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Real-Time Quantitative Ultrasonic Inspection

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Abstract

Most frequently applied ultrasonic inspection techniques measure the reflectivity of geometric scatterers that are caused by impurities, flaws and defects in the material. Based on the echo sounder principles, the reflector has to be insonified by directed sound pulses. This requires a large number of transducers with different incident angles and sound field patterns, which are more and more replaced by phased array sensors. Phased array inspection systems can control the insonification direction and the focus of the applied sound field, but they do not alter the principles of multi-angle and multi-focus inspection; the resulting scanning speed limitation is obvious. In addition, flaw imaging only displays the position and amplitude height of the reflection and does not provide an image of the actual shape of the reflector. Thus, the evaluation of state-of-the-art ultrasonic imaging is based on the extension and maximum amplitude of the identified reflector applied to specified reference reflectors. A more quantitative assessment of the findings requires human or future artificial expert knowledge.
We have developed a new concept for real-time quantitative ultrasonic imaging at high speed scanning. The “Sampling Phased Array” ultrasonic system and the use of distributed apertures based on “SynFoc” algorithms permit imaging of reflectors independent from the insonification direction. Only one insonification is required to image the cross section (Sector Scan or B-Scan) with an arbitrary number of virtual incidence angles at repetition rates of up to 6 kHz. Due to the virtual coverage of all incidence angles and the simultaneous focusing of each image pixel using the synthetic aperture algorithms (SynFoc), the real-time 3-D result presentations approach today’s demands for quantitative defect imaging.
We have planned to integrate the interaction of the sound field with structured geometric scatterers, including mode conversion phenomena, for example. We are

confident that we will be able to display the actual geometry of a flaw or defect isolated from its scattering properties.

Keywords: Quantitative NDT, Ultrasonic Imaging, Sampling Phased Array, Distributed apertures, Efficient Computing

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 Figure 1).

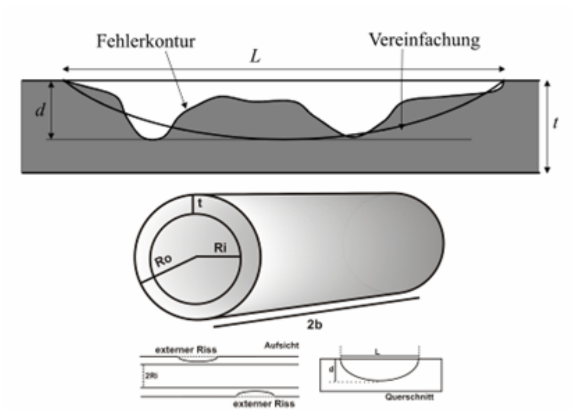

Figure 1. Correlation of an Actual Flaw with a Modeled Flaw

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.

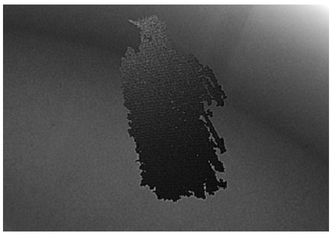

Figure 2. 3-D Image of a Transverse Crack

- 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].

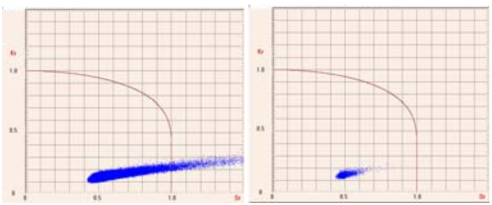

Figure 3. FAD-Diagram without (left) and with (right) NDT data input

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.

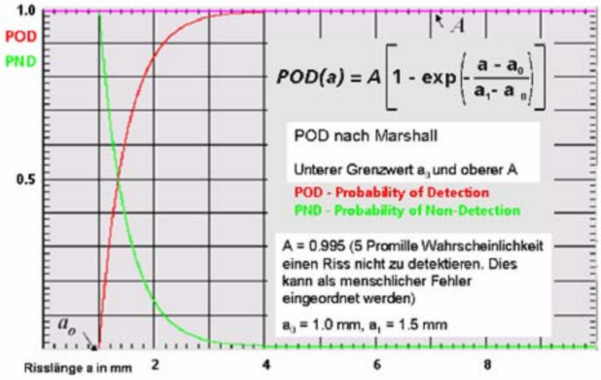

Figure 4. Flaw Detection Probability Function (W. Marshall)

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.

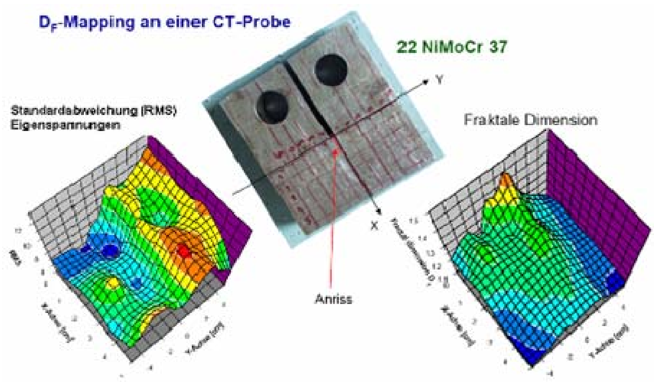

Figure 5. Comparison of Residual Stress to Fractal Dimensions in a Fatigue State

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).

Figure 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.

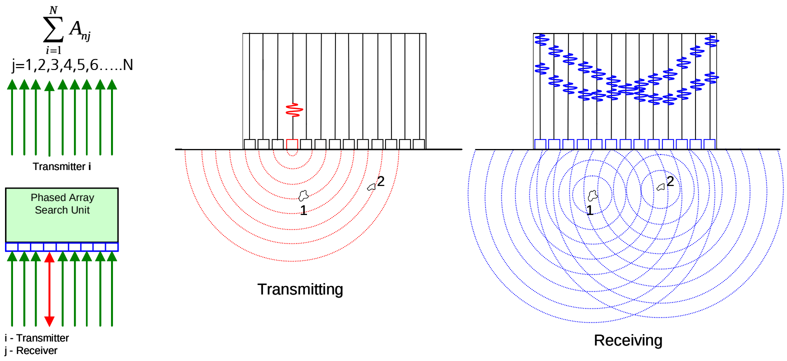

Figure 7. Sampling Phased Array Principle

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.

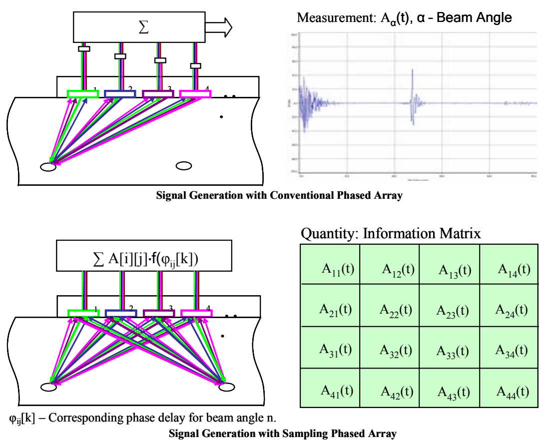

Figure 8. Signal Generation using Conventional PA and SPA

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.

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 8, can be obtained after the cycling of all individual transmitter elements.

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

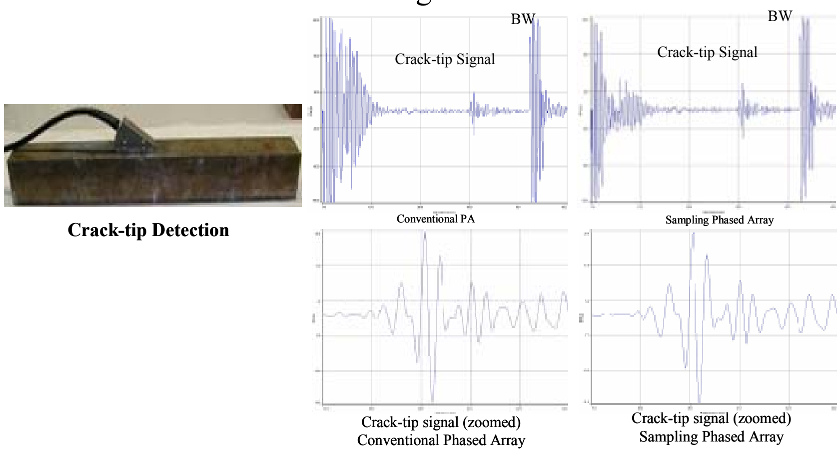

Figure 9. Crack-tip Signals conventional PA and SPA

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 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).

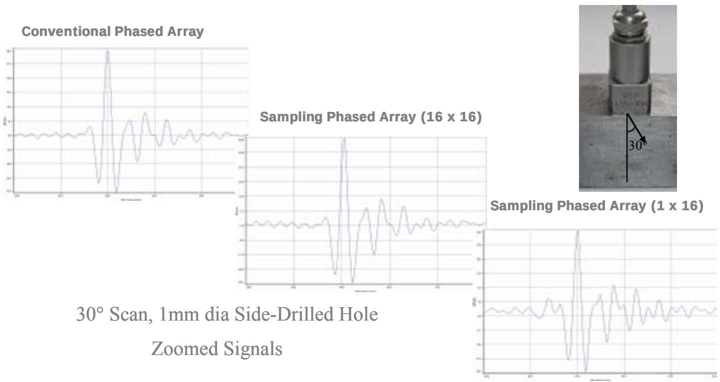

Figure 10. A-Scan Comparison, Conventional PA vs. SPA with Complete and Partial Information Matrix

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.

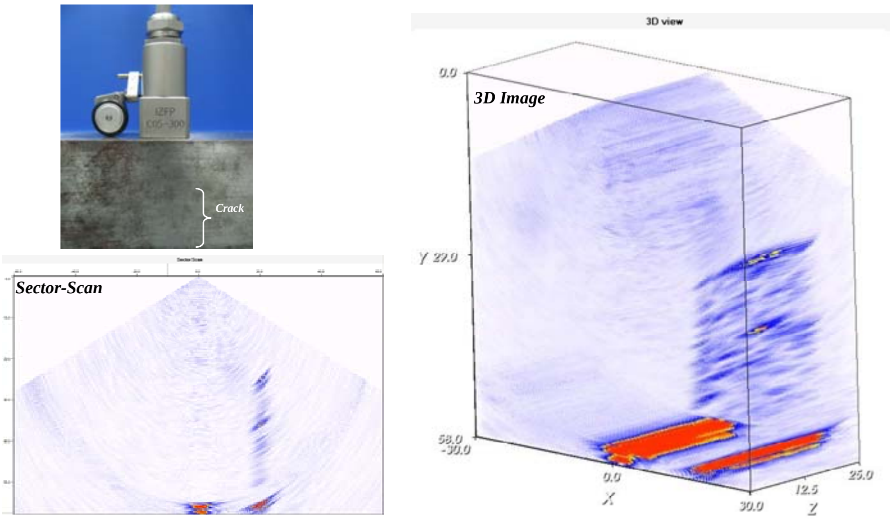

Figure 11. Crack Image

Figure 11 shows an image of a crack, reconstructed from a single transmitter cycle (Sector-Scan) and from a scan along the crack (3D-View).

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.

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 Figure 12 below. For each image point, the travel time to the individual transducer elements is computed and the time-related amplitude value is assigned.

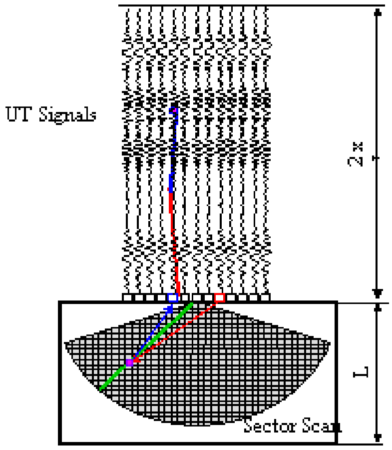

Figure 12. "SynFo" SPA Reconstruction of Cross-section Image Using a Linear Array

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].

