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Quantitative Ultrasonic Testing of Pressurized Components Using Sampling Phased Array

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Abstract

Ultrasonic testing and evaluation procedures typically depend on reference reflectors to establish detection sensitivity and evaluation of test data. Rules and regulations governing safety-related components emphasize on test procedures that assure the detectability of discontinuities at all over the component and oriented in any arbitrary direction. Existing procedures, however, do not provide information for a quantitative presentation of type and size of the detected discontinuities. To size the defects it requires additional measurements and analysis, involving complex inspection procedures and highly qualified expert personnel, are required. Furthermore, critical flaws evaluated with fracture-mechanics analysis appear much larger than comparable detectable reference reflectors.

For ultrasonic testing results to become relevant input for the fracture-mechanics analysis, the ultrasonic test data must deliver high-quality flaw images that are quantifiable. For industry to use such an approach these test techniques and procedures should be able to perform inspections at normal inspection speeds and without the need for specialized or extraordinary inspection resources. To satisfy the condition to detect defects oriented in any direction requires the inspection to be done with all beam angles (from -90° to +90°), with high sensitivity and resolution.

Fraunhofer Institute Nondestructive Testing has developed sampling phased array technique to overcome the existing limitations of ultrasonic imaging. Using well-adapted reconstruction algorithms and highly efficient integrated computer architectures the Sampling Phased Array technique is capable of producing quantifiable flaw images for various industrial applications. A special adaptation of this technique with virtually controlled aperture high resolution focusing is possible at long sound paths.

This paper presents the results of the applications where this technique is used on industrial components, such as heavy wall components, piping system weld joins and turbine shafts.

Keywords: *Quantitative NDT, Fracture mechanics, Phased array, SAFT, TOMOSAFT*

1. Quantitative Nondestructive Testing

The concept of "Quantitative Nondestructive Testing" paraphrase a fundamental problem associated with NDT. The reality of most testing results is that the detected indications can only be described as acceptable or unacceptable indications. This qualitative result is not useful for determining the load bearing potential or expected life of the material or the components, band is therefore limited to a judgment during design and operation of load bearing structures and components.

The need to eliminate material anomalies, which can propagate and reach critical dimensions under load conditions, demands high testing sensitivity qualified using controlled prepared test specimens that contain artificial reflectors, e.g. disc-shape reflectors (DSR) for ultrasonic testing, flaws that are significantly smaller than those considered critical flaws [1].

Qualitative NDT does not provide the means to determine safety margins, particularly in lightweight construction, nor does it provide information about residual life expectancy or operational life of components, or repair/maintenance intervals. Currently, NDT does not provide the quantitative information that would be useful for determining the impact of component and material anomalies under load, resulting in a degree of uncertainty about the test results. For crack-like flaws for example, it would be useful to compare the detected and sized discontinuity with the effective geometry relevant for fracture mechanic analysis [2]. However, this is, generally speaking, currently impossible.

During Ultrasonic Testing (UT), information from the reflecting ultrasonic characteristics of material displacement or cracking and the interface information from materials with different acoustic impedance are correlated with fracturemechanics data from specimens with controlled implanted flaws (see Figure1).

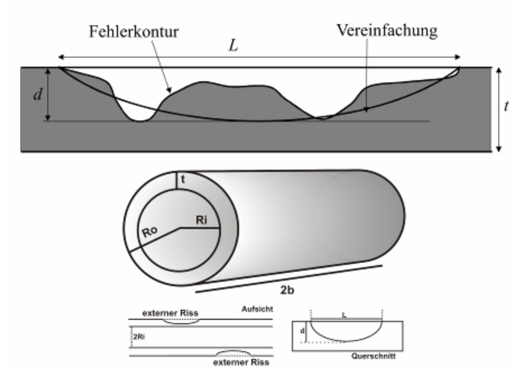


Fig.1: Correlation of an Actual law with a Modeled Flaw

Three approaches will be considered [3] for providing quantitative evaluation results and will be explored through NDT test experiments:

- Improvements in NDT techniques to achieve better image presentations [4, 5] of material discontinuities via contrast enhancement techniques. An example is the image of a 3-dimensional X-Ray tomography confirming the presence of transverse cracking in an aluminum weld joint of a lightweight structure, see Figure 2 below.

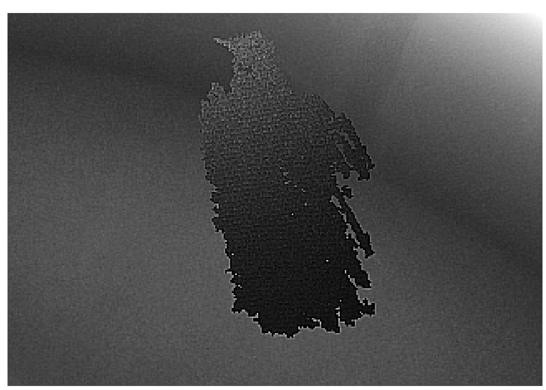


Fig. 2: 3-D Image of a Transverse Crack

- Fracture mechanics analysis for the determination of critical flaw sizes for load-bearing structures [6, 7, & 8]. The NDT data provided for the fracture mechanics analysis are not absolutely deterministic due to their inherent anomalies. In addition, the real flaw description only rarely depicts the exact situation when compared to the fracture mechanics model. In these cases, the analysis must consider the probabilistic nature of the data. The reverse approach is to probabilistically predicting the fracture mechanics results and then formulating the critical flaw parameters for an optimized test procedure.

- The resulting "Failure Assessment Diagram" (FAD) is the fundamental tool to evaluate fracture mechanics for cracking. Figure 3 below shows an example of an FAD and the probabilistic computation of the effect of a discontinuity. The comparison clearly shows the contrast in results from the two approaches [9].

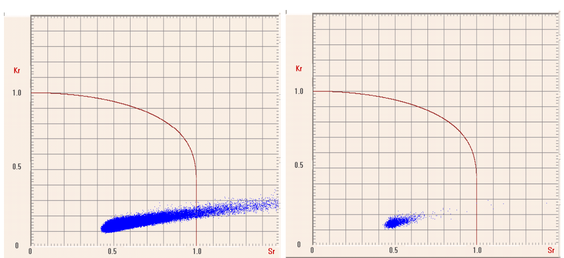


Fig. 3: FAD-Diagram without (left) and with (right) NDT data input

However, the example from [9] also demonstrates the rather vague state of technology to statistically validate the data collected from the flaw. The flaw detection probability function (POD), as depicted in Figure 4 below, based on studies by W. Marshall in 1982 [10], proves not more than the finite probability of not detecting very large cracks and presents a threshold for flaw detectability.

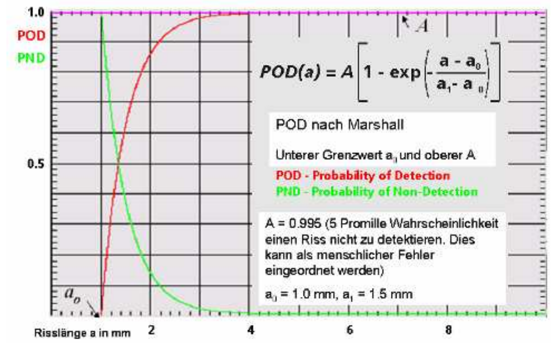


Fig. 4: Flaw Detection Probability Function (W. Marshall)

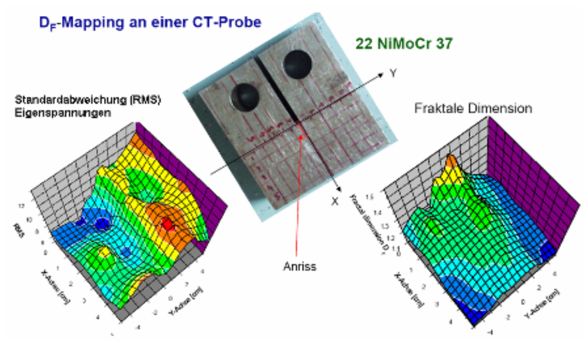


Fig. 5: Comparison of Residual Stress to Fractal Dimensions in a Fatigue State

In any case, Fraunhofer-IZFP considers FADs to be very useful, since they provide the inspector a good indication of critical flaw dimensions and locations. FADs have been established in various rules, standards and regulations [6, 8, & 11].

- The third approach uses the stress-loaded material or component as a "sensor" to capture "effective" crack parameters. Successful measurements and evaluations of fatigue phenomena, caused by material discontinuities and resulting in accelerated weakening and subsequent formation of cracking, can be quantitatively analyzed with the aid of fracture mechanics techniques.

An example of such approach is the measurement of dynamic magnetization in ferromagnetic materials permitting to conclude accelerated fatiguing and crack formation [12, 13]. Figure 5 from [13] demonstrates the current state-of-the-art technology from such a fatigue phenomena experimental measurement.

2. Requirements for Quantitative Ultrasonic Testing

This section provides progress information and discusses related development activities for improving the quantitative analysis capabilities of ultrasonic testing. UT techniques are particularly useful for the detection and evaluation of cracks and crack-like discontinuities. However, the subjective to providing quantitative imaging is difficult to achieve, in spite of the fact that much progress has been made as shown in the image of an unborn child in Figure 6 below [14].

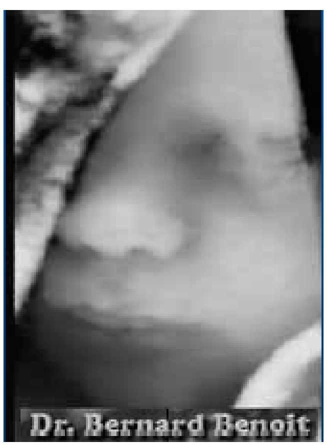


Fig. 6: UT Image of a Unborn Child [14]

As discussed later, this progress achieved in medical technology may, in principle, also be applied to material testing and evaluation. Obstacles do exist at this time but are mainly of practicable implementation and economical nature. Further development is required in the areas of testing speed, regulatory implementation and economic efficiency for the industrial acceptance of these new techniques.

2.1 Testing Methodology Development Goals

The development goals for quantitative ultrasonic testing are readily identifiable:

1. To permit the detection of flaws with arbitrary orientation, i.e. using any beam angle (in a conventional meaning).
2. Discontinuities must be identifiable with high resolution to minimize interference with (adjacent) scattered signals. This can be achieved using synthetic aperture techniques applied to all image points and sufficiently broadbanded ultrasonic pulses.
3. The image of the material discontinuity must be very clear and non-ambiguous, such that their location, size and type can be identified. Of particular importance is the suppression of artifacts, e.g. caused by mode-conversions at material interfaces.
4. The most demanding objective is the identification and characterization of geometry reflectors through their inherent scatter characteristics in the ultrasonic wave front.

2.2. Testing System Development Goals

The requirements for ultrasonic testing and evaluation are derived from a longstanding practical experience. Therefore further technology developments must assure that any new techniques will provide as good or better information than those existing, and with high levels of confidence. This would include the possibility to generate (transit) time- corrected A-Scans to allow the evaluation of indications using reference reflectors such as disc-shaped reflectors (DSR) without using side-drilled hole (SDH) reflectors.

Production-line integrade testing systems in particular, required high inspection speeds of several meters per second. At the same time, the search unit assembly shall be both, simple and robust, and requires the minimization of the number and size of the ultrasonic transducers to be deployed. Ultrasonic transducers and associated electronics should be designed such that interface cable lengths are minimized. Where possible, "Sensor-on-Chip" technology should be employed.

Last but not least and in contrast to medical applications, the entire testing process, including the testing system must be suitable for a far-reaching industrial environment and associated economic efficiency.

3. Development Status

To meet the goals outlined in 2.1 and 2.2, Fraunhofer-IZFP developed the Sampling Phased Array System (SPA) [15, 16], which, in combination with the SynFo® image reconstruction software, permits imaging with distributed apertures (TomoSAFT®).

3.1 Sampling Phased Array (SPA) Principles

The SPA system is an advancement of conventional Phased Array systems that have been in use for practical testing and evaluation since many years and is fully described in the literature [18]. The SPA system ignores the majority of the available information by signal summation via electronic phase-shifting. Thus, the phased array search unit is equivalent to conventional search units that generate a soundbeam from a selected beam angle provided that the "Sampling Therorem" principles are followed. However, the advantage phased array search unit in conventional phased array systems is limited to eletronical beam steering. If the time-domain signals are generated by a single transmitting element and received by multiple elements of the transducer array (see Figure 7) a complete information matrix, as depicted in Figure, can be obtained after the cycling of all individual transmitter elements.

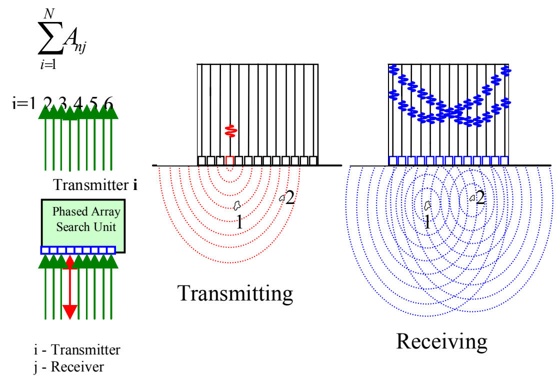


Fig. 7: Sampling Phased Array Principle

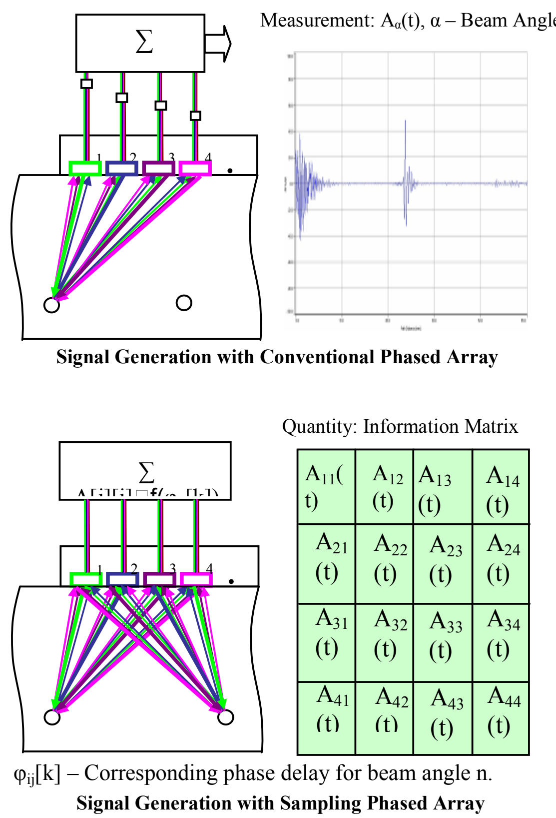
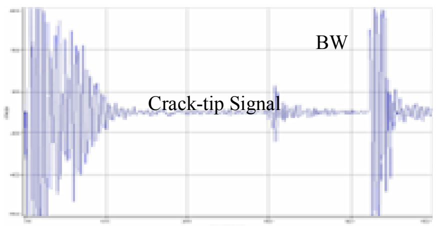


Fig. 8: Signal Generation using Conventional PA and SPA

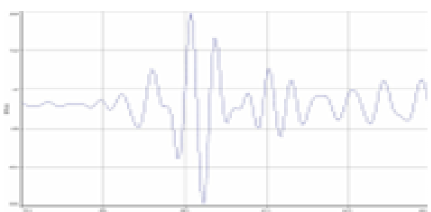
The time-domain signals can now be arbitrarily summarized, i.e. a single data set permits the computation of any beam angle and any focal point.

