size of the synthetic aperture due to increasing displacement of the probe. Here the minimum size of the point image is that of the wavelength. The length of the acoustic impulse is crucial in depth direction, as indicated by the comparison of the rectified and HF SAFT image in Figures 4a and 4b.

1.2 Phased array probes for SAFT

The single transducer element of a phased array probe is of the correct size and thus provides a sufficiently large sound beam divergence (Fig. 5a) well suited for SAFT. This characteristic is actually used in the so-called Sampling Phased Array [1, 2], where the elements of a phased array are excited sequentially and other elements act as receivers. The phased array probe as a whole has a swivel angle range which is determined by the divergence of the sound beam for each individual transducer element (cf. Figures 5a and 5c). It is capable of sending and receiving sound in an equally wide angular range as a single small probe, with the additional benefit of a much better SNR. The results from a phased array are comparable to those from a single transducer of the same size if suitable control, sensitivity and sound field form (see Fig. 5b) is used.
1.3 SAFT using phased arrays. Principle

The sound beam is swivelled at each measuring point, an HF A-scan is taken for each swivel angle (Fig. 6) and all A-scan data are evaluated in the SAFT reconstruction. This procedure was suggested and examples put into practice about a decade ago [3]. While the instrument and computer technology used at that time prevented the technology from spreading, the situation is different today [4].

The amount of raw data is increased by the number of swivel angles which are needed in order to cover the desired aperture with the given sound beam width. Even if the respective sound beam width is taken into account in the SAFT algorithm, the calculation time for SAFT reconstructions is not extended. Contrary to SAFT using a small probe or a Sampling Phased Array, the individual A-scans remain able to be interpreted or conventionally evaluated due to good SNR.

Since the measurement data are available in a form selected according to the angle, reconstruction can also be performed according to that angle. Thus artefacts can be detected and avoided in certain cases. For phased arrays with a sound path within the wedge the relative shift of the virtual source point in space and time must be considered as a function of swivel angle. This can be completed both in the phased array device and in the SAFT software. In contrast to taking into account the sound path within the wedge for SAFT using a small probe [5], calculation of the virtual source point for a phased array can start by using the angle of the sound beam axis.

1.4 Model calculations

In order to be able to determine the different parameters of the probe, the interaction with the reflector and the characteristics of the SAFT reconstruction software, these parameters were integrated in BAM’s ultrasonic model system (Arraycalculus + Echo3D using SAFT algorithm).

The simulation to produce reconstructed SAFT images from artificial echo data can be performed in the following steps:

- calculation of the phased array sound field from its structure data for the swivel angles used and, if applicable, focusing
- construction and arrangement of model reflectors
- calculation of the HF echo signals using the ‘measurement parameters’, swivel angle, probe displacement, measuring point distance, A-scan pixeling, etc.
- manual selection of the image range for reconstruction, resolution etc.
- automatic selection of the relevant A-scans from all measurement data
- SAFT reconstruction/image production

FIGURE 6. Measurement of suitable SAFT echo data using a phased array and model reflector surface
Fig. 6 shows a model reflector surface composed of both flat and curved elements, but otherwise of the same reflection characteristics. The probe was moved so that all places of the model reflector surface were scanned at all swivel angles (± 60° in 4° steps). Fig. 7,left indicates that the surface of the reflector is fully represented but with different amplitudes. If the spatial dependence of the echo heights in the probe’s sound field is compensated for by an amplitude correction function (Fig. 7, right), the surfaces appear in the SAFT reconstruction with the same amplitude. This in itself is remarkable as the reflector surfaces have very different directional effects, but the integral assumes nearly the same value across all directions in the aperture for all parts of the surface. The section of surface on the right of the reflector is an exception, where the inclination is greater than 60°, i.e. the largest swivel angle. That leads to a collapse in echo height. The picture of the gap in the centre of the model reflector gives an idea of spatial resolution. It is 1 mm = 0.83λ wide.

The numerical result of SAFT reconstruction is presented as a HF image (Fig. 8). This contains the structure of the acoustic impulse without being a characteristic of the reflector. However, the illustration does give a good impression as to how precisely the position of the surface can be determined.

2 SAFT USING PHASED ARRAYS, MEASUREMENTS

2.1 Test samples

Different test samples with flat and cylindrical surfaces (Figures 9 and 10) were manufactured, into which depressions consisting of continuous zigzag sections which had inclinations and radii of different sizes were machined. The goal was to test the possibilities and limitations of the technology and to verify the reliability of the model calculations or determine whether there was any need for correction. The measurements were performed using the ‘Compas’ phased array device and integrated SAFT software. The device and the software were developed in BAM.

FIGURE 7. Left: Model reflector (top) and reconstruction (bottom). Right: Reflectivity-true reconstruction after compensation of probe sensitivity

FIGURE 8. HF illustration of SAFT reconstruction, same data as in Fig. 7, right
FIGURE 9. Test samples with flat surfaces and continuous surfaces of defect of very different inclinations and radii

FIGURE 10. Cylindrical test samples with continuous surfaces of defect of very different inclinations and radii

2.2 SAFT – Reconstruction from phased array tests on test samples

Test sample Ts 1 was scanned using a 5-MHz probe with a wedge and a swivel range of 0° - 60° for the longitudinal wave in two steps scanned from the right and left. The SAFT reconstructions in Fig. 11 in each case show those surfaces which are facing the sound beam. The line of the depression is indicated in black in the picture.
5-MHz longitudinal wave in steel, wavelength 1.2 mm

**FIGURE 11.** SAFT reconstruction of measurement results on Ts 1 measured from two sides

Fig. 12 summarizes the results from both scanning directions using image processing. Amalgamation of these data in the SAFT calculation would only be possible if the probe positions relative to each other were known precisely enough (order of magnitude $\lambda/7$) from both scans. As already indicated in connection with the model results, those surfaces, that are not hit perpendicularly at some time within the sound beam range, are reproduced either weakly or not at all.

**FIGURE 12.** SAFT reconstruction, measurements from two sides superimposed optically

An amplitude correction, which was calculated based on the structure data of the phased array probe, was used in the reconstruction. The evaluation angle range was limited to $0^\circ$ to $45^\circ$ for Figures 11 and 12. Having a swivel angle of the longitudinal wave of $60^\circ$, the transversal wave component that can be emitted from and received by the probe is so large, that echoes of the transversal wave appear in the reconstruction image (Fig. 13). The signals are indistinct because the spatial arrangement is not correct. The echoes come from different places in the object since they spread at a lower speed, but in the image, they are assigned based on their flight time. This problem is well-known.

Contrary to measurements using small probes and/or single transducer elements, phased array measurements make it possible to omit those ranges of the acoustic irradiation angle that contain noise components. It is particularly advantageous that this subsequent and simple angle-selective evaluation is possible.
When the exterior of a cylinder is measured, the aperture extends beyond the sound beam range by the angle at which the probe turns on its path around the potential reflector position or pixel. This depends on the radial position of the pixel. An angular field range of 360° is reached in the centre even if the sound beam spread is very small.

A discussion of the additional consequences of cylinder geometry on the spatially dependent aperture and the subsequent effects on the amplitude in the image would go beyond the scope of this paper. Of course, the SAFT algorithm must take into account the cylindrical geometry. The larger the range of the probe movement, the more precisely the cylinder radius must be known in order to evaluate measurement data.

Fig. 14 shows the HF SAFT reconstruction of measurements on the cylindrical test sample Ts 3. The probe sole was adjusted for curvature. The probe was moved around in a semi-circle above the zigzag depressions. The angular range for the evaluation was limited to ± 32° because the sound beam axis is always outside of the zigzag depressions when the acoustic irradiation angle is greater. The zigzag depression is indicated in black above the reconstruction.

The result is impressive partly because it indicates surfaces of very different inclination and the clear contour due to the short acoustic impulse of the phased array. The following comments are of a rather speculative character because of our limited experience: some places, which are probably largely shaded, are not illustrated. If parts of the zigzag depression, e.g. lines approaching peaks, ‘are seen’ by the ultrasound with only a small aperture, then the resolution is reduced locally and the lines in the reconstruction are too long and form the x-shaped marks.
3 SAFT USING PHASED ARRAYS, ADVANTAGES AND DISADVANTAGES

3.1 Advantages over the well-known SAFT technique using a small probe

- Measurements suitable for SAFT are possible using common phased array instrument techniques, which can be digitized and save HF A-scans and probe position data.
- All types of phased array probes which enable the sound beam to be swivelled are suitable (i.e. up to ring arrays which are only capable of focusing for instance).
- Only one test system is needed for search and analysis technology.
- The SNR is very much larger in the A-scans, i.e. as large as in conventional probes, thus common evaluation techniques can be applied to measurement data that are also suitable for SAFT.
- Individual echoes are evaluated at only a small angle of the sound beam divergence of the phased array for a swivel angle. Thus only minor assignment errors occur at the boundary of the sound beam.
- The sequential structure of the probe aperture within the swivel angle range enables a subsequent reconstruction to be adapted to use selected angles for detection and reduction of artefacts on the one hand, and to assist in error analysis on the other.
- Angle- and distance-dependence of the amplitude can be compensated for both in measurement (equipment dynamics can be better used) and evaluation in order to represent equally reflecting surfaces in an equally bright manner.

3.2 Disadvantages compared to the well-known SAFT technique using a small probe

- The amount of raw data is increased by the number of swivel angles.
- Where phased arrays use sound path within the wedge, the relative spatial and time shift of the virtual source point must then be taken into account.

FIGURE 14. HF SAFT reconstruction, measurement data from the semi-circle above the crack surface
SUMMARY

The investigations demonstrate the suitability of phased arrays for SAFT and show the possibilities and limitations to be expected in the analysis of crack surfaces. Nearly all automated phased array test systems can handle measurement data which are suitable for SAFT. In addition, only one type of SAFT reconstruction software is needed. Many test systems can thus be used at relatively small additional cost for error analysis using SAFT.

Surfaces of the same reflection characteristics in the tested range are illustrated using the same amplitude in the SAFT image independently of their curvature due to compensation of the sensitivity distribution of the probe. Spatial resolution of the size of a wavelength should normally be achievable, unless special restrictions of the aperture prevent this or for example the speed of sound in the material varies too extensively.

REFERENCES