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Applying the Algorithm of Calculation in the Frequency Domain to Ultrasonic Tomography

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Abstract—Applying ultrasonic-tomography systems makes it possible to precisely determine the shape and dimensions of flaws with the aim of establishing the degree to which the flaws influence safe operation of tested objects. This problem is solved by using special algorithms that make use of echo-signals recorded by an ultrasonic transducer to generate synthesized images of flaws in the sample. The use of phased arrays in ultrasonic tomography is explained by their ability to provide exhaustive data about the internal structure of a test object, thus allowing formation of the high-quality synthesized images of flaws in the object. Increasing the speed of ultrasonic tomography by using phased arrays necessitates the development and implementation of fast data-processing algorithms. In this connection, of interest are calculation algorithms in the frequency domain, which ensure the high speed of producing synthesized images. An ultrasonic-tomography algorithm is proposed that is based on calculations in the frequency domain. The algorithm takes the complex nature of the propagation of ultrasonic waves into account and is connected with the presence of media with different acoustic properties (e.g., in the case of immersion tests). Possibilities offered by the algorithm are investigated by computer simulations using the licensed CIVA 2016 software package and experimentally.

Keywords: nondestructive ultrasonic testing, ultrasonic tomography, phased arrays, ultrasonic-tomography algorithms

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INTRODUCTION

Pulse-echo ultrasonic testing is extensively used in construction, power engineering, and other industries owing to its high accuracy and speed and the low costs of running inspections. One of the complications in traditional ultrasonic testing is determining the shape and dimensions of flaws in samples. This problem is solved with a high accuracy by using ultrasonic-tomography systems that produce synthesized images of flaws in a test object. Such systems involve the use of algorithms for the post-processing of recorded ultrasonic echo-signals, which are also called Synthetic Aperture Focusing Techniques. The full diversity of existing algorithms for the post-processing of recorded echo-signals can be divided into algorithms for calculation in the frequency domain and algorithms for calculation in the time domain. The time-domain algorithms for the post-processing of recorded echo-signals are currently being given preference in the practice of ultrasonic tomography [1].

Applying phased arrays (PA) to ultrasonic tomography reflects the need for increasing its speed and quality. PAs are multielement ultrasonic transducers in which the generation and reception of ultrasound is controlled by multichannel electronics units. The use of PAs in ultrasonic tomography necessitated adaptation of existing algorithms for the post-processing of recorded echo-signals, which had been originally developed for single-element transducers [2, 3]. The Total Focusing Method with a double scanning mode [4, 5] was developed to solve this problem. This method assumes in-turn probing by each PA element with the echo-signals being recorded simultaneously by all elements in the ultrasonic transducer. This PA operation mode is also called the Full Matrix Capture [6]. It should be noted that Digital Focus Array, Sampling Phased Array, and Inverse Wavefield Extrapolation use the same principles [7–9].

All the above ultrasonic-tomography algorithms are based on calculations in the time domain. The continuously increasing requirements for the reliability of materials and articles applied in different industries necessitate improvements in the quality of produced synthesized images of flaws in tested objects.

This problem can be solved by increasing the number of elements in PAs, thus also enlarging the volume of data to be processed when generating synthesized images, with the enlarged data volume, in turn, increasing the time needed to obtain the result. Due to this, particular interest is drawn to algorithms of calculation in the frequency domain, in view of their ability to increase the speed of post-processing by using fast Fourier transform [1]. Such algorithms should allow for the complex nature of propagation of ultrasonic waves due to the presence of domains with different acoustic properties, a case that is exemplified by immersion testing, which is widely used in ultrasonic nondestructive testing. In order to develop such an algorithm, approaches used for single-element transducers can be adapted to the case of using PAs in the double scanning mode [10–13]. The existing frequency-domain algorithms for single-element transducers are based on the Phase Shift Migration Algorithm and Stolt interpolation [14, 15].

RESEARCH PROCEDURE

Description of the Algorithm of Calculation in the Frequency Domain for Ultrasonic Tomography using PAs Operating in the Double Scanning Mode

Let us consider the general case of conducting ultrasonic tomography. It assumes the three-dimensional geometry of testing, including the immersion liquid and the sample itself, and the use of a matrix PA in the double scanning mode. In this case, the set of signals recorded by array elements can be represented as a function $P(t, x, y, z)$, where t is time and x, y, z are the coordinates of the median point between a PA element that serves as the source of ultrasound and a PA element receiving the reflected echo-signal. The echo-signals are recorded by PA elements in a plane parallel to the test-object surface, which implies that the z-coordinate remains constant for any x and y. The considered algorithm consists of the following actions:

- the Fourier transform of function $P(t, x, y, z)$;
- extrapolating the acoustic field to the water–test-object interface using the phase shift method;
- producing a synthesized image by means of the Stolt Interpolation followed by the inverse Fourier transform.

The first step in the algorithm is the three-dimensional Fourier transform of function $P(t, x, y, z)$

$$P(\omega, k_x, k_y, z) = 0.125\pi^{-3} \int\int\limits_{-\infty}^{\infty}\int p(t, x, y, z) \exp\left[-i\left(k_x x + k_y y - \omega t\right)\right] dxdydt, \tag{1}$$

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

Extrapolation of the acoustic field by the phase shift method is needed to determine the properties of the acoustic field at the water–test-object interface, which, in turn, is required for producing the synthesized image using the Stolt interpolation. The extrapolation is carried out by the formula

$$P(\omega, k_x, k_y, z + \Delta z) = P(\omega, k_x, k_y, z) \exp\left[i\left(k_z \Delta z\right)\right], \tag{2}$$

where the wave-vector component k_z is expressed as [11]

$$k_z = -\frac{\omega}{|\omega|}\left(\frac{\omega^2}{\hat{c}_l^2} - k_x^2 - k_y^2\right)^{1/2}, \tag{3}$$

where $\hat{c}_l$ is half the velocity of sonic waves in the immersion liquid.

The synthesized image is generated using the Stolt interpolation and the expression

$$I(x, y, z + \Delta z) = \int\int\limits_{-\infty}^{\infty}\int P(k_x, k_y, k_z, z) \exp\left[i\left(k_z \Delta z\right)\right] \exp\left[i\left(k_x x + k_y y\right)\right] dk_x dk_y dk_z, \tag{4}$$

where

$$P(k_x, k_y, k_z, z) = A(k_x, k_y, k_z)\, P\left(\omega(k_x, k_y, k_z), k_x, k_y, z\right), \tag{5}$$

$$A(k_x, k_y, k_z) = -\frac{k_z}{|k_z|} c_l \left(1 + \frac{k_x^2 + k_y^2}{k_z^2}\right)^{-1/2}. \tag{6}$$

The two-dimensional geometry of ultrasonic tomography with a linear PA is a special case of the above algorithm. In this case, echo-signals recorded by the PA elements are represented as a function $P(t, x, z)$, and the algorithm is implemented using the two-dimensional direct and inverse Fourier transforms.

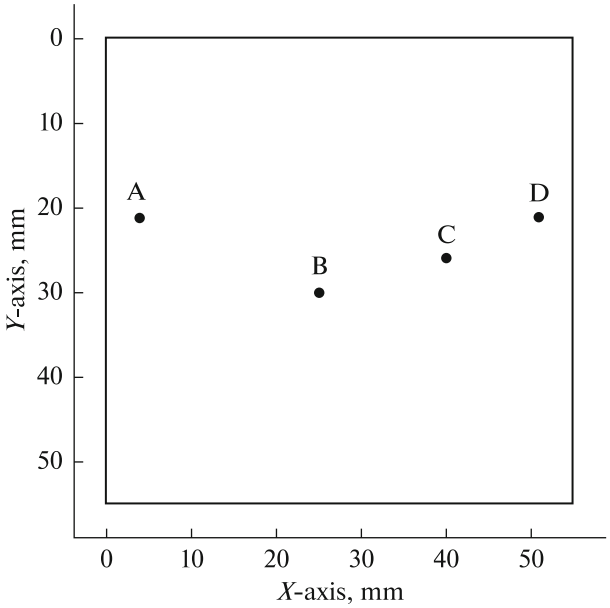

Fig. 1. Location of flaws in the sample.

Computer Simulations

The proposed algorithm was tested using the certified CIVA 2016 software [16], which has the undoubted advantage of incorporating the Total Focusing Method (TFM) algorithm, which can be applied to simulated echo-signals recorded by PA elements and is based on calculations in the time domain [17]. In such a manner, by comparing synthesized images obtained using the TFM algorithm in the CIVA and the proposed algorithm, one can draw the conclusion on whether the latter is suitable for solving the problems of ultrasonic tomography.

The considered ultrasonic-tomography algorithm based on calculations in the frequency domain was computer-implemented using the licensed Matlab R2016b software. The input data for the software were CIVA-2016–simulated echo-signals recorded by PA elements. Applying the algorithm to these echo-signals resulted in a synthesized image of flaws in the test object.

Computer simulation parameters were chosen as close as possible to the conditions of the planned real experiment. For the test object, we took a steel block with dimensions of 55 × 55 × 50 mm with side-drilled 1-mm-in-diameter holes centered at (mm): A(3,9; 21,2), B(25,1; 30), C(40,1; 26), D(51,1; 21,23). A linear PA consisting of sixteen elements operating at a frequency of 5 MHz with the distance between the centers of neighboring elements of 0.6 mm was selected as the ultrasonic transducer. Ultrasonic data were recorded by the PA operating in the double scanning mode with a pitch of 1 mm along the surface of the inspected object (Fig. 1).

Experiment

Further testing of the possibilities offered by the proposed algorithm was performed experimentally. A steel block with side-drilled holes (the block dimensions and the locations of flaws were similar to those in the CIVA 2016 computer simulation (see Fig. 1)) was used as the test sample. An Olympus 5L16-A10 linear PA consisting of 16 elements operating at the frequency of 5 MHz was employed as the ultrasonic transducer. The distance between the centers of neighboring PA elements was 0.6 mm. Ultrasonic data were recorded as the transducer moved 1 mm along the inspected object surface.

