Optical wave fields measurement by digital holography methods

M.S. Kovalev[1], G.K. Krasin[1], S.B. Odinokov[1], A.B. Solomashenko[1], Yu.V. Fedotov[1]

[1]Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5/1, Moscow, Russia, 105005

Abstract. The solution of a wide range of research and application problems of modern science and technology is connected to the measurement of the wave field of optical radiation. The methods of digital holography allow not only to improve the accuracy of measurements of optical wave field parameters, but also to increase the compactness of devices without losing speed. Digital holography gives a push to the development of new approaches to the construction of devices such as a wave front sensor.

Keywords: Wave field measurement, Digital Holography, Computer optics.

1. Introduction

The measurement of the parameters of the wave fields of optical radiation is associated with the solution of a large range of scientific and applied problems of modern fundamental and applied science [1-3]. First of all, these are tasks of precision measurements of linear and angular displacements [4,5], distances [6], angles, refractive indices [7], surface shapes, medium uniformity, film thickness, wavelength of light and gravitational waves, star sizes and many other quantities. Such measurements are necessary in solving problems for the diagnosis of nanostructures and in nanometrology.

One of the main problems associated with solving the problem of recording the optical wave field is the measurement of the spatial distribution of the phase. To date, a variety of methods have been developed to measure and record the profile of the phase front. The most known are measurements based on various interferometers, sensors based on the methods of Hartmann [8] and Shaka-Hartman [9]. The greatest accuracy in measuring the phase of light fields was achieved by means of interferometric methods. However, they make it possible to measure only the phase difference of two coherent light beams, one of which serves as a reference beam, which substantially limits the field of their application. Other phasometric methods are much inferior in accuracy to interferometric and also do not give a satisfactory solution to the problem of recording the optical wave field. It should be noted that most sources of optical radiation are incoherent or partially coherent. The problem of measuring the parameters of an incoherent wave field is of interest. The only phaseometric method suitable for working with incoherent wave fields is the Hartmann method and its modifications: the Shack-Hartmann sensor and the Hartmann scanning sensor.

However, all these methods allow us only to measure the slope of the phase front of optical radiation. In the general case, such a description of the incoherent field is not sufficiently complete. Thus, the problem of developing alternative methods for measuring the phase of light fields is still of interest. In addition, the problem of eliminating systematic errors in recording the spatial structure of the intensity of optical radiation is topical.

2. Basic calculation relations

The development of computer technologies and modern design capacities have made logical the intensive development of methods for the computer synthesis of holograms. By analogy with classical holography, computer models for calculating Fourier, Fresnel, and loseless holograms of Fourier and others appeared [10]. The questions of comparing the resolution of the computer-generated holograms (CGH) of Fourier and Fresnel and the justification of the choice of the type of CGH are important for the development of various devices. In analog holography, their resolving powers can be considered comparable when using a high-aperture optical system (in comparison with the size of the recorded object) in the recording scheme of a Fourier hologram and a high-resolution photosensitive material in the Fresnel hologram recording scheme.

Computer synthesis of the Fresnel hologram. The essence of obtaining such a CSG is to calculate the interference pattern from the reference and object waves. As an object we choose a wave that passed through the transparency in the form of a circular hole Ø = 2b = 100 μm, located at a distance z from the observation plane-the recording plane of the hologram. The reference wave is a wave with a unit amplitude and a phase distribution corresponding to the type of aberration being tested (according to the mathematical decomposition of the Zernike basis [11]). The objective wave is a wave with a spherical wave front. Accordingly, in the hologram plane, the phase distribution of this wave is represented as a classical set of Fresnel zones. As a LCG output device, a liquid crystal spatial light modulator (for example, a Holoeye PLUTO SLM, 1080x1920 pixels and 8 μm pixel) may be used (Figure 1). One pixel of LCD-PMS displays one point of the hologram and determines the resolution of the hologram. In accordance with this, the interference pattern recorded on the hologram should have a period of at least 4 pixels.

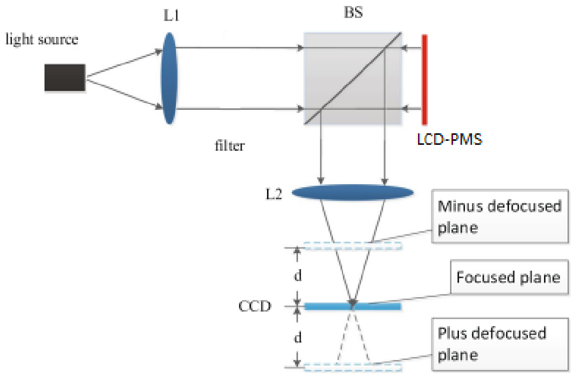


Figure 1. Simplified block diagram of the verification experiment system.

According to the above, the following parameters were chosen for the synthesis of Fresnel holograms: plane wave front with wavelength $\lambda = 632.8$ nm, number of samples (along the x, y axis) $N_x = N_y = 768$, distance from the diffraction plane to the observation plane $z = 3$ m , a sampling step in the image plane of 36 μm.

When such a hologram is illuminated by a reference wave in the plane of the receiving device at a distance z, there will be a circular spot - the image of the transparency. The position of the spots, the geometric position of each of which corresponds to the effect of the WF with its type of aberration (a certain value) of the phase function on the CSG, form a given intensity distribution. In the case when the unknown wave front has distortions used in the synthesis of such a structure, then, based on the analysis of the intensity distribution on the photodetector device and comparison of this distribution with a predetermined one, one can draw a conclusion about the degree and magnitude of the distortions. To distinguish aberrations during the restoration at the stage of calculating the interference pattern, the position of the transparency is specified with the displacement dr relative to the central point.

Figure 2 shows the transverse profiles of Fresnel holograms for the type of "defocusing" distortion with amplitudes of 0.02λ and 0.04λ. The shift of the interference fringes is 72 μm and is equal to the size of two cells of the LC-PMS. Thus, the condition for the solvability of the two interference patterns is satisfied and we can make a preliminary conclusion that such structures will make it possible to determine the distortions of the incident wavefront to within two hundredth of a wavelength.

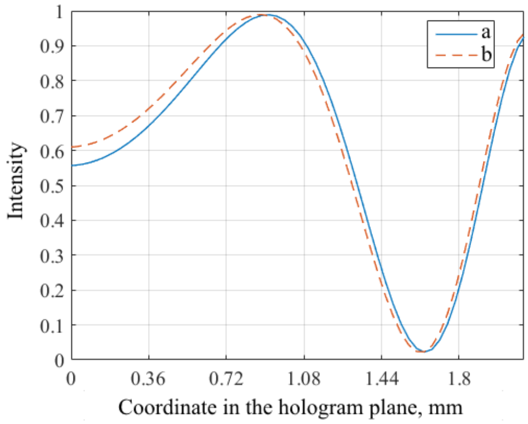


Figure 2. Interference bands in the recording plane of the hologram (an enlarged vicinity to the right of the ordinate axis is shown) with the same position of the transparency (on the optical axis - without displacement) and a wave with the defocus type of the value a) 0,02λ; b) 0.04λ.

Figure 3 shows the transverse profiles of Fresnel holograms, in the synthesis of which, for each type of aberration, the parameter of the circular aperture displacement relative to the center of the field dr was chosen. This approach makes it possible to distinguish images when reconstructing a hologram. Figure 3 illustrates that for each parameter a curve different from the others appears, which makes it possible to apply these interference patterns in the detection problem. The sinusoidal character of the curves is due to the choice of the circular aperture as the illuminated object and the mathematical description of the Fresnel transform via the Fresnel integrals.

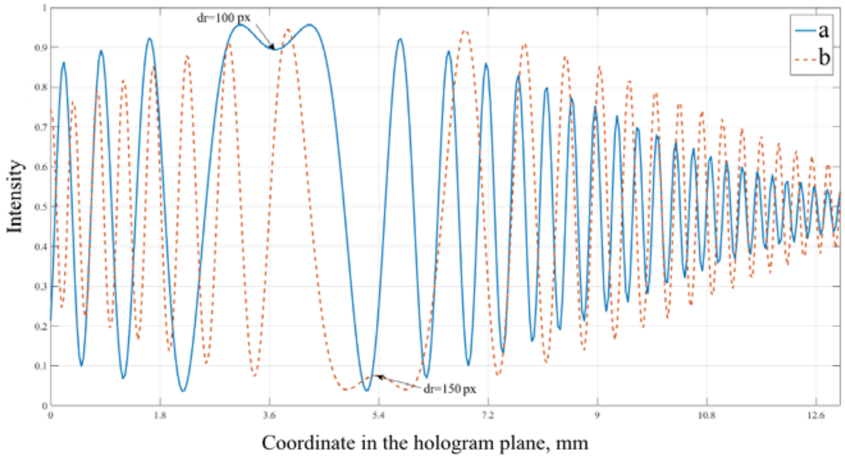
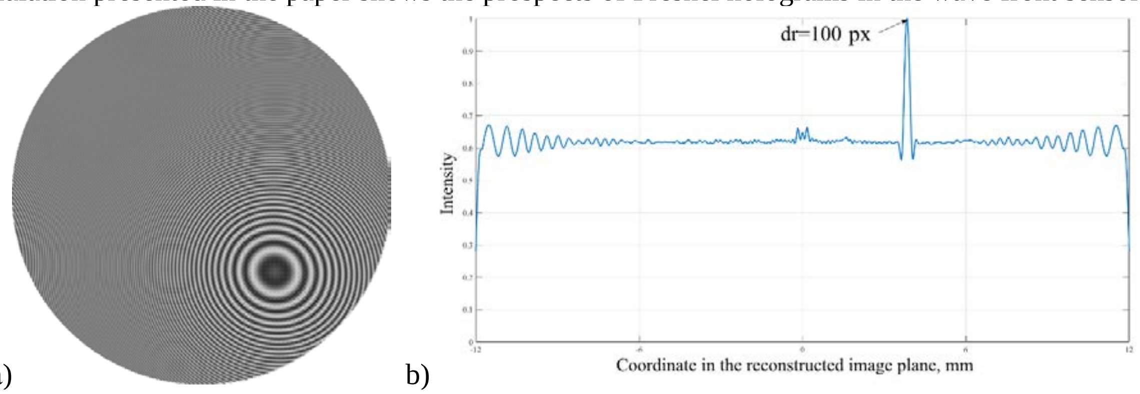


Figure 3. Interference bands in the recording plane of the Fresnel hologram at different position of the transparency and the distortion value of 0.5λ type a) defocusing (displacement of the transparency dr = 100); b) horizontal coma (dr = 150).

Below, in Figure 4, the type of the resulting structure is shown, as well as the reconstructed images using the displacement parameter dr = 0 and dr = 40.

3. Conclusion

The main theoretical positions necessary for the synthesis of Fresnel holograms are considered, an algorithm for creating Fresnel holograms as an operating element of a holographic wavefront sensor is developed and implemented. In the future, experimental studies of the practical possibilities of such holograms are planned. The claimed accuracy in determining the aberrations at 0.02λ will in practice be reduced due to the presence of cross-modulation noise, as well as the problems associated with multiplexing such structures for use in a wave front sensor. Nevertheless, the preliminary numerical simulation presented in the paper shows the prospects of Fresnel holograms in the wave front sensor.



a) b)

Figure 4. a) view of the Fresnel hologram for aberration defocusing with a value of 0.5λ (dr = 100); b) restoration of the hologram (dr = 100).

4. Acknowledgments

The study was supported by the Ministry of Education and Science of the Russian Federation: agreement No. 14.577.21.0258 of September 26, 2017 (project identifier RFMEFI57717X0258).

