



## *Journal Reprints*

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# Sampling phased array – a new technique for signal processing and ultrasonic imaging

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## 1. Introduction

In the field of non-destructive testing, conventional manual ultrasonic testing techniques are increasingly being replaced with automated ultrasonic inspections. The availability of economically priced and powerful micro-electronic and computer components often justify the investment in ultrasonic phased array systems<sup>[1]</sup>.

The phase-controlled generation of ultrasound permits the electronic control of scan angles and focal depth and offers powerful image reconstruction for a quantitative image evaluation with a reduced number of search units.

Sampling Phased Array (SPA), a novel phased array technology developed by Fraunhofer-IZFP, permits the meaningful reconstruction of flaw images at high inspection speeds and facilitates the inspectability of anisotropic materials. High sensitivity for the inspection of heavy-wall components along with coexisting resolution is an additional objective to achieve a quantitative rateable test result.

Development of SPA results in a substantial contribution to the inspectability of lightweight construction material<sup>[2]</sup> and the detectability of small discontinuities in highly-stressed materials<sup>[3]</sup>.

## 2. Sampling phased array principle

In conventional phased array technique electronic control of beam angles and focal depth drastically decreases the number of required search units and therefore significantly reduces the mechanical complexity and the handling of an ultrasonic testing system.

However, the number of cycles, *ie* inspection speed, remains the same. To improve the image quality by increasing the number of beam (scan) angles, for example image enhancements of sector-scan images, the overall inspection time also increases and may become impractically long.

A detailed analysis of the time-domain aperture information<sup>[4]</sup> 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. This can be attained 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  $A_{ij}(t)$  with  $j = 1 \dots N$  of the information matrix ( $i =$  transmitting element,  $j =$  receiving element,  $N =$  number of elements in a linear phased array search unit).

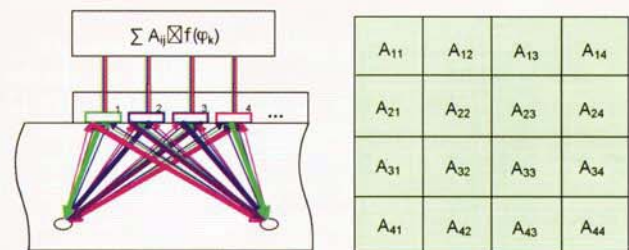


Figure 1. Information matrix of a 4-element phased array search unit

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,  $A_{ij}$  equals  $A_{ji}$  ( $A_{ij} = A_{ji}$ ). The diagonal elements  $A_{ii}$  ( $i = 1, N$ ) correspond to the information from element '*i*', scanning the entire search unit aperture similar to the image reconstruction based on the Synthetic Aperture Focusing Technique (SAFT) principle<sup>[5]</sup>.

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<sup>[6, 7, 8]</sup>.

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<sup>[9]</sup>.

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### 3. UT data reconstruction

Virtual A-scan presentations can be produced from the time-signals ( $A_{ij}$ ) 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 (analogue) 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 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.

In principle, the SPA technique permits the development of data reconstruction techniques superior to today's state-of-the-art. One of the endless opportunities is the application of the synthetic aperture, a consideration that particularly applies to the expansion of the information matrix ( $A_{ij}$ ) 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<sup>[10]</sup>.

Figure 2 depicts the key difference between reconstruction techniques; both techniques can produce all conventional types of ultrasonic images.

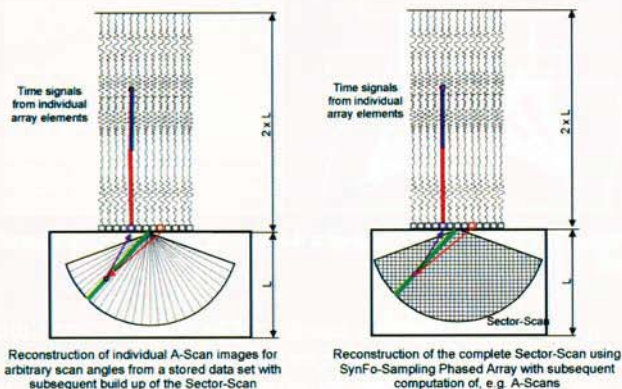


Figure 2. Options for UT image reconstruction

### 4. Technology validation

Essential for the practical application of this technique is the documented evidence that virtual A-scans are equivalent to conventionally acquired A-scans. This validates the SPA technique and enables 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<sup>[7]</sup>. Figure 3 depicts A-scans from a 1 mm-diameter side-drilled hole (SDH). Both signal images are equal in every detail, including the acoustic noise when utilising the complete information matrix.

### 5. SPA advantages

The SynFo-sampling phased array technique offers a variety of technical advantages; some of these are exemplarily discussed below.

