Progress In Acoustical Defect Sizing NDT Methods for the Inspection of Power-Plant Components

Marc KREUTZBRUCK, Jens Prager, Rainer BÖHM, Jessica KITZE, and Gerhard BREKOW
1 BAM Federal Institute for Materials Research and Testing, Division 8.4, Unter den Eichen 87, 12205 Berlin, Germany, marc.kreutzbruck@bam.de

Abstract

The demand of improved NDT methods with proper visualization and sizing capabilities is a persistent trend in maintenance and manufacturing quality inspection. Especially when dealing with high quality standards in conjunction with safety-critical components in the sector of energy and transportation quantitative NDT techniques are vital to provide reliable quality control systems and a corresponding deeper insight into the component structure for a further fracture-mechanical estimation. The paper thus focuses the progress of the defect sizing capabilities of modern Ultrasonic Testing (UT). In Ultrasonic Testing the SAFT-algorithm (Synthetic Aperture Focusing Technique) currently experiences a renaissance. The method is based on combining the data of different transducer positions with their corresponding varied propagating time and it is currently applied in several industrial applications. SAFT enhances the SNR and the spatial resolution and is thus a valuable tool when it comes to improved defect detection and sizing. A tomographic-like data mapping is illustrated on several examples, where adapted phased array systems were used for the inspection of turbine components and also for a cladded mock-up of a nuclear reactor pressure vessel. In a statistical investigation we also performed a comparison with other defect sizing methods like TOFD (Time of flight diffraction).

Keywords: Phased Array, SAFT, TOFD, cracks.

1. Introduction

In Ultrasonic Testing the SAFT-algorithm (Synthetic Aperture Focusing Technique) currently experiences a renaissance. The method is based on combining the data of different transducer positions with their corresponding varied propagating time and it is currently applied in several industrial applications. SAFT enhances the SNR and the spatial resolution and is thus a valuable tool when it comes to improved defect detection and sizing. A tomographic-like data mapping is illustrated on several examples, where adapted phased array systems were used for the inspection of turbine components and also for a cladded mock-up of a nuclear reactor pressure vessel. In a statistical investigation we also performed a comparison with other defect sizing methods like TOFD (Time of flight diffraction), which shows to be more susceptible to defect orientation than SAFT.

As a further modern NDT approach with sizing capabilities the paper demonstrate the use of small magnetoresistance sensor arrays for the magnetic detection of surface breaking cracks. In particular GMR-sensors (Giant Magneto Resistance) are suitable because of their high field sensitivity, high signal-to-noise ratio and high spatial resolution. A GMR-gradiometer and a 3D-GMR-magnetometer was used to detect artificial and fatigue surface breaking cracks with a depth of smaller than 50 µm, with which a reconstruction of the length and depth can be reliably carried out. Also the detection of subsurface defects and fatigue defects will be presented.
2. Ultrasonic SAFT Algorithm - Increasing the Crack Detection-Reliability

In case of macro sized defects (size larger than wavelength) the SAFT-algorithm (Synthetic Aperture Focusing Technique) currently experiences a renaissance. The method is based on combining the data of different transducer positions with their corresponding varied propagating time and it is currently applied in several industrial applications. SAFT enhances the SNR and the spatial resolution and is thus a valuable tool when it comes to improved defect detection and sizing [1]. SAFT is a travel time based analysis method. It combines a special measurement scheme with a subsequent image reconstruction. Even if the method is also available in 3-D, for sake of simplicity, only the 2-D reconstruction will be described in the following.

During the scanning process the test volume – Region Of Interest (ROI) – is insonified by ultrasound waves as sketched in Figure 1. Echo signals from a wide angular range of the test specimen received at the probe position are a prerequisite for the reconstruction. Therewith the scanning provides an insonification of possible defects from various angles of incidence. Accordingly, the test specimen has to be scanned using a divergence angle as large as possible in a linear path (in 3-D also a meander shape). The large divergences can be achieved using a conventional probe with a small transducer area or by phased array probes using a swivelled sound beam. The transducer and the subsequent receiver hardware delivers high-frequency (RF) digitized ultrasound data $\Phi(x,d,t)$.

![Figure 1: Isochrones for SAFT reconstruction at different scanning positions.](image)

For the reconstruction the ROI given as $(x,z \leq d)$ is discretized into a pixel grid where each pixel is considered successively as a reflector and gets assigned a reflection amplitude $o(x',z')$. Therefore, the SAFT-method arranges the echo signals $\Phi(x,d,t)$ into this grid according to their time of flight and divergence angle. From each scanning position $(x,d)$ with $x \in S_M$, where $S_M$ is the scan path, isochrones can be constructed as

$$ct = \sqrt{(x-x')^2 + (d-z')^2}.$$  \hspace{1cm} (1)

Note, in pulse-echo technique this distance is travelled twice. Summing up the contributions from all scanning positions along $S_M$ yields the amplitudes in each pixel as

$$o(x',z') = \int_{S_M} \Phi(x,d,t) \left(1 - \frac{2}{ct} \sqrt{(x-x')^2 + (d-z')^2}\right)dx.$$ \hspace{1cm} (2)
In this numerical superposition of the time-of-flight-dependent echoes the phase positions are taken into account and constructive interference provides a large resulting echo only for the actual reflection spots \( o(x', z') \). For all other pixels the superposition yields only small or negligible echoes due to destructive interferences.

