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A Lens Acoustic Microscope with a Two-Dimensional Ultrasound Array

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Abstract—A lens acoustic microscope is proposed in which a two-dimensional high-frequency ultrasound array is used instead of a single converter. In this microscope, electronic scanning of the region of naturally occurring focus of the acoustic lens can be performed and the focus can be held electronically at different distances, including inside solid objects. It was demonstrated that the multielement microscope has potentially higher performance compared with a single-element scanning microscope and is not inferior in resolution power.

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A scanning lens acoustic microscope is used to study the elastic-viscous properties of different objects with high spatial resolution [1]. In a conventional confocal circuit of the microscope, both the radiation of a probing ultrasonic wave and the reception of the wave reflected is implemented by converter *1*, located at the end of the acoustic transmission line with acoustic lens *2* (Fig. 1a). To construct the acoustic image, two-coordinate mechanical scanning of the entire acoustic unit relative to object is used, which leads to a long duration of studies. Moreover, the focal length of the microscope is constant and the acoustic image formed turns out to be focused at a predetermined depth of an object.

Ultrasound imaging devices based on phased arrays offer adaptive management of the radiation patterns in the transmission and reception of waves and electronic scanning [2]. In such devices, the array period should not substantially exceed half the wavelength so as to avoid artifacts in the images. However, direct implementation of the phased array devices at frequencies characteristic of acoustic microscopy seems difficult because of technological limitations present in the production of arrays with a rather small size of elements.

The goal of this work is to create a lens acoustic microscope with electronic scanning that has improved performance and an adjustable focal length. High-frequency two-dimensional ultrasound array *3* is used in the proposed microscope instead of a single converter, the dimensions of elements of which greatly exceed the wavelength (Fig. 1b). In this circuit, the ultrasonic beams emitted by the elements of the array converge in the focal region of the lens. By controlling signals emitted by the elements of the array and processing signals received by them, it becomes possible

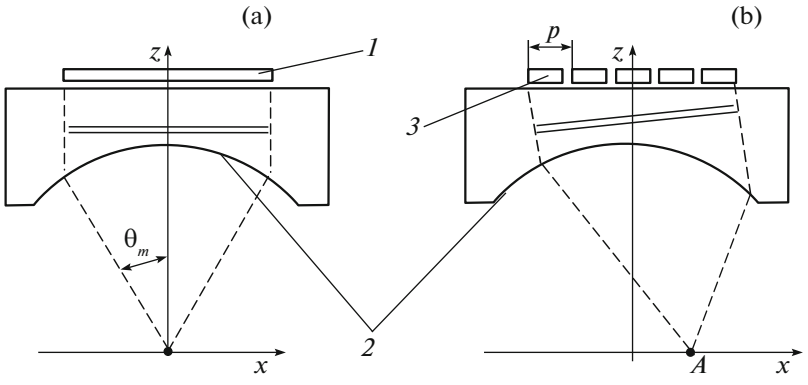

Fig. 1. Acoustic microscope with (a) a single converter and (b) an ultrasound array: (*1*) converter, (*2*) lens, and (*3*) array.

to produce an electronic focusing and scanning in the longitudinal and transverse directions in the field of the natural focus of the lens. In addition, the focal distance and angular aperture can be adjusted in such a circuit and the aberrations that occur in imaging the interior regions of solid objects can be compensated.

An experimental prototype of a microscope was constructed based on a two-dimensional array consisting of square elements 1.2 mm in size arranged with a period of $p = 1.25$ mm. The number of elements along the side of the array was $N = 8$; however, three elements in each corner of the array were not used. Thus, the active array aperture was within a circle with a diameter of approximately $L = 10$ mm. The central frequency was 15 MHz, and the relative band of elements was 60%. A more detailed description of the array can be found in [3]. This array was attached to the acoustic transmission line of polystyrene with a spherical lens (Fig. 1b). The focal length of the lens was $F = 29$ mm, and the half angular aperture of the lens was $\theta_m \approx 10°$.

Images were formed in the multielement microscope using methods developed in the theory of phased arrays [2]. To focus the probe wave at some point of the focal plane of the lens, the elements of the array are excited with a time shift changing linearly along the array aperture. Let Δt is a relative time shift between the excitation signals of adjacent elements, lying along one axis, for example, the x axis. The array then emits a quasi-plane wave that is converged by the acoustic lens into point A in the focal plane with coordinates $(x, 0)$, where

$$x = F\Delta t C_W p^{-1}, \quad (1)$$

and C_W is the ultrasound velocity in the immersion fluid (water). In the recording of the wave scattered by an object, the compensation of delay Δt and summation of the signals received by the elements of the array are performed to focus it at the same point.