Figure 9 below shows the A-Scans resulting from conventional PA and SPA tests.

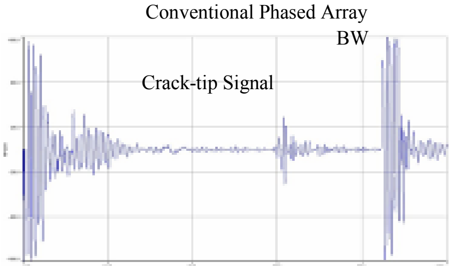
Crack-tip Detection



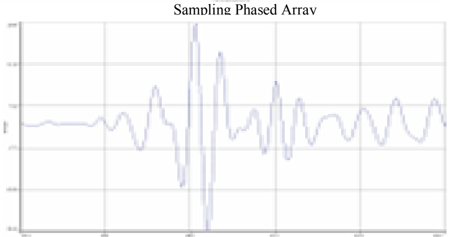
Conventional PA



Crack-tip signal (zoomed)
Conventional Phased Array



Sampling Phased Array



Crack-tip signal (zoomed)
Sampling Phased Array

Fig. 9: Crack-tip Signals conventional PA and SPA

The differences between the conventional PA and SPA scans are limited to a marginal increase of the signal-to-noise ratio when high gain settings are required

Figure 10 below demonstrates that a single transmitter element generally provides a good image with sufficient resolution. The associated signal-to-noise ratio are proportional increased by the factor √N (N = number of array elements).

This inherent shortcoming can be remedied through further enhancements, that are beyond the scope of this paper.

The current SPA technology provides a technique that permits the generation of 5KHz sector scans to compute any user-defined A-Scan with various beam angles including all code required beam angles.

Figure11 below shows an image of a crack, reconstructed from a single transmitter cycle.

3.2 Synthetic Aperture (SynFo®) – Image Reconstruction

Alternatively to the above described techniques involving beam angles computed via phase shifting, synthetic aperture

techniques can be used for sector scan image reconstruction. The SPA information matrix contains all necessary data, embedded in diagonal elements, for a conventional Synthetic Aperture Focusing analysis (SAFT), where the transducer, as an elemen of the phased array search unit, is virtually scanned along the entire phased array search unit aperture.

As mentioned before, the remaining matrix elements contain considerably more data than necessary, which are used in the SynFo® algorithm for image reconstruction.

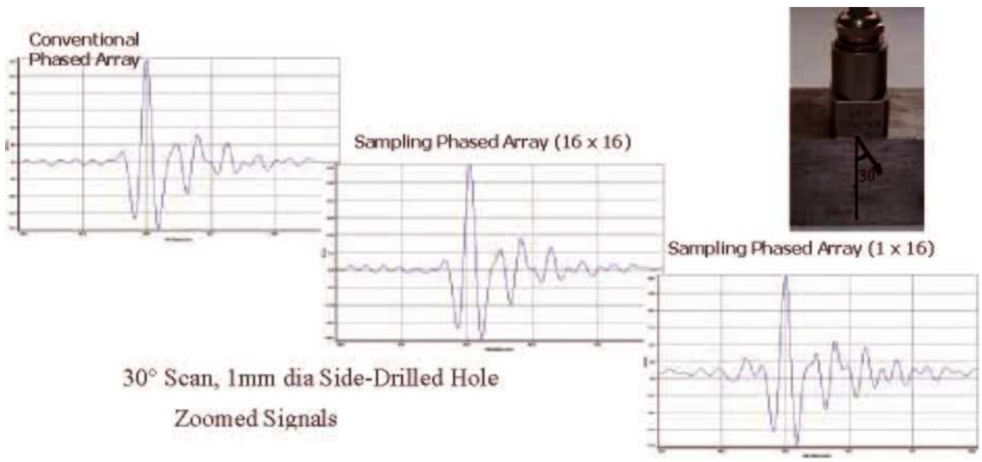


Fig. 10: A-Scan Comparison, Conventional PA vs. SPA with Complete and Partial Information Matrix