To record ultrasonic data, a laboratory facility built around an OPTUS (I-Deal Technologies GmbH) 128-channel ultrasonic electronics unit, which implements both combined and double-scanning PA operation modes.

Echo-signals recorded by the electronics unit were used as input data for the considered algorithm. The application of the algorithm resulted in the synthesized image of the flaws in the inspected object.

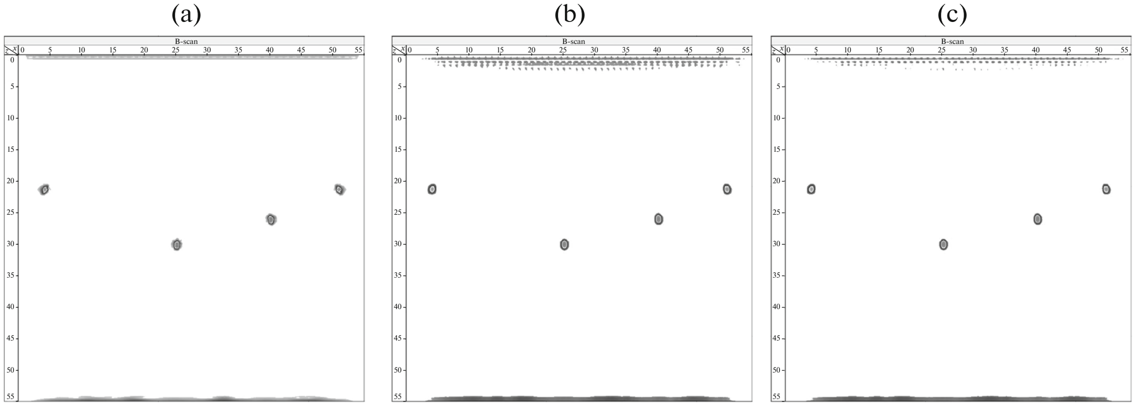

Fig. 2. Synthesized images obtained by applying (a) CIVA TFM algorithm to simulated data, (b) proposed algorithm to simulated data, and (c) proposed algorithm to experimental data.

RESULTS AND DISCUSSION

Figure 2a shows a synthesized image obtained as a result of applying the TFM algorithm in CIVA 2016 to the simulated data in the case of the two-dimensional geometry of testing using a linear PA, while Figs. 2b and 2c present synthesized images obtained when applying the proposed algorithm of calculation in the frequency domain to the simulated and experimental data, respectively.

The quality of the reconstruction of reflectors was evaluated by the Array Performance Indicator (API) [18], calculated according to the formula

$$\mathrm{API} = \frac{S_{-6\ \mathrm{dB}}}{\lambda^2}, \tag{7}$$

where $S_{-6\ \mathrm{dB}}$ is the area around a reflector in which the amplitude of the synthesized image is above the threshold of –6 dB of the maximum amplitude that corresponds to this reflector in the synthesized image and λ is the wavelength of ultrasound in the test object.

Table 1 compares the API values for each of the reflectors when applying the proposed algorithm and TFM algorithm in CIVA to the simulated data. Table 2 compares the application of the proposed algorithm to the simulated and experimental data.

Based on these comparisons, one can conclude that there is a high degree of correlation in the quality of images produced by the CIVA 2016 TFM algorithm and the considered algorithm. The high degree of correspondence in the quality of images obtained when applying the proposed algorithm to the simulated and experimental data confirms the results obtained at the stage of computer simulations.

Table 1. Values of API of reflectors for the proposed and CIVA TFM algorithms applied to simulated data

Flaw	TFM	Considered algorithm	Difference, %
A	3.47	3.31	4.69
B	3.38	3.49	3.25
C	3.72	3.84	3.25
D	3.49	3.48	0.48

Table 2. Values of API of reflectors for the proposed algorithm applied to simulated and experimental data.

Flaw	Considered algorithm, simulated data	Considered algorithm, experimental data	Difference, %
A	3.31	3.47	4.57
B	3.49	3.51	0.45
C	3.84	3.99	3.75
D	3.48	3.59	3.24

CONCLUSIONS

An ultrasonic-tomography algorithm using PAs operating in the double scanning mode has been considered in the present article. This algorithm is based on calculations in the frequency domain and allows for the presence of media with different acoustic properties along the propagation path of ultrasonic waves, a case that is typical of ultrasonic immersion testing. The possibilities offered by the proposed algorithm have been investigated by computer simulations and experimentally. The quality of ultrasonic-tomography results obtained with the proposed algorithm is similar to the results obtained using the TFM algorithm in the commercial CIVA 2016 software. Based on the results obtained, one can conclude that the proposed algorithm is suitable for solving the problems of ultrasonic tomography when using PAs operating in the double scanning mode.

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