Ultrasonic inspection of spent nuclear fuel casks

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Abstract. The paper describes the main aspects of ultrasonic non-destructive inspection of casks with spent fuel. Digital Focus Array technique is proposed for acoustic imaging of spent nuclear fuel casks' closure weld. Scientific and engineering basics and imaging algorithms of this technique are discussed. Advantages of Digital Focus Array technique in comparison with common techniques of acoustic images processing are revealed.

Introduction

Spent nuclear fuel (SNF) is potentially the most hazardous product of nuclear energy application, it contains up to 98% of total radioactivity which is concentrated in all materials of nuclear fuel cycle. Presence of fissionable materials, hypertoxicity of radionuclies and residual heat release in SNF requires advanced safety measures as well as special technologies of its treatment. 8,500 tons of SNF out of approximately 10,500 tons of annually accumulated SNF in the world is placed in SNF storages, the rest amount is placed for long term storage and reprocessing. International Atomic Energy Agency (IAEA) does not establish any regulations related to methods or terms of storage, however IAEA states that the terms of storage of SNF in dry storage casks can reach a hundred years period. For instance, Nuclear Regulatory Commission (NRC) reached the decision about the possibility of SNF storage in dry casks for the period of 60 years after the reactor fuel uploading. However the problem of long-term storage remains the most important problem for nuclear industry of all countries. It is evident that to perform such long-term storage an effective technique of quality control of constructions is required which would not infringe the integrity of technological processes related to storage and transportation of controlled objects.

1. Ultrasonic Inspection of SNF Casks

The necessity of weld joints inspection and residual life assessment of SNF casks leads to development of new techniques in non-destructive testing [1, 2]. One of the promising inspection techniques is ultrasonic inspection.

However the transducers positioning for ultrasonic inspection represents serious problem in relation to SNF casks. At nuclear power plants manual ultrasonic inspection can be performed only in case of the shutdown situation in order to avoid unacceptable exposure of NDT inspectors. Accessibility and ecological factors do not allow to perform such inspection for SNF casks. Scanning is proposed to be performed by the means of steel rod with the ultrasonic transducer positioned at one of its ends or by the means of robot caterpillar chassis.

In one of the published papers [3], ultrasonic inspection of cask is performed by the means of phased array transducers. Preliminary the cask lid area is divided into two control zones as it is shown in Figure 1. Taking into consideration that the thickness of each zone varies, different focal depth is applied during scanning.

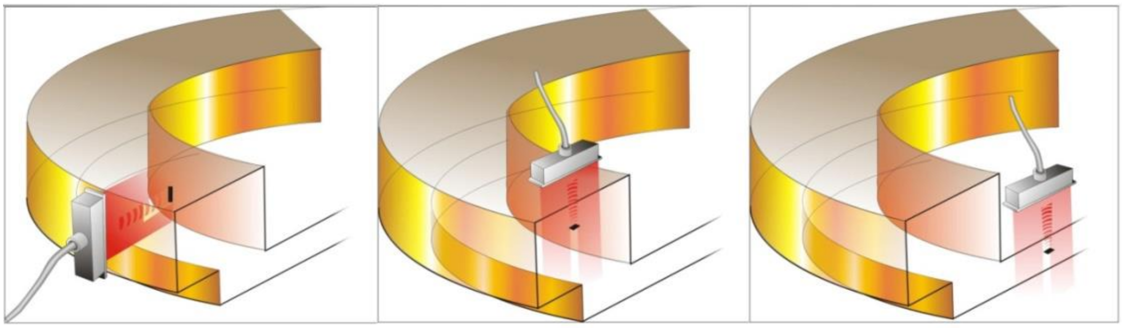

Figure 1. Ultrasonic inspection of cask lid.

In the paper [4] inspection of friction welded joint was performed by the means of ultrasonic testing and radiography (Figure 2). Linear phased array transducer is used for ultrasonic inspection; the transducer is positioned on the cask lid surface. Digital radiography is performed with 9 MeV linear accelerator in combination with linear X-ray detector.

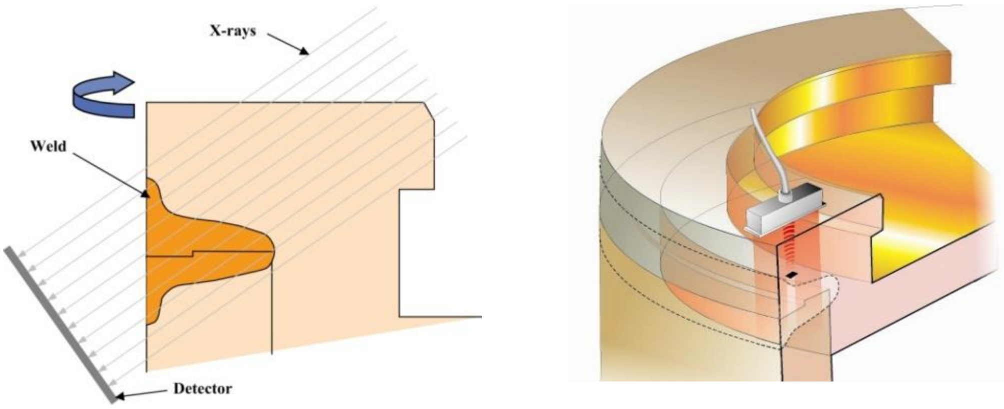

Figure 2. Radiography (left) and ultrasonic inspection (right) of friction welded joint.

2. Digital Focus Array Imaging Visualization Technique

Unfortunately the commercially available image reconstruction algorithms and inspection equipment do not allow to reconstruct 3D images of the controlled object. Reconstruction algorithms applied in X-ray inspection use Radon transform defining varying degrees of X-ray attenuation passed through the controlled object with flaw and flawless controlled object. During ultrasonic inspection almost total ultrasonic wave reflection takes place at boundaries between flaw and flawless area. Due to this, direct application of such algorithm becomes not feasible. Special algorithms for acoustic data treatment need to be developed to obtain 3D image of the controlled object. The algorithms will allow to determine the coordinates of defects locations as well as defects size enabling objective evaluation of product condition and its further service life.

A new technique of measurement and images reconstruction with application of typical multielement transducers was developed at Tomsk polytechnic university in collaboration with Fraunhofer Institute for Nondestructive Testing (IZFP) [5, 6]. Digital Focus Array Technique (DFA) is applied with only one phased array element transmitting a signal, while the rest elements are receiving it. Received time signals are saved. For example, one of the tacts of measurement is sending out *i* element, the elements from 1 to *N* receive the signal, the matrix Aij is formed (Figure 3). After N tacts the matrix is full – it contains time signals of each combination transmitter-receiver.

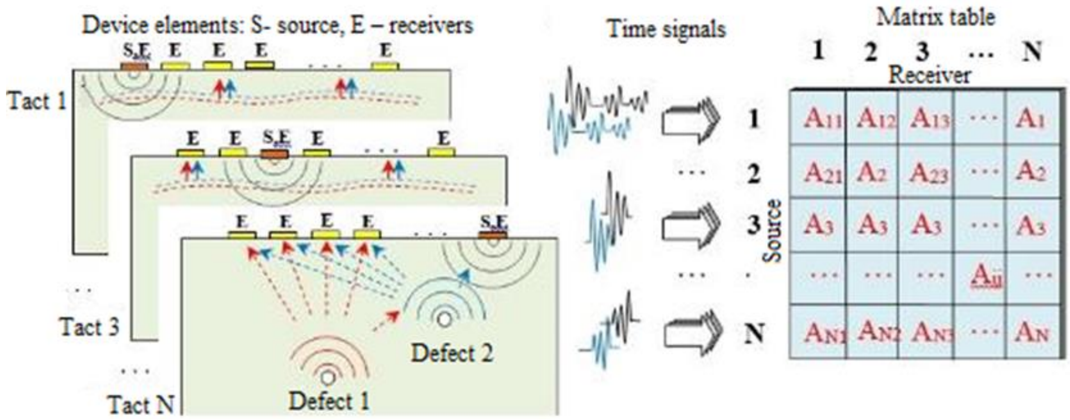

Figure 1. DFA technique principles.

