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SAMPLING PHASED ARRAY, A NEW TECHNIQUE FOR ULTRASONIC SIGNAL PROCESSING AND IMAGING NOW AVAILABLE TO INDUSTRY

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ABSTRACT

Over the past 10 years the improvement in the field of microelectronics and computer engineering has led to significant advances in ultrasonic signal processing and image construction techniques that are currently being applied to non-destructive material evaluation.

A new phased array technique, called “Sampling Phased Array” has been developed in the Fraunhofer Institute for non-destructive testing [1]. It realizes a unique approach of measurement and processing of ultrasonic signals.

The sampling phased array principle makes use of the measurement of elementary waves generated by individual elements of a sensor array to reconstruct the composite phased array signal for any arbitrary angle or focus depth.

The use of special signal processing and image reconstruction algorithms, allows generating A-Scans of several angles and / or Sector-Scans, which can be implemented in real time. With parallel computing structures, this principle is used for automatic testing systems at very high inspection speed.

A comparative study was done with Conventional Phased Array and the Sampling Phased Array technique. The study shows that the signal characteristics in both techniques are equal. In addition, the Sampling Phased Array technique is significantly beneficial in many aspects like quality of information in specific cases, inspection speeds and adaptability to specific inspection tasks in comparison to conventional Phased Array.

The development results, including relevant test methodology and equipment aspects are presented in the current work, together with the benefits for industrial ultrasonic inspection.

The electronics required to enable the application of Sampling Phased Array, was, in the first instance created as a development platform for high speed automated ultrasonic inspection systems. This came from the requirement to speed up the inspection of manufacturing testing and of course the testing of critical components.

Sonovation have now adapted Sampling Phased Array in their data acuistion and display equipment line, “Sonovision”.

HISTORY

Over the past 40 years the inspection of items using manually applied pulse echo techniques has gradually improved with the advances in equipment, codes and standards and training. During this time the inspection technician has dreamt of systems that remove the uncertainty and subjectivity of his profession.

Let us go back to those days and look at the task for the poor operator who for instance, is commissioned to sentence the quality of a weld in a newly fabricated vessel. Working with equipment with relatively unknown performance, transducers which may have been inadequately certified, and procedures which were not fit for purpose.

This made repeatable inspections very difficult, sizing of flaws often based on flaw amplitude, and subjective sizing methods.

Reporting was not formalised and often not understood by the end client. These factors led to a lack of confidence in the method within industry..

COMPUTERS TO THE RESCUE

The general availability of portable electronics and computing power have lead to automation of many of the tasks of the UT technician and, where possible, to supply him with the information needed to justify his decision on the position, size and acceptability of a flaw taking away the subjectivity and uncertainly he has always encountered.

Where in the past the technician would make his calculations by hand, later with a pocket calculator, this is now carried out by the microprocessor build into his flaw detector. Calibrations are also in the system and therefore he will not have to completely calibrate, but merely check differences against data stored.

All of this is very helpful, but the fundamental principles still remain the same: we are still assuming sound beams to be travelling along straight lines at an angle determined by the angle of the probe used. More importantly we still assume that the reflectivity of a flaw gives us information on reporting level and indeed size, which still are the basis of acceptance of flaws for pulse echo ultrasonic examination.

PHASED ARRAY TECHNOLOGY

Over the past years, many companies have introduced systems making use of Phased Array technology.

Phased Array holds the promise of being able to efficiently detect all significant flaws by combining many angles and focus depths into one probe and image the resulting reflections in an understandable way. Nevertheless, a few stumbling blocks are still prevalent. Codes and Standards that uniformally prescribe how to set up the equipment are not yet freely available. Flaw acceptance still requires the comparison of flaw reflections represented as an A-scan to the A-scan of a known artificial reflector such as a side drilled or flat bottomed hole, or a spark eroded notch.

Phased Array training courses for operators usually address general principles and only few examples of real applications. One of the major pitfalls often ommitted during training and in practice, is the actual coverage of Phased Arrays. It is easily to say that a sector scan will detect all defects in a material as it passes through a large range of probe angles. Although a high probability of detection can be achieved, certainly a lot higher than manual UT, it is by no means guaranteed that all defects will be detected. The resolution in terms of the step width between angles and the focus depth range are of major importance to detect defects and discriminate between adjacent flaws. The angle at which an ultrasonic reflector is detected, is not only dependant upon the angle of incidence of the transducer array, but is also dependant upon the position of the transducer relative to the weld axis. When these parameters are not adequately addressed, these factors can seriously affect the degree of success of Phased Array inspection.