The image of a metal ball having a diameter of $d_b = 0.5$ mm was obtained using this prototype of a multielement microscope. The effective reflection diameter of the ball can be estimated as $d_b \sin\theta_m = 0.09$ mm. This size is smaller than the characteristic wavelength of ultrasound of $\lambda \approx 0.1$ mm; therefore, this object can be used as an experimental model of a point reflector. The image of the ball located in the focal plane at a point with coordinates $x = -0.7$ mm, $y = 0.4$ mm is shown in Fig. 2a. The image is represented as a grayscale chart displaying the maximum amplitude of the received signal $C(x, y)$. Figure 2b shows the normalized dependence of $C(x, 0)$ obtained at different positions of the ball along the x axis and $y = 0$ mm.

The spatial resolution power of the multielement microscope is approximately the same as the resolution of a single-element microscope, the acoustic lens of which has the same parameters, and the diameter of the converter is the same as the array aperture. Indeed, if all elements of the array emit and receive in phase, their combined effect is close to the effect of a single large converter. The focusing of the microscope is adjusted to the geometric focus of the lens, so the width of the pulse spatial response and the resolution power can be evaluated by means of the known equation [4]

$$\delta \approx \frac{0.5\lambda}{\sin\theta_m} = \frac{\lambda F}{L}. \quad (2)$$

Focusing to points located outside the z axis is associated with some decrease in effective angular aperture. However, in the paraxial approximation, this change is insignificant and the degradation of the spatial resolution can be neglected.

The resolution power can be determined experimentally from width of the main lobe of the response $C(x)$ at the center position of the point reflector. As it follows from Fig. 2b, the width of the lobe at a level of 0.5 is approximately 0.35 mm, which is consistent with the estimate (Eq. (2)) of resolution power $\delta \approx 0.3$ mm. With the reflector moving to the edge of the image, the response amplitude decreases, which can be explained by a fall of the radiation pattern of the array element diagram in the deviation from the normal to its surface.

In addition to direct reflections from the ball, noise signal e is present in the image (Fig. 2a), which is located at some distance from the main response along the array axes and diagonals. Such noise signals are generated by additional, secondary maxima of the radiation pattern of the array in which period p of arrangement of elements exceeds the wavelength [2]. As shown in [5], the relative amplitude of noise reaches the value of N^{-1} when pulses received by the array elements do not overlap in time and $\Delta t > T$, where $T \approx \lambda C_W^{-1}$ is the pulse width. However, the noise signal becomes small due to destructive interference if these alternating pulses substantially overlap at $\Delta t < 0.5T$. For the central location of the reflector, $x = 0$, the scan area free from noise can be estimated based on Eq. (1) as follows:

$$2|x_p| \approx F\lambda p^{-1}. \quad (3)$$

For the prototype, this estimate is $x_p \approx 1.2$ mm, which is consistent with the experimental plot given in Fig. 2b (solid line). By moving the reflector from the center, the region occupied by the source of noise also shifted, but its relative level in any position of the reflector is less than -20 dB. In addition, the noise level can be lowered by selecting the scan area smaller than $2x_p$. Thus, in the multielement lens microscope, the size of the area for electronic scanning is limited by the acceptable level of interferences of the type considered. It should be noted that the area size may be

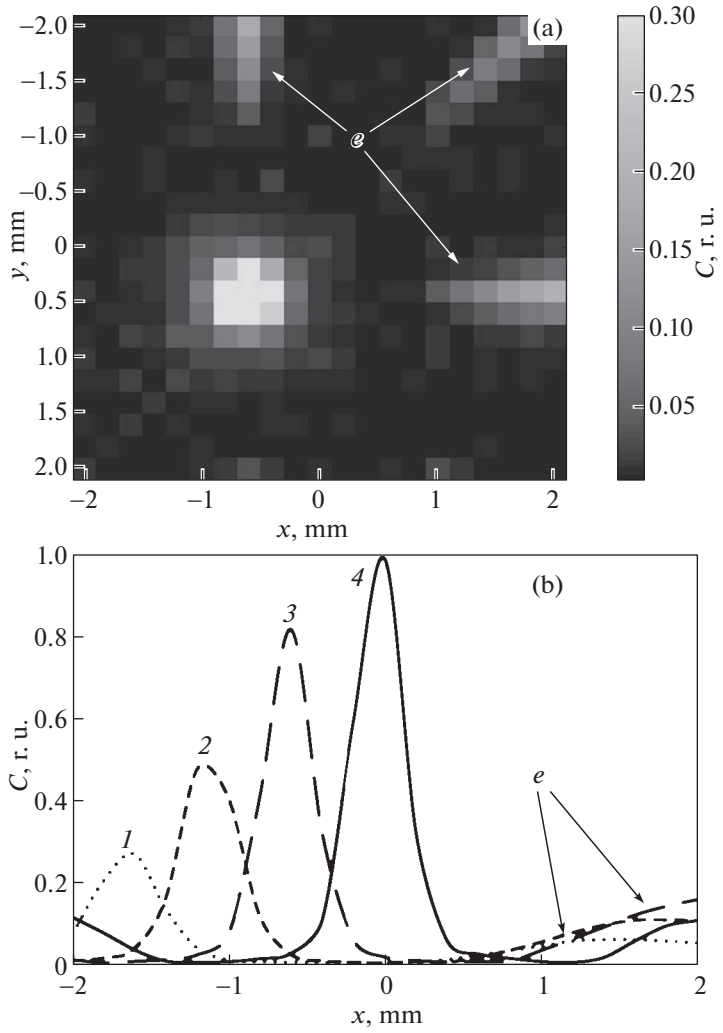

Fig. 2. (a) Image of a ball; (b) signal amplitude at the reflector position x = (*1*) –1.7, (*2*) –1.2, (*3*) –0.7, and (*4*) 0 mm.