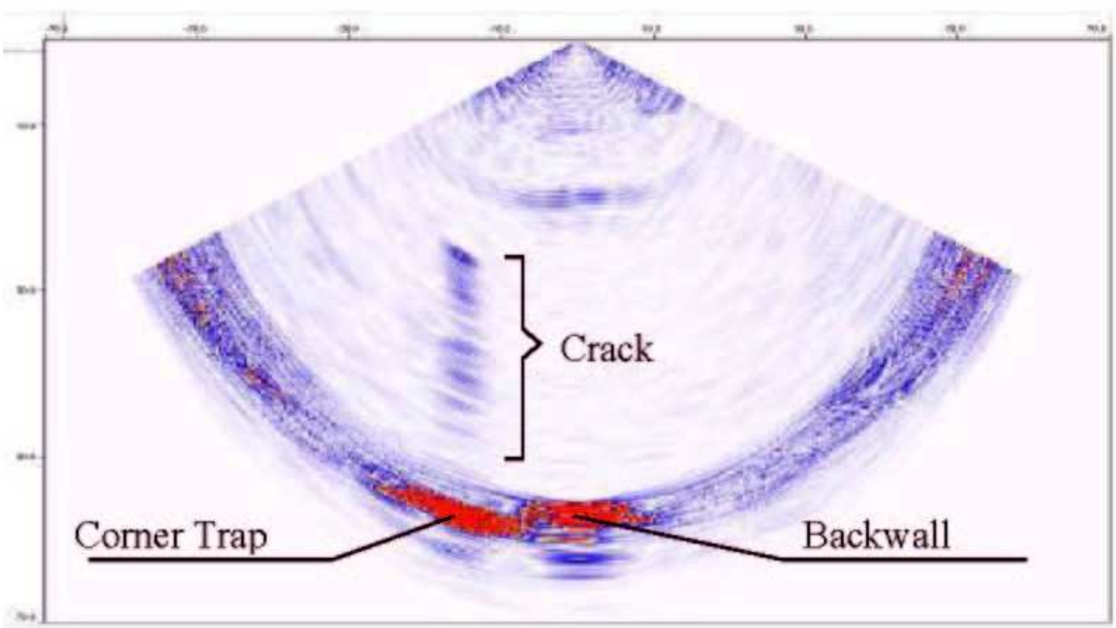


Fig. 11: Crack Image (Sector Scan)

