On the Visualization of Biological Object using the Acoustic Holography

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***Abstract* – The visualization with ultrasonic waves is one of the most widely used in medicine methods. Currently in medicine mainly is spread echographyc ultrasound method, less exposure to radiation. These methods are acceptable in defectoscopy, as there is important to the discovery of the defect. In contrast to the defectoscopy, in medicine aims to not only detect the object and visualize organs and different formations in them. Satisfy these requirements may acoustic holography. This article is devoted to acoustic holography, which, as well as optical holography provides a three-dimensional image of the object. Is considered the method of the surface relief, based on the ability of the fluid to deform under pressure in the acoustic wave. The basic theoretical standings necessary for calculation of devices, grounded on this method are analyzed. We derive the expressions needed to calculate the geometric position of the image, as well as its size. Based on these results it is concluded that there will now optoelectronic matrix with a pixel size of the order of nanometers make a very promising imaging of small size, derived from acoustic holography. In addition, these images can be processed by powerful computers, thus suppressing noise, especially from stray light.**

***Index Terms* — ultrasonic holography, visualization of biological objects, method of the superficial relief, ultrasonic methods, introscopy.**

I. INTRODUCTION

Acoustic imaging techniques have now become one of the most common in biology, especially in medicine. Several reasons demand for this. The first is that the sound waves of low intensity have no adverse effect on biological objects, so that they can be used often and for a long time. The second reason is that the penetration and reflection properties of the acoustic waves are very dependent on the density. The latter two features distinguish the acoustic imaging of the methods that use X-rays. Finally, the acoustic waves do not interact with a ferromagnetic material, as it is the case with imaging based on nuclear magnetic resonance.

Despite these advantages, acoustic methods of biological objects have not taken proper place in medicine and biology. First of all, it is due to the low resolution of the method by which realized the acoustic method. Currently in medicine is mainly used ultrasound method, less exposure to radiation. In both cases, an acoustic signal is received either a single sensor or array of sensors - a method that is borrowed from the defectoscopy, which first began to use acoustic methods to detect defects. The dimensions of the electro-acoustic elements much more used wavelength. For defectoscopy these methods are acceptable, as there is important to the discovery of the defect itself. In medicine, the aim is to visualize organs and different formations in them, that is, to determine their size, shape, and character.

A version of acoustic monitoring methods that can meet these requirements is the acoustic holography. In this method, due to the interference of two sound waves (reference and reflected from the object) get the picture sound field on which to rebuild a three-dimensional image of the object of control. The idea of acoustic holography emerged simultaneously with the practical realization of optical holography, that is, with the advent of coherent light sources - lasers in the early seventies of the last century, although the theory of optical holography was developed by Gábor Dénes in 1948 for use in microscopy. [1].

One of the most promising methods for acoustic holography seemed the method of surface relief. This method is based on the ability of the medium, in particular fluid deformed by the pressure of the acoustic wave. There are two divergent beam of ultrasonic waves (one - the reference and the other – diffused or reflected by object), which intersect at the free surface of the medium and the strain it, forming a surface standing wave. The resultant pattern of ripples on the surface is an analog optical phase hologram. If it is submitted to coherent light from a laser, in the reflected light waves it is possible to gain the recovered image of a object.

Despite the apparent attractiveness of this method in its implementation have significant difficulties, of which the most should be made low resolution of recorders optical radiation (film) and stray light, which is much stronger than the desired signal. These and other difficulties led to the fact that interest in the method of the surface relief, but like other methods of acoustic holography, gradually waned. This is evidenced by the fact that the majority of papers on this subject refer to the 70-th, 80-th years of the last century [2-7]. Moreover, it is difficult to find a paper, which would be consistent presentation of the theory of the method.

However, technological advances, we are seeing now forced to look with optimism at the prospects of this method. These circumstances have led to the idea of this article, which describes a method of surface relief acoustic holography, and also displays the basic theoretical principles necessary for the calculation of devices based on this method.

II. BASIC PRINCIPLES OF THE OPTICAL HOLOGRAPHY

Acoustic holography closely intertwined with optical holography, so at first we recall the basic principles underlying the optical holography. Conventional image recorders (film, video matrix, various screens) record information about the average light wave, that is, only information about the amplitude of the light waves, the phase information is lost. Therefore, when displayed, the image is flat, so it is impossible to determine from which parts of the object light wave arrives earlier and which to later. Holography is different in that to the wave reflected from the object and incident on the registrar adds a coherent reference wave. The standing wave is as a result formed, and in the recording medium is recorded interference pattern, which carries complete information, i.e., information as the amplitude and the phase of the wave reflected from the object.

Reference and illuminating the object wave can be obtained by dividing the light from a laser into two parts (Fig. 1). The beam of the laser 1 is transmuted into plane-parallel radiation by means of optical system 2. Part of this radiation by the mirror 3 forms a reference wave 5. The other part is reflected from the object of observation and forms a wave scattered by the object 6. The interference of these two waves is registered in the medium 7.

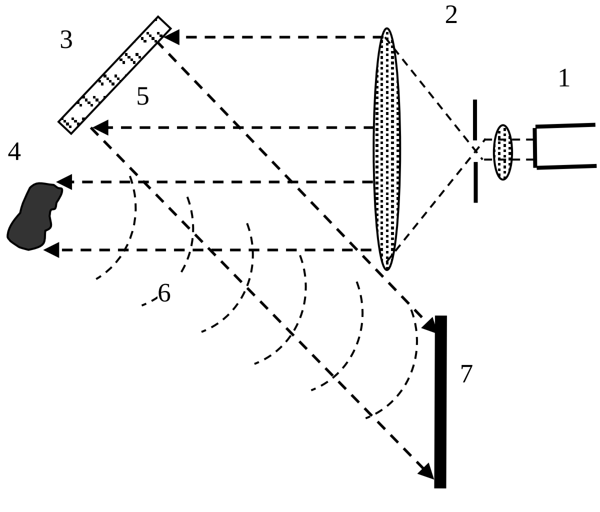

Fig.1. The scheme of hologram recording of three-dimensional optical scattering object.

If the hologram, recorded in such a way, to shine with a light beam 3 from the laser 1 (Fig. 2), dilated by optical system 2, the hologram will modulated it and will reproduce light front 6. The latter consists of three light beams 4, 5 and 6. Beam 4 is a not modulated light. 5 - corresponds to the virtual image 8, and 6- to real image 9. These images can be observed directly, without additional optical devices, this is due to the fact that the beams 5 and 6, modulated by hologram 7, reproduce structure of the wave reflected from the real object.

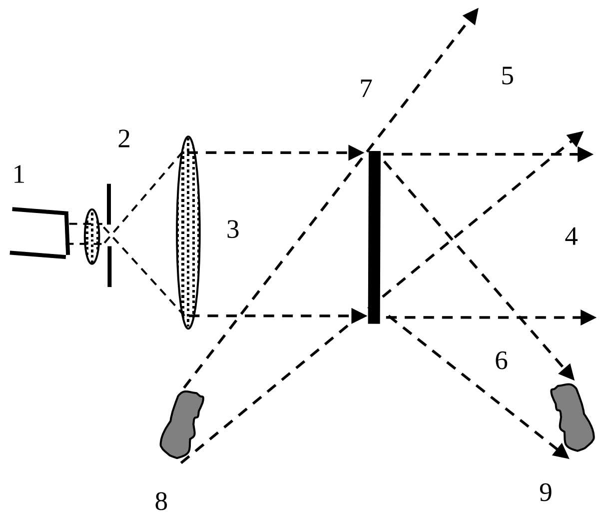

Fig.2. The scheme of image reconstruction of object.

III. PRINCIPLE OF THE ULTRASONIC HOLOGRAPHY USING BOUNDARY OF TWO MEDIUMS

The basic principle of imaging with acoustic holography is similar to optical holography: at first is recorded the pattern, obtained from the interference of two sound waves – diffuse by object and the reference, and then the resulting record - acoustic hologram is used for reconstruction of the object image. The most frequently as an acoustic hologram is used the boundary between two media. This is the so-called surface relief method. It is based on the ability of the fluid to deform under pressure in the acoustic wave (Fig. 3).

In this method, two beams of ultrasonic waves (one - reference 6, and the other - 7, diffused by object 8) are intersect on the free surface of the liquid and strain it, forming a surface standing wave 5. This is standing wave, since the both acoustic transducer 9, 10 are connected to the same generator 11. The resultant pattern of ripples on the surface is an analog optical phase hologram. If on it to guide coherent optical radiation 3 treated by projection optics 2, from the laser 1, in the reflected light waves can be reconstructed the image of the object 4.

Method of surface topography has many modifications. Our paper describes a method close to the method of recording the hologram by scheme Denisyuk when object and reference beams are on opposite sides of the holographic plate [8]. Further we consider the deduction of relations, which determine the position of the image and its size.

Field, which creates light (acoustic), diffused by object in the plane of the hologram can be written in the form of:

$$p(r) = A(r)e^{i\varphi(r)}, \tag{1}$$

where *r* - the radius vector in the plane of the hologram $A(r)$ and $\varphi(r)$ the amplitude and phase of light waves in the point with radius vector *r*.

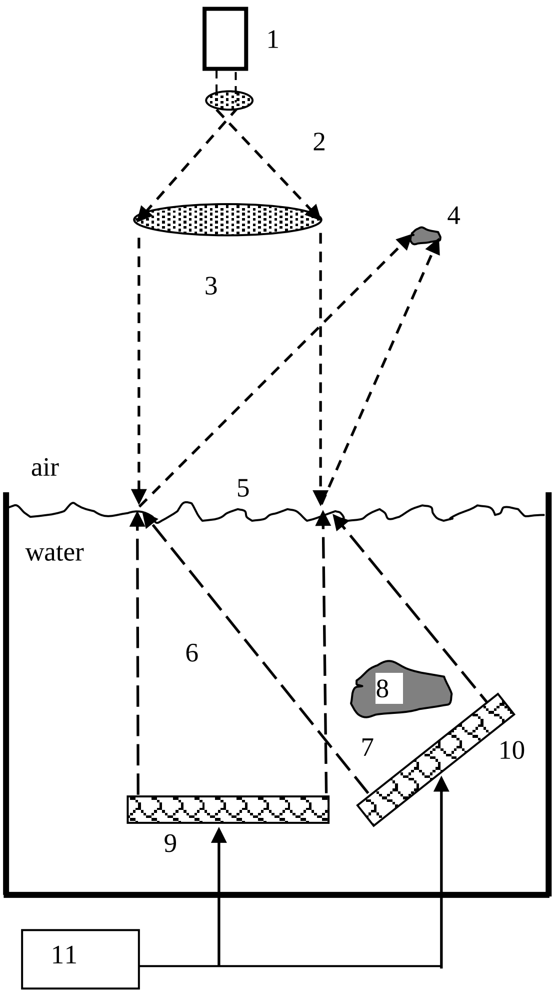

Рис. 3. Scheme of the surface relief acoustic holography

$$p_R = A_R e^{ik_R r_1}. \quad (2)$$

Here k_R - wave number; A_R - plane reference wave amplitude; r_1 - radius vector of an arbitrary point in space. If the origin of coordinates is placed on the surface of the liquid, i.e., in the plane of the hologram, the reference wave field becomes:

$$p_R = A_R e^{ik_R r}. \quad (3)$$

The total field (pressure) on the surface of the liquid, i.e., in the hologram plane

$$p_\Sigma(r) = p(r) + p_R(r) = A(r)e^{i\varphi(r)} + A_R e^{ik_R r}. \quad (4)$$

Density of an internal energy of a ultrasonic wave [10].

$$I = \frac{1}{2}\beta p^2, \quad (5)$$

where β - compressibility of medium. Let's substitute (4) in (5)

$$I(r) = \frac{1}{2}\beta\left[\left|p^2(r)\right| + \left|p_R^2(r)\right| + p^*(r)p_R(r) + p(r)p_R^*(r)\right] \quad (6)$$

We assume that the average for the period of the acoustic wave reflection coefficient T of the laser light from the ripples on the surface of the liquid is proportional to the energy density of the acoustic wave. That is

$$T(r) = T_0 I(r), \quad (7)$$

here T_0 - coefficient of light reflection from the undisturbed surface. Generally speaking, it depends on the angle of incidence of light. At normal incidence to the surface T_0 = 0,02 [11].

