Formation of the holographic lateral shear interferograms in diffusely scattered fields to control the wave front

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The conditions of formation of the lateral shear interferograms to control the aberrations of both the convergent and diverging wave fronts are analyzed in the paraxial approximation for the case of double-exposure records of the Fresnel hologram of a mat screen. Results of the experimental study carried out are in a good agreement with theoretical conclusions.

As shown in Ref. 1 one can control the convergent wave front aberrations by use of double-exposure records of the lensless Fourier hologram of a mat screen if compensating linear phase shift arising in the coherent diffusely scattered wave at a transverse displacement of a mat screen before the repeated exposure. On the stage of reconstruction of a record this condition provides the formation of a lateral shear interference pattern in the bands of infinite width. This interference pattern is localized in the far diffraction zone when the spatial filtration of the diffracted field is carried out in the plane of the double-exposure hologram by illuminating it with a small-aperture laser beam.

In this paper some peculiarities in the formation of the lateral shear interferogram in the bands of infinite width to control the aberrations of the convergent or diverging quasi-spherical wave front are analyzed for the case of a double-exposure record of the Fresnel hologram of a mat screen.

As shown in Fig. 1, the mat screen *1*, which is in the plane (x_1, y_1), is illuminated by a coherent radiation with a convergent quasi-spherical wave with the radius of curvature l_1. The photoplate *2* is placed at a distance l from the screen *1* in the plane (x_2, y_2). The object, diffusely scattered, wave and a diverging quasi-spherical reference wave with the radius of curvature l_2, where $l_2 = l - l_1$, are recorded with a photoplate *2* during the first exposure. Before the repeated exposure the mat screen is displaced in its plane, for example, in the direction of the axis x at a distance a, and the photoplate is displaced in the opposite direction at a distance b.

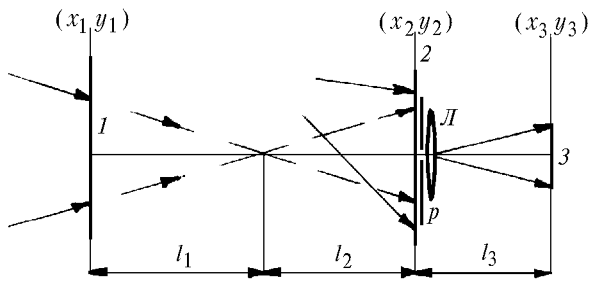

Fig. 1. The diagram of recording and reconstruction of the double-exposure hologram: mat screen (*1*); photoplate-hologram (*2*); plane of the interferogram recording (*3*); aperture diaphragm (*p*); lens (*L*).

In the Fresnel approximation, neglecting the constant factors, the distribution of the complex amplitude of the object wave, which corresponds to the first exposure, has in the photoplate plane the form

$$u_1(x_2, y_2) \sim \exp\left[ik/(2l)(x_2^2 + y_2^2)\right]\left\{F(x_2, y_2) \otimes \otimes \Phi_0(x_2, y_2) \otimes \Phi(x_2, y_2) \otimes \exp\left[(ikl_1)/(2l_2 l)(x_2^2 + y_2^2)\right]\right\}, \quad (1)$$

where $\otimes$ is the symbol of the convolution operation; k is the wave number; $F(x_2, y_2) = \iint_{-\infty}^{\infty} t(x_1, y_1) \exp - [(ik) \times \times (x_1x_2 + y_1y_2)/l]\, dx_1 dy_1$ is the Fourier image of the complex amplitude of transmission of the mat screen $t(x_1, y_1)$ which is a random function of coordinates; $\Phi_0(x_2, y_2) = \iint_{-\infty}^{\infty} \exp i\alpha(x_1, y_1) \exp[-ik\,(x_1x_2 + y_1y_2)/ /l] dx_1 dy_1$ is the Fourier image of a complex function; $\alpha(x_1, y_1)$ is the determinate function characterizing the phase distortions in the controlled wave due to possible imperfections in the optical quality of the mat screen substrate; $\Phi(x_2, y_2) = \iint_{-\infty}^{\infty} \exp -i\varphi_1(x_1, y_1) \times \times \exp[-ik\,(x_1x_2 + y_1y_2)/l]\, dx_1 dy_1$ is the Fourier image of a complex function; $\varphi_1(x_2, y_2)$ is the determinate function characterizing the phase distortions in the controlled wave front due to aberrations of the forming optical system.

