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Improving the Inspectability of Stainless Steel and Dissimilar Metal Welded Joints Using Inverse Phase-Matching of Phased Array Time-Domain Signals

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Abstract

The ability to perform nondestructive testing of stainless steel piping and dissimilar metal joints in excess of 10.0mm (.4") wall thickness is very limited. In particular the use of ultrasound to detect closed (tight) cracking, which is not detected by X-ray techniques, is very difficult due to the acoustic anisotropic structure of the welded seam. Several Reactor Safety Program projects have presented extensive knowledge and better understanding of how to enhance the test procedures for this type of welded joint. Resulting standards and regulations for the qualification of applicable techniques and procedures provide evidence of the limitations of conventional X-ray and ultrasonic methods.

Fundamental results were provided by simulating the sound propagation in model-described welded joints against the manufactured form.

In principle, this permits the application of ultrasonic migration techniques, which allows for the consideration of phase influences during the summation process of the received time-domain signals.

The fundamental capabilities of the Inverse Phase-Matching technique have been successfully demonstrated on heterogeneous and anisotropic design models and test samples supplied by the Reactor Safety Program. This paper discusses the principles and first application results of this technique.

Keywords: *Phased array, Inverse phase matching, Anisotropic, Stainless steel welds, Reactor safety*

1. Introduction

Applications of austenitic stainless steel materials are found extensively in plant construction, power plants and equipment [1, 2] due to their unique and advantageous material properties. They are used for the primary recirculation system components in nuclear power plants and associated facilities where safety is the principle consideration during construction and operation [3]. Many nondestructive testing techniques (NDT) are implemented to verify the quality and serviceability of these components, with particular emphasis placed on testing welded joints.

This testing is mandated by construction and manufacturing codes and regulations to verify finished product quality and extends to periodic in-service inspections required for continued certification and operation and to determine any restrictions on operation due to aging or weakening of these components. For nuclear power plant primary recirculation system components, the regulations dictate detailed testing requirements which have been developed to assure that all conceivable discontinuities can be detected with a high degree of sensitivity and reliability. Examples include the KTA Regulations and the ASME Code [4, 5]. The scope and sensitivity of these NDT methodologies are intended to guarantee that all detectable material discontinuities are well below the critical flaw sizes and will not affect the capability of the components to withstand design and operational loads or degrade the design safety margins.

At the present time, the capability to produce such high NDT standards is only partially achievable for stainless steel and dissimilar metal welded joints. The factors that limit the capability of current commonly used NDT methods include variations in the grain structure (coarse grain) of the base material, the solidification point of the welded material and associated residual stresses combined with load induced stresses in the weld area. Despite continuing optimization of manufacturing processes to improve the testability by reducing coarse-grained base materials [6] and welding technology advancements [7], the testability of welded joints and components is still limited.

Experience has shown that plant and equipment operation continue to reveal process-induced flaws and manufacturing defects. Examples include intergranular stress corrosion cracking (IGSCC), which occurs in weld material and the adjacent heat-affected zone, as well as manufacturing flaws, which either escape detection during production acceptance testing, or are not detected during periodic re-inspection, or can not be properly evaluated. Extracts from available technical literature on these issues dealing with flaws in stainless steel and dissimilar metal welds and their technical response are provided in the references [8, 9, 10, & 11].

In Germany, since 1975, the government has developed criteria to determine, and mandated the reporting of, safety related events or technical findings in nuclear power plants. [12]. As directed by the (German) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), such reportable observations are then technically evaluated by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH. Reference [13] contains findings relevant to cracks detected in a dissimilar metal welded joint and includes the following statement: “the significance of the event lies in the finding that a manufacturing quality defect was not recognized during a special technical inspection. The ultrasonic inspection performed on this component in the location in question was not properly interpreted by both the ultrasonic inspection personal and the authorized inspector. In summary, this finding identified a systemic weakness in the Quality Control System”.

2. Current State-of- the-Art: NDT Test Technology

The primary NDT technologies used for these types of inspections are X-Ray and Ultrasonic (UT) based. Despite great advancements made in X-Ray technology, particularly for sensors/detectors and the implementation of Computer Tomography [14], UT techniques continue to be extremely useful and effective. Reasons for this include the difficulties associated with X-Ray inspections for closed (tight) cracks, as well as limitations related to component geometry and instrumentation access to the inspection points. A detailed description of current UT inspection technology capabilities can be found in Reference [15]. References [16] and [17] contain recommendations that came out of practical experience and fundamental research testing performed by various laboratories, and provide all encompassing research results on acoustic wave propagation in austenitic material welded test specimens [18, 19]. In particular, the above cited research and follow-on testability improvements have contributed significantly to welding technology and techniques [20].