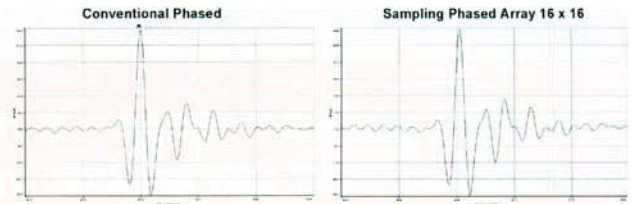


Figure 3. Equivalence of conventional and sampling phased array (1 mm-diameter SDH, 30° longitudinal wave, 5 MHz, 30 mm sound path)

For almost all practical applications faster inspection time is vitally important. The example below describes the potential for accelerated inspection frequency attributed to the SPA technique.

When 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 assessable ultrasonic image reconstruction, for example a sector-scan image, the time savings can improve by a factor of up to one thousand.

An additional advantage is provided by the fact that the SPA technique principally employs the pitch-catch mode, where the dead-zone (or near-surface) in the test material is significantly reduced. Additionally, the virtual sound field displays all reflectors with optimised focusing. This benefit makes certain special ultrasound techniques unnecessary, for example creeping waves for near surface flaw detection and evaluation (see Figures 4 and 5).

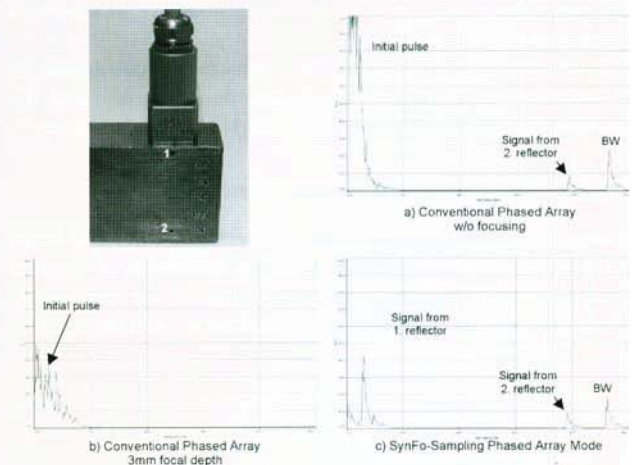


Figure 4. Comparison of conventional phased array with SynFo-sampling phased array for near-surface reflectors

### 6. New solutions to existing testing problems

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

#### 6.1 Quantitative imaging in high-speed steel section UT

The deployment of conventional phased array systems for high-speed product line-integrated industrial applications, for example testing of steel bars and billets, is limited to processes with relatively long process cycles. 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 definition of ultrasonic test results at very high speeds.

The test results can be evaluated in accordance with existing standards and procedures, for example A-scan images using the

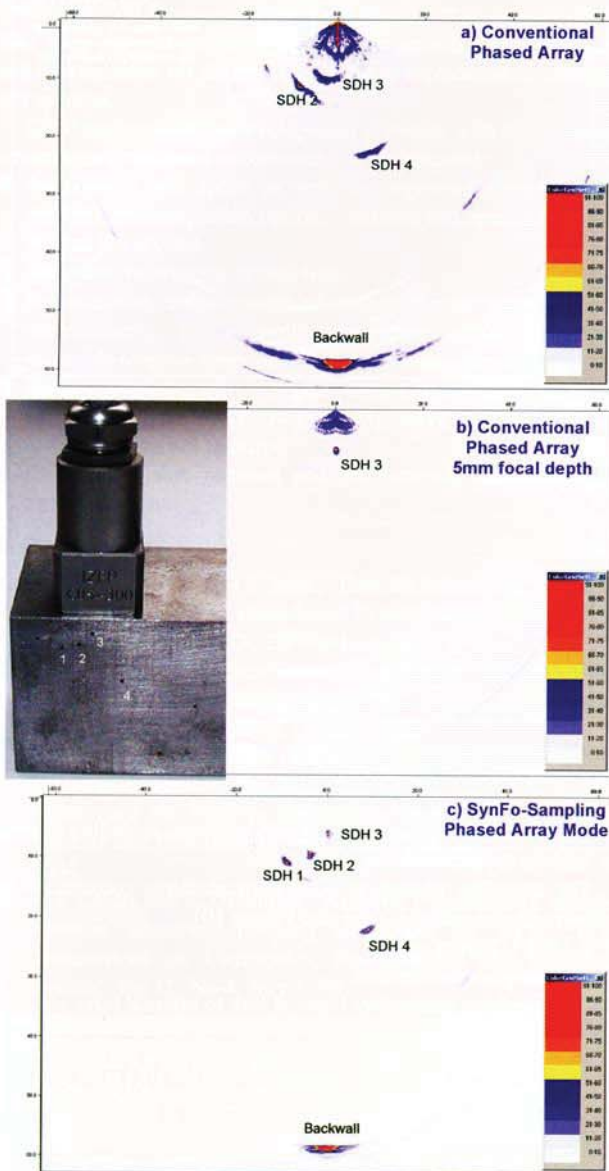


Figure 5. Test data from the near field, conventional phased array vs sampling phased array

DGS method, or by using real-time reconstruction analysis of two-dimensional B-scans (Figure 6).