For the used approximation the distribution of complex amplitude of the reference wave in the plane (x_2, y_2) in a general case, when its possible phase distortions characterized by the determinate function $\varphi_2(x_2, y_2)$ are taken into account, is determined by the expression

$$\exp\{i\,[k\,(x_2^2 + y_2^2)/2l_2) + k\,x_2 \sin\theta + \varphi_2\,(x_2, y_2)]\},$$

where θ is the angle between by the normal to the photoplate plane and the axis of the spatially bounded reference beam.

If before the repeated exposure of the photoplate the displacement value is $b = al_2/l_1$, then the distribution in the plane (x_2, y_2) of the complex

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amplitude of the object wave, which corresponds to the second exposure, has the form

$$u_2(x_2, y_2) \sim \exp\{ik[(x_2 + al_2/l_1)^2 + y_2^2]/2l\} \times$$
$$\times \exp\left(\frac{ikax_2}{l}\right)\{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \exp\left(-\frac{ikax_2}{l}\right) \times$$
$$\times \Phi(x_2, y_2) \otimes \exp[ikl_1(x_2^2 + y_2^2)/2ll_2]\}, \quad (2)$$

and for the reference wave it is

$$\exp i\{(k/2l_2)[(x_2 + a\, l_2/l_1)^2 + y_2^2] +$$
$$+ k(x_2 + a\, l_1/l_2)\sin\theta + \varphi_2(x_2 + al_2/l_1, y_2)\}.$$

The hologram is recorded by fixing the result of interference of the scattered object wave bearing information on the mat screen with the reference wave on a thin light-sensitive layer. When the linearity of the plate sensitivity is satisfied and the waves diffracted on it are spatially separated[2] the distribution of the complex amplitude of a field in the plane (x_2, y_2) in the (-1)st order of diffraction at the stage of reconstruction of the double-exposure hologram by a copy of the reference wave is determined by the following expression:

$$u(x_2, y_2) \sim \exp[ik(x_2^2 + y_2^2)/2l] \times$$
$$\times \{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \Phi(x_2, y_2) \otimes$$
$$\otimes \exp[ikl_1(x_2^2 + y_2^2)/2ll_2] +$$
$$+ \exp i[\varphi_2(x_2, y_2) - \varphi_2(x_2 + al_1/l_2, y_2)] \times$$
$$\times \{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \exp(-ikax_2/l) \times$$
$$\times \Phi(x_2, y_2) \otimes \exp[ikl_1(x_2^2 + y_2^2)/2ll_2]\}\}. \quad (3)$$

Because the controlled wave front is spatially bounded the field diffusely scattered by the mat screen has a nature of an objective speckle-field. In contrast to Ref. 1 the displacement of the mat screen in its plane before the repeated exposure is accompanied by the displacement of speckles in the plane (x_2, y_2) (see Fig. 1). Besides, the linear phase shift between the speckle-fields of two exposures arises. The condition of coincidence between the identical speckles of the two exposures in the plane (x_2, y_2) is achieved by the proper, in value and direction, displacement of the photoplate, and correspondingly chosen radius of curvature of the diverging quasi-spherical wave front of the reference wave to provide the compensation for the linear phase shift between the speckle-fields in the two exposures. As a result, as it follows from the expression (3), the objective speckle-fields of the two exposures are superposed in the hologram plane, thus causing identical speckles to coincide, thus conditioning, as in the Ref. 1, the localization in it of the interference pattern that characterize the phase distortions of the reference wave front.

Let the positive lens L (see Fig. 1) with the aperture diaphragm p is placed in the hologram plane, the diameter of this lens does not exceed the width of an interference fringe in the interference pattern which is localized in it. Then in the plane (x_3, y_3) that is at the distance l_3 from the lens L the distribution of the complex amplitude of the field is determined by the expression

$$u(x_3, y_3) \sim \iint_{-\infty}^{\infty} u(x_2, y_2)\, p(x_2, y_2) \times$$
$$\times \exp\{i\psi(x_2, y_2) \exp[-ik(x_2^2 + y_2^2)/2f] \times$$
$$\times \exp\{ik[(x_2 - x_3)^2 + (y_2 - y_3)^2]/2l_3\}\, dx_2\, dy_2, \quad (4)$$

where $p(x_2, y_2)$ is the aperture function[3] (for convenience the aperture diaphragm is assumed, in this expression, to be installed on the optical axis); $\psi(x_2, y_2)$ is the determinate function characterizing possible phase distortions which are introduced in the light wave by the hologram substrate and the lens L; f is the focal length of the lens L.