Due to their statistical phase high Signal to Noise Ratios (SNR) can be achieved by averaging the signals. In contrast to this possible increase, the SNR is limited when small conventional probes with large beam divergence are used as the emitted energy depends on the transducer area. Since the large divergence is essential for the method, one way to further increase the SNR and improve resolution capability is the use of phased array probes whose transducer area no longer needs to be small to achieve high beam divergence. Phased array probes allow for angle swivelling where the superposition of the various swivel-angles provides artificially a highly divergent sound field with sufficient sound pressure and a sufficiently large synthetic aperture [1] - [3]. Practice has proven ultrasonic testing using longitudinal waves combined with a consecutive SAFT reconstruction is most appropriate. Especially the defect detection is better by using longitudinal than transversal waves [4].

3. SAFT Algorithm for Improving the Signal - To - Noise Ratio

As a first example we show the detection of a small reflector in big components like a turbine wheel. A sketch of the turbine wheel is shown in Fig. 2, left. It has a diameter of about 1.5 m and posses several artificial defects, which were introduced as flat bottom holes (FBH) with different sizes. The reflector 3 and 4 has a diameter of 1mm. For the detection we used a 16-element Phased-Array transducer, which was operated with a frequency of 3 MHz. The angle of incidence was 12.5° and each 3 mm one measuring point was recorded. The virtual divergency was generated by using different swivel-angles, each of which providing a higher sound pressure in the certain angle segment. The sound field and its swivel-angle were altered in 0.5°-steps from 12° - 15°. The corresponding A-scan for an angle of 13° is depicted in Fig. 2, right. One can observe a significant high back wall signal, starting at about 876 mm. In front of the back wall signal a slight indication with a SNR of about 6 dB can be seen at 858 mm. After performing the SAFT algorithm, the data show a significant higher SNR. Fig. 3, left shows the SAFT reconstruction which contains both the back wall signal and the 1mm-sized FBH. Fig. 3, right shows a somewhat smaller ROI, which only contains the reflection of the FBH. In comparison to the Fig. 3, left the amplitude is scaled with a new false colour representation. The SNR was estimated to be 17 dB which is more than 10 dB higher than it was determined in the A-scan data. The spot size (using the 6 dB attenuation) is in the order of the wave length, which is here approximately 2 mm.

Figure 2: Left: Sketch of the turbine wheel segment. Right: A-scan.
4. SAFT Algorithm for Improving the Spatial Resolution

As a second example we apply SAFT to the UT-RF data of a turbine shaft, a special test specimen of SIEMENS AG having a weight of more than 40 tons and a maximum diameter of 1.6 m. The measured RF-raw data were detected using an operation frequency of 4 MHz. Besides the bore hole signals and the signals generated by the changing diameter (Fig. 4, left), the SAFT-data also show a number of indications in the centre regime of the shaft, which looks like a cluster of stars within the cross section. A closer look reveals numerous indications in the core regime of the shaft, which nicely can be separated from each other. The smaller indications show a size as small as 1.5 mm, which corresponds to the wavelength. In comparison to the standard A-scan the information content of this tomographic-like SAFT representation is distinctly enhanced and provides information which otherwise lies below the noise level. Considering that such bulky components can only be tested by Ultrasonic Testing this SAFT approach offers new ways to increase the reliability of the inspection of the complete shaft volume.

Figure 4: Results of a phased Array inspection of a turbine shaft with 0.8 m and 1.6 m after applying SAFT. Left: SAFT reconstruction (1.6 m x 1.6 m) of the whole cross section containing four side drilled holes. Right: Magnification of the core regime (100 mm x 100 mm) indicated by the square at the left hand side.
5. SAFT Algorithm for Defect Sizing