In the basis of the Digital Focus Array concept is the idea that physical superposition of elementary ultrasonic waves formed in material by phased arrays can be generated artificially. Elementary waves can be presented by matrix elements using impulse multielement transducer. Having summed up the signals in relation to desired focusing it becomes evident that sound wave propagation periods from the transmitter to the point in material volume obtained by artificial net A-scan are absolutely equivalent to periods obtained by common transducers.

DFA-reconstruction principle is explained using the linear phased array example. In case of linear array processor the reconstruction area is the surface perpendicular to the controlled object surface. The corresponding image is represented by sector-scan on analogy with the common technique.

The back projection of measured time signals is realised in the following way: sector diagram is divided into separate pixels. For each pixel of the reconstruction area the wave propagation time T_{ij} to and back from the pixel (X_m, Z_m) is calculated considering actual transmitter position (X_i, Z_i) and receivers position (X_j, Z_j) with determined wave propagation speed. Further the amplitude value of wave propagation time is summed up to the already saved value for the pixel (Figure 4). This procedure is repeated for each combination «receiver-transmitter».

Whereas the multielement transducers create divergent acoustic field, separate elements do not provide data about azimuth location of reflector – geometrical location of projected signals A_{ij} answers to hemisphere with $i=j$ or to semiellipse with $i\neq j$ (Figure 5). With increase of data received (number of multielement array transducers) the defect in the material is more visible in reconstructed sector-scan (Figure 5).

Wave propagation time of each wedge element for each volume point can be calculated and recorded in so-called subsidiary table. Thus the process of image reconstruction can be accelerated. Physically realized focusing area and subsequently improved resolution power of multielement transducers techniques in wedges is limited to the area of immediate fields. This means that for components with greater thickness the advantage of the technique is only in the speed of data processing and image reconstruction. Based on the size of the area of study the conclusion can be made that frequency of images receiving and processing can reach one KHz that corresponds to the speed of about one meter per second in measurement automation.

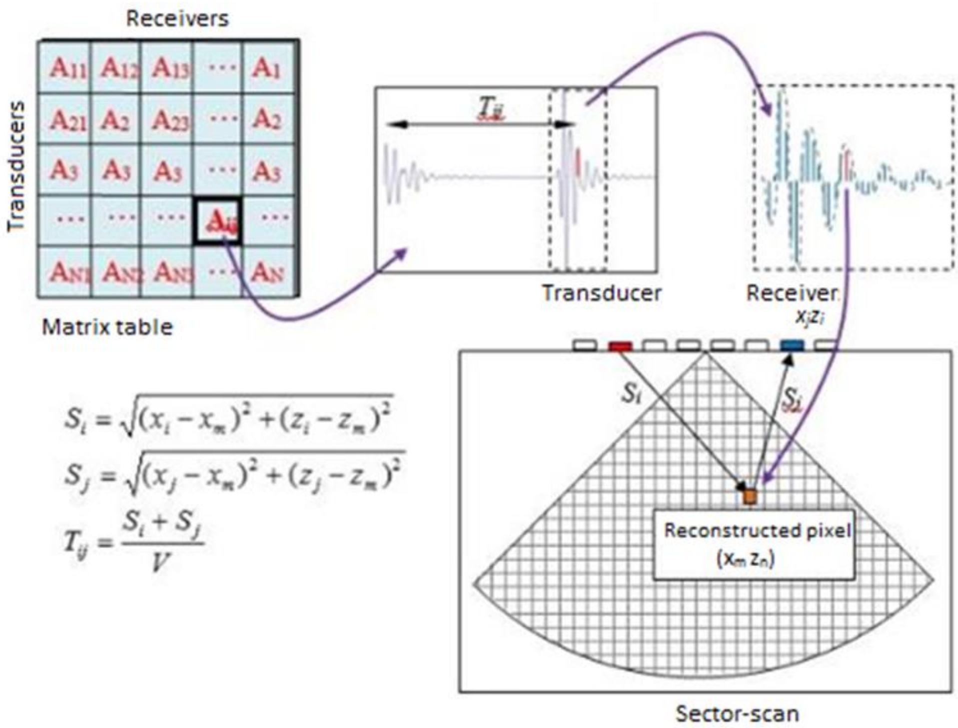

Figure 4. Sector-scans reconstruction principles.

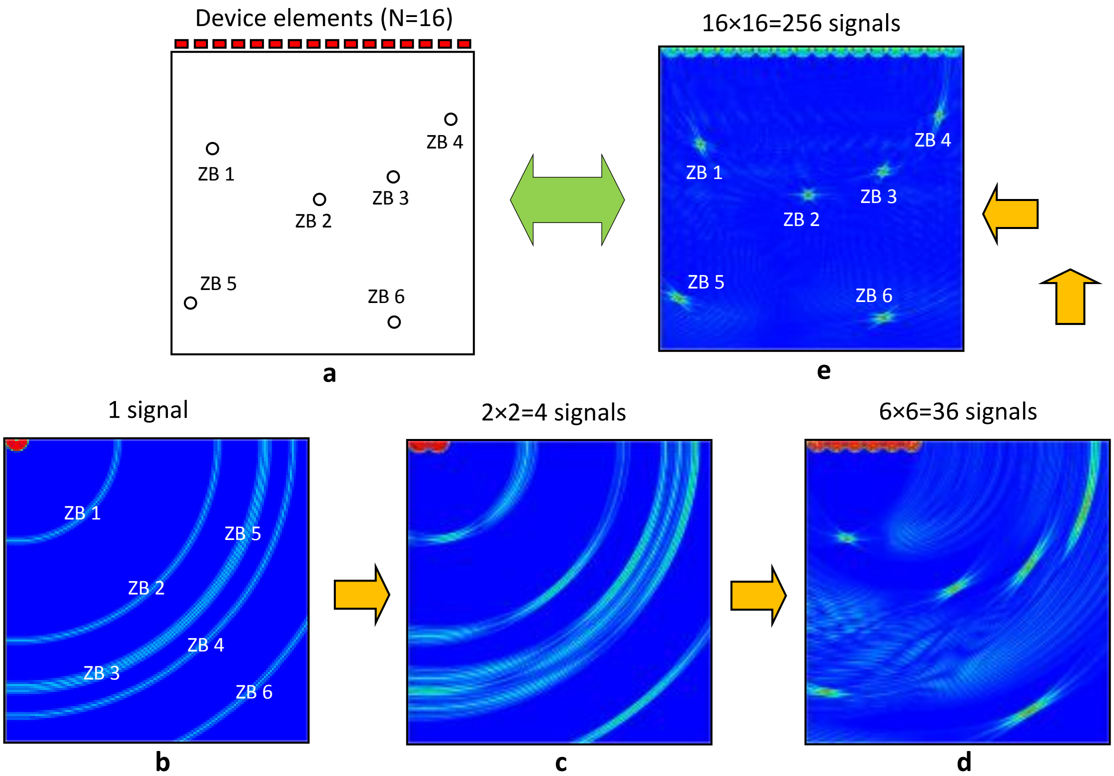

Figure 5. Example of image reconstruction for Sector-scan for 16 element transducer. Times of propagation of waves reflected by six side-drilled holes form the image according to DFA technique.

If 2-D sector diagrams (sector-scans) of neighboring transducer positions are imposed on one another the situation can be improved for materials with greater thickness thus enabling the opportunity to increase the focal area by constructing 1-D synthetic aperture (Figure 6).

