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Ultrasonic Sampling Phased Array Testing as a Replacement for X-ray Testing of Weld Joints in Ship Construction

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ABSTRACT: According to European Standard EN 1712 ultrasonic testing of thin-walled welded joints is mandatory for wall thicknesses of more than 8 mm only. Any thinner components do have to undergo X-ray inspection.
Besides various advantages of X-ray testing viz. high sensitivity to smallest inclusions, high acceptance in the ship building sector and "automatic" documentation of inspection results, there are also several deficiencies (like radiation protection issues, inspection time expenditure etc.) creating a reasonable request for more cost-effective alternatives.
Sampling Phased Array technology introduced by Fraunhofer-IZFP provides significant improvement of flaw detectability also in thin-walled welded joints due to its tomographic approach in processing of signals obtained by ultrasonic phased array transducers. It allows high-quality imaging of welded joints and detection of relevant material flaws. Real-time ultrasonic imaging with tomographic quality offers a great alternative to X-ray testing with respect to inspection speed and modern documentation of inspection results.
The basic principles of Sampling Phased Array are presented in the paper and several application results obtained on welded joints of marine objects are presented.

1 INTRODUCTION / TASK DEFINITION

In ship structural design and assembly standard non-destructive testing methods include visual, eddy-current, liquid penetrant, ultrasonic and x-ray testing as well as leakage tests. Prevalent techniques for welded joint inspection are x-ray and ultrasonic testing as the most cost-effective and efficient in respect for flaw detection.

Non-destructive testing operations are performed in the scope of quality assurance arrangements according to classification instructions, specifications of ship design and regulations of the manufacturing process [1]. Thus a written procedure for welded joint testing has to be established for any new ship design where the inspection areas have to be defined. Through classification instructions the minimum requirements to be fulfilled for non-destructive testing are defined. Those have to be implemented in the written procedures for particular construction elements.

The non-destructive testing of welded joints is described in the currently generally admitted European codes and standards DIN EN 12062, DIN EN 25817, DIN ISO 5817, ISO 6520.

Since many years x-ray testing is considered as a proven technique for inspection of welded joints in ship construction. Generally speaking its advantages and disadvantages can be seen as follows [2]:

Table 1: Advantages and disadvantages of x-ray testing

Advantages	Disadvantages
Sensitive to both surface and volume flaws	Limitations for thick-walled components
Direct documentation of the inspection results by film	Inspection sensitivity is related to the wall thickness
Flaw size and shape can be directly seen and evaluated	Crack orientation must be known for optimal flaw detection
No direct access to the component is required	Defect height normally can't be defined
	Time consuming technique with significant equipment expenses
	Radiation hazard

Though, this method requires significant operating effort for adherence of radiation protection a spatial separation of inspection area is required. Hence no further work can be simultaneously conducted in the neighborhood. This can lead to significant decrease in manufacturing productivity.

Ultrasonic testing of welded joints is a significant alternative to x-ray testing that can be applied, which in general has the following advantages and disadvantages [2].

Table 2: Advantages and disadvantages of ultrasonic testing

Advantages	Disadvantages
Testing of thick-walled components is possible without limitations	Acoustic coupling (surface contact) is required. Limitations due to surface roughness are possible
Evaluation of flaw size, type, orientation can be obtained.	High requirements on inspection staff due to rather complex calibration of UT instrument
Fast, cost-effective testing with immediate conclusion about indication	
Automated or half-automated inspection and evaluation can be implemented	Limitations on flaw detectability due to suboptimal insonification position or flaw orientation
NEW!: Imaging techniques like phased array allow documentation and quantitative evaluation of inspection results	

For being able to replace x-ray by ultrasonic testing the following tasks must be solved:

- Equal or better flaw detectability of relevant flaws compared to x-ray
- Fast representation and evaluation of inspection results
- Cost-efficient implementation of inspection system and inspection procedure
- Mobile inspection system for in-situ applications

2 SAMPLING PHASED ARRAY TECHNIQUE

The novel ultrasonic inspection technique rapidly coming into industrial application is phased array [3, 4]. Phased array testing offers significant advantages for ultrasonic testing (UT) of welded joints due to its extended information content provided by beam steering capability. Hence the combination of mechanical scanning and electronic beam steering increases flaw detectability, since it is being insonified from various angles of incidence.

Phased array techniques may also have their limitations in certain applications with respect to spatial resolution in the far field of phased array transducers or inspection speed while beam steering over a big angle range and finite signal-to-noise ratio of the system can be seen as an advantage.

Sampling Phased Array (SPA) technology developed by Fraunhofer IZFP is a next step in Phased Array technology. On the one side the technique is capable of fast synthesis of phased array ultrasonic signals for arbitrary angles of incidence with focusing in all the depths within the probe near field. On the other hand the back projection and overlapping in the volume the elementary wavelets obtained by SPA according to synthetic aperture focusing technique (SAFT) principles offers the best possible image reconstruction quality.