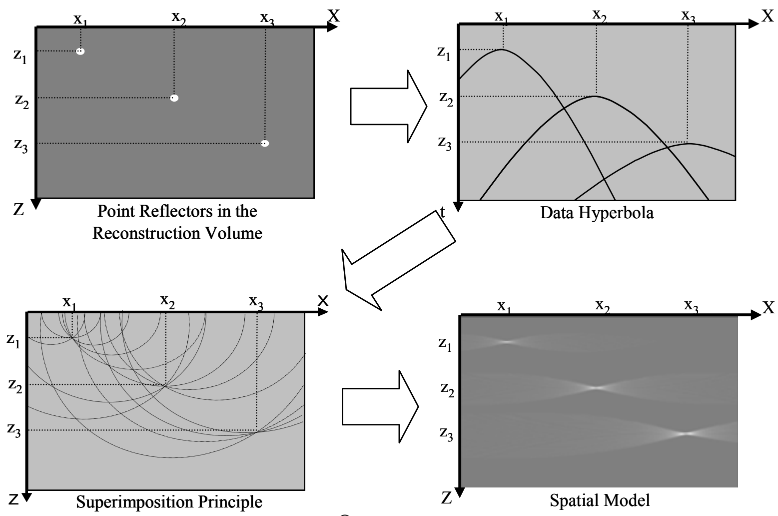

Figure13. *SynFoc*® Reconstruction Principle

The advantage of this technique, utilizing all time-domain signals AiJ(t), lies in the automatic focusing of every image point and almost total elimination of the near-surface "Dead Zone", as shown in Figure 14 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.