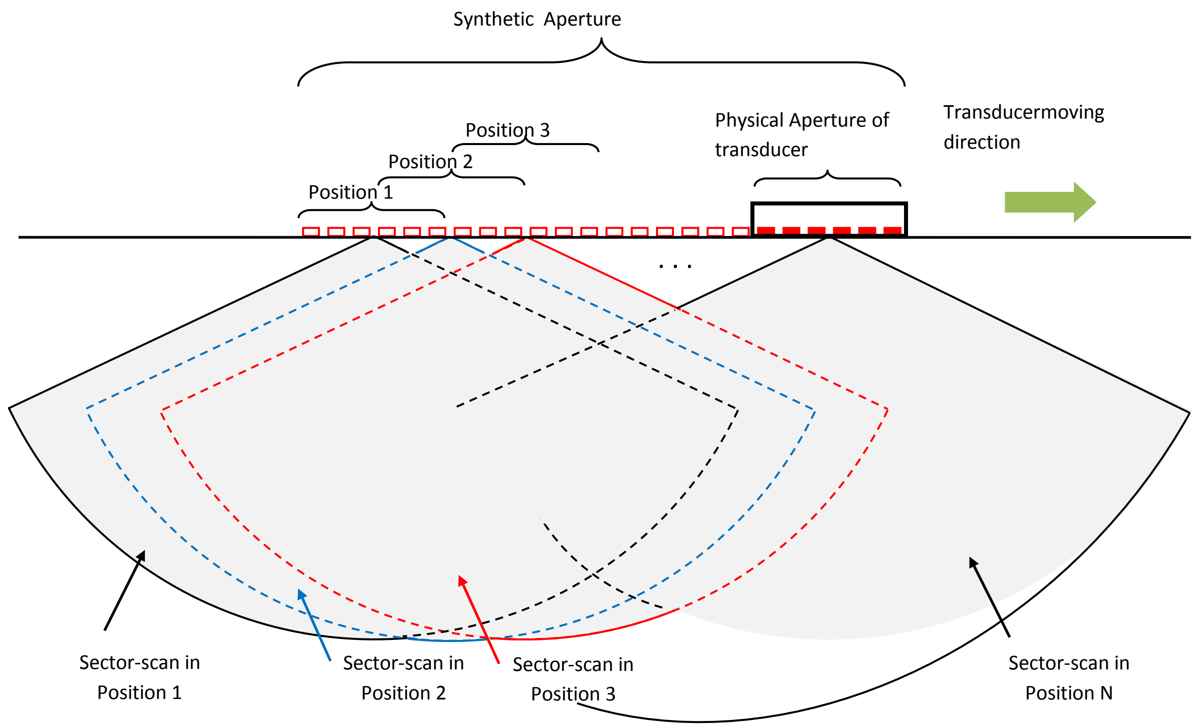

Figure 6. Construction of synthetic aperture.

In contrast with common reconstruction using SAFT algorythm, here not separate time signals are summed up but rather 2-D amplitude fields. Thereby as well as during SAFT-reconstruction physically realized focal area is increased, in which the 2-D data field (compound scan) is built in sectional plane. Among other ultrasonic reconstruction techniques DFA technique demonstrated higher effectiveness, inspection results are notable for high resolution capacity and contrast [7, 8].

3. Conclusion

Application of radiographic, thermographic, eddy current and ultrasonic inspection techniques is known in the world practice. Radiographic inspection involves additional radiation exposure for personnel, as well it does not allow to detect a number of critical defects, for example «kissing bond» defect. Thermographic inspection requires thermal dynamics of an object hence additional heating of an object is required. Eddy current inspection has fundamental limitation in the depth of defect occurrence (about 1 mm). Complexity of received data interpretation and high requirements to the level of operating personnel qualifications are referred to as the main limitations of ultrasonic inspection. Suggested advanced ultrasonic visualization and image reconstruction techniques are free from the limitations mentioned above.

Currently existing common techniques of presenting accosting data are not sufficiently informative. With development of signals digital processing the quality of inspection results became comparable with the level of data detail acquired during radiographic inspection. The most efficient direction of technologies development is considered to be SAFT and Digital Focus Array technique (developed at TPU in collaboration with Fraunhofer Institute for Nondestructive Testing (IZFP)) which represent further development of phased array techniques.

The paper reveals that the suggested new technique of measurement and ultrasonic signals reconstruction - Digital Focus Array (DFA) possesses high details of data in comparison with common methods of acoustic data representation. The technique allows to perform tomographic reconstruction of defects` images in controlled object in real-time mode, ensures high data validity, reliability, reproducibility and high efficiency of ultrasonic nondestructive inspection techniques.

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