The SPA technique offers the following practical advantages:

1 Ultra-fast virtual beam sweep for arbitrary angle range
2 Improved sensitivity and resolution in the near field of the transducer
3 Fast 2D / 3D imaging

Unlike conventional Phased Array technique insonifying the inspection volume by directed sound fields under different angles of incidence, Sampling Phased Array performs data acquisition by exciting cylindrical or spherical waves that propagate in all directions. This can be implemented by firing single array elements or applying defocusing delay laws (Figure 1). Hence a very wide angle range can be covered after a single shot.

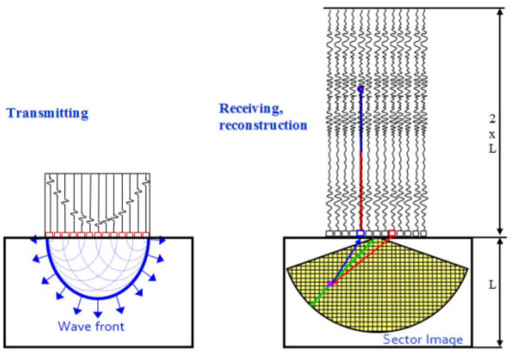


Figure 1: Defocused transmission and sector image reconstruction by SPA

The ultrasonic signals acquired and saved in each probe position for every single array element serve as an input data for image reconstruction. The reconstruction occurred according to the SAFT algorithm [5]. Since the sound field of array elements is very divergent, every time signal (A-scan) received contains overlapped echo-signals from available reflectors in different volume positions. The reconstructed image in one position of linear array visualizes a cut plane perpendicular to insonification surface, the so called sector-scan. For every point within this plane the propagation times from the transmitting elements and back to the receiving elements are calculated. The amplitude values from all A-scans with matching propagation times are added up in each image point [6].

Thus all angles of incidence and focal depths within the near field of the transducer can be realized even after one single transmitting/receiving act. Since the sound beam steering at each volume point, i.e. for all angles of incidence and focal depth, is performed not physically but virtually through the computer, a significant increase in inspection speed can be achieved by implementation of the SPA principle [7]. Furthermore the synthetic focusing in the near field of the UT transducer by the SAFT principle improves sensitivity and resolution (Figure 2).

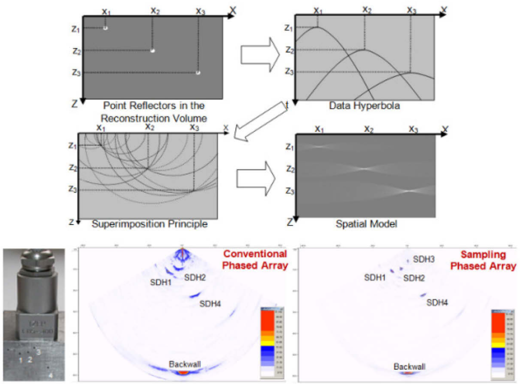


Figure 2: Principle of image reconstruction by SPA

Thus for weld inspection the material flaws can be represented in tomographic quality that allows their exact sizing (Figure 3).

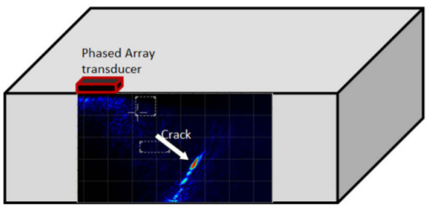


Figure 3: Tomographic Image of an inclined lying crack

3 INSPECTION SYSTEMS FOR INDUSTRIAL APPLICATIONS

Modern instrument engineering, e.g. latest signal processors and computers, offer sufficient computation power for performing SPA image reconstruction and processing, that outmatches conventional phased array systems in speed and quality. Versatile reconstruction techniques [8] can be implemented in a portable manual flaw detector (Figure 4).

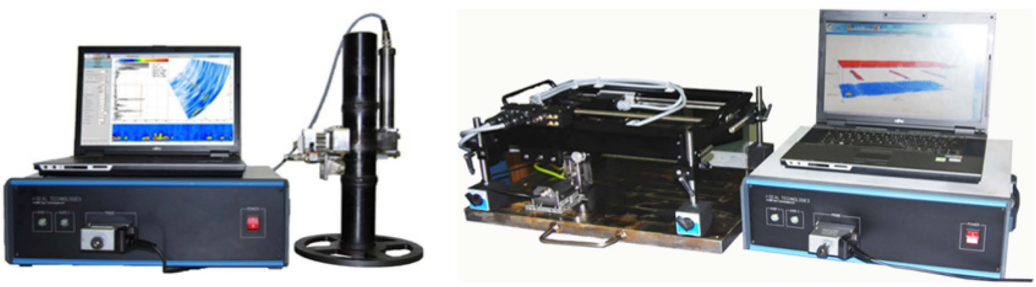
Figure 4: Manual ultrasonic tomograph A1550 IntroVisor by ACSYS

One of the main advantages of ultrasonic testing is its ability to be implemented in automated or semi-automated way, providing fast and cost-effective inspection solutions for industrial applications.