The ripples on the surface of liquid modulate the reflectivity, and forming, in fact, an acoustic hologram. In this case, the latter is the average for the period of the acoustic wave function of the reflection coefficient of the coordinate. Thus, to recover the image it is possible by means of a beam of laser light. It should be noted that the optical hologram is also a time-averaged picture.

The laser light reflected from the surface is modulated in accordance with the interference pattern of acoustic standing wave on the surface of the liquid. We denoted by $E(r)$ the total field on the surface of the interference pattern and E_0 field illuminating laser light.

Then

$$E(r) = T(r)E_0(r) = T_0 I(r)E_0(r). \quad (8)$$

Considering expressions (5), (1) and (3) from the formula (8) within a constant factor, following formulas follow:

$$E(r) = E_1(r) + E_2(r) + E_3(r),$$
$$E_1(r) = T_0\left[\left|A_R\right|^2 + \left|A(r)\right|^2\right]E_0(r), \quad (9)$$
$$E_2(r) = T_0\left|A_R\right|^2 E_0(r),$$
$$E_3(r) = T_0\left|A_R\right|^2 E^*(r)e^{2ik_0 r}.$$

These equations are similar to the equations obtained by Denis Gabor [1], with the only difference being that instead of the amplitudes are illuminating the object and reference optical wave containing these acoustic waves. Furthermore hologram is not static, as in the case of optical holography, and dynamic. That is, the image restoration is directly from the interference pattern formed by a standing acoustic wave. In other words, in our case is the intermediate recording medium such as a photographic film is not used.

Component $E_1(r)$ characterizes the field of radiation that passes through the surface of the water. $E_2(r)$ corresponds to the field, forming a virtual image, which is located in front of the hologram. It can be observed directly without additional optics.

The real image is a hologram, in this case, in the water, so it does not interest us. For this scheme interest is the virtual image, which is formed in front of the hologram. Finally, a term of E3 (r) describes the real image, which is located behind the hologram, i. e. in the depth of the liquid. This component is not of interest to us. The image will be a similar to object, provided that the reference ultrasonic and recovering laser light incident perpendicular to the water surface.

In the case of optical holography, the reference and readout beams are usually the same wavelength. In the case of acoustic holography situation is different. Below we shall view how this affects the position and size of the image.

IV. CALCULATION OF THE LOCATION OF THE IMAGE

In the paper [12] the question is viewed in case of when the optical holography is used for obtain an enlarged image. Following the procedure featured in a quoted source, we shall gain expressions which feature the image in case of a ultrasonic holography.

In the deduction given above, we guessed, that a reference wave is flat, however it is possible to use and a spherical wave as a reference wave. In this case expression (3) should be exchanged on

$$p_R = A_R e^{ik_R|l_R - r|}, \quad (10)$$

where l_R - the radius vector of the center of a spherical wave. Since according to (5) the intensity of the acoustic wave on the surface of the liquid is proportional to the square of the amplitude of the pressure, the virtual image is the same as for a plane wave.

Let's designate: L_S - the distance between the transmitter, illuminating the object and hologram; L_R - the distance from the transmitter of to the reference wave the hologram; L_L - the distance from the source of the reconstructed image. Vectors r_S, r_R and r_L - determine the position of these vectors in the plane of the hologram.

Oscillatory fields that correspond to the three radiations, described by:
- the field which is created by the ultrasonic emitter shining object in a plane of the hologram can be written down in the form of

$$p(r) = Ae^{[ik_S|L_S + r_S - r|]}; \quad (11)$$

- the reference wave is described by

$$p_R = A_R e^{[ik_S|L_R + r_R - r|]}; \quad (12)$$

- the field, of highlighting laser.

$$E_R = E_0 e^{[ik_L|L_L + r_L - r|]}. \quad (13)$$

Here $k_S = 2\pi/\lambda_S$ and $k_L = 2\pi/\lambda_L$ wave numbers of the sound and light accordingly .