These scientific developments have proven to be vital contributors to success in conducting and evaluating the associated testing techniques. Proven test technologies, as well as qualified test personnel, are crucial for austenite based material test qualification [21, 22].

This combination of expert knowledge and experience uses specially selected search units for successful testing and evaluation [23]. The implementation of phased array techniques is currently being recommended for automated test systems, which permit multiple selectable test functions and sequences [24]. Of primary importance is the appropriate preparation of test specimen surfaces to assure optimum acoustic coupling between the phased array search units and the test specimen. However, it must be emphasized that the implementation of phased array techniques does not provide any improvement in the testability of anisotropic materials due to the inherent problems with acoustic wave propagation.

3. Technology Developments for Improving the Inspectability of Anisotropic Materials

In the medical and seismic sciences, anisotropic media are examined using elastic waves providing excellent detailed images (Fig. 1).

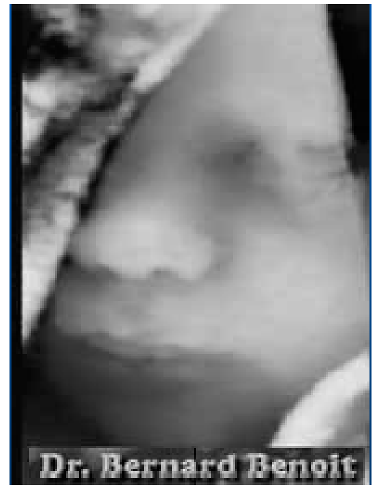

Fig.1: Acoustic Image of an Unborn Child [25]

Seismology is primarily applied to oil exploration and the examination of geophysical structures. Seismic sensor systems can be arranged in groups and result in sensor antennas with distributed apertures producing composite images of the examined volume and area (Fig. 2).

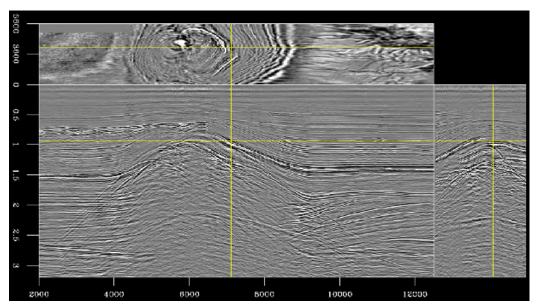

Fig. 2: Measurement and Reconstruction of a Seismic Profile [26]

The analysis of these techniques reveals that high sound propagation velocities in steel and the required testing rates impose new challenges that make the practical implementation of material testing quite difficult. Recent advancements in computerized analysis of real time data have facilitated further developments of material testing and measurement technology and have been integrated into related instrumentation and electronics with high throughput algorithm modules (integrated high efficiency computing). These advancements have greatly improved almost all NDT technologies and applications [27].

3.1 Phased Array Technology

The Phased Array technology provides test data via an array of individual transducers which transmit and receive as directed by the electronics and software [28]. The implementation of Phased Array systems for material testing and evaluation utilizes only a small portion of the overall data acquisition capability since the acoustic transmissions for specific incidence angles are time-phased and the received signals are then summarized. This means that the entire array acts as a single transducer in accordance with the Sampling Theorem. However, if the time-domain signals from the individual transducer elements are acquired, the resulting data can then be summarized with arbitrary phase information to permit data processing of all possible incidence angles and all physically available focus points from a single data set. This concept is referred to by Fraunhofer-IZFP as the "Sampling Phased Array" system (Figs. 3 & 4).

Figure 5 illustrates a comparison of conventional Phased Array systems with the Sampling Phased Array (SPA) described above and highlights the advantages of the SPA system.

The sector image depicts results from a single test sequence using SPA and is evaluated in real time, whereas a conventional Phased Array system, with electronic steering for phase delays and incidence angle, required 161 individual sequences in 1° increments per sequence.

Based on the T/R principle during the acquisition of the time signals, the near-surface area (dead-zone) decreases significantly. Each point of the sector scan is processed by the SPA system with the best possible resolution as illustrated below.

3.2 Synthetic Aperture Technique

The measurement of signals in a time domain $A_{iJ}(t)$ with $i = j$ (i: transmitter elements, j: receiver elements) is the essence of the Synthetic Aperture Focus Technique (SAFT) where one Phased Array element is virtually steered over the aperture of the array. The additional acquisition of the time domain signals A_{iJ} with $i \neq j$ can be used as a data set for the solution of migration algorithms (e.g. Kirchoff Algorithm), for image reconstruction, as previously shown in Figures 1 & 2 and described in References [30] and [29], respectively. This reconstruction principle is illustrated in Fig. 6.

The bottom image in Fig. 5 shows the results using the SynFo technique.