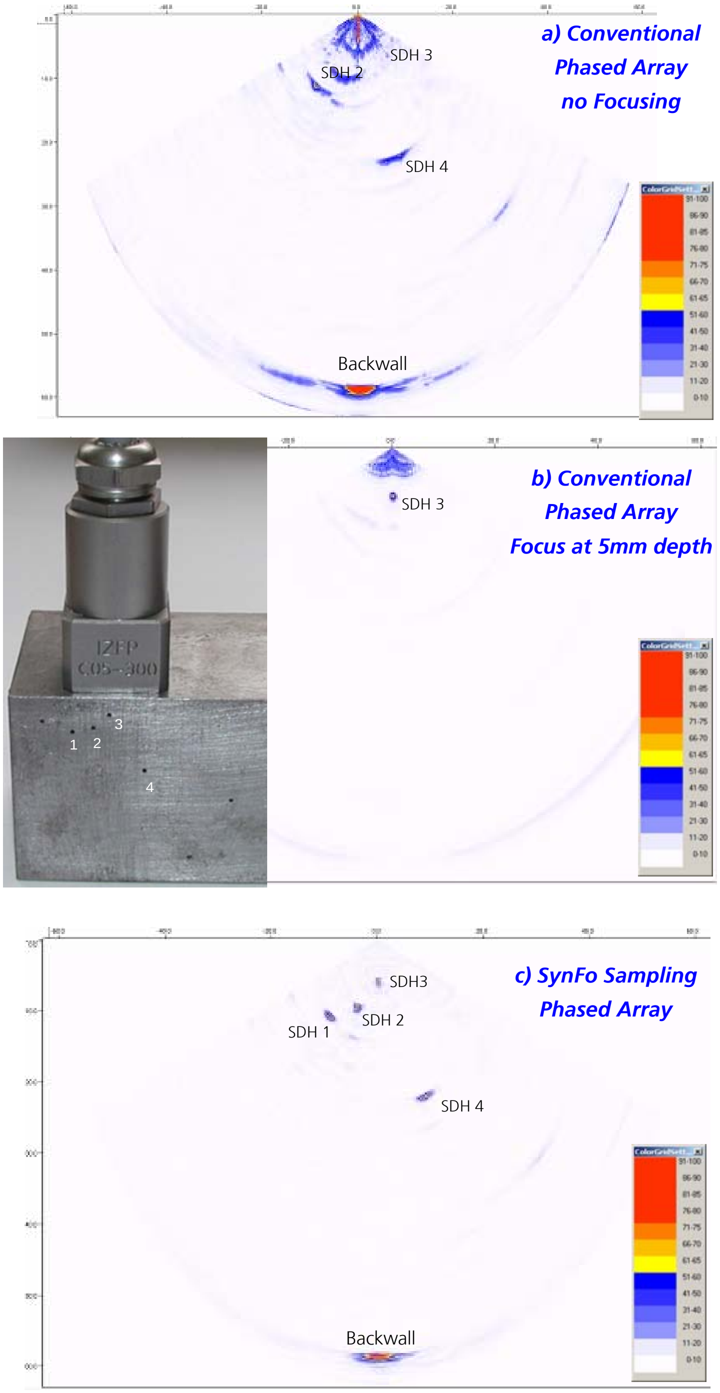

Figure14. Test Results: Conventional PA vs. SPA

The end result is a very high image quality, as shown in Figure 15. 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.

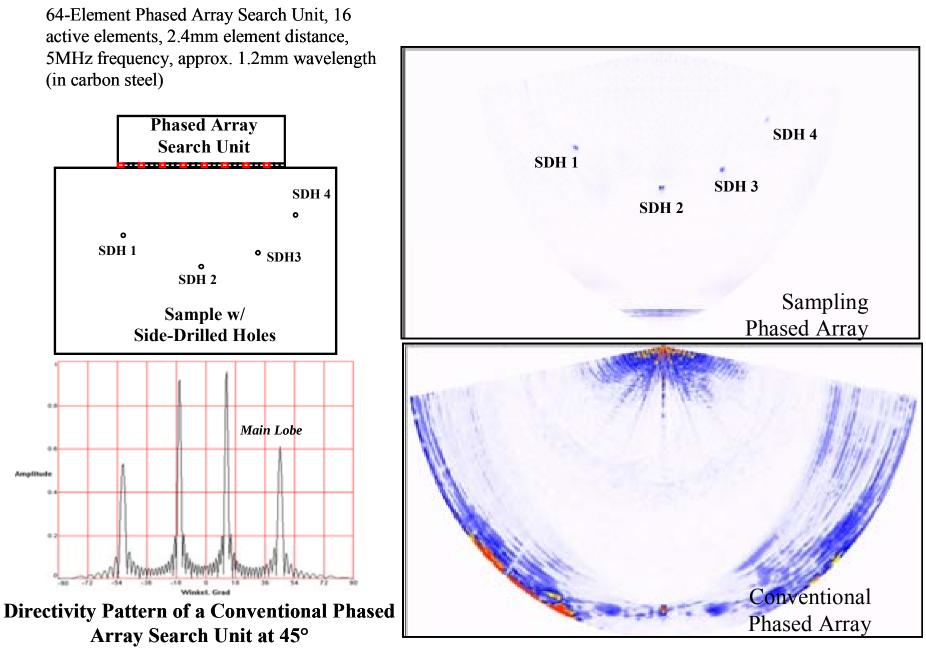

Figure 15. Comparison Considering Sampling Theorem Violation

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.

5. Ultrasonic development platform

An innovative ultrasonic development platform was developed in the Fraunhofer-Institute for non-destructive testing, which realizes the above techniques of sampling phased array and conventional phased array This platform can be used for conventional multi-channel inspection systems and also with single element probes.

The ultrasonic development platform "Sampling Phased Array" consists of following modules (Figure 16):

1. Ultrasonic Front-End electronic module μ-USE
2. Computation module (CM)
3. CM-Interface (optical transceiver)
4. Coordinate interface
5. Master-PC for integration of computation modules
6. Application software