By substituting Eq. (3) to Eq. (4) and taking into account that the $\varphi_2(x_2 + al_2/l_1, y_2) - \varphi_2(x_2, y_2) \le \pi$ when the condition $\frac{1}{f} = \frac{1}{l} + \frac{1}{l_3}$ is satisfied and neglecting the factor characterizing the distribution of the spherical wave phase, which is inessential for the further consideration, we obtain

$$u(x_3, y_3) \sim \{[\exp i\varphi_1(-\mu x_3, -\mu y_3) +$$
$$+ \exp i\varphi_1(-\mu x_3 - a, -\mu y_3)] \times$$
$$\times t(-\mu x_3, -\mu y_3) \exp i\alpha(-\mu x_3, -\mu y_3) \times$$
$$\times \exp[-ikll_2(x_3^2 + y_3^2)/2l_1 l_3^2]\} \otimes P(x_3, y_3), \quad (5)$$

where $\mu = l/l_3$ is the coefficient of scale transformation; $P(x_3, y_3) = \iint_{-\infty}^{\infty} p(x_2, y_2) \exp i\psi(x_2, y_2) \exp[-ik(x_2 x_3 + y_2 y_3)/l_3]\, dx_2 dy_2$ is the Fourier image of the corresponding function.

It follows from the expression (5) that in the plane of formation of the mat screen image the subjective speckle-fields of the two exposures are superposed and identical speckles determined by the width of the function $P(x_3, y_3)$ coincide. Hence, the interference pattern is localized in this plane. Really, if a period of the function $\exp i\varphi_1(-\mu x_3, -\mu y_3) + \exp i\varphi_1(-\mu x_3 - a, -\mu y_3)$ exceeds the size of an subjective speckle at least by an order of magnitude[4] then this function can be removed from the integrand of the convolution. Then the distribution of the illuminance in the plane (x_3, y_3) (see Fig. 1) takes the form

$$I(x_3, y_3) \sim \{1 + \cos[\varphi_1(-\mu x_3 - a, -\mu y_3) -$$
$$- \varphi_1(-\mu x_3, -\mu y_3)]\} \,|\, t(-\mu x_3, -\mu y_3) \times$$
$$\times \exp i\alpha(-\mu x_3, -\mu y_3) \exp[-ikll_2(x_3^2 + y_3^2)/2l_1 l_3^2] \otimes$$
$$\otimes P(x_3, y_3)\,|^2. \quad (6)$$

According to expression (6) the subjective speckle-structure is, in this case, modulated by the interference fringes. The interference pattern has a form of the lateral shear interferogram in the bands of infinite width, which characterizes the aberrations in the convergent wave front controlled.

It is quite obvious, that for recording the diffraction of the interference pattern which is localized in the hologram plane in the (−1)st order it is necessary, as in Ref. 1, to carry out a spatial filtration, with a positive lens, of the diffracted field in the plane of formation of the mat screen image.

From the above analysis of operation of the holographic lateral shear interferometer, that uses a coherent diffusely scattered light, it follows that, on the one hand, the phase distortions in the object wave channel due to imperfections in the interferometer's optical components do not change the interference pattern characterizing the controlled wave front, because they are concentrated within a speckle conditioning its broadening. On the other hand, the phase distortions in the channel of the reference wave lead to the formation of the interference pattern at the stage of reconstruction of the double-exposure hologram. But, it is localized in another plane, and, as a result, the spatial filtration of the diffracted field provides the independence from it of the form of interference pattern characterizing the controlled wave front.

Let us consider the conditions for making double-exposure record of the Fresnel hologram of the mat screen which provides a possibility to control the diverging quasi-spherical wave front with the radius of curvature R in its plane. In this case the distribution of the complex amplitude of the object wave, which corresponds to the first exposure, is determined in the plane (x_2, y_2) of the photoplate placed at the distance l from the mat screen by the expression

$$u_1(x_2, y_2) \sim \exp\,[ik(x_2^2 + y_2^2)/2l] \times \times \{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \Phi(x_2, y_2) \otimes \otimes \exp[-ikR(x_2^2 + y_2^2)/2l(R + l)]\}\,, \quad (7)$$

which is written neglecting a change of sign of the phase function $\varphi_1(x_2, y_2)$.