The image reconstruction algorithm principally tolerates infractions to 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. We called this procedure the TOMO-SAFT technique.

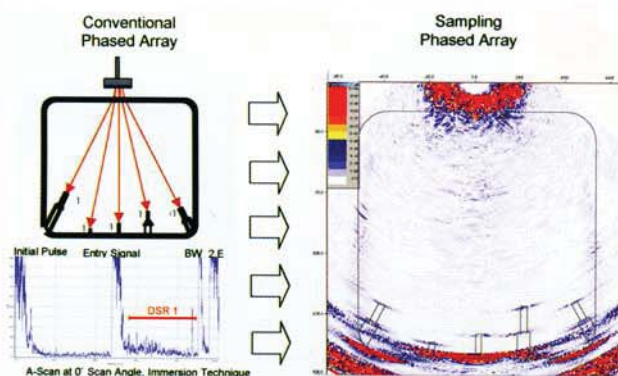


Figure 6. Potential of fast quantitative imaging of billet UT

## 6.2 Inspection of acoustical 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<sup>[11]</sup>.

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 'Inverse phase matching'<sup>[12]</sup>.

State-of-the-art algorithms are used to calculate the sound wave propagation<sup>[13]</sup>. Figure 7 depicts ultrasonic testing results obtained from a composite carbon-fibre sample.

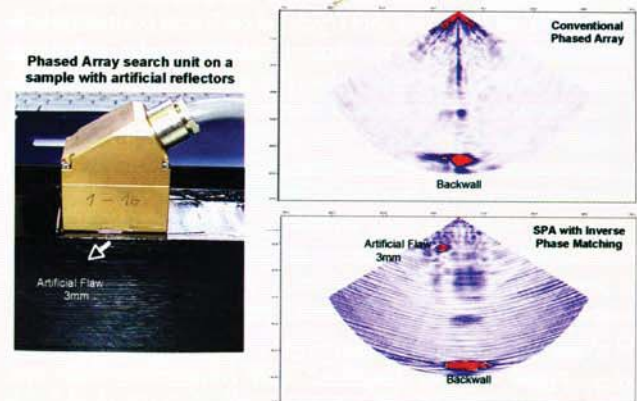


Figure 7. Ultrasonic inspection of carbon-fibre materials; obvious benefits of sampling phased array with inverse phase matching

The inverse phase matching technique offers the following advantages:

- The SPA technique in the inverse phase matching mode permits flaw detection and image reconstruction in anisotropic materials.
- This technique allows the characterisation of anisotropic materials by using calculative variations of structural assumptions.
- The number of transmitting elements, the displacement and the arrangement of the search unit 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 set-up and also reduces the costs involved in the design and manufacture of search unit systems and assemblies.

## 6.3 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 characterisation 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 m 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 punctiform sound source), 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 search unit and lower reflector resolutions when conventional phased array techniques are used.

Utilising a synthetic aperture while scanning the test object can resolve the above described difficulties. 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:

- 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 ( $0^\circ$ ,  $\pm 7^\circ$ ,  $\pm 14^\circ$ ,  $\pm 21^\circ$  and  $\pm 28^\circ$ ) and therefore nine shots, whereas the SPA technique fires only one shot resulting in a speed improvement by a factor of nine.
- 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, as illustrated in Figures 8 and 9.

A test sample (turbine shaft with 3 mm-diameter side-drilled holes, Figure 8) was inspected with conventional and SPA techniques. Even with relatively small apertures (16 positions at 1.8 mm 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 (Figure 9). The synthetic aperture in this example is double the size of the aperture of a conventional 16-element phased array search unit.

