Ultrasonic testing via three-dimensional post-processing of non-uniform matrix phased array data

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Abstract. The tomography based on post-processing of phased array signals is of great potential for ultrasonic testing to accurately size the detected flaws. The use of matrix phased arrays in ultrasound tomography can provide three-dimensional data both at one measuring position and during scanning. However, application of these transducers implies processing of a large amount of data, which affects the data processing time. In this study, the post-processing frequency-domain algorithm based on the application of non-uniform fast Fourier transform was experimentally verified. This algorithm is allowed to restore correct results when approaches of optimised set of signals acquisition (sparse and non-uniform phased arrays) are applied. The experimental verification showed that the developed algorithm yields high-resolution results with a high signal-to-noise ratio.

1 Introduction

The transfer from the task of flaw detection to flaws sizing task is of high relevance for development of ultrasonic testing methods and equipment. In this regard, industrial ultrasonic tomography performed via post-processing of phased array ultrasonic signals based on the Synthetic Aperture Focusing Technique is of interest. This approach provides testing results in the form of high-resolution images of flaws, that allows high accuracy of flaw sizing.

Ultrasonic tomography with matrix phased arrays provides three-dimensional images of flaws both at one measuring position and during scanning. However, this approach involves post-processing of a significant amount of ultrasonic signals. This directly affects the time of data processing and, hence, testing efficiency, which limits a widespread use of ultrasonic tomography based on matrix phased arrays in ultrasonic testing. Therefore, it is essential to develop approaches to increase the speed of data processing in ultrasonic tomography with matrix probes.

In order to increase the speed of the image restoration using the matrix phased arrays sets of signals, several approaches can be considered. For example, approaches aimed at the reduction of the size of matrix phased arrays data can be applied. This includes the application of sparse and non-uniform probes [1-4]. Another approach is the application of

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computationally efficient post-processing algorithms [5]. However, there is no research devoted to the combined application of the aforementioned approaches.

2 Experimental part

In this paper, we consider a frequency-domain algorithm that provides correct post-processing of ultrasonic signals of non-uniform and sparse matrix phased arrays (i.e., transducers with a nonconstant step between elements). For this purpose, we adapted the algorithm considered in [6] for the case when matrix phased arrays and transceiver mode of their operation are applied. Aforementioned algorithm is based on non-uniform fast Fourier transform [7] application. The use of frequency-domain algorithms increases the speed of flaw image reconstruction compared to time-domain algorithms. In contrast to conventional uniform transducers, sparse and non-uniform transducers can reduce the amount of signals to be processed without sacrificing the quality of the results obtained.

In this study, the developed algorithm was verified experimentally. Its efficiency was assessed for a non-uniform matrix phased array with elements distributed in the form of a Poisson disk [8]. In such transducers, the elements are arbitrary arranged with a restriction imposed on the minimum distance between them. The coordinates of the elements in the non-uniform matrix phased array with elements distributed in the form of the Poisson disk depend on the parameter that determines physical dimensions of the aperture (D) and the parameter that restricts the minimum distance between the adjacent elements (r). In the experimental verification, the parameters D=16 mm and r=1 mm were used to obtain a transducer that consists of 194 elements. Figure 1 presents element distribution in the considered transducer.

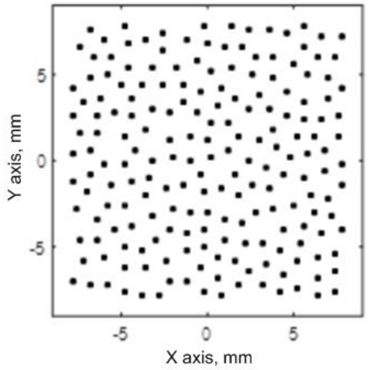


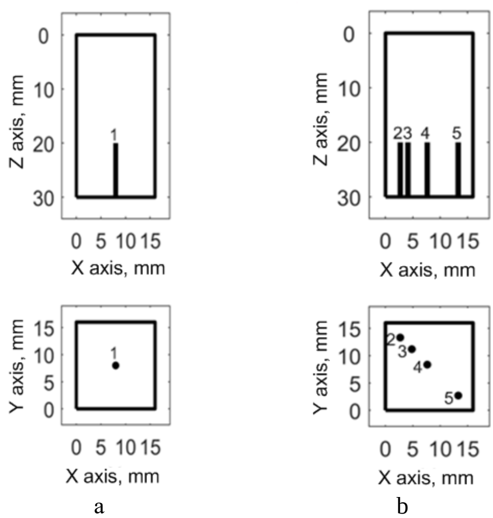
Fig. 1. Element distribution in the considered non-uniform transducer