TIME OF FLIGHT DIFFRACTION

Time Of Flight Diffraction (TOFD) has been proven to be many times more accurate in its ability to size defects than Pulse Echo and Pulse Echo based techniques during a large range of well documented round robin exercises. As TOFD also has an excellent Probability Of Detection (POD), TOFD is now accepted as a fast and reliable alternative for radiography during manufacture of pressure equipment. No technique in the world has all the answers and no limitations, and TOFD is no exception. The methods limited ability to detect and size flaws in the near surface zone is a real restriction in many cases for the application of TOFD as a stand alone technique.

For those of us who have grown up with Pulse Echo, thinking in wave patterns and diffractions combined with reflected signals TOFD is not so easily understood. This has in many cases lead to beliefs and misunderstandings which have hindered an even faster and wider spread introduction for TOFD in modern day industry, of which the perception that restricted detection and sizing ability in the far surface region is unique to TOFD is an example.

For both present day Phased Array and TOFD, there still is little acceptance that the modern day operator of advanced UT systems is, or at least should, be a educated and trained professional engineer with a much higher level thought process and interpretation skills than the manual UT operator of yesteryear.

SAMPLING PHASED ARRAY PRINCIPLE

In the conventional phased array technique electronic control of beam angles and focal depth drastically decreases the number of required inspection sensors and therefore significantly reduces the mechanical complexity and the handling of an ultrasonic testing system. To achieve the expected high Probability of Detection (POD) whilst covering an entire cross section, the quality of Sector-Scan images needs to be improved. This necessitates the increase of the number of beam (scan) angles and focal depths and in doing this the overall inspection time is increased, which may become impractical.

In contrast with conventional Phased Array, the same can be achieved in sampling phased array with a single insonification (single shot). The returning ultrasonic echo signals from a single shot by one transducer element are captured by every one of the transducer elements. (Figure 1) This forms the basis of the sampling phased array technology. The signals received are used to reconstruct A-scans for one or more arbitrary angles and/or focus depths. The reconstruction is greatly enhanced through the use of SynFo, a build in software algorithm which eliminate noise and enhances sensitivity. Whether signals emerge from diffractions of reflections is of no concern; both are taken into account.

A detailed analysis of the time-domain aperture information [4] from the individual transducer elements reveals that often time signals disappear due to the phase-controlled generation and summation of these signals. Fast data acquisition, data storage and data processing capabilities permit the analysis of individual time-signals received from the information matrix of the Phased Array.

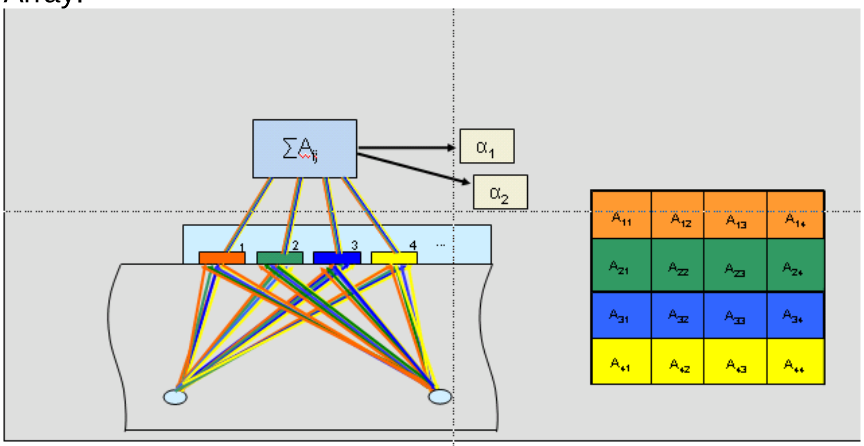


Figure 1: Information matrix of a 4-element Phased Array Search Unit

This can be achieved if only one transducer element is programmed to transmit the sound into the material and all other elements are set to receive and store all returned signals. For example, in Figure 1, if the i-* element is transmitting, it is equivalent to elements Aij (t) with j = 1…N of the information matrix (i = transmitting element, j = receiving element, N = number of element in a linear Phased Array search unit).
A complete information matrix can be obtained when this process (pulse cycle) is repeated for all elements (i).

By virtue of the reciprocity of transmitter and receiver, Aij equals Aji (Aij = Aji).
The diagonal elements Aii (i = 1, N) correspond to the information from element "i", scanning the entire search unit aperture similar to the image reconstruction based on the SAFT (Synthetic Aperture Focusing Technique) principle [5]. Of particular interest is the fact that each individual transmission row (i) in the information matrix contains the entire array of all transducer elements of the selected receiving group. Irrespective of sound field interactions with potentially strong interference signals, a single information matrix row contains all essential information required to produce a reconstructed image. In other words, a single transmission cycle can provide a complete reconstructed image. Signal to noise ratio issues and the detection of planar flaws with distinct directivity patterns can be avoided due to the simultaneous transmission of all elements combined into a virtual point source or linear source [6, 7, 8]. This approach allows a complete sector-scan reconstruction with any scan (beam) angle and at arbitrary focal points for

each transmission cycle. Suitable real-time signal processing methods are available today for integrated highly-efficient parallel computing [9].

UT Data Reconstruction

Virtual A-Scan presentations can be produced from the time-signals (Aij) by considering relevant phase relationships. From the physical perspective the computed A-Scans should be equivalent to conventionally produced A-Scans assuming that the discontinuity is not insonified by a unidirectional sound beam. The complete sound field is virtually composed by the processor and not the conventional way (analog) when collected from individual transducer element wave portions. The presence of heavy non-linear test conditions would impose a limitation to this technique.

The reconstruction capability of A-Scan images is of utmost importance for the Sampling Phased Array technique to comply with existing Codes, Standards and Regulations for NDT.

B-Scan, C-Scan and Sector-Scan images can be produced in an almost the same way as in conventional Phased Array from any of the acquired A-Scans with various scan (beam) angles and individually selectable focal length.

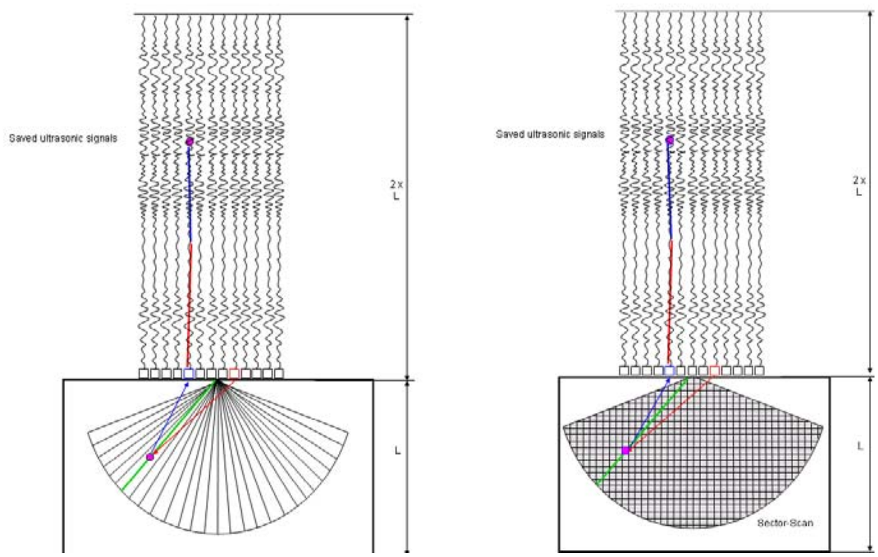


Figure 2: Options for UT image reconstruction

In principle, the SPA technique permits the development of data reconstruction techniques superior to what is state-of-the-art today. One of the limitless possibilities is the application of the synthetic aperture, a consideration that particularly applies to the expansion of the information matrix (Aij) during search unit scanning to achieve larger group-apertures and associated testing benefits.

The integration of SAFT algorithms results in the SynFo-Sampling Phased Array system allowing real-time reconstruction of Sector-Scans with automatic focusing to each pixel of the image within the physical boundaries (near field).

A real-time solution is given by using the Kirchhoff Algorithm, known from seismic applications [10].
Figure 2 depicts the key difference between reconstruction techniques; both techniques can produce all conventional types of ultrasonic images.

Technology Validation
Until codes and standards become available that allow acceptance of defects based upon images, it is essential for the practical application of this technique to provide documented evidence that virtual A-Scans are equivalent to conventionally acquired A-Scans. This would validate the SPA technique and enable the application of current rules and test standards.
A-Scan images of various reflector types acquired using conventional techniques were compared to virtual A-Scans in order to demonstrate their equivalence [7]. Figure 3 depicts A-Scans from a 1mm diameter side-drilled hole (SDH). Both signal images are equal in every detail, including the acoustic noise when utilizing the complete information matrix.

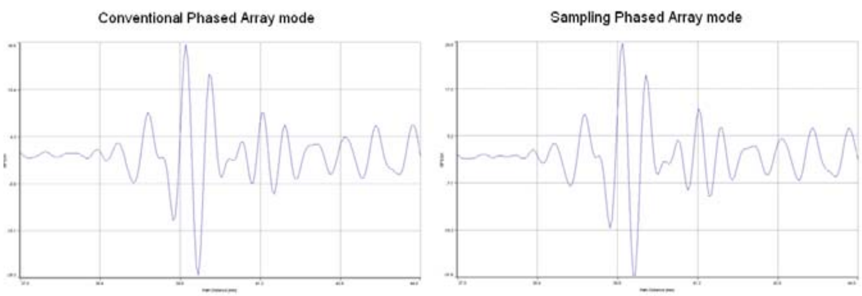


Figure 3: Equivalence of conventional and Sampling Phased Array

SPA ADVANTAGES
The SynFo-Sampling Phased Array technique offers a variety of technical advantages; some of which are discussed below.
For almost all practical applications faster inspection time is vitally important. The example below describes the potential for accelerated inspection frequency attributable to the SPA technique.
Where five scan (beam) angles are required, the SynFo technique is capable of collecting all data in a single scan cycle and can evaluate the data in real-time, leading to time savings by a factor of five. For a quantitative ultrasonic image reconstruction, e.g. a Sector-Scan image, the time savings can improve by a factor of up to one hundred and more depending on the angular resolution required.

An additional advantage is provided by the fact that the SPA technique principally employs the transmitter-receiver mode, where the dead-zone (or near-surface) in the test material is significantly reduced. Additionally, the virtual sound field displays all reflectors with optimized focusing. This benefit makes certain special ultrasound techniques unnecessary, e.g. creeping waves for near surface flaw detection and evaluation (see Figure 4).

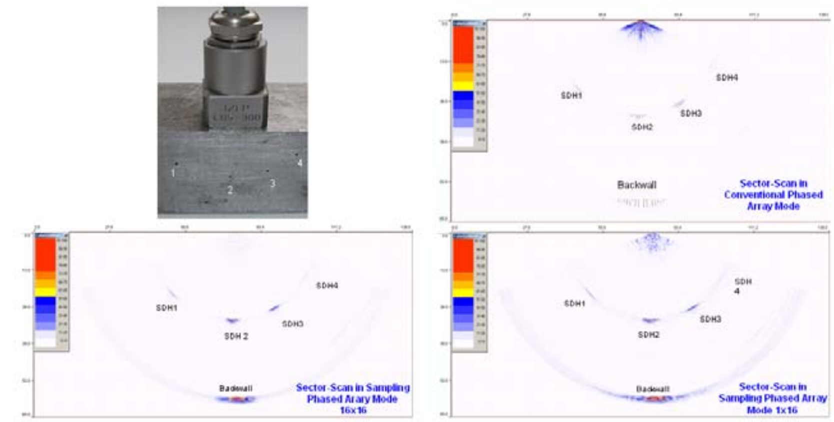


Figure 4: Near Field data of conventional Phased Array versus Sampling Phased Array

NEW SOLUTIONS TO EXISTING TESTING PROBLEMS

Besides the improvement of test speed with concurrent quantitative ultrasonic images, Sampling Phased Array provides innovative testing solutions that cannot be achieved with existing conventional techniques. Three examples are discussed below.

Quantitative Imaging in High-Speed Steel Section UT inspection

The deployment of conventional Phased Array systems for high-speed product line-integrated industrial applications, e.g. testing of steel bars and billets, is limited to processes with relatively long cycle times. The Sampling Phased Array technology allows that all scan (beam) angles are activated and processed simultaneously in one single scan cycle. This means that the SPA technique significantly improves the information content of ultrasonic test results at very high speeds.

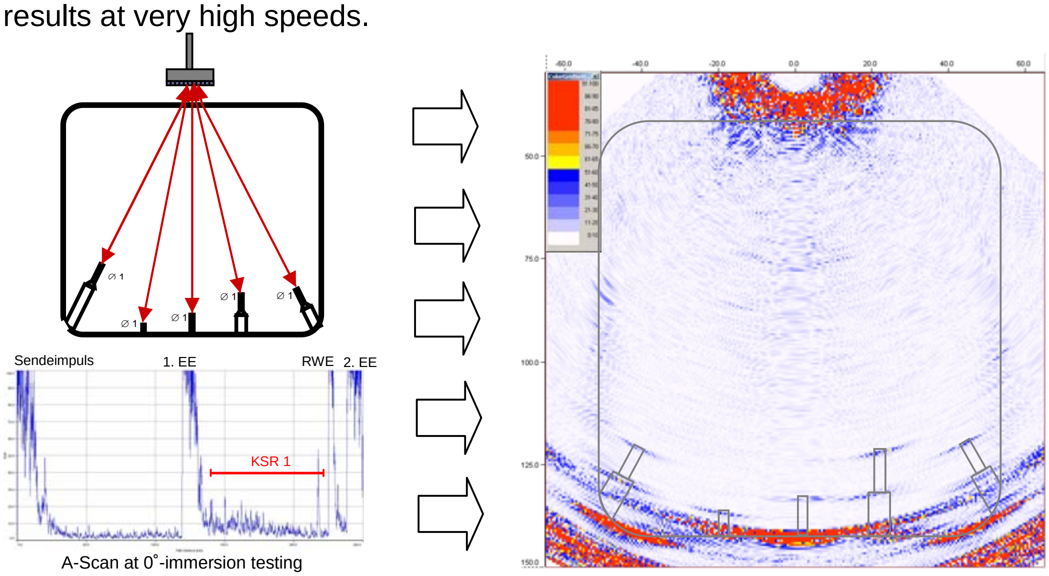


Figure 5: Potential of fast quantitative imaging of a billet inspection

The test results can be evaluated in accordance with existing standards and procedures, for example A-Scan images using the DGS method, or by using real-time reconstruction analysis of two-dimensional B-Scans (Figure 5).

The image reconstruction algorithm principally tolerates infractions of the Sampling Theorem, which provides the basis for the Sampling Phased Array technique. Thus, standard transducers, optimally arranged around the test object, may be employed. IZfP Fraunhofer called this procedure the TOMO-SAFT technique.

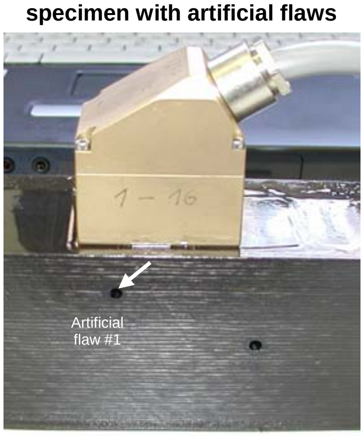
Inspection of Acoustically Anisotropic Materials

The wave fronts of elementary waves in isotropic materials are spherical and the sound propagates in perpendicular direction to the wave front. In anisotropic materials, the wave fronts are non-spherical and the sound field is rather distorted [11].

Elementary wave phase conditions and relations, assessable with SPA, can be adjusted (considering the anisotropy of the material) to a quasi-normal test condition of anisotropic materials. The pixel-to-element transit time can be derived from the stiffness matrix or from experimentally obtained directional sound velocities. This technique is identified as “Reverse Phase Matching” [12].

State-of-the-art algorithms are used to calculate the sound wave propagation [13]. Figure 6 depicts ultrasonic testing results obtained from a composite carbon-fiber sample.

Phased Array search unit on a test specimen with artificial flaws



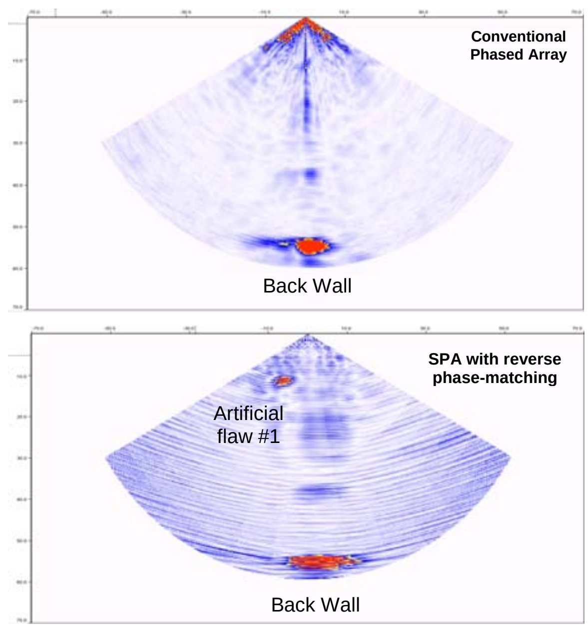


Figure 6: Ultrasonic inspection of carbon-fibre materials

The Reverse Phase Matching technique offers the following advantages:

1. The SPA technique in the Reverse Phase Matching mode permits flaw detection and image reconstruction in anisotropic materials.
2. This technique allows the characterization of anisotropic materials by using calculative variations of structural assumptions.

3. The number of transmitting elements, the displacement and the arrangement of the inspection system can be adjusted to meet the requirements of the anisotropic structure of the test sample

As the inspection is performed using the immersion technique, considered to be an inspection of heterogeneous materials, complicated surface configurations will not require elaborate adjustments to the transducer elements. This leads to significant resource savings during system setup and also reduces the costs involved in the design and manufacture of inspection systems and assemblies.

Ultrasonic Inspection of Heavy-Wall Components

Ultrasonic inspection of heavy-wall components, such as turbine shafts, are usually very time consuming as the long travel paths require relatively low pulse repetition rates. An additional problem associated with long travel paths is the poor resolution of flaw reflectors and thus the characterization of discontinuities in compliance with high detection sensitivity. Conventional Phased Array techniques currently in use cannot overcome this type of physical limitation. The complete inspection of a large turbine shaft (up to 1.5 meters in diameter) using conventional Phased Array may take several days to complete and thus significantly impacts the production schedule.

The application of the SPA technique allows the implementation of several scan (beam) angles with a single transmission cycle. However, an insufficient S/N ratio (another side-effect of long travel paths) caused by the energy transmitted in each cycle must be expected; the transmitter energy, even during defocused transmitting with all transducer elements (used to increase the sensitivity through the emulation of a point source transmitter), is insufficient to result in adequate S/N ratios. In theory, the aperture of the Phased Array search unit has to be increased to achieve the desired S/N ratio, which would lead to a large sized inspection system and lower reflector resolutions when conventional Phased Array techniques are used.

The above described difficulties can be resolved utilizing a synthetic aperture while scanning the test object.

The ultrasonic signals received from each individual transducer element at different locations are synthetically reconstructed for all scan (beam) angles; this approach provides the following advantages:

1. The SPA only fires one shot (cycle) at each scan position, where conventional Phased Array requires multiple cycles, depending on the number of scan angles. For example: a turbine shaft inspection with conventional Phased Array involves nine scan angles (0°, ±7°, ±14°, ±21° and ±28°) and therefore nine shots, whereas the SPA technique fires only one shot resulting in a speed improvement by a factor of nine.
2. At equal or better testing sensitivity (depending on the size of the available synthetic aperture) the synthetic aperture technique permits a better resolution given by the effect of the element aperture.

A test sample (turbine shaft with 3mm diameter side drilled-holes) was inspected with conventional and SPA techniques. Even with relatively small apertures (16 positions at 1.8mm distance) the Sampling Phased Array technique achieves the same test sensitivity and S/N ratio as the conventional Phased Array technique. The SPA technique provides a far better angular resolution. The synthetic aperture in this example is double the size the aperture of a conventional 16 element Phased Array search unit.

Other practical applications
In addition to the examples given, the following are practical applications where Sonovation is working on.

- New weld construction
- In service inspection of welds
- Inspection of stainless steels,
- Inspection of turbines
- Accurate detection and sizing of Hydrogen Induced Cracking.
- Assesment of hydrogen damage
- Steel Product inspection.

ULTRASONIC SYSTEM

The above mentioned principles of conventional Phased Array and Sampling Phased Array were the basis for the development of an ultrasonic platform, developed at the Fraunhofer-IZFP. The ultrasonic front end was initially an ultrasonic module featuring 16 completely independent (parallel) ultrasonic channels. In collaboration with Sonovation, this was expanded to 64 channels and can also be used for conventional multi-channel applications. The UT front end is based on cutting-edge micro-electronic components and satisfies even the most advanced UT test equipment requirements [14] in a compact design.

Figure 7: Sonovision Sampling Phased Array system

The CM computation module has been developed for fast data processing using parallel computer architectures. All necessary data and image reconstruction algorithms are incorporated into the CM module. Additional modules, such as CPU interface, coordinates interface, are incorporated in the Sonovision system (Figure 7).

