Three – deminshional ultrasound tomography using multi–angle bistatic sounding

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***Abstract* — The method of three-dimensional ultrasound tomography in the air based on the linear array of microphones and single transmitter, revolving around the studied object is proposed in this paper. The experimental setup based on a linear array of 64 microphones working in the frequency range from 20 to 30 kHz is designed. Results of experimental studies are presented demonstrating the possibility of images restoration with a resolution about 15 mm.**

Keywords—ultrasound tomography; multi-angle souding; synthetic aperture sonar.

I. Introduction

The ultrasound tomography is widely used in defectoscopy and hidden objects detection tasks [1]. As a rule, ultrasonic sensing is used in dense media, liquids, metals and plastics. It is possible to carry out ultrasound tomography through the immersion medium using synthetic aperture sonar approach [2]. Multiposition measurements and processing of evanescent fields allows to archive subwavelength resolution [3]. Planar geometry measurements frequently applied in ultrasonic tomography according to it's simplicity and compatibility with fast algorithms of return task solution [4]. Usually, sounding through the air is not carried out because the waves propagating in the air almost completely reflected from the surface of dense objects, and do not penetrate inside. Ultrasound tomography in air mostly used to detect and visualize sound sources [5,6], such as working machines or specking people. However the ultrasound in air penetrates through thin barriers – fabric or packing materials. Thus, ultrasound can be used for tasks inspection people at checkpoints. In addition, ultrasound can be used in the air for the modeling of physical radio wave tomographic systems [7].

To speed up the process of sounding is advisable to use a single transmitter and a lot of receivers. Signals from receivers are digitized in parallel. To restore the three-dimensional image of scattering objects it is necessary to carry out measurements in three-dimensional parameter space. For example, sounding can be carried out by scanning of a two-dimensional surface by the locator, and scanning of the signal frequency. The two-dimensional spatial scan requires considerable time measurements. Instead, it is possible to apply two-dimensional arrays of microphones. However this solution is technically difficult and costly. Use of a linear array of microphones with scanning in one axis is the compromise solution allowing to carry out scanning with the acceptable speed and doesn't require application of difficult technical solutions. It is proposed to apply a linear array with fixed microphones in the center of the radiator on it. This arrays microphones revolves around the studied object and implement locating sounding over a wide band of frequencies. On the basis of the measured data of locational sounding it is necessary to restore the three-dimensional image of the scattering object.

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II. Scheme of Souding

The scheme of broadband ultrasonic sounding presented in fig. 1 is offered.

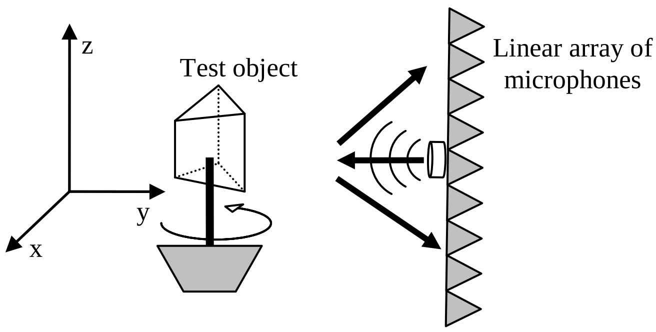

Fig. 1. Scheme of ultrasound measurements

The linear array of microphones located vertically, and in its center the transmitter is established. The investigated object is placed on a rotating platform. The axis of rotation of the object is located at a distance R from the linear array of microphones. Transmitter irradiates the object by the signal with linear frequency modulation of a frequency band from f_1 to f_2. The waves passed onto the array of microphones are digitized. Results of measurements we will represent as a function $S(z,\varphi,t)$, where z – height of placement of a microphone in the receiver array, φ – an angle of rotation of the investigated object, t – time. These measurements by means of Fourier's transformation we convert in the form of complex function $U(z,\varphi,\omega)$ in the frequency domain, where ω – cyclic frequency. We will write the solution of the direct problem in the single-scattering approximation. Field in the measurement area for a given distribution of scatterers is calculated by the formula:

$$U(z,\varphi,\omega)= \\ =\iiint_V p(x',y',z')\frac{\exp\left(ik|\mathbf{r}-\mathbf{r}_0|+ik|\mathbf{r}-\mathbf{r}_1|\right)}{|\mathbf{r}-\mathbf{r}_0||\mathbf{r}-\mathbf{r}_1|}dx'dy'dz', \quad (1)$$

where $p(x',y',z')$ – distribution of the scattering heterogeneities; $\mathbf{r}=(x'y'z')$ – point on the scattering object; $\mathbf{r}_0=(R\cos\varphi, R\sin\varphi, 0)$ – coordinate transmitter; $\mathbf{r}_1=(R\cos\varphi, R\sin\varphi, z)$ – coordinate the microphone; R – radius of rotation of the array of microphones around the object; $k=\frac{\omega}{c}$ – wave number; c – speed of sound in air; V – volume of placement of the scattering heterogeneities.