The main component in the experimental setup was the Optus electronic unit (I-Deal Technologies GmbH, Figure 2). A uniform phased array Doppler 5M8×8BP 1.0 was used as an ultrasonic transducer (Figure 3). This probe was used for the modeling of the non-uniform transducer operation. For this purpose, the scanning was performed in such a way that the first element of the matrix probe in each measuring point was located in a point that corresponds to the center of one of the elements of non-uniform transducer depicted in Figure 1. For this purpose, the applied matrix phased array was placed on the two-axis manipulator which allows to perform the precise movement of the probe during the scanning. In each measuring position, only the first element of the probe took part in ultrasonic wave emission and receiving of echo-signals. Subsequently, the obtained set of signals was used for the restoration of the images of the flaws.

Fig. 2. OPTUS electronic unit

Fig 3. Components of the experimental setup

The test objects for the experimental verification were two sections of the test sample with flat bottom holes. Drilling depth and relative position of the flaws are shown in Figure 4.



Section of the test sample with one flat bottom hole (a); section of the test sample with several closely spaced flat bottom holes (b)
Fig. 4. Test objects used in the experimental verification

3 Results and discussion

Scanning of the test objects resulted in a set of echo signals used as input data for the developed post-processing algorithm. The algorithm yielded three-dimensional images of the flaws detected in the test objects (Figure 5). Figure 6 presents 3D projections onto the XY plane for both test samples.

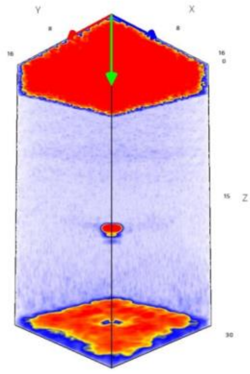
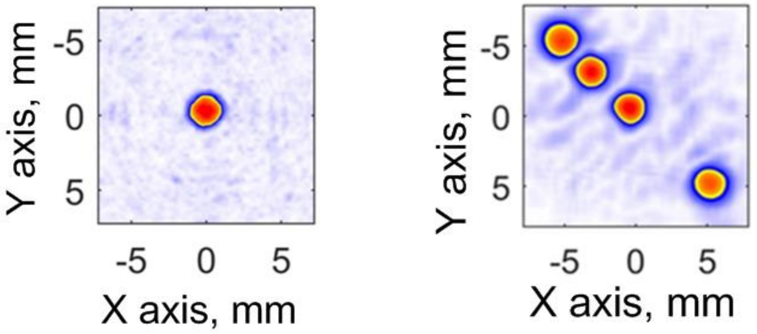


Fig 5. An example of a 3D post-processing result



Section of the test sample with one flat bottom hole (a); section of the test sample with several closely spaced flat bottom holes (b)
Fig. 6. Results obtained by ultrasonic tomography for the test objects

The results can be evaluated numerically based on the obtained resolution and the signal-to-noise ratio (SNR). The resolution of the resulting images can be estimated using the Array Performance Indicator (API) value. For 3D images, the API value can be calculated for each reflector using the following equation:

$$API = \frac{V_{-6dB}}{\lambda^3}, \quad (1)$$

where V_{-6dB} is the reflector volume with the amplitude of the synthesized image above -6 dB with respect to the maximum amplitude corresponding to this reflector in the image; λ is the wavelength of ultrasonic waves in the test object [9].

SNR can be calculated using the following equation:

$$SNR = 20\log_{10}\left(\frac{I_1}{I_2}\right), \quad (2)$$

where I_1 is the maximum amplitude of the voxel corresponding to the reflector in the synthesized image; I_2 *i*s the maximum amplitude of the voxel located in the area of the synthesized image that does not contain a reflector [10].
The calculated API and SNR values are summarized in Table 1. The numbering of flaws is presented in Figure 4.

Table 1. API and SNR values for each flaw in the testing objects

Flaw no.	API	SNR, dB
1	0.865	20.9
2	0.903	17.2
3	0.855	18.2
4	0.837	18.6
5	0.932	16.4

4 Conclusion

The experimental verification proved the efficiency of the developed algorithm. The experimental verification for all artificial flaws in the test objects showed high API and SNR values. The study results obtained can provide the basis for further research and development. For example, it is feasible to perform part of the calculations by GPUs to maximize the speed of the algorithm. In addition, of interest is a comparative analysis of the developed algorithm and the approach conventionally employed in ultrasound tomography, which includes uniform transducers used in combination with post-processing frequency-domain algorithms.

The study was supported by the Russian Science Foundation grant No. 22-79-00244, https://rscf.ru/project/22-79-00244/

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