expanded by increasing the number of array elements and the use of known methods for suppressing noises that are based on nonuniform distribution of elements over the array aperture and application of digital signal processing.

In the multielement microscope, it is possible to hold the focus at different depths of object without changing the vertical position of the acoustic assembly. For this purpose, the changes in delays in signals of the array elements caused by the passage of waves in the material of the sample to the desired depth are compensated. The responses of a spherical cavity with a diameter of 1.5 mm, the center of which was located at a depth of 4 mm in a duralumin sample, is presented in Fig. 3a. It is seen from comparison of results that the maximum amplitude of the response is achieved upon focusing at a depth that coincides with the distance to the center of the sphere.

Usually, the size of the sample area under study exceeds the field of electronic scanning. Therefore, to construct the image of extended objects, electronic scanning with a multielement microscope is supplemented by discrete mechanical movement along two transverse coordinates with increment $2x_p$. An example of the construction of such a frame-by-frame image is shown in Fig. 3b, where the results of imaging of internal pores with diameters of 0.6–0.9 mm in epoxy compound are shown. The acoustic image is made up of 4 × 4 frames with a size of 1.5 × 1.5 mm.

It should be noted that, in a multielement microscope, the time required for forming one pixel of the frame can be brought to characteristic time τ of propagation of ultrasound in the acoustic path. In a single-element microscope, the time per one pixel is determined by the velocity of mechanical movement. However, this time should be substantially larger than τ; otherwise, the emission and reception of ultrasound

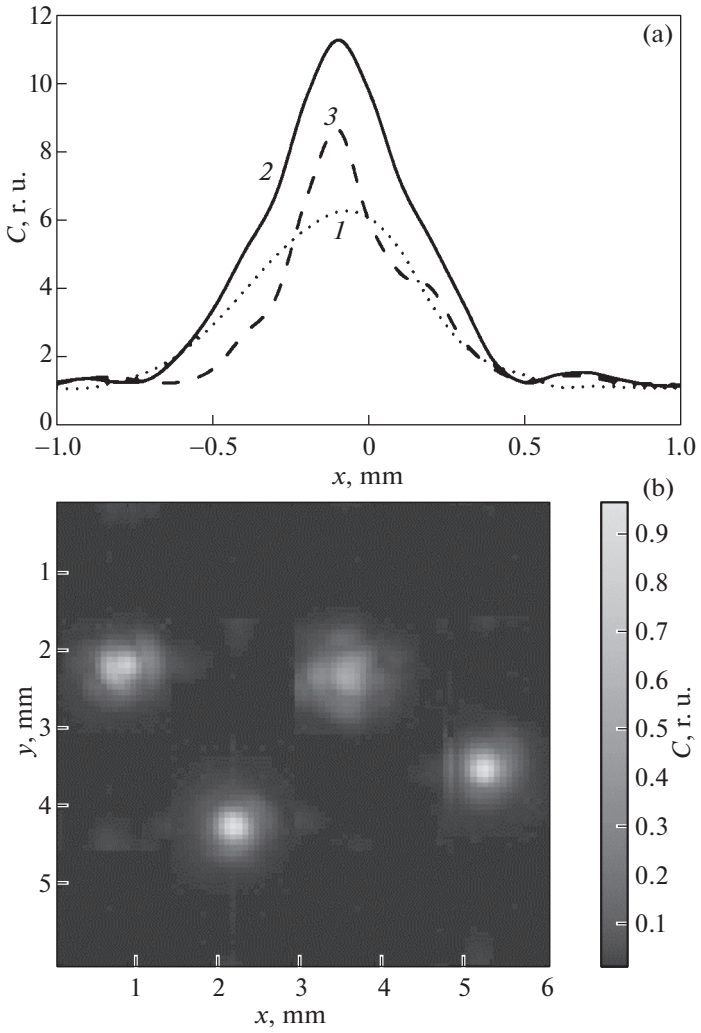

Fig. 3. (a) Response $C(x)$ of a spherical cavity in duralumin in the focusing at a depth of (*1*) 3, (*2*) 4, and (*3*) 5 mm; (b) image of pores in epoxy compound.

will be performed at different positions of the ultrasound unit and the image will be distorted. Thus, the multielement microscope has potentially better performance than does a single-element instrument.

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