Optical system for monitoring ultrasonic waveguide

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Abstract. An optical system for visualization of ultrasonic waveguide aimed to estimate its vibrations is proposed. The optical method does not affect the observed fluctuations, is non-contact and allows you to take measurements quickly. An analytical calculation of the optical system was carried out. According to the results of numerical modeling, an optical system was assembled, which is a microscope. Using the developed microscope, the tip of the ultrasonic waveguide was visualized.

1. Introduction
Ultrasonic vibrations are used in flaw detection, medicine, tomography and remote sensing [1–4]. The problem of measuring the amplitude of ultrasonic oscillations, in particular for ultrasonic waveguides, is relevant. The use of ultrasonic vibrations allows us to accelerate the course of physicochemical processes, both in technological processes and in biological media. The most important parameter characterizing the operation of the ultrasonic oscillatory system is the amplitude of oscillations. Depending on the process under consideration, the amplitude of oscillations is chosen to be maximum in a certain narrow frequency range, and it should be taken into account that if the amplitude is too high it will lead to the destruction of the oscillatory system. Currently, both contact and contactless methods are used to measure the amplitude of oscillations. In the case of contact methods, the measuring sensor is in direct contact with the measured surface. Among contactless methods, optical methods are the most common.

An optical method for imaging ultrasonic vibrations based on a microscope, digital video camera and stroboscopic illumination is proposed. Strobe lighting with a frequency of tens of kilohertz is carried out using high-speed infrared LEDs.

2. Numerical modeling
For the analytical calculation of the geometric dimensions of the optical system, a number of approximations were adopted. First, we consider that the following approximation is valid: the lenses are thin, that is, any beam passing through the optical center of such a lens does not experience refraction and does not change the direction of propagation. The second is that the lens system is considered centered. This means that the main optical axes of all lenses are the same. Consider an optical system consisting of a combination of 4 convex and concave lenses: three convex and one concave (Figure 1). The concave lens allows reducing the size of the optical system.
A numerical simulation of the lens system was carried out to verify the possibility of upscaling the image. We consider the image of the object in Figure 2, which is located at distance $a$ from the lens which is equal to the focal length of the lens $F_1$, i.e., $F_1 = a$. This test image has elements that would be easy to recognize after passing through the optical system.

Let's produce calculation of the optical field passing through the lens system and falling on the matrix of a digital video camera using the representation of the field in the spectrum of plane waves. The wave field created by a source we denote by function $M(x, y)$. A 2D Fourier transform allows us to go into the spectrum of plane waves.

$$
\tilde{M}(k_x, k_y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} M(x, y) e^{-ik_x x - ik_y y} \, dx \, dy
$$

(1)

The process of wave propagation in the area from a source to a plane-convex collecting lens will be described by the multiplier $e^{ik_z z}$ that is derived from a solution of the Helmholtz equation. Spectrum of the field passed in space distance $z_0$, we will present in the following form:

$$
\tilde{U}_0(k_x, k_y) = \tilde{M}(k_x, k_y) e^{ik_z z}, \quad k_z = \sqrt{k^2 - k_x^2 - k_y^2}, \quad k - \text{wave number.}
$$

Taking the inverse Fourier transform of the field spectrum, we obtain the field itself at the input of the first lens:

$$
U_0(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \tilde{U}_0(k_x, k_y) e^{ik_x x + ik_y y} \, dk_x \, dk_y
$$

(2)

Accounting of the influence of the first and second lenses on the field is described by a multiplier:

$$
L_1(y, x) = e^{-ik_1 \sqrt{F_1^2 + x^2 + y^2}} e^{ik_2 \sqrt{F_2^2 + x^2 + y^2}}.
$$

The field at the output of the first two lenses can be represented as follows: $U_1(x, y) = U_0(x, y) L_1(y, x)$ in the approximation of the phase screen for a flat
lens. Taking the Fourier transform of the field at the output of the first system of two lenses, we obtain the spectrum of the field past the lens system:

\[
\hat{U}_1(k_x, k_y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U_1(x, y) e^{-i(k_x x + k_y y)} \, dx \, dy
\]  

(3)

We consider the process of wave propagation in the next section from the second flat-convex lens to the flat-concave lens in the form of a spatial spectrum multiplier: \(e^{i\phi(x)}\). The spectrum of the field passed in the distance \(z_1\) we will present in the following form: \(\hat{U}_2(k_x, k_y) = \hat{U}_1(k_x, k_y) e^{i\phi(x)}\). Taking the Fourier transform of the field spectrum, we obtain the field itself at the output of a flat-concave lens:

\[
U_2(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{U}_2(k_x, k_y) e^{i(k_x x + k_y y)} \, dk_x \, dk_y
\]  

(4)

Taking into account the influence of concave and convex lenses on the field described by the phase factor \(L_2(y, x) = e^{i\phi(x)}\), the field at the output from a concave and convex lens is represented as follows: \(U_3(x, y) = U_2(x, y)L_2(y, x)\). Taking, the Fourier transform from the field at the output of a concave and convex lenses we obtain the spectrum of the field, which passed the lens system:

\[
\hat{U}_3(k_x, k_y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} U_3(x, y) e^{-i(k_x x + k_y y)} \, dx \, dy
\]  

(5)

Then the travel of wave from output of lens system to video camera is characterized by multiplier of spatial spectrum \(e^{i\phi(x)}\). Spectrum of the field passed in space distance \(z_3\) we present in the following form: \(\hat{U}_4(k_x, k_y) = \hat{U}_3(k_x, k_y) e^{i\phi(x)}\). Taking the inverse Fourier transform from the field spectrum, we get the field itself at the video camera matrix aperture:

\[
U_4(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{U}_4(k_x, k_y) e^{i(k_x x + k_y y)} \, dk_x \, dk_y
\]  

(6)

An image of a given test source after passing through such a lens system will be enlarged (Figure 3).