In this solution of the direct problem the constant multipliers are not taken into account and the transmitter and receiver are considered as point and isotropic.

III. Recovery of Three – Dimensional Images

To solve the inverse problem we use the method of space-match filtration. In paper [8] has been proposed a method for reconstruction of scattering object images by location measurements on nonplanar surfaces. It was demonstrated that space-match filter can be applied for nonplanar apertures. In particular case it’s applicable for cylindrical apertures. The space-match filter is formed as reaction of system on point scatterer. Reconstructed three-dimensional distribution of scattering heterogeneities can be written as:

$$P(x',y',z')= \\ =\int_0^{2\pi}\int_{z_1}^{z_2}\int_{\omega_1}^{\omega_2} U(z,\varphi,\omega)\frac{\exp\left(-ik|\mathbf{r}-\mathbf{r}_0|-ik|\mathbf{r}-\mathbf{r}_1|\right)}{|\mathbf{r}-\mathbf{r}_0||\mathbf{r}-\mathbf{r}_1|}d\omega dz d\varphi, \quad (2)$$

where $P(x',y',z')$ – reconstructed distribution of heterogeneities; z_1, z_2 – limits of microphone placement along the axis z; $\omega_1=2\pi f_1$ – lower frequency sounding signal; $\omega_2=2\pi f_2$ – upper frequency sounding signal.

Solution (2) requires significant computational resources, since numerically implemented six inner cycles of complex multiplication and summation operations. For accelerate the calculation of integral (2) it is offered to lead to a type of integral of convolution which can be calculated on the basis of algorithm of fast Fourier transformation. Due to homogeneity measurement over the angle, the integral (2) is an integral of convolution over φ. In the approximation that R is much larger than z the integral over z also reduces to an convolution integral.

Proposed method has been tested on numerical model of a square with a side of 128 mm in the air sensing by ultrasonic waves in the frequency range from 2 to 30 kHz. In fig. 2 the result of numerical modeling of a cosine quadrature of a field in microphones at 20 kHz frequency is presented.

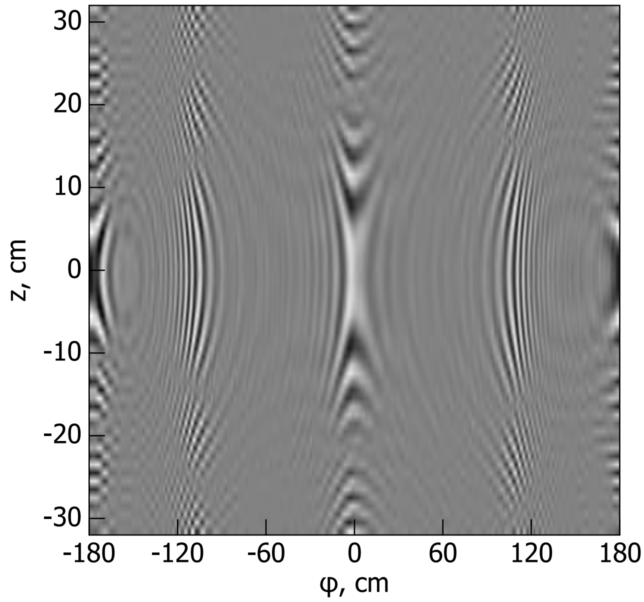

Fig. 2. Numerical model of the field in the receiver at 20 kHz

The field maxima on the result of the numerical modeling of the direct problem correspond to the faces of a square. By means of processing of the numerical modeled result of measurements the method of the space -match filtration at one frequency 20 kHz the image of a square has been restored (fig. 3).