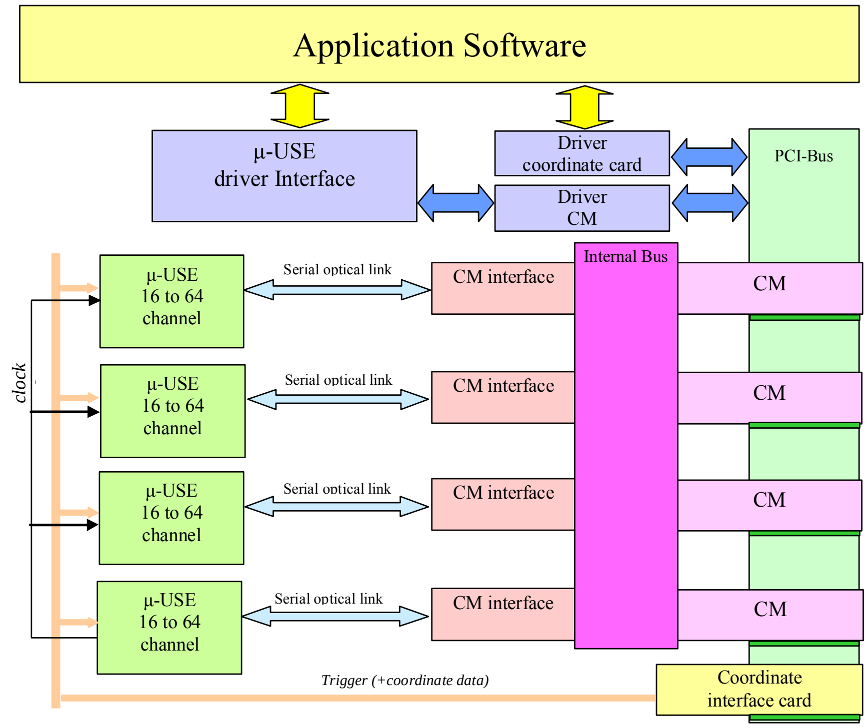

Figure 16. Ultrasonic development platform µ-USE

Ultrasonic Front-End unit µ-USE is a 16- to 64-channel module with parallel structure. This uses modern microelectronics and is very compact in design (Figure 17).

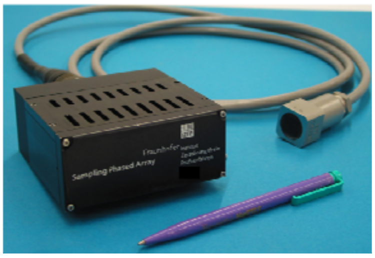

Figure 17. 16-channel ultrasonic front-end module µ-USE

Another version of Front-End electronic module µ-USE has FireWire data interface instead of optical data link and can be directly connected to PC. In this case the signal processing and image reconstruction is performed on Central Processor Unit (CPU) of PC or on Graphical Processor Unit (GPU).

6. Efficient computing

US-Frontend is capable to provide the measured data at a very high speed. The peak data transfer rate of the FireWire interface is 400 Mbit/s. In case of the fiber channel (FC) the rate reaches almost 2Gbit/s. Indeed, such a fast data transaction rate creates an opportunity for extremely fast imaging based on SinFoc reconstruction technique.

The amount of data provided by the US-Frontend is a very "bottle neck" for data interfaces implemented in common PCs. Unfortunately, the inspection system, which incorporates data transaction through PCI to CPU and RAM can not be considered as a real-time one.

Moreover, a huge amount of the input data to be processed under SinFoc assumptions requires a rapid single access to RAM. This forces common PCs to perform rather as sequential machines so that a real-time testing becomes impossible.

In order to overcome a real-time problem two solutions are under consideration. The first is FPGA based platform with parallel architecture. The second solution is based on Graphic Processor Units (GPU).

6.1 FPGA implementation

In order to perform real-time processing of a number of SynFoc A-Scans from ultrasonic data the special hardware architecture was developed. A flow chart of the architecture is represented in Figure 18. This architecture is implemented in FPGA platform.