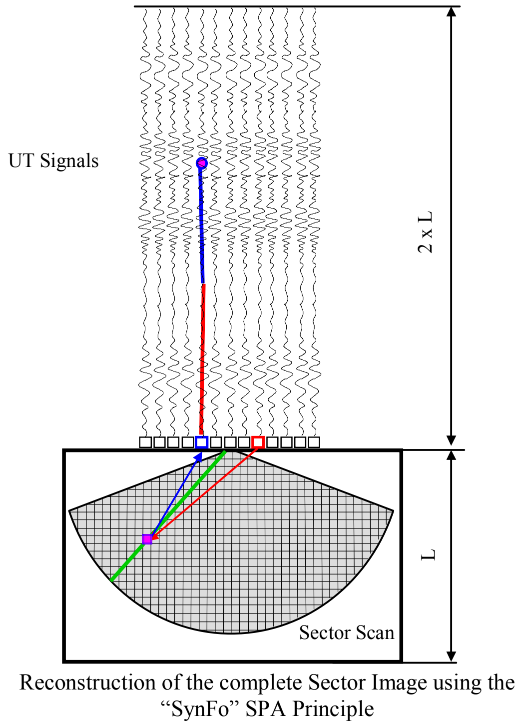


Fig. 12: Cross-section Reconstruction Using a Linear Array

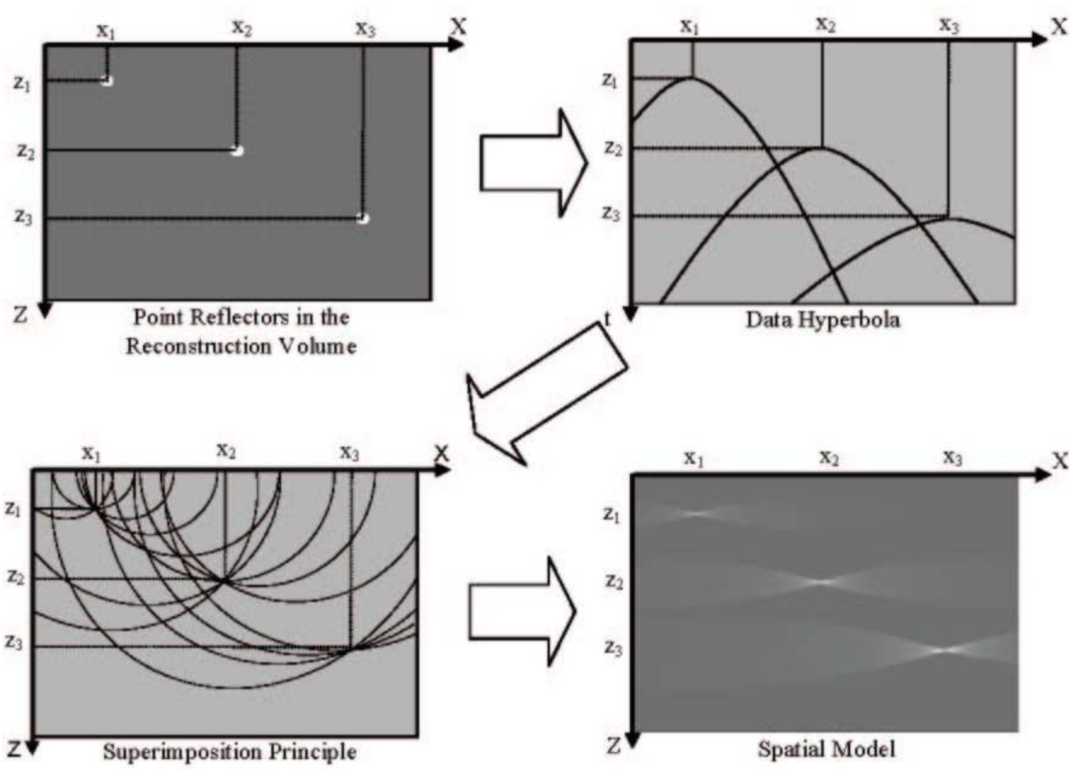


Fig.13: *SynFo*® Reconstruction Principle

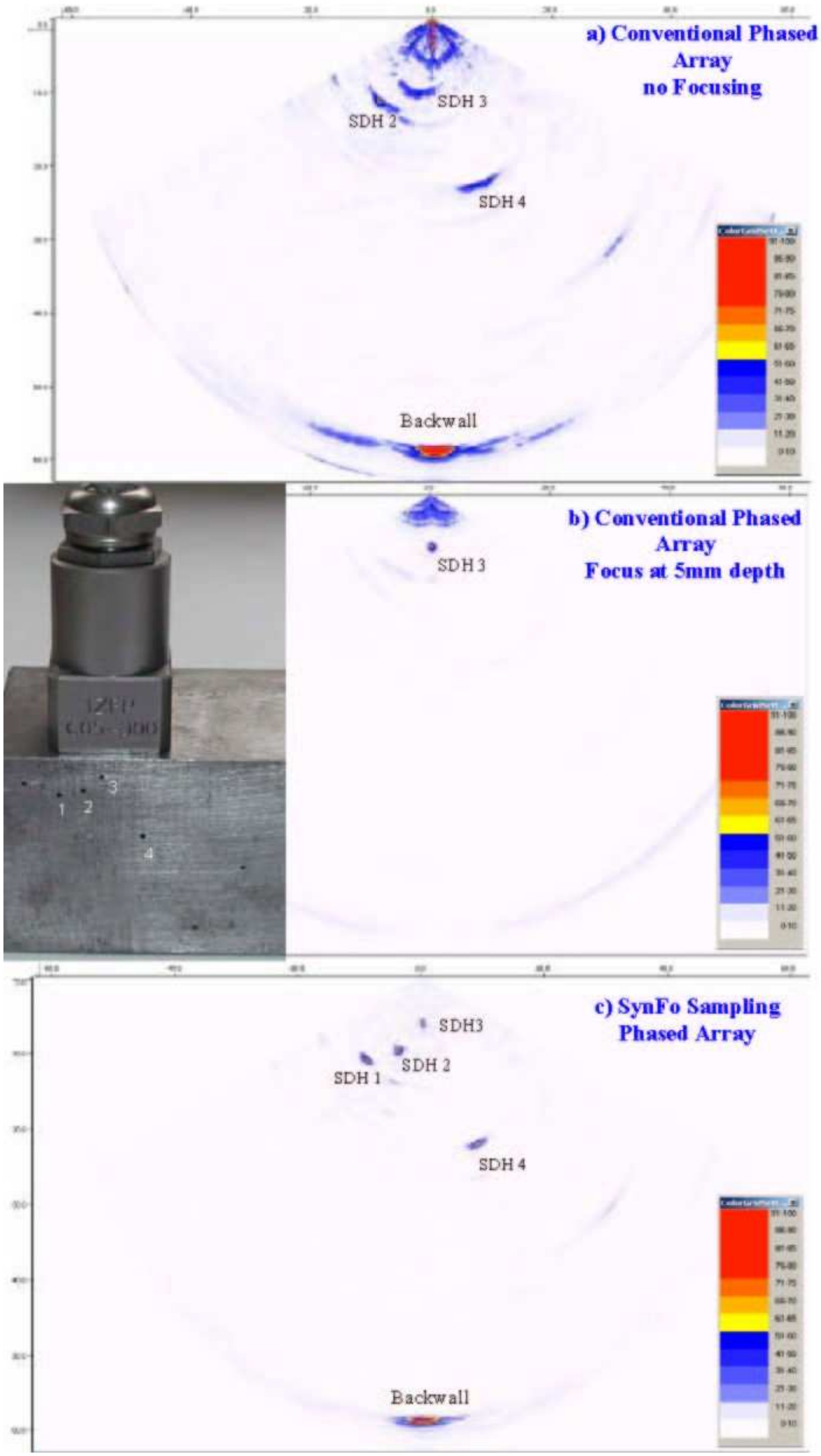


Fig. 14: Test Results: Conventional PA vs. SPA

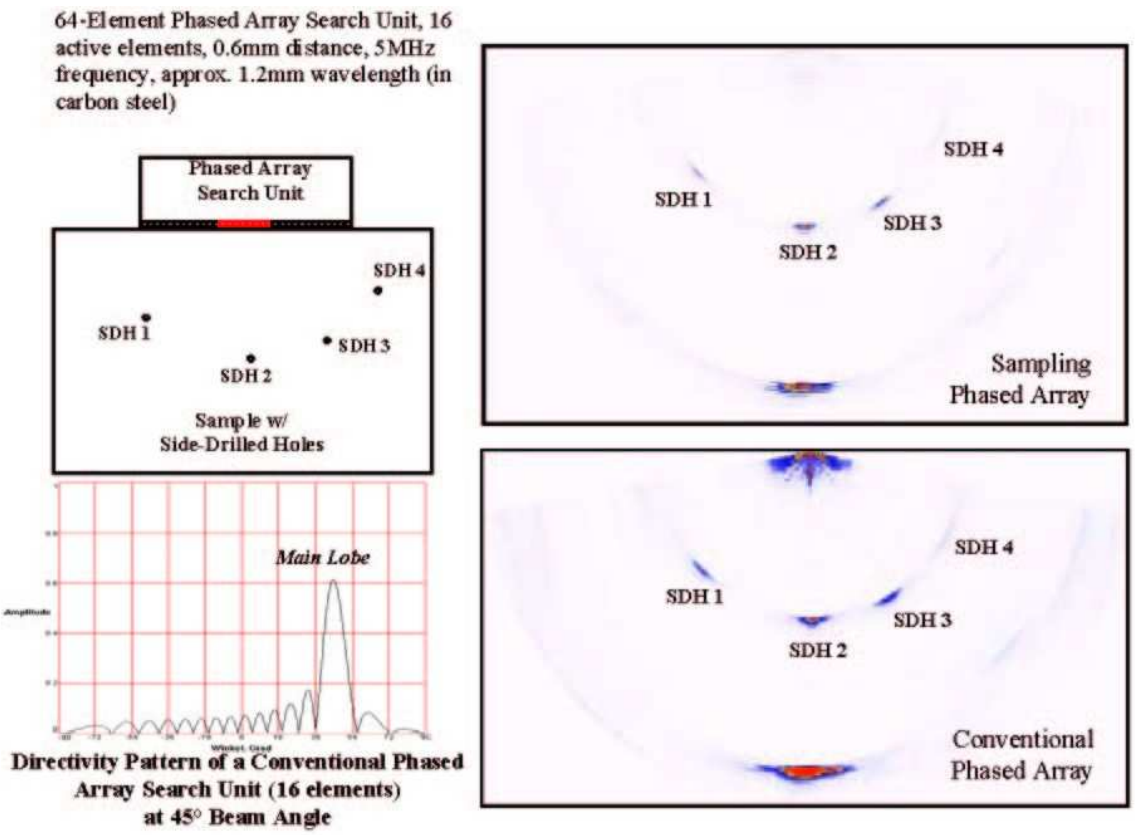


Fig.15: Comparison Considering Sampling Theorem Agreement

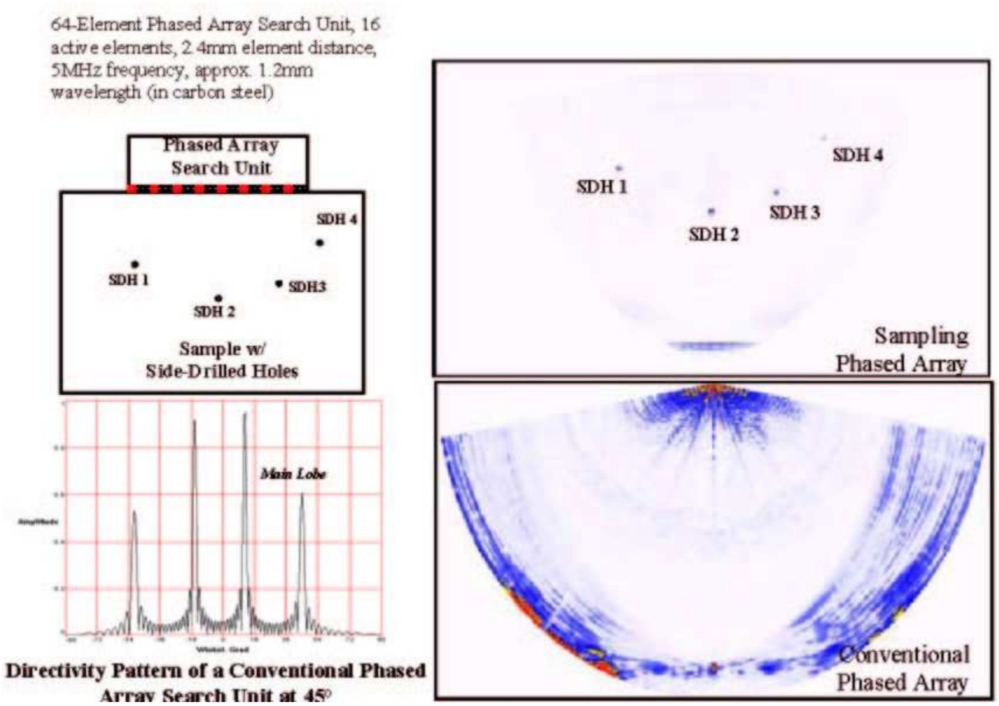


Figure 16: Comparison Considering Sampling Theorem Violation

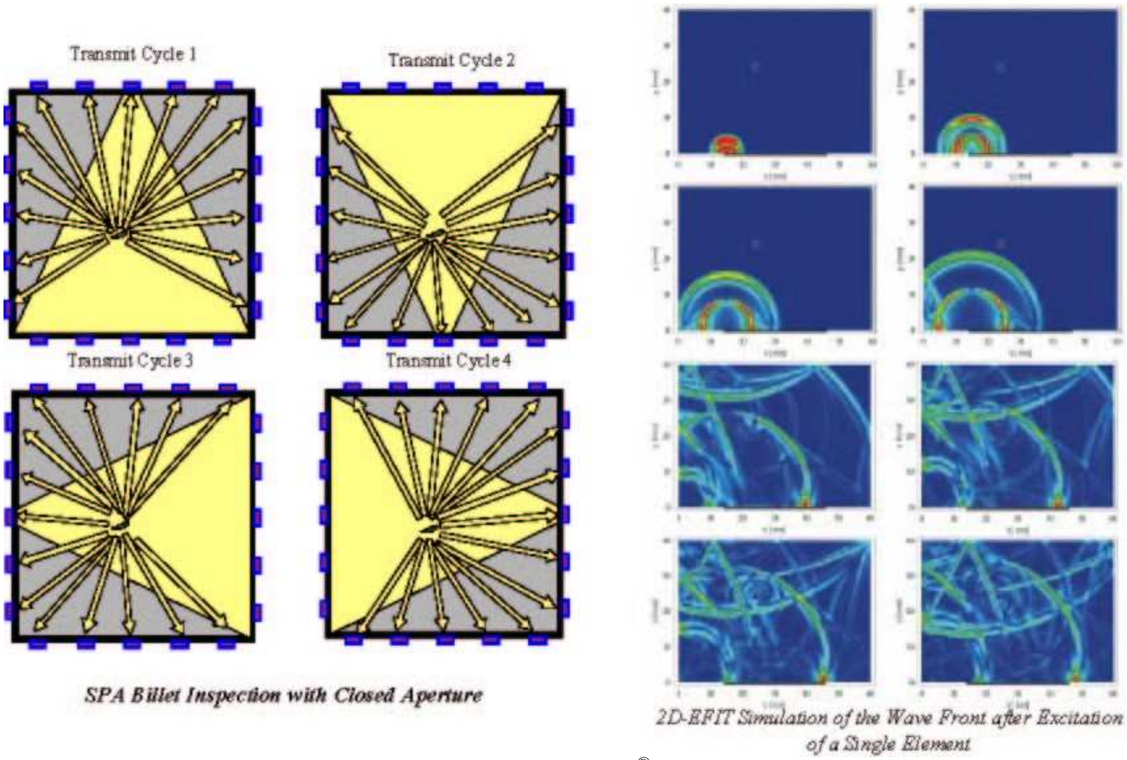


Fig. 17: Schematic Presentation of the TomoSAFT® Principle and EFIT Simulation of the Sound Wave Propagation from a Single Transducer Element

Similarily to the SAFT algorithm, the cross section, or volume for 3-D exams, under inspection is divided into pixels producing the image point, see Figure12 below. For each image point, the travel time to the individual transducer elements is computed and the time-related amplitude value is assigned. Figure 13 below illustrates the image reconstruction principle for a single pixel as a function of element location with a hyperbolic distribution of the travel time, and for image reconstruction correlated with the image point location [19].