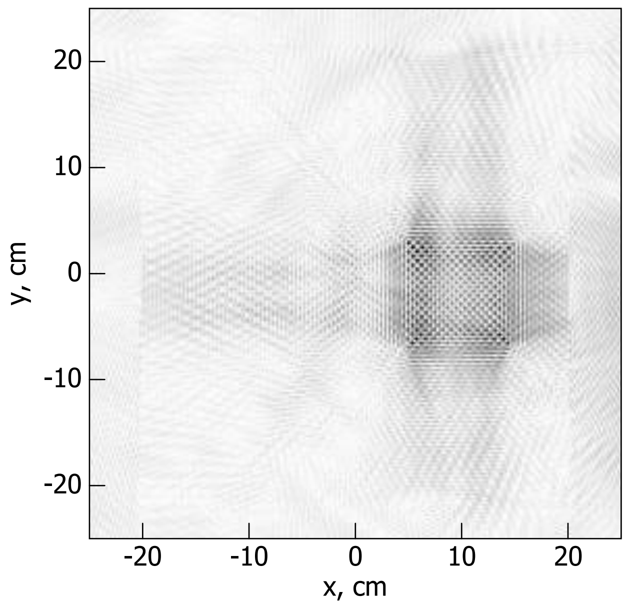

Fig. 3. Recovery results at a single frequency of 20 kHz

By the processing at one frequency the reconstructed image of object is distorted, however it is possible to estimate its existence. To improve the quality of the reconstructed image it is necessary to produce broadband processing. After processing by the method of space-match filtration in the range of frequencies from 2 to 30 kHz the image of the square has been restored (fig. 4).

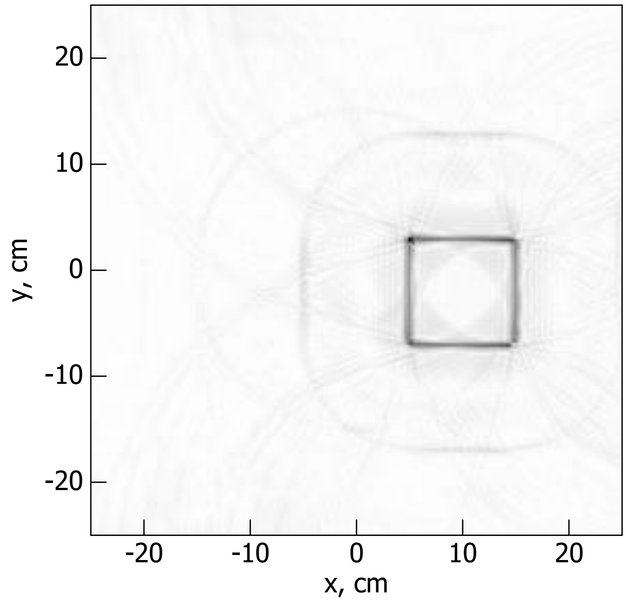

Fig. 4. Reconstructed image of a square by processing in the frequency band from 2 to 30 kHz

Due to broadband sounding signal we gain spatial resolution about 6 mm. Thus, the resolution in the plane provided by the broadband signal and an angular scanning.

IV. EXPERIMENTAL RESEARCH

For experimental research the setup based on the microphones linear array has been developed (fig. 5). The linear array consists of 64 electret microphones EM9767, located in steps of 1 cm. Microphones installed in a linear array in separate module by of 8 pieces, altogether 8 modules. In each module installed 8-channel multiplexer 74HC4051, which provides a connection of one of the microphones to the amplifier which is based on bipolar transistor BC547C. The signal from the amplifier is supplied to one input of an analog-digital converter (ADC) of microcontroller STM32F407. Altogether microcontroller involved 8 ADC channels, one for each module. Digitizing frequency for each channel is 100 kHz. Digitized signals are transmitted by microcontroller to a personal computer for further processing. On a linear array of microphones in its center installed the ultrasound transmitter W06A. The transmitter connected to the microcontroller through the amplifier. The microcontroller generates by digital-analog converter a linearly frequency-modulated signal with a frequency band from 20 to 30 kHz. The array of microphones is positioned vertically. The rotating platform controlled by the stepper motor is placed at a distance R from the array. On the rotating platform a test object is installed. The test object has a shape of a prism with facets 20 cm, 19 cm, 15 cm.

Fig. 5. Photograph of the experimental setup

The whole measurement process is controlled by the personal computer, which controls the stepping motor and the microcontroller. The measurements are carried out in the following sequence: stepping motor rotates an object with steps of 1 degree in the angular range from 0 to 360 degrees; in each position of the stepper motor the sensing by array of microphones is performed.

As a result of the experiment the three-dimensional data was obtained for 64 frequencies, 64 microphones and 360 angular positions of the object rotation. Such measurements took around 50 seconds. Cosine quadratures of signals at frequencies of 20 kHz and 25 kHz are shown in fig. 6 and fig. 7.

