Fusion Engineering and Design 126 (2018) 124–129

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Fourier-domain post-processing technique for Digital Focus Array imaging with Matrix phased array for ultrasonic testing of ITER components

D.O. Dolmatov[a,*], D.G. Demyanyuk[a], A.H. Ozdiev[a], R.V. Pinchuk[b]

[a] National Research Tomsk Polytechnic University, 634050 Tomsk, Russia
[b] ACS-Solutions GmbH, Science Park 2, 66123 Saarbrücken, Germany

A R T I C L E I N F O

Keywords:
Ultrasonic nondestructive testing
Ultrasonic imaging
Matrix phased arrays
Quality control

A B S T R A C T

The high demands on the quality of the components of the International Thermonuclear Experimental Reactor (ITER) create the need to apply methods of nondestructive testing which are able to provide accurate and reliable results. One such technique is Digital Focus Array ultrasonic imaging with Matrix phased arrays. The application of this approach is linked with the need to process huge sets of data in order to obtain images of controlled objects. In this article, we propose the technique of computationally efficient Fourier-domain post-processing. This algorithm is based on Fast Fourier transformations and calculations in frequency domains and can be applied in immersion and contact testing. The performance of this technique was examined experimentally.

1. Introduction

The fabrication of International Thermonuclear Experimental Reactor (ITER) components demands strict quality control. An important part of this quality control is the application of nondestructive testing methods. Immersion pulse-echo ultrasonic testing is considered as one of the methods which can be used for the inspection of ITER components [1,2].

Advanced approaches can be used to increase the versatility, precision and accuracy of immersion ultrasonic testing. The application of Local Immersion technique allows obtaining the consistent coupling in case of big objects inspection. The Local Immersion technique is based on the formation of the water layer between the ultrasonic transducer and the controlled object by the application of a local water bath; this provides the required acoustic contact between the surface of controlled object and the transducer. This technique could be useful for the testing of objects which cannot be inspected through the conventional method of immersion ultrasonic testing due to their size or in the scenario of in-site inspections [3].

Furthermore, it is possible to increase the precision and reliability of ultrasonic inspections by applying systems which process the measured echodata. Such systems allow obtaining high resolution images of the flaws in a controlled object. These images allow determining size of the flaws, their shape and location in specimen. This information can be used for reliability assessment of the controlled objects.

Ultrasonic post-processing techniques aim to solve the inverse scattering problem. The quality of results is determined by the accuracy of applied post-processing technique and the size of measured data. Phased array probes can be used to obtain comprehensive data about the internal structure of a controlled object. These type of ultrasonic probes consist of numerous elements (which are mounted in a singular casing). Multi-channel electronic units operate transmission and reception of ultrasonic signals for each element. Application of Digital Focus Array or Full Matrix Capture techniques by using phased arrays presupposes the utilization of all combinations of transmitter and receiver elements for the sampling of ultrasonic data [4]. The main advantage of applying the Digital Focus Array technique is linked with the ability to obtain high-resolution images of the flaws in a controlled object.

All varieties of existing phased array probes could be divided into linear and matrix arrays. Matrix phased arrays are ultrasonic probes which use the two-dimensional locating of elements; this allows us to obtain a three-dimensional image in a single position. These probes in immersion testing could provide us with precise results and reduce inspection time. However, huge sets of data need to be processed in order to obtain such an image. In this case, the computationally efficient post-processing techniques could be applied for obtaining the high-resolution images of the flaws in controlled objects with acceptable speed.

* Corresponding author.
E-mail address: dolmatovdo@tpu.ru (D.O. Dolmatov).

https://doi.org/10.1016/j.fusengdes.2017.11.020
Received 21 July 2017; Received in revised form 9 November 2017; Accepted 22 November 2017

2. Materials and methods

In the areas that are based on physical principles which are close to pulse-echo ultrasonic nondestructive testing (e.g. radars and seismology), Fourier-domain methods of data post-processing are used extensively due to their high computational efficiency [5]. The application of Fourier-domain techniques in ultrasonic testing has been considered in numerous publications. Stepinsky [6] considers applying such an approach to ultrasonic imaging with a single transducer and contact testing. The idea of contact ultrasonic testing with Linear arrays and Full Matrix Capture imaging was considered by Hunter et al. [7]. The adaptation of Fourier-domain techniques for immersion testing and inspections of multilayered objects was considered by Skjelvareid et al. [5]. Furthermore, such techniques were adapted for ultrasonic testing of non-planar specimens. Skjelvareid et al. and Wu et al. considered the application of Fourier-domain methods for inlet and outlet pipe inspections [8,9]. The application of frequency domain techniques for complex-shaped specimens by using single transducers and linear arrays was considered by Lukomski [10] [11]. All of the cases discussed above are based on the Phase Shift Migration algorithm [12] and Stolt interpolation [13] which first found their application in seismology.

The task of Digital Array imaging with Matrix phased arrays in the case of immersion ultrasonic testing is a special issue which is conditioned by the necessity to take into account the several factors include the necessity to make three-dimensional ultrasonic imaging, the presence of media with different acoustic properties and the fact that Digital Focus Array imaging is not a monostatic case. In this case, existing approaches in Fourier-domain imaging should be adapting for the solution of this specific task. In this article, we propose the algorithm for Digital Focus Array imaging with matrix phased arrays based on Phase shift migration algorithm and Stolt transform.