Finally, in this section a defect sizing example is shown for a cladded mock-up of a nuclear reactor pressure vessel containing many different kind of artificial defects, which were sized by detecting the diffraction signal of the upper and lower crack edges. The cladded mock-up model of a reactor pressure vessel with a horizontal weld consists of a ferritic base material of the vessel wall with a thickness of 140 mm and an additional austenitic cladding layer with a thickness of 9 mm (see Fig.5). The specimen contains 55 artificial test reflectors of known size, geometry and position. In the cladding area tests were performed at swivel angles ranging between 30° and 60° with 5° step size and additionally at 0° for normal incidence. With the additional normal sound beam the back wall becomes visible in the reconstruction which simplifies the interpretation of the results. The angles of incidence between 0° and 30° were omitted because no relevant contributions to the reconstruction were expected. The manipulator scanned the volume of the specimen on both horizontal and vertical tracks. Figure 5 shows the false color coded SAFT reconstructions of a 8 mm deep notch in the cladding for two test frequencies but with different directions of incidence. The pictures indicate that the notch dimension can be determined with high accuracy directly from the SAFT reconstruction with both frequencies. In addition to the plain reflector at \( y = 720 \text{ mm} \), the reconstruction indicates a lateral side-drilled hole on the left, which was located at the cladding boundary and is exactly localized at \( y = 690 \text{ mm} \). The interface between ferritic material and cladding is not identifiable from the diagram; however the SNR is slightly decreased in the cladding, resulting from the austenitic grain structure. The images again show clearly the influence of frequency on the resolution capabilities. Both axial and lateral resolution improves with increasing frequency. As expected, the defect sizing is more accurate at 2.25 MHz.

![Figure 5: SAFT reconstruction of a 8 mm deep notch in cladding area using 1.5 MHz and 2.25 MHz, schematic experimental set-up (top).](image)

6. A Comparison with TOFD

The Time Of Flight Diffraction technique (TOFD) is an ultrasonic testing technique, with two angle probes arranged in V-transmission. Figure 6 shows a typical experimental set-up. For the TOFD inspection, the probe spacing was set to 110 mm. To ensure the
whole thickness range of the specimen could be inspected the volume was subdivided into 4 sensitivity zones where the central beams of transmitter and receiver overlap at 30 mm, 80 mm, 115 mm and 140 mm, respectively. Various angles are needed to achieve the required depth ranges. The use of phased array probes enables an adaption of the swivel angle to the required sensitivity zones. Varying this angle subsequently at one transducer position allows all measurement to be made in one pass.

Figure 6: TOFD technique using longitudinal waves

Both the SAFT and the TOFD techniques were in a first investigation step used as search methods to identify the defects in the designated areas and later in a second step as analysis methods using optimized parameters for the quantitative determination of defect position, size and orientation. Generally, it has been shown that both methods are suited to localize and characterize defects on cladded and welded components. Looking on the results of the defect analysis in more detail, it clearly indicates that for the underlying application SAFT is more suited as analysis method than TOFD, especially for defect sizing. The main reason is its better spatial resolution. Beside this, the results are more intuitive and easier to interpret. For defect identification, however, the TOFD method has shown to be unsuitable. It was impossible to get a comprehensive overview of all defects.

Even if SAFT delivers more reliable results for the defect identification, one should consider the large effort on calculation power required for the reconstruction. Although, in the presented investigation the areas and tracks scanned by both techniques are not always similar, having as consequence that not all reflectors could be investigated with both techniques, the overall performance of the two methods will be assessed in the following. Figure 7 and 8 show on survey the suitability of SAFT and TOFD for detection as well as for sizing of reflectors. The results are presented in two ways, first selecting only those reflectors where both methods were applied (column pairs 1 and 2) and second an overall performance where all reflectors were incorporated independently if they were analyzed using either SAFT or TOFD or both methods (column pair 3 and 4). Shown is the percentage of defects located and sized correctly related to all incorporated reflectors. Assessed using both methods and therewith directly comparable are 32 reflectors at 1.5 MHz but only 9 reflectors at 2.25 MHz. From the figures it can be concluded that for the given specimen and independent of the probe frequency the reliability of the SAFT results is significantly higher than those from TOFD inspections. This difference considerably increases when using a higher test frequency.
It is clearly visible, that SAFT has its capability in defect sizing. Because only a small number of tests were included in the survey any statistical conclusions and a generalization of the outcome should be done very carefully.

Figure 7: Percentages based on the total number of reflectors for SAFT and TOFD showing detection and reflector size determination at 1.5 MHz.

Figure 8: Percentages based on the total number of reflectors for SAFT and TOFD showing detection and reflector size determination at 2.25 MHz.

7. Conclusion

The results shown in section 2 substantiate that post processing algorithms like SAFT provide more information about the defects compared to conventional UT-inspection techniques. The averaging along several A-scans with different phase information in conjunction with the accurate transducer position leads to a data representation which provides an increase in signal-to-noise ratio and an improved spatial resolution. This can be very helpful when it comes to inspect very bulky components, as in this case UT is the only volume inspection method available. In doing so SAFT can also be used as a sizing technique in which the
diffraction echo from the top and bottom edge of a defect can be detected. Having in mind that diffraction echo have an amplitude which are in the order of 20 -30 dB lower compared to the typical reflection response, SAFT supports this technique due to its amplification effect. Especially when dealing with thick components and the corresponding long propagating paths the use of a Phased Array transducer turned out to be very helpful. Here the required divergency was generated by using a lot of swivel angles which in total resembles the high divergency of a conventional small 0°-transducer. We then are able to generate a high sound pressure in a narrow angle segment leading to a better SNR which enables us to detect reflectors of smaller 1 mm in more than 80 cm distance.

References