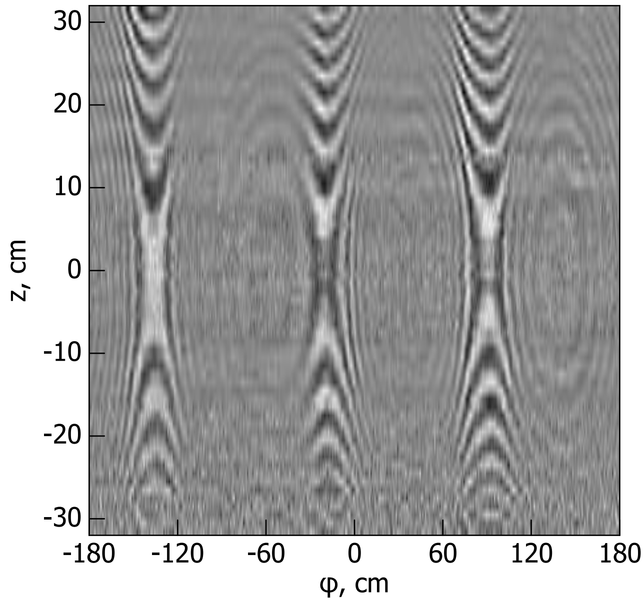

Fig. 6. Cosine quadratures of signals at 20 kHz frequency

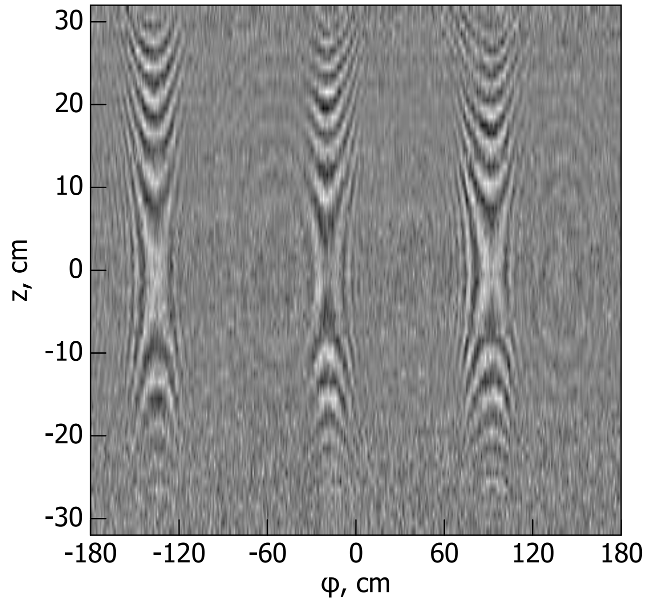

Fig. 7. Cosine quadratures of signals at 25 kHz frequency

A wave pattern is distinctly observed on the measured data. We can see three maximum signals for rotation angles -135 degrees, -15 degrees and 90 degrees. These maximums correspond to the wave reflection from the flat faces of the prism. As a result of spatially-match filtration processing method application to measured data the image of the test object was restored, which is presented in fig. 8.

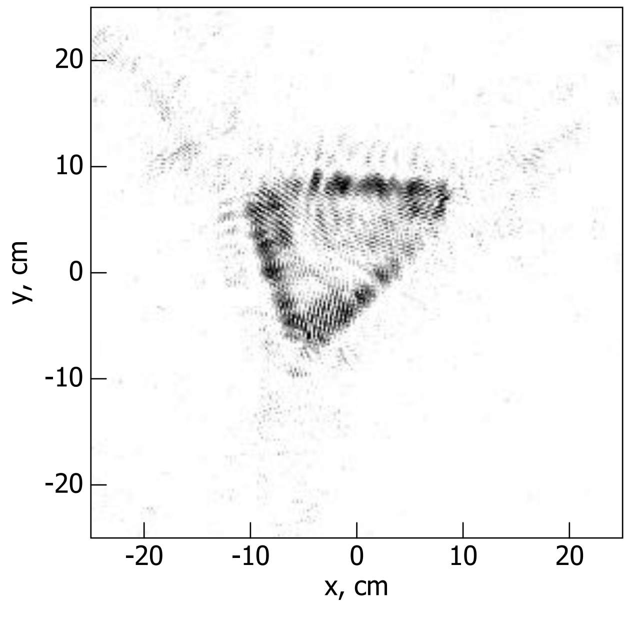

Fig. 8. Reconstructed image of the test object

On the reconstructed image we can see the shape of the object cross-section with resolution of about 15 mm.

Conclusion

We proposed a method of broadband multi-angle ultrasound tomography with application a linear array of microphones and single transmitter. Here is provided a method for three-dimensional image reconstruction of scattering objects based on space-match filtration of the measured fields at different frequencies. The results of numerical modeling and experimental studies demonstrate the applicability of the proposed method. The experimental setup allows to reconstruct images with a resolution of about 15 mm. Combination of linear array and mechanical angular scanning allow to produce measurements in appropriate time. The proposed methods can be generalized to the case of radio wave sensing in the scalar approximation.

Acknowledgment

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