3. Theory

3.1. Wavefield equation

Firstly, we will consider the single-element mode of matrix phased array operation. In this mode, the transmitter and receiver of the ultrasonic waves are the same element. In this case, the acoustic field can be denoted as a function p(t, x, y, z), where t is the time and x,y,z are coordinates of the matrix array element. Coordinate z is a constant for every element due to the fact that data sampling occurs in one plane. In this case, the three-dimensional wave equation is valid:

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^{\,2}}{\partial z^2}-\frac{1}{\hat{c}_l}\frac{\partial^2}{\partial t^2}\right]p(t, x, y, z)=0, \tag{1}$$

where $\hat{c}_l$is a half of the speed of longitudinal waves in the media.

The application of half of the speed is created by the fact that the proposed technique is based on so-called Exploding Reflector model [5]. Application of such Model is aimed at the adaptation of considered approaches to the ultrasonic testing. Fig. 1 illustrates the concept of exploding reflector model for the two-dimensional case. Three-dimensional case is straightforward. According to these Model pulse-echo measurements is considered as a measurement of single acoustic event where flaws are acting as a source of acoustic waves.

The partial solution of Eq. (1) can be written in the following form:

$$p(t, x, y, z)=Pe^{i(k_x x+k_y y+k_z z-\omega t)}, \tag{2}$$

where ω is the angular frequency and k_x,k_y,k_z are the components of wavenumber vector.

The following dependence between wavenumber components and angular frequency can be obtained by inserting the partial solution 2 to the Eq. (1):

$$\frac{\omega^2}{\hat{c}_l{}^2}=k_x^2+k_y^2+k_z^2. \tag{3}$$

The relation 3 can be transformed to the following form by conceding that k_z as a dependent value and acoustic waves propagate in negative z direction according to explosive reflector model [5]:

$$k_z=-\frac{\omega}{|\omega|}\sqrt{\frac{\omega^2}{\hat{c}_l{}^2}-k_x^2-k_y^2}. \tag{4}$$

The general solution of the Eq. (1) is a linear combination of linearly independent partial solutions. It is possible to present partial solutions in the following form:

$$p(t, x, y, z)=\int\int_{-\infty}^{\infty}\int P(\omega, k_x, k_y)e^{i(k_x x+k_y y+k_z(\omega,k_x,k_y)z-\omega t)}dk_x dk_y d\omega\,. \tag{5}$$

The following assumption can be made:

$$P(\omega, k_x, k_y, z)=P(\omega, k_x, k_y)e^{ik_z(\omega,k_x,k_y)z}\,. \tag{6}$$

In this case the Eq. (5) can be written in the following form:

$$p(t, x, y, z)=\int\int_{-\infty}^{\infty}\int P(\omega, k_x, k_y, z)e^{i(k_x x+k_y y-\omega t)}dk_x dk_y d\omega \tag{7}$$

Integral 7 is three-dimensional inverse Fourier transform of the complex function$P(\omega, k_x, k_y, z)$.

3.2. Wavefield extrapolation and imaging by using Phased Shift Migration algorithm

The dependence between acoustic fields on the depth $z+\Delta z$ and on the depth z by using relation 6 can be written in the following form:

$$P(\omega, k_x, k_y, z+\Delta z)=P(\omega, k_x, k_y, z)e^{ik_z\Delta z} \tag{8}$$

The application of dependence 8 allows writing integral 7 for the acoustic field on the depth$z+\Delta z$:

$$p(t, x, y, z+\Delta z)=\int\int_{-\infty}^{\infty}\int P(\omega, k_x, k_y, z)e^{ik_z(\omega,k_x,k_y)\Delta z}e^{i(k_x x+k_y y-\omega t)}dk_x dk_y d\omega \tag{9}$$

The application of integral 9 allows us to extrapolate the wavefield to the desired depth. Furthermore, it is possible to derive the image of the layer $z+\Delta z$by using imaging conditions [14]:

$$I(x, y, z+\Delta z)=p(t=0, x, y, z+\Delta z). \tag{10}$$

The following formula for layer imaging is derived by inserting 10–9:

$$I(x, y, z+\Delta z)=\int\int_{-\infty}^{\infty}\int P(\omega, k_x, k_y, z)e^{ik_z(\omega,k_x,k_y)\Delta z}e^{i(k_x x+k_y y)}dk_x dk_y d\omega\,. \tag{11}$$

Application of relation 11 makes it possible to implement the slice-by-slice imaging of the specimen. This approach is called Phase Shift migration algorithm.

3.3. The imaging through the stolt transform

In the case of multiple layers with the similar acoustic properties including speed of the acoustic waves Stolt transform is more computationally efficient and can be implemented instead of Phase Shift Migration algorithm [5,15].

According to this approach in relation 3, angular frequency is chosen as a dependent variable:

$$\omega(k_x, k_y, k_z)=-\frac{k_z}{|k_z|}\cdot\hat{c}_l\cdot\sqrt{k_x^2+k_y^2+k_z^2}\,. \tag{12}$$

Inserting the 12–11 causes the following