## 7. Development platform

The abovementioned principles of conventional phased array and sampling phased array were the basis for the development of an ultrasonic platform, developed at the Fraunhofer-IZFP. This new

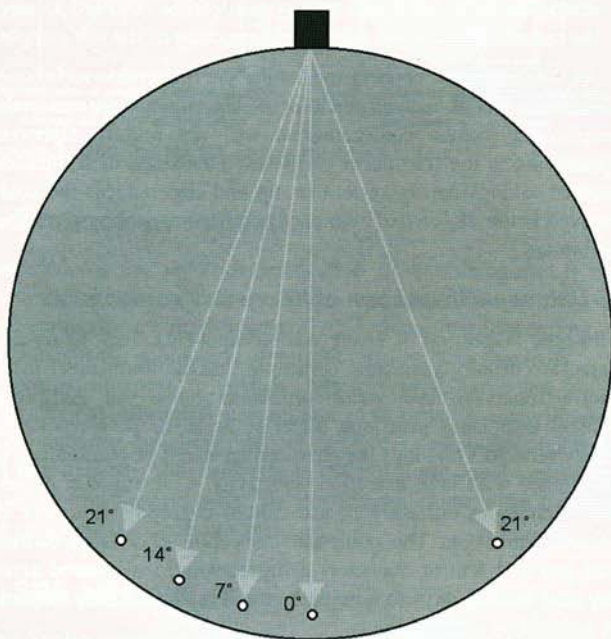


Figure 8. Test sample for ultrasonic inspection of turbine shafts

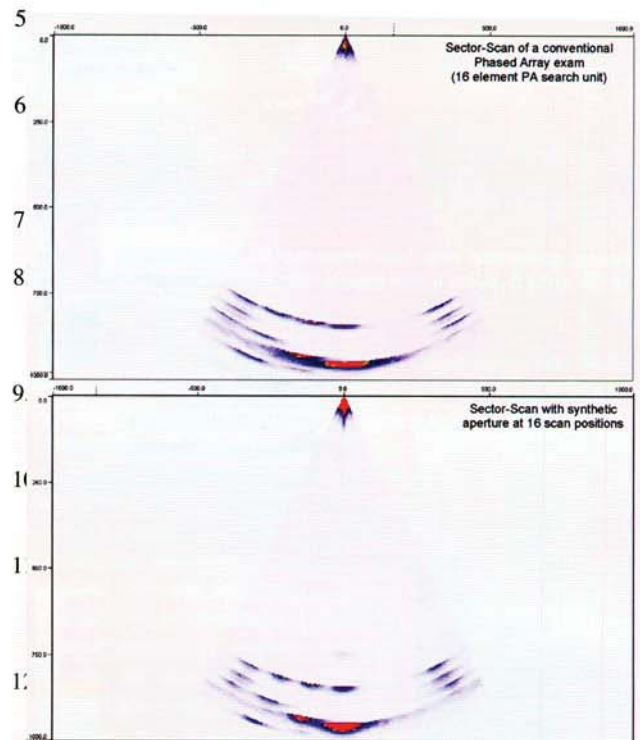


Figure 9. Ultrasonic inspection results of a 940 mm (37") diameter turbine shaft January 2006.

platform permits the assembly of SPA systems, including systems for custom applications, on short notice.

The sampling phased array system platform consists of the following basic modules (see also Figure 10):

- $\mu$ -USE UT front end.
- CM computation module.
- CM interface: transceiver (optical link to internal bus).
- Coordinate interface.
- Master PC w/ PCI-bus for up to four CM modules.
- Control software and data acquisition/analysis software.

The  $\mu$ -USE ultrasonic front end is an ultrasonic module featuring 16 completely independent (parallel) ultrasonic channels, and is expandable to 32- or 64-channels; this front end 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<sup>[14]</sup> in a very compact design (Figure 10, top).

The CM computation module (Figure 10, bottom) 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, etc. are inexpensive commercially available components of the UT system platform.

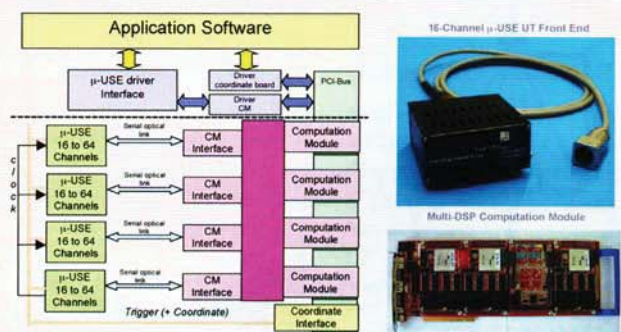


Figure 10. SPA ultrasonic platform

## 8. Summary

The sampling phased array technology permits new approaches and opportunities for the development and application of ultrasonic test systems.

IZFP has provided a development platform with the following advantages (compared to conventional techniques):

- Increase of test speed as well as improved definition with product line integration options enabling test speeds of several metres per second.
- Quantitative imaging in real-time.
- Inspectability enhancement of materials with otherwise poor inspectability, for example non-homogeneous anisotropic materials (carbon fibre, stainless steel, dissimilar welds).
- Economically-priced electronic components based on latest micro-electronic technology; expensive phase shifting electronics are not required.
- Compliance with national and international standards, codes and regulations.

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