5. References

[1] Poleshchuk, A.G. Hartmann wavefront sensor based on multielement amplitude masks with apodized apertures / A.G. Poleshchuk, A.G. Sedukhin, V.I. Trunov, V.G. Maksimov // Computer Optics. – 2014. – Vol. 38(4). – P. 695-703. DOI: 10.18287/0134-2452-2014-38-4-695-703.

[2] Betin, A.Y. Projection multiplex recording of computer-synthesised one-dimensional Fourier holograms for holographic memory systems: mathematical and experimental modeling / A.Y. Betin, V.I. Bobrinev, N.M. Verenikina, S.S. Donchenko, S.B. Odinokov, N.N. Evtikhiev, E.Y. Zlokazov, S.N. Starikov, R.S. Starikov // Quantum electronics. – 2015. – Vol. 45(8). – P. 771-775. DOI: 10.1070/QE2015v045n08ABEH015567

[3] Kovalev, M.S. Wave front sensor based on holographic optical elements / M.S. Kovalev, G.K. Krasin, P.I. Malinina, S.B. Odinokov, H.R. Sagatelyan // Journal of Physics: Conference Series 2016. – Vol. 737(1). – P. 012064. DOI: 10.1088/1742-6596/737/1/012064.

[4] Gurylev, OA. Development and investigation of the optical system of a linear displacement sensor based on a four-section diffraction grating / O.A. Gurylev, S.B. Odinokov, D.S. Lushnikov, A.Yu. Zherdev, M.V. Shishova // Collection of scientific papers MEPhI. – 2017. – P. 280-281.

[5] Kiryanov, A.V. Using the differential method of measurement to control the accuracy of precision angle measuring structures / A.V. Kiryanov, V.M. Vedernikov, V.P. Kiryanov, S.A. Kokarev, V.G. Nikitin // Optoelectronics Instrumentation and Data Processing. – 2016. – Vol. 52(4). – P. 354-359. DOI: 10.3103/S8756699016040063.

[6] Turukhano, B.G. Automated ultra-precise length-meter holographic with holographic touch sensor DG-DK-200 / B.G. Turukhano, E.A. Vilkov, V.V. Dobyrn, O.G. Ermolenko, L.A. Konstantinov, Yu.M. Lavrov, I.V. Ladatko, V.G. Tolchin, N. Turukhano, S.N. Khanov, N.A. Shchipunova // Devices and systems, management, control, diagnostics. – 2016. – Vol. 9. – P. 35-43.

[7] Belousov, D.A. Monitoring a spatial intensity distribution of transmitted and reflected light in a diffractive structure / D.A. Belousov, A.G. Poleshchuk, V.N. Khomutov // Computer Optics. – 2015. – Vol. 39(5). – P. 678-686. DOI: 10.18287/0134-2452-2015-39-5-678-686.

[8] Poleshchuk, A.G. Hartmann wavefront sensor based on multielement amplitude masks with apodized apertures / A.G. Poleshchuk, A.G. Sedukhin, V.I. Trunov, V.G. Maksimov // Computer Optics. – 2014. – Vol. 38(4). – P. 695-703. DOI: 10.18287/0134-2452-2014-38-4-695-703.

[9] Gladysheva, Ya.V. Algorithm for reconstructing a profile of a flat high-precision optical surface / Ya.V. Gladysheva, I.V. Zhivotovskii, D.G. Denisov, N.V. Baryshnikov // Measuring technique. – 2016. – Vol. 2. – P. 28-32.

[10] April, J. Optical holography: Per. from the English / J. April, A. Arseno, ed. G. Colfield. - Moscow: Mir, 1982. – 376 p.

[11] Born, M. Foundations of Optics / M. Born, E. Wolf // The 2-nd. Translation from English. The main edition of the physical and mathematical literature of the publishing house «Nauka», 1973. – 713 p.