A significant benefit of this reconstruction technique, referred to by Fraunhofer-IZFP as the "SynFo" technique, is that small test sampling errors in the algorithm solution will not adversely affect the image reconstruction.

Figure 7 shows a comparison of conventional and sampling Phased Array results, while Figure 8 compares the results using the synthetic aperture focusing technique.

This means that individual elements of a Phased Array search unit can be distributed over a larger test aperture [31]. This allows for a uniform distribution of the synthetic focusing over all image points at larger travel paths with the maximum possible image resolution determined by the aperture of the individual transducer element.

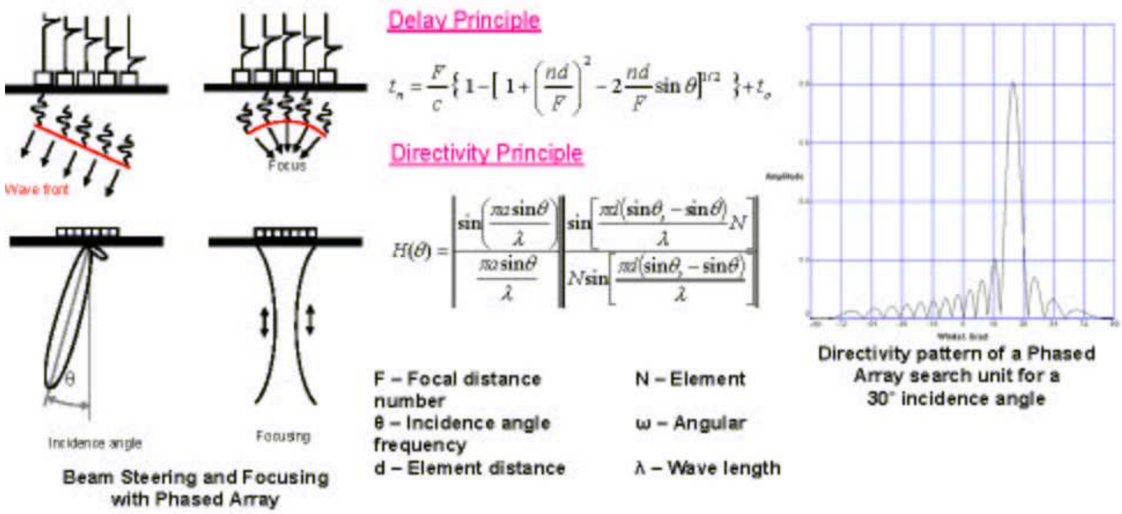

Fig. 3: Data acquisition and processing for conventional phased array

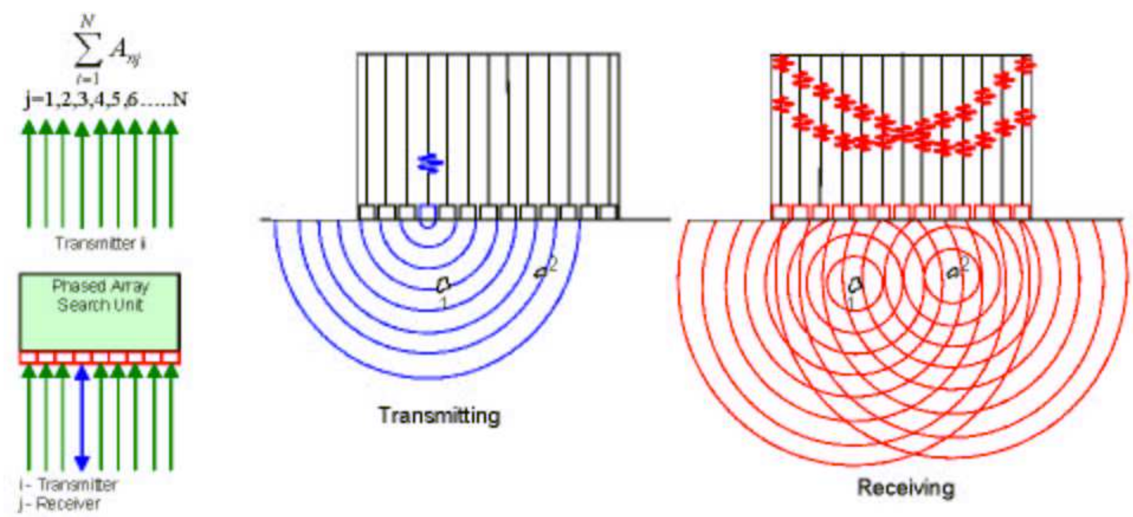

Fig. 4: Data acquisition and processing for sampling phased array

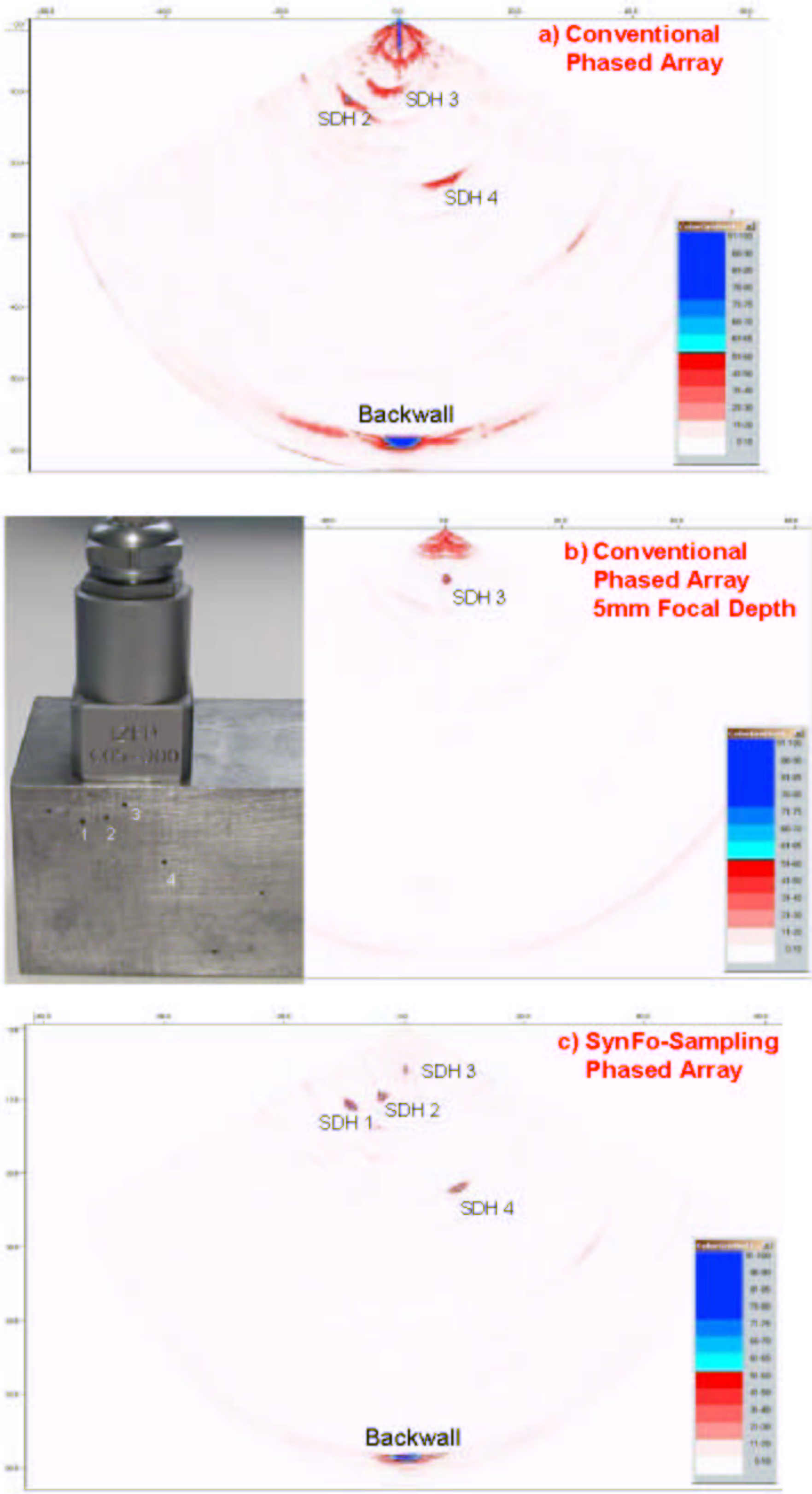

Fig. 5: Near-field measurements with conventional PA and SPA

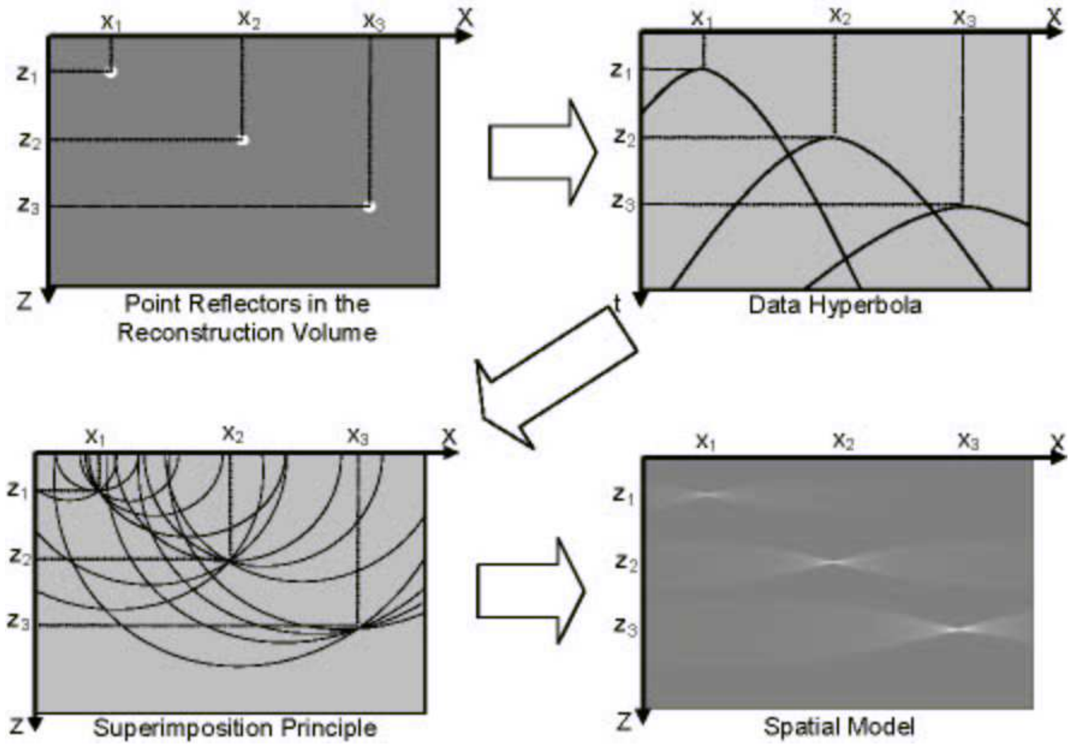

Fig. 6: Image reconstruction via Kirchoff Algorithm

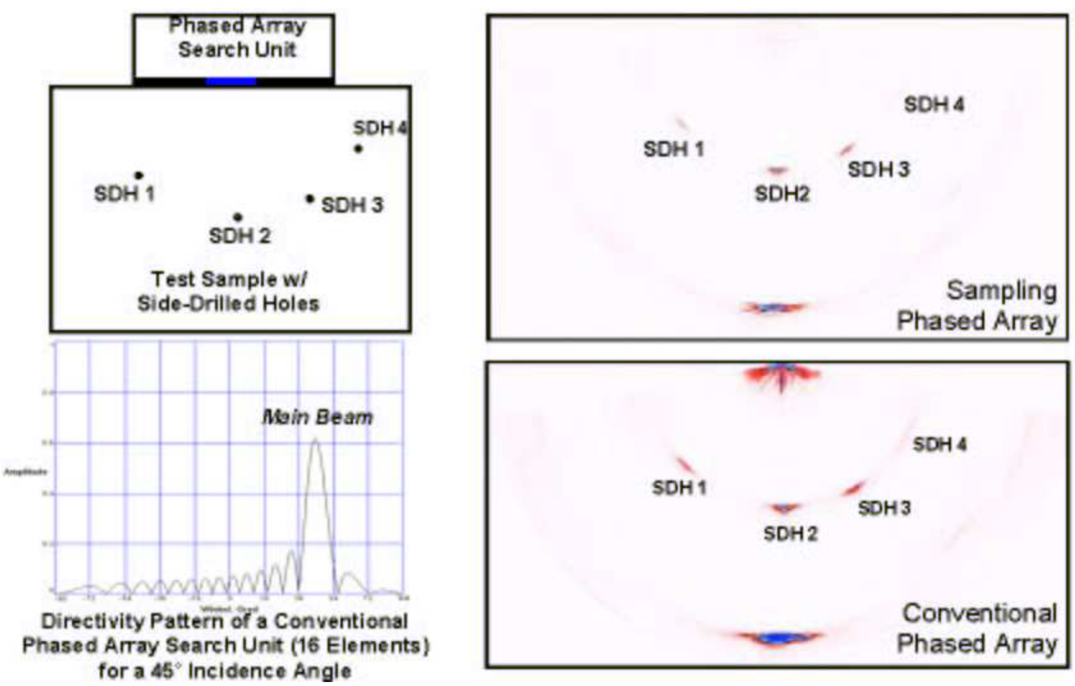

Fig. 7: Result comparison for a "Sampling Theory" application

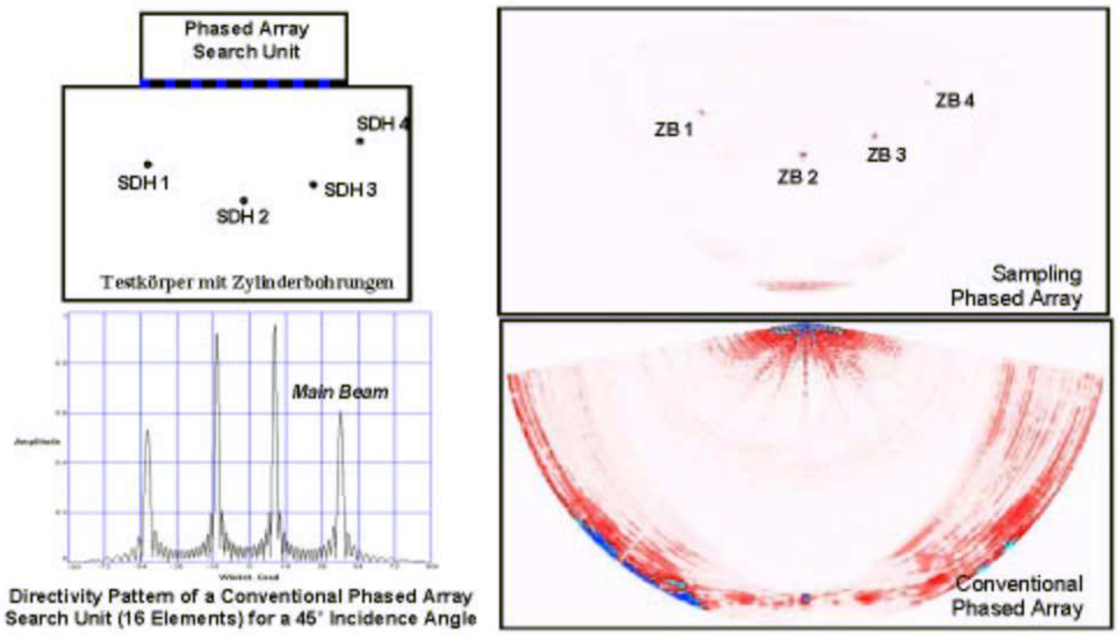

Fig. 8: Image reconstruction with distributed aperture

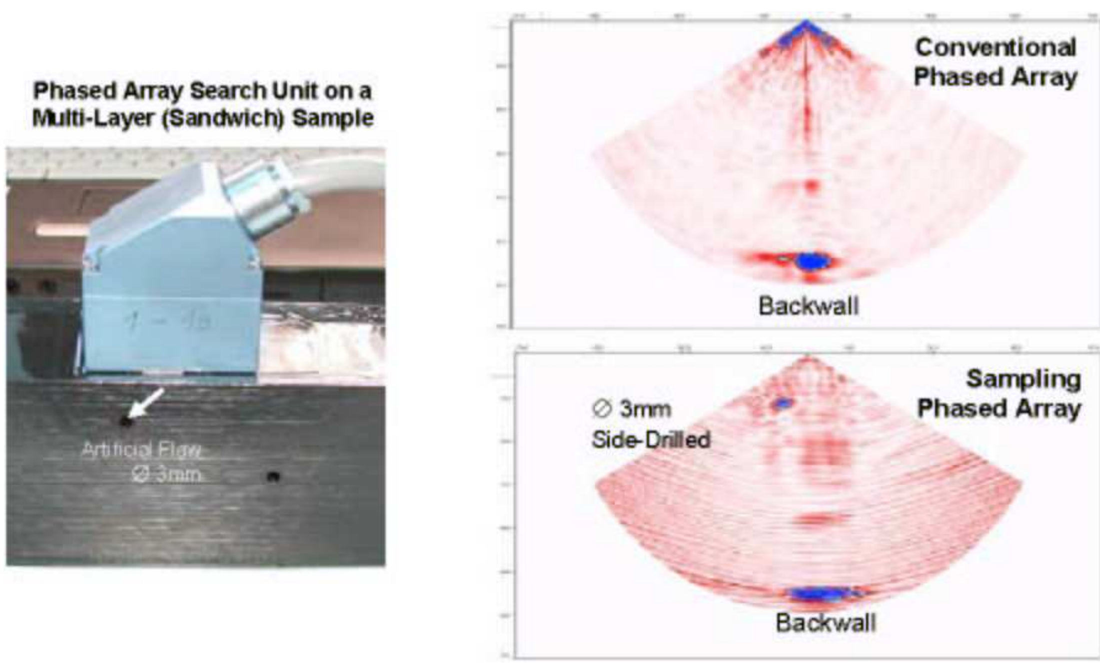

Fig. 9: Test results from a monolithic carbon-fiber sample using conventional PA and SPA

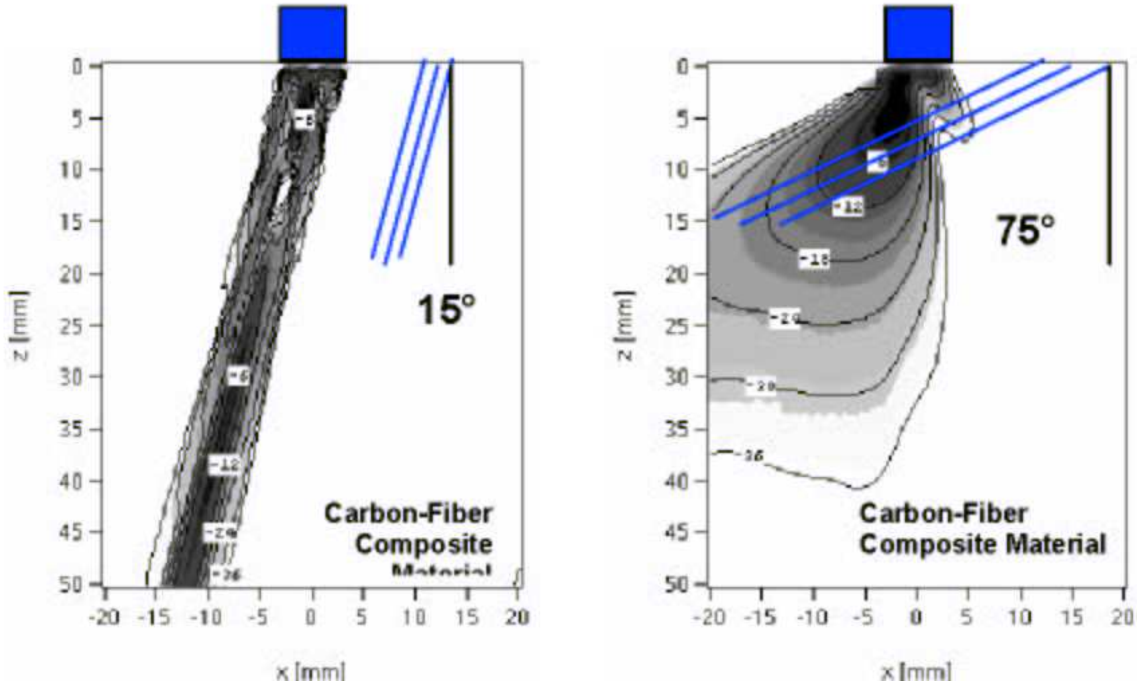

Fig. 10: Test results from a multi-layer Carbon-fiber sample using PA and SPA techniques

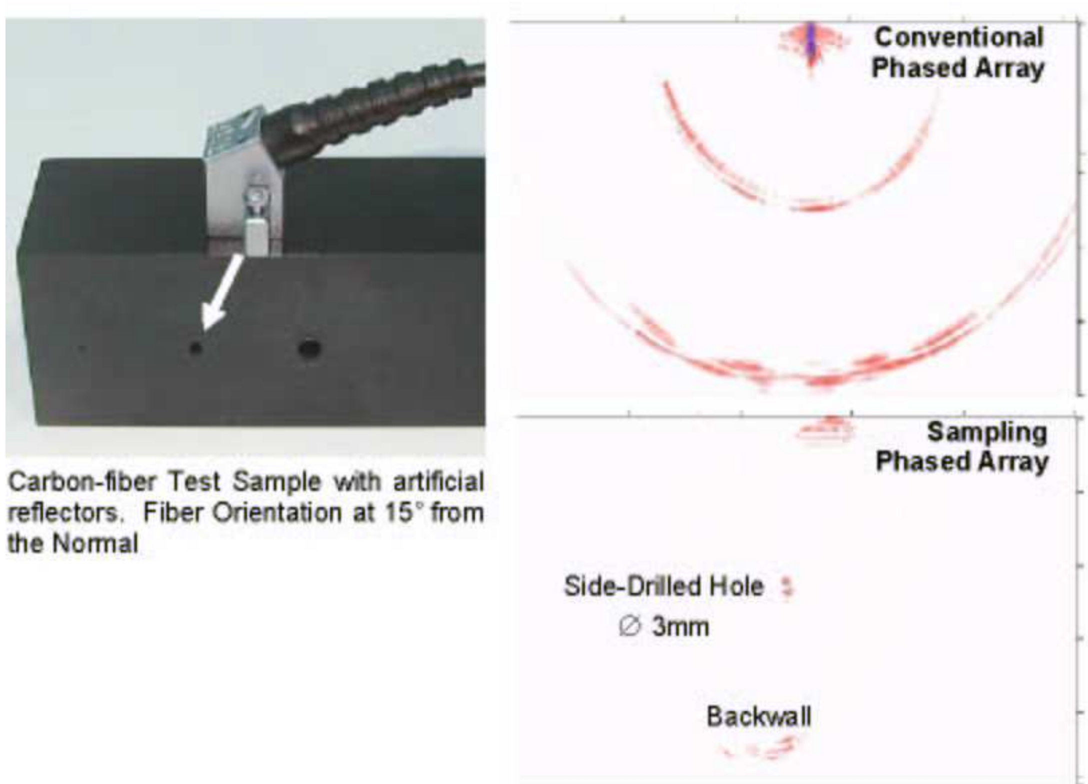

Fig. 11: Sound field distribution of a 2 MHz straight beam transducer on a Carbon-fiber composite material (anisotropic) test sample