SUMMARY

Sampling Phased Array (SPA) does not claim to have all the answers, but it is certainly a big step in the direction of producing real images of flaws in material, which will render a significant improvement in the quality of ultrasonic inspections and the ease of interpretation. SPA permits the meaningful reconstruction of defects at high inspection speeds and facilitates the inspection of anisotropic materials. The technique provides higher sensitivity for the inspection and along with corresponding high resolution enables quantitative NDT. Further, the development of SPA results in a substantial contribution to the improved inspectability of welds, lightweight construction material [2] and increases the probability of detection of small discontinuities in highly stressed materials [3].

Before technologies like Sampling Phased Array inspection can be adapted to its full capability, codes and standards will have to be produced to allow for sentencing of defects based upon their image, rather than the amplitude produced relative to an arbitrary reference reflector.

The Sampling Phased Array technology enables new approaches and opportunities for the development and application of ultrasonic test systems.
IZFP Fraunhofer and Sonovation are now making these new approaches available to industry with the following advantages:

- Increase of test speed with implications for throughput and productivity
- Improved resolution and detectability of small defects throughout the whole volume inspected, including near surface
- Quantitative imaging in real-time
- Easier interpretation of inspection results
- Enhanced ability to inspect non-homogeneous anisotropic materials (carbon fiber, stainless steel, dissimilar welds)

REFERENCES

[1] A. Bulavinov et al., Sampling Phased Array A New Technique for Signal Processing and Ultrasonic Imaging, Berlin, ECNDT 2006
[2] J. Klenner: Werkstoffvisionen im Verkehrsflugzeugbau, Konferenz „Werkstoffinnovationen für Industrie und Gesellschaft“, Weimar, 29. – 31. Oktober 2003
[3] P. Ciorau: A Contribution to Detecting and Sizing Linear Defects by Phased Array Ultrasonic Techniques, 4th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurised Components, London, 6-8 December 2004
[4] R.Y. Chiao, L.J. Thomas: Analytic Evaluation of Sampled Aperture Ultrasonic Imaging Techniques for NDE, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control, Vol. 41, No.4, July 1994
[5] W. Müller, V. Schmitz, G. Schäfer, Reconstruction by the Synthetic Aperture Focusing Technique. Nuclear Engineering and Design, 1988, pp. 393 –404
[6] Kröning M., Hentschel D., von Bernus L., Bulavinov A., Reddy K. M.; Deutsche Patentanmeldung Nr. 10 2004 059 856.8, Verfahren zur

zerstörungsfreien Untersuchung eines Prüfkörpers mittels Ultraschall. Tag der Anmeldung: 10.12.2004

[7] Bulavinov A.: Der getaktete Gruppenstrahler. Saarbrücken 2005 (Dissertation).

[8] Kröning M., Bulavinov A., Reddy K. M., von Bernus L.: Deutsche Patentanmeldung Nr. 10 2005 051 781.1, Verfahren zur zerstörungsfreien Untersuchung eines Prüfkörpers mittels Ultraschall. Tag der Anmeldung: 28.10.2005

[9] Ananth Grama, Anshul Gupta, George Karypis, Vipin Kumar: Introduction to Parallel Computing, 2nd Edition, Addison-Wesley, Februar 2003

[10] Jon F. Claerbout, Cecil and Ida Green Professor of Stanford University, EARTH SOUNDINGS ANALYSIS: Processing versus Inversion, March 23, 2004

[11] P. Fellinger, R. Marklein, K. J. Langenberg, S. Klaholz, "Numerical modeling of elastic wave propagation and scattering with EFIT - elastodynamic finite integration technique", Wave Motion 21, 47-66, 1995

[12] Kröning M., Bulavinov A., Reddy K. M.: Deutsche Patentanmeldung Nr. 10 2006 003 978.5, Verfahren zur zerstörungsfreien Untersuchung eines wenigstens akustisch anisotropen Werkstoffbereich aufweisenden Prüfkörpers. Tag der Anmeldung: 27.01.2006

[13] J.D. Achenbach, Wave propagation in elastic solids, North-Holland, Elsevier, Amsterdam, 1984

[14] Zerstörungsfreie Prüfung - Charakterisierung und Verifizierung der Ultraschall-Prüfausrüstung; Deutsche Fassung EN 12668-1:2000