4 ULTRASONIC IMAGING SYSTEMS AS REPLACEMENT FOR X-RAY IMAGING

While position related data acquisition provided by a manipulator or encoder wheel the ultrasonic image can be reconstructed in such a way that it represents the inspected area similar to the X-ray film (Figure 6). The Sampling Phased Array technique with its improved image processing capabilities, e.g. eRDM technique [9], can provide especially sharp and high-contrast images for detecting relevant welding defects. The evaluation of inspection results can be performed based on equivalent flaw size, e.g. by calibrating on artificial defects like notch or side drilled hole or by use of novel image processing algorithms for fast quantitative flaw sizing.

Especially for thin-walled welded joints the Sampling Phased Array technique offers specific advantages due to improved sensitivity and resolution in the near field of array transducer.



SPA System for circumferential weld seams SPA System for longitudinal weld seams

Figure 5: Semi-automated SPA systems with 2D and 3D imaging capabilities

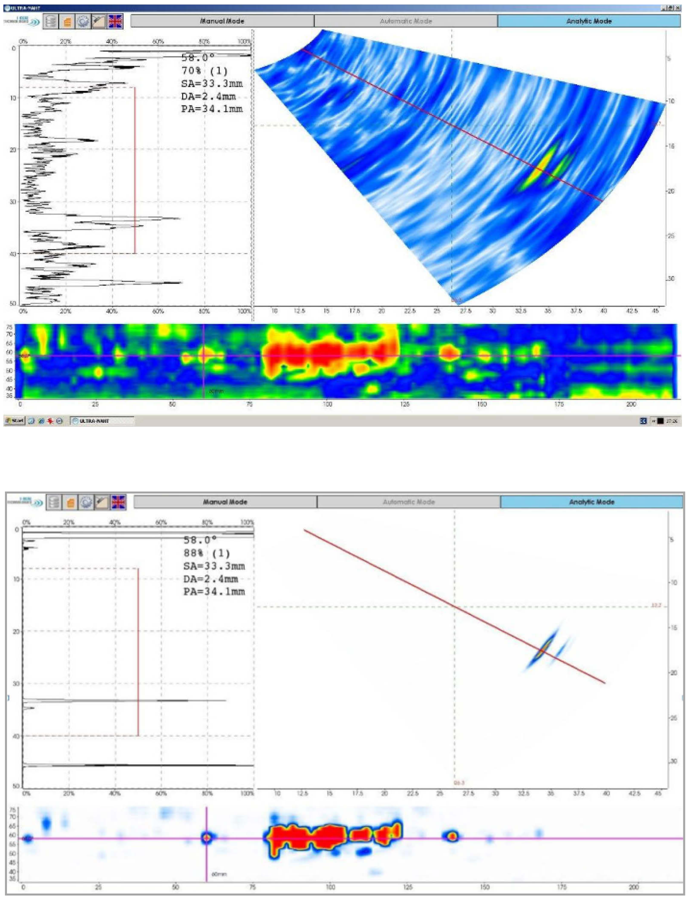


Figure 6: Ultrasonic inspection results on the weld seem with a wall thickness of 6 mm with an elongated cavity in conventional and Sampling Phased Array mode

The current state of standardization of ultrasonic Phased Array testing in Europe is significantly behind schedule when compared to state of the art technology. Codes required like ISO DIS 13588 are in preparation phase.

Fraunhofer IZFP has gathered positive experience in introducing novel phased array techniques to the industrial market as a replacement for X-ray testing of heat exchanger pipes in power plants [9]. The technique was especially developed for testing thin-walled pipes. The ultrasonic testing procedure applied is in accordance to a TÜV Süd specification. Despite novelty of the testing method it could be shown that the ultrasonic imaging provides equivalent performance and reliability like established testing procedures.

5 CONCLUSION

The Sampling Phased Array technique is an enhancement to conventional phased array which does processing of the single shot data sampling taken off-line but in principally real time. Enhanced sensing and data sampling rates allow large data samples to be taken which again lead to 3D images to be generated at comparatively high resolution. Enhanced introduction of SPA into areas where X-ray testing is currently dominating will lead to:

- Comparable or better flaw detectability
- Higher cost-effectiveness
- Prompt evaluation of inspection results
- No radiation protection
- Mobile and stationary inspection set-ups

This may be achieved through handheld as well as automated inspection systems on site, being a considerable advantage in qualifying large ship hull structures.

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