Figure 3. Image of the source after passing through the lens system (for comparison, the original image is shown in the center).

The scaling factor of the considered optical system will be calculated by the following formula:

\[
k = \frac{F_2}{F_1} \frac{F_3}{F_2}
\]  

(7)
where \(-F_1, F_2, F_3, F_4\) are the focal lengths of the lenses. Formula (7) is derived by geometry optics approximation and corresponds to the numerical results presented on Figure 3. According to (7) for lens system with \(F_1 = 90\) mm, \(F_2 = 250\) mm, \(F_3 = -90\) mm, \(F_4 = 200\) mm.

On the basis of analytical calculations, the optical system of four lenses Figure 4 was proposed.

![Figure 4. Scheme of the proposed optical system.](image)

3. Experimental results

The principle of operation is based on one of the main optical properties of light - the refraction of light rays when passing the boundary of media with different densities. On the basis of the carried out analytical calculations, two blocks of lenses were assembled. The first block of lenses consists of two flat convex lenses with a diameter of 50 mm with focal lengths \(F_1 = 90\) mm and \(F_2 = 250\) mm. The first lens is focused on the source at distance \(z_0 = 90\) mm (the focal length of the lens \(F_1 = F_2\)). The lenses are placed closely to reduce the geometric dimensions of the optical system, but as shown by the results of analytical calculation they could be separated. On distance \(z_1 = F_2 - F_3 = 160\) mm placed the second block of lenses with a diameter of 50 mm. This block consists of a flat-concave lens with focal length \(F_3 = -90\) mm and flat-convex lens with focal length \(F_4 = 200\) mm, which are placed close to each other. The flat-concave lens was taken from the idea that such a lens has a focus behind the lens, which allows us to reduce the geometrical dimensions of the entire system. On distance \(z_2 = F_4 = 200\) mm the matrix of the video camera (with the resolution 640x480 pixels) is placed. The image of the source is formed on the matrix of video camera. According to (7) a 6.17 upscale is provided. According to analytical calculations, an optical system was manufactured, which, in essence, is a microscope (Figure 5).

![Figure 5. Photos of the microscope design containing: movable lens unit.](image)

A microscope is a construction of two blocks: the first block is a lens block; the second block is the video camera matrix located in box of a larger size. A block with lenses is slid into the block of camera matrix; this allows changing the distance from the camera to the blocks of lenses and, thus, changing the magnification of the microscope.
With the help of the developed optical system, the ultrasonic waveguide was monitored. The installation consists of a developed microscope, a two-coordinate positioning system (a two-axis support), an ultrasonic wave guide, a stroboscopic illumination, a personal computer Figure 6.

**Figure 6.** Photograph of the installation for monitoring oscillations of the tip of the ultrasonic waveguide.

Monitoring the oscillations of the tip of the ultrasonic waveguide is carried out as follows. The ultrasonic waveguide is placed in a holder placed on a two-axis support so that its tip is in the focus of the microscope, and is connected to the control unit. The microscope is located on the platform and is connected via a USB interface to a personal computer. The tip of the ultrasonic waveguide is illuminated with stroboscopic illumination with a frequency close to the resonant frequency of the ultrasonic waveguide carried out using high-speed infrared LEDs. The light reflected from the surface of the tip of the ultrasonic waveguide falls on the lens system of the microscope and forms the image on the digital matrix of the video camera. This allows us to observe the vibrations of the ultrasonic waveguide on the screen of a personal computer. Figure 7 shows the image of ultrasonic waveguide boundary.

**Figure 7.** Image of ultrasonic waveguide tip border.
Thus, the developed optical system allows us to observe the boundary of the tip of the ultrasonic waveguide and monitor the vibrations of its tip. Observation of ruler image showed that applied camera allows to achieve spatial resolution of 1.25 mkm per pixel.

4. Conclusion
A numerical simulation of the optical system representing of the microscope was carried out. The calculated magnification factor of the optical system calculated from the simulation results coincided with analytical estimates based on the approximation of geometric optics. A microscope was assembled, which allows visualization of the air-wave guide boundary with an analytically predicted increase. The possibility of obtaining images with a resolution of 1.25 μm per pixel, which is sufficient for observing ultrasonic vibrations of waveguides, was experimentally shown.

Acknowledgments
The work was supported by the Ministry of Education and Science of Russia within the framework of the project "Creation of a high-tech complex of ultrasound surgery" (Unique identifier of the project RFMEF157517X0163).

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