From the results above, A-Scan images can now be reconstructed directly from computed sector scans (corresponding to the phase-reconstruction principle).

3.3 Synthetic Aperture Principle: TOMOSAFT®

The main advantage of the SynFo® algorithm results from the fact that the Sampling Theorem permits certain violations: side-lobes of a transducer array violate the Sampling Theorem, but average towards zero for SynFo® reconstruction. This advantage is implemented in the TomoSAFT® technique developed by Fraunhofer-IZFP, shown in Figures 15 and 16 below.

As a result, the aperture of the transducer array can be increased to permit focusing at larger depths without any increase in complexities of transducer arrays and ultrasonic channels

The end result is a very high image quality, as shown in Figure16. Detail image resolution is largely determined by the aperture of the transducer array. Of special interest is the definition of the backwall of the test sample.

In summary, the image quality was vastly improved and high inspection speeds are made possible at reduced system expenditures primarily caused by omitting electronic phase shifting components and the reduction in the number of required transducer array elements.

An additional requirement for this SPA technique is the use of integrated efficient algorithms and appropriate computer hardware and software architecture.

4. Future Development

The current SPA system serves as a development platform and can instantly be modified for custom-tailored applications.

Currently, work is progressing on the optimization for the distributed aperture to be used on large turbine shafts.

Follow-on development includes the system qualification for primary codes, standards, rules and regulations, e.g. Druckbehälterverordnung, TRB (Rules & regulations for pressurized components and containers).

In addition, and of practical importance, is the development of a simulation software package for determining optimal distributed apertures (Figure17). It is conceivable that meaningful engineering rules for future test procedures will soon be developed.

This technology has the potential for a quantification of material discontinuities via the directional dependency of the scattered sound field. Corresponding approaches are currently being formulated

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