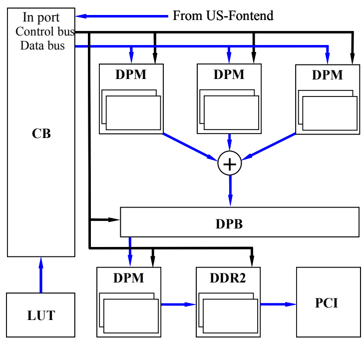

Figure 18. FPGA hardware architecture

The architecture contains several blocks such as control block (CB), dual port memory (DPM), data processing block (DPB), look-up table container (LUT), DDR2 memory and PCI interface. The input port of the CB is physically connected to the output data port of the front-end electronic. The CB reorganizes the input data flow so that data from each channel are saved separately in DPMs. A DPM is the two-page cash which supports read and write operations simultaneously. As soon as the first pages in DPMs are full the reconstruction starts. While the reconstruction is being performed the second page of DPMs is written. If the first page is exhausted the CB switches DPMs' on the second page simultaneously writing in to the first page.

By using LUT the CB reads 16-bit values from each channel (i.e. corresponding DPM). This allows reconstruction of one sample of the output data per one clock (200 MHz). The reconstructed sample is forwarded toward DPB. The DPB applies required in-stream data processing with the lowest latency. It also compresses the output data by filtering out irrelevant information.

After DPB data are saved in the intermediate cash (also DPM). This DPM is used to prepare data for block DDR2 transactions at the speed up to 400 Mbit/s. Afterwards, data are transferred to the host by the user request through PCI by means of DMA channel.

The architecture given in Figure 18 allows fast ultrasound NDT based on SynFoc technique. In dependency on the data length the testing can be done with a frequency up to 5KHz.

6.2 GPU implementation

Modern GPU are extremely complex and powerful devices. A multi-processor architecture of GPU is originally developed to support fast texture and image processing. The unique processor greed and optimal interconnection between shared and local memory allow splitting the task on to independent parallel-executed paths. Extremely high clock frequencies reduce time of RAM access in comparison with PCs and FPGAs.

Generally, GPU can not be considered as a truly real-time system because data transfer between GPU and any external device goes through PCI–like interface. However, as soon as the GPU receives data the reconstruction can be done extremely fast. Thus, by using GPU it is possible to compute not just a number of A-scans but Sector-scans.

In dependency on the data length the testing by using Sector-scans can be done with a frequency up to 1000 frames per second.

7. 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 (Figure19). It is conceivable that meaningful engineering rules for future test procedures will soon be developed.

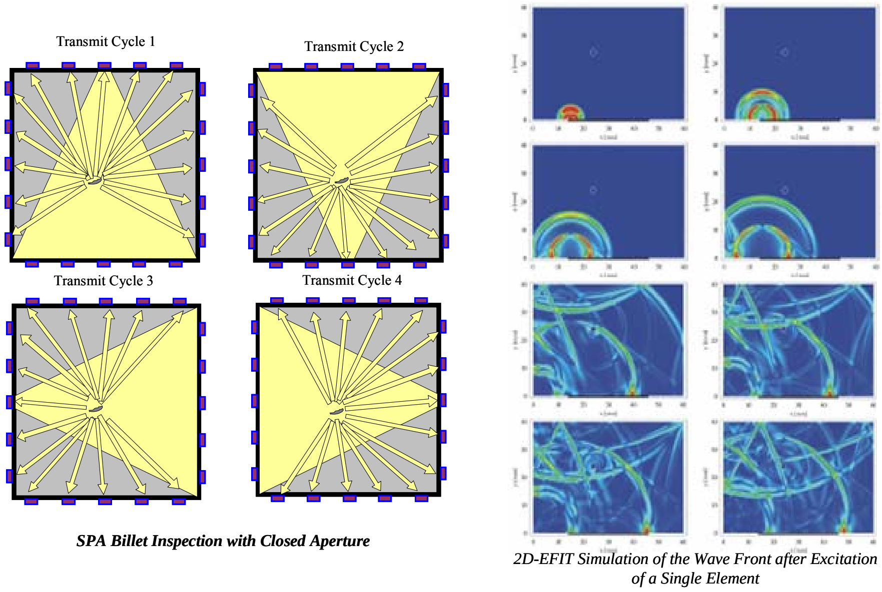

Figure 19. Schematic Presentation of the TomoSAFT® Principle and EFIT Simulation of the Sound Wave Propagation from a Single Transducer Element

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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