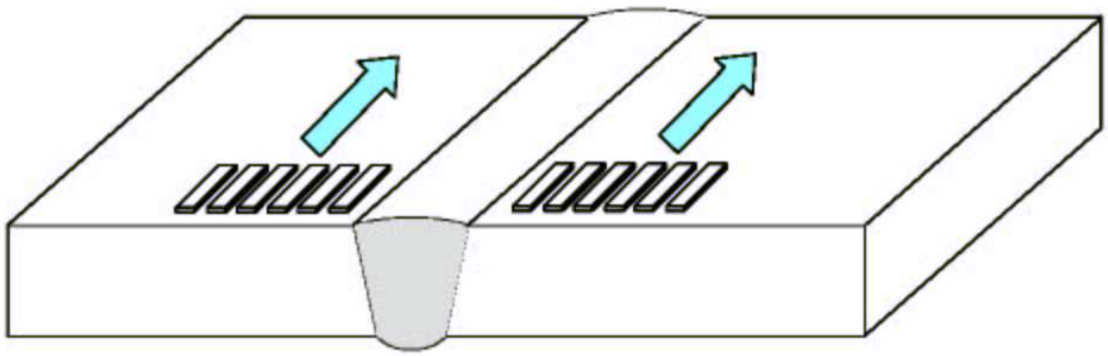

Fig. 12: Transducer array for detecting and evaluating longitudinally oriented flaws; the search unit is moved parallel to the weld

Figure 8 also shows the detection and reconstructed image of the test specimen back wall.

3.3 Inverse Phase-Matching Technique

The application of SynFo-Technique in combination with acquisition of time-domain signals results in a wide-ranging improvement in the testability of anisotropic and/or heterogeneous materials. This principle is referred to by Fraunhofer-IZFP as the "Inverse Phase-Matching" technique [32, 33]. The SynFo algorithm is used to process the contribution from each individual transducer element in the test aperture for every image point. In homogeneous acoustically isotropic materials, this computation is quite simple and requires the determination of the geometric distance of the image point location to the individual transducer elements. In the case of anisotropic and/or heterogeneous materials, differing acoustic velocities, which can be direction dependent, must be considered for data processing.

If the material structure is well known, the current technology permits quick and accurate computing of the travel times from all image points to the individual transducer elements so that the image reconstruction from the time domain signals $A_{iJ}(t)$ is phase matched.

If the material structure can only be estimated through modeling, the reconstruction can, in principle, be enhanced through variation of model parameters or, analogous with medical technology, through correlation techniques. This will permit not only flaw detection and confirmation, but also structural characterization.

Figures 9 and 10 show results from the evaluation of a sample with artificial flaws in a homogeneous anisotropic structure with various orientations.

The sample shown in Figure 9 was used to verify elasto-dynamic simulations. Figure 11 shows the complexity of the sound propagation in such materials [34].

4. Technology Forecast

The recent developments in ultrasonic technology described above are expected to result in NDT techniques which will permit more effective and more meaningful evaluation of austenitic stainless steel and dissimilar metal welds.

Appropriate equipment is available to conduct the necessary evaluation experiments on test specimens as part of the effort to qualify the newly developed approaches.

The goals of these experimental evaluations include:

- Demonstrate conformity to codes, regulations and existing practices
- Expanding the technology capability for matrix array evaluation
- The compilation of a database and models for the analysis of sound wave propagation in welded materials correlating to form of manufacture and welding technologies
- The development of a practicable field-deployable technique to verify test results (demonstrator)

Initial experiments to demonstrate practicable techniques for the evaluation of longitudinal oriented flaws are depicted in Figure 12. The transducer array consists of elements which can individually follow the surface contour to assure optimized acoustic coupling (e.g., pipe curvature). The transducer array aperture covers the entire test area and volume in such a way that assures that focusing is uniform over the whole area of interest.

The use of computer simulations can optimize the number and positioning of the search units to be employed for existing systems and for the design of systems to be built. The same applies for determining the transducer element apertures, optimized test frequencies and sound mode selection.

This linear arrangement of the transducer elements satisfies the requirements for the detection and evaluation of longitudinal oriented flaws, and may be expandable, using the same principles, for the detection and evaluation of flaws with arbitrary orientations [35, 36].

5. References

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