If, before taking the repeated exposure, the mat screen is displaced along the direction of the axis x by the distance a, and the photoplate is displaced in the same direction by the distance $b = a\,(R + l)/R$, then the distribution of the complex amplitude of the object wave that corresponds to the second exposure takes the form

$$u_2(x_2, y_2) \sim \exp\,(ik/2l)\,\{[x_2 - a(R + l)/R]^2 + y_2^2\} \times \times \exp\,(ikax_2/l)\{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \otimes \exp\,(-ikax_2/l)\Phi(x_2, y_2) \otimes \otimes \exp\,[-ikR(x_2^2 + y_2^2)/2l(R + l)]\}\,. \quad (8)$$

Let the double-exposure record of the hologram be performed using a diverging quasi-spherical wave with the radius of curvature $R + l$ in the photoplate plane:

$$u_{01}(x_2, y_2) \sim \exp\,\{i[k(x_2^2 + y_2^2)/2(R + l) + + kx_2 \sin\theta + \varphi_2(x_2, y_2)]\}\,;$$

$$u_{02}(x_2, y_2) \sim \exp\,i\,\{k[(x_2 - a(R + l)/R)^2 + + y_2^2]/2(R + l) + k(x_2 - a(R + l)/R)\sin\theta + + \varphi_2(x_2 - a(R + l)/R, y_2)\}\,.$$

Then at the stage of the reconstruction of a record by a copy of the reference wave the distribution in the hologram plane of the complex amplitude of a field diffracted in the (−1)st order is determined by the expression

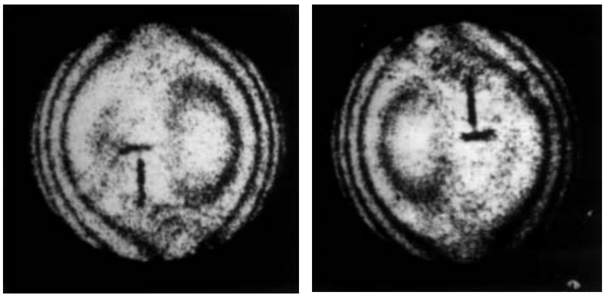
$$u(x_2, y_2) \sim \exp\,[ik(x_2^2 + y_2^2)/2l] \times \times \{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \Phi(x_2, y_2) \otimes \otimes \exp\,[-ikR(x_2^2 + y_2^2)/2l(R + l)] + + \exp\,i\,\{\varphi_2(x_2, y_2) - \varphi_2[x_2 - a(R + l)/R, y_2]\} \times \times \{F(x_2, y_2) \otimes \Phi_0(x_2, y_2) \otimes \otimes \exp\,(-ikax_2/l)\,\Phi(x_2, y_2) \otimes \otimes \exp\,[-ikR(x_2^2 + y_2^2)/2l(R + l)]\}\}\,. \quad (9)$$

If the above conditions are stratified, it follows from expression (9) that the coincidence of the objective speckle-fields in the hologram plane of the two exposures with the compensation for linear phase shift between them is achieved, that leads to the formation of interference patterns which are similar to the case of the control of a convergent wave front. So, to record the interference pattern that is localized in the plane of formation in the (−1)st order of diffraction of the mat screen image and characterizes the controlled wave front, it is necessary to carry out spatial filtration of the field in the hologram plane. Its form is determined by the expression

$$I(x_3, y_3) \sim \{1 + \cos\,[\varphi_1(-\mu x_3 - a, -\mu y_3) - - \varphi_1(-\mu x_3, -\mu y_3)]\}\left|\,t(-\mu x_3, -\mu y_3) \times \times \exp\,i\alpha\,(-\mu x_3, -\mu y_3) \times \times \exp\,[-ik(R + l)l(x_3^2 + y_3^2)/2Rl_3^2] \otimes P(x_3, y_3)\right|^2. \quad (10)$$

It should be noted that in the limit, at $R \to \infty$, when the displacement of the mat screen and photoplate before the repeated exposure is realized along same direction and by the same distance the coincidence of the objective speckle-fields of two exposures in the absence of a linear phase shift between them is provided, because the reference wave must be quasi-plane. As a result we come to the known holographic control method of a quasi-plane wave front using coherent diffusely scattered fields.[5,6]

In the experiments the Fresnel double-exposure holograms of a mat screen were recorded on the photoplates of the Mikrat VRL type with the radiation from a He–Ne laser with the wavelength 0.63 μm. As an example, set out in Fig. 2*a* is the lateral shear interferogram recorded, according to Fig. 1, when the spatial filtration of diffraction field in the (−1)st order was carried out in the hologram plane with the aperture diaphragm with the diameter 2 mm is represented.



a *b*

Fig. 2. The lateral shear interferograms characterizing the convergent wave front in the case of reconstruction of the hologram using the radiation with a diverging spherical wave (*a*) and with a plane wave (*b*).

The interference pattern characterizes primarily the spherical aberrations with the beyond-focus defocusing of the controlled converging wave front with the radius of curvature 165 mm and diameter 40 mm in the mat screen plane. The interference pattern is localized in the plane of formation of the mat screen image, the mark in the form of the letter “T,B which has been drawn on the mat screen, shows this. The hologram was recorded with the distances $l_1 = 165$ mm and $l_2 = 240$ mm using a diverging spherical reference wave with the radius of curvature 240 mm in the photoplate plane. Before the repeated exposure the mat screen was displaced by the distance $a = (0.3 \pm 0.002)$ mm, and the photoplate was displaced in the opposite direction by the distance $b = (0.435 \pm 0.002)$ mm.

In the case when the spatial filtration of the diffracted field in the (−1)st order is carried out in the plane (x_3, y_3) (see Fig. 1) of formation of the mat screen image with the aperture diaphragm 2 mm of the positive lens that forms the image in the hologram plane[1] the lateral shear interferogram which is shown in Fig. 3 is recorded. This interference pattern with the spatial extent of 30 mm which is localized in the hologram plane characterizes the phase distortions of the reference wave front.

The displacement of filtering diaphragm in the hologram plane, as in Ref. 1, does not change the interference pattern shown in Fig. 2*a* except that its phase changes by π (that is not essential for the differential interferometry) when the center of the aperture filtering diaphragm passes from the maximum of the interference pattern (see Fig. 3) to its minimum. In its turn, the same fact is observed when the spatial filtration of the diffracted field is carried out in the plane of formation of the mat screen image.

It is quite obvious that reconstructing a double-exposure hologram by use of a small-aperture (≈ 2 mm) laser beam, as it was carried out in Ref. 1, provides an increase by many times in the brightness of the mat screen image and conditions for making spatial filtration in it of the diffraction field are satisfied. It follows from the general methodical approach to the formation of image of an object by the Fresnel hologram when it was recorded in accordance with Fig. 1 and the reconstruction was carried out by use of a plane wave,[7] that a virtual image of the mat screen is formed in the (+1)st order of diffraction at the distance ll_2/l_1 from the hologram, and a real image is formed at the same distance in the (−1)st order. So, Figure 2*b* presents the interference pattern which is localized in the plane of the mat screen image, the interference pattern was recorded using the reconstruction of the considered double-exposure hologram in the (+1)st order of diffraction using a small-aperture laser beam.

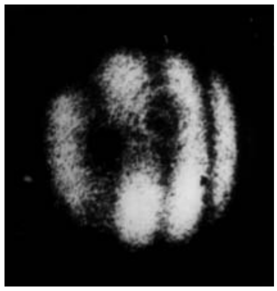
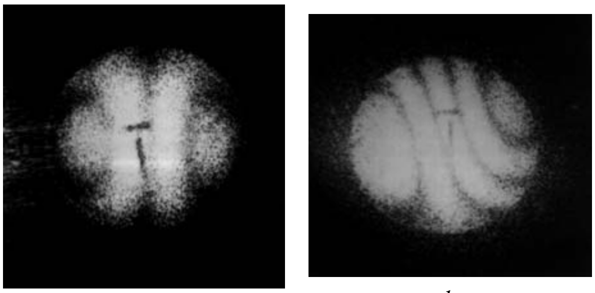


Fig. 3. The interference pattern localized in the hologram plane.

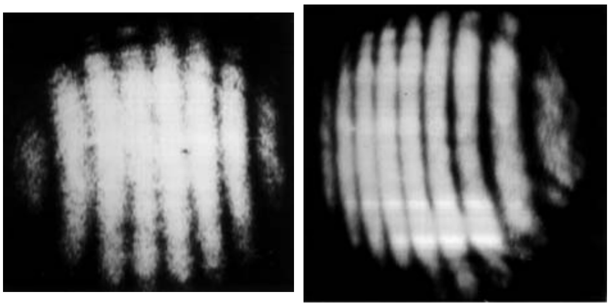
In the case of illumination of the hologram with an expanded beam and using spatial filtration of the diffracted field in the plane of the mat screen image a view of the observed interference pattern which is localized in the hologram plane (see Fig. 3) is kept also. Moreover, in the case when the hologram is displaced with respect to the small-aperture laser beam reconstructing it and the filtering diaphragm is displaced in the plane of formation of the mat screen image the view of the interference pattern shown in the Fig. 2*b* and Fig. 3 remains practically unchanged except for changes by π of their phases.

As an example the double-exposure record of the Fresnel hologram to control the diverging wave front with the radius of curvature $R = 140$ mm and diameter 35 mm was carried out for the distance between the mat screen and photoplate $l = 405$ mm. The radius of curvature of the diverging quasi-spherical reference wave was 545 mm. Before the repeated exposure the mat screen was displaced by the distance $a = (0.4 \pm 0.002)$ mm, and the photoplate was displaced in the same direction by the distance $b = (1.557 \pm 0.002)$ mm. The hologram was reconstructed in the (−1)st order of diffraction by a copy of the reference wave when the spatial filtration in its plane was carried out with the aperture diaphragm of a positive lens, which constructs the mat screen image. The figure 4*a* presents the recorded interference pattern that is localized in the image plane and characterizes the spherical aberration with beyond-focus defocusing of the controlled diverging wave front. In its turn, the spatial filtration of the diffracted field in the plane of formation of the mat screen image provides the record with the spatial extension of 45 mm of the interference pattern which is localized in the hologram plane and characterizes the phase distortions in the reference wave front. The view of this interference pattern is presented in Fig. 5*a*.



a *b*

Fig. 4. The lateral shear interferograms characterizing the diverging wave front in the case of reconstruction of the hologram by the radiation with a diverging spherical wave (*a*) and with a plane wave (*b*).



a *b*

Fig. 5. The interference patterns recorded in the plane of hologram when it is reconstructed with a diverging spherical wave (*a*) and with a plane wave (*b*).

In reconstructing the above considered double-exposure Fresnel hologram with the use of a small-aperture laser beam in the (−1)st order of diffraction a virtual image of the mat screen is formed at the distance $l(R + l)/R$ from it. In this case in the plane of formation of the mat screen image the interference pattern changes its view when displacing the hologram with respect to the laser beam reconstructing it. So, the interference pattern in Fig. 4*b* corresponds to the hologram reconstructed at its edge point on the axis x. For the case of hologram illumination by a collimated laser beam when the spatial filtration of the diffracted field is carried out in the plane of construction of the mat screen image the interference pattern in its plane also changes because of the displacement of the filtering diaphragm. The interference pattern in Fig. 5*b* corresponds to the case when the spatial filtration is carried out on the optical axis.

The appearance of the “liveB interference fringes when their shape and frequency change is explained by the absence of the exact localization of the interference pattern in the plane where the spatial filtration of the diffracted field is carried out.[8] In its turn, violation of the exact localization of the interference fringes in the plane is caused by aberrations in the Fresnel hologram.[9] So, in the case of reconstruction of the double-exposure hologram made with a plane wave to control the converging wave front, the hologram aberrations are equivalent to the aberrations of a lens with the focal length $f_1 = \sqrt[3]{l^2 l_2^2/(3l_1)}$. In case of the off-axis holographic optical arrangement its principal plane does not coincide with the hologram plane. For the double-exposure hologram taken to control the diverging front the hologram aberrations are equivalent to the aberration of a lens with the focal length $f_2 = \sqrt[3]{l^2(l + R)^2/(3R)}$. If in the former case the hologram aberrations are larger by the factor of 2 ($f_2^3/f_1^3 \simeq 2$), then in the latter case the sensitivity to the hologram aberrations of the differential interferometer is almost four times higher. Moreover, the hologram aperture is larger in the latter case. All this is a cause of the emergence of the dynamic interference fringes and, as a result, the error of the wave front control when a double-exposure Fresnel hologram of the mat screen is reconstructed using a small-aperture laser beam.

Thus, the above theoretical and experimental results show that for the double-exposure record of a Fresnel hologram of a mat screen based on the coincidence of the objective speckle-fields of the two exposures with the compensation for linear phase shift between them the control of wave front is provided for both the converging and diverging wave fronts. In this case the lateral shear interference pattern characterizing the controlled wave front is localized in the plane of formation of the mat screen image when the hologram is illuminated, at the stage of its reconstruction, by a copy of the reference wave from a source of a coherent light used at the stage of its recording. The reconstruction of the double-exposure hologram using a small-aperture laser beam in order to increase the image brightness and carry out the spatial filtration of the diffracted field can lead, in a general case, to the errors in control due to the aberrations in the Fresnel hologram which do not occur in the case of the double-exposure record of a lensless Fourier hologram of a mat screen.

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