Let's remind, that the equations (11) and (12), feature ultrasonic waves, and (13) – an optical wave. Using the same reasoning's by means of which we have gained relations (9) we shall obtain the expression describing the virtual image interesting us:

$$E_2(r) = T_0 A_R^* A_R' E_0(r) e^{[i\psi(r)]}, \quad (14)$$

where

$$\psi(r) = k_S|L_S + r_S - r| - k_S|L_R + r_R - r| + k_L|L_L + r_L - r| \quad (15)$$

- phase of the oscillation at the point with radius vector r.

Assume that the size of the hologram is much less than the distance to the oscillator, then

$$L_S >> r_S - r; \qquad L_R >> r_R - r; \qquad L_L >> r_L - r \quad ,(16)$$

then the oscillation phase in a point *r* can be presented in the form: [12]:

$$\psi(r) = \frac{k_L}{2L_1}|r - r_1| + \psi_0. \quad (17)$$

The value ψ_0 does not depend from *r*, and r_1 and L_1 are defined by relations:

$$\frac{k_L}{r_1} = \frac{k_S}{L_S} + \frac{k_L}{L_L} + \frac{k_S}{L_R} \quad , \quad (18)$$

$$k_L\frac{r_1}{L_1} = k_S\frac{r_S}{L_S} + k_L\frac{r_L}{L_L} + k_S\frac{r_R}{L_R} \quad . \quad (19)$$

Formulas (18) and (19) determine the coordinates of the image of point object r_1 and L_1 provided that the object is located in the point with coordinates L_S and r_S.

V. CALCULATION OF THE SIZES OF THE IMAGE

Let's view now a question on the sizes of the image. We shall displace a point-object parallel to plane of the fluid's surface on Δr_S. The image of object also will be displaced on Δr_L. In conformity with expression (19):

$$\Delta r_L = \frac{k_S}{k_L}\frac{L_1}{L_S}\Delta r_S. \quad (20)$$

The result would be the same if the values Δr_S and Δr_L represent vectors which are joined among themselves with two points of object and the image accordingly.

Coefficient

$$V = \frac{\Delta r_L}{\Delta r_S} = \frac{k_S}{k_L}\frac{L_1}{L_S} = \frac{1}{1 - \frac{L_S}{L_R} + \frac{k_L}{k_S}} \quad (21)$$

characterizes the ratio of the traversal dimensions of the image and object.

The longitudinal aspect ratio image and object is defined as the displacement of the image of a point object to a shift in the object itself. From expression (18):

$$U = \frac{dL_L}{dL_S} = \frac{k_S}{k_L}\left(\frac{L_1}{L_S}\right)^2 = \frac{k_S}{k_L}V^2. \quad (22)$$

From (21) and (22) we conclude that, in general, the longitudinal image resizing is not equal to the transverse change. The image will be similar to the object only if the following condition is satisfied: $L_S = L_1$. This corresponds to the position of an object, which is described by the formula:

$$\frac{1}{R_S} = \frac{1}{k_L - k_S}\left(\frac{k_L}{L_L} - \frac{k_S}{L_S}\right). \quad (22)$$

The condition of the longitudinal and transverse changes in size will be the same and will be equal to the ratio of the wave:

$$V = U = \frac{k_S}{k_L} = \frac{\lambda_L}{\lambda_S}.$$

In medicine frequencies *f* up to 10 MHz are used. If to accept velocity of a sound in water c_S = 1450 km/s, this corresponds to a wavelength:

$$\lambda_S = \frac{v}{f} = \frac{1{,}45\cdot 10^3\, m/s}{10\cdot 10^6\, 1/s} = 1{,}45\cdot 10^{-4}\ m = 0{,}145\ mm.$$

The reading beam is obtained by *He-Ne* laser with a wavelength λ_L = 632,8 nm. Then

$$\frac{\lambda_S}{\lambda_L} = 212. \quad (23)$$

The expression (23) means, that at the given parameters the image recovered by means of a viewed method in 212 times is smaller, than object. It is thanks to this fact the method of the ultrasonic holography has not gained in due time major distribution. However now have appeared optoelectronic matrixes with the sizes of pixels of the order nanometers, which allows possible to visualization of images of the small sizes gained by means of a ultrasonic holography. In addition, these images can be processed by powerful computers, thus suppressing noise, especially from stray light.

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