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DIGITAL HOLOGRAPHIC INTERFEROMETRY OF A WIDE SPECTRAL RANGE IN THE SYSTEMS OF NONDESTRUCTIVE TESTING OF DYNAMICS OF MICRO- AND MACROSYSTEMS

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Modern digital holographic interferometry is used to study the objects of various nature and various spatial scales. In this case, a wide spectral range of coherent electromagnetic radiation from long-wavelength infrared to deep ultraviolet is used. In this work, we present the results of studying dynamic processes in construction materials by the methods of digital holographic interferometry using radiation with a wavelength of up to 9.3 μm. The holographic method for testing of microelectromechanical structures is also considered. The method of digital holographic interferometry, which uses an automated holographic microscope, is proposed to study microscopic biological objects.

1. INTRODUCTION

The methods of digital holographic interferometry are based on comparison of two wave fields obtained by recording the holograms for various object states and are referred to the optophysical methods of measurement and testing.

In modern experiments, holograms are recorded by the digital means and the interference pattern with distributed phase variations is calculated numerically. Then hardware realization of the method involves a digital video camera in combination with stroboscopic recording. The phases are calculated on the basis of Fourier transform.

Modern technical means of digital holography [1, 2] can use radiation in a wide spectral range from infrared to ultraviolet (the wavelengths from 190 nm to 10 μm).

The main task of this research work was to develop the methods of digital holographic interferometry, which allow us to use the potential of the optical-range spectrum. This permits one to vary the method sensitivity and study different-nature objects.

2. THEORETICAL BASIS OF THE METHOD

The spatial distribution of the interference fringes as a result of simultaneous addition of the reference and object waves is recorded by the digital video-camera matrix. Then the recorded optical signal is converted to digital format. Correct digitizing of the hologram requires the fulfillment of the Nyquist theorem [3] conditions, which imposes restrictions on the spatial frequency and, consequently, the angle $\alpha_{\max} = \lambda/(2\,\Delta x)$ between the object and reference beams, where Δx is the pixel size and λ is the wavelength. An additional restriction of the spatial-frequency spectrum is imposed by a diaphragm located in the object beam. After the hologram recording, the phase is calculated using a two-dimensional Fourier transform. If

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the holograms are recorded at the time instants t_1 and t_2, which correspond to different object states, then the phase difference can be calculated and the digital interferogram can be developed after recording the arrived waves [4].

The total intensity recorded by the camera matrix can be written as

$$I = |E_{\mathrm{R}} \exp[-i\varphi_{\mathrm{R}}(x, y)] + E_{\mathrm{O}} \exp[-i\varphi_{\mathrm{O}}(x, y)]|^2, \tag{1}$$

where E_{R} and φ_{R} are the amplitude and phase of the reference wave, respectively, and E_{O} and φ_{O} are the amplitude and phase of the object wave.

Using a two-dimensional Fourier transform allows us to separate the reference and object components of the recorded light field in the Fourier domain. The subsequent filtering of the object component and using a inverse two-dimensional Fourier transform for the latter for different object states allow one to obtain the phase difference

$$\Delta\varphi = \arctan[\tan(\varphi_{\mathrm{O}1} - \varphi_{\mathrm{O}2})] = \arctan \frac{\mathrm{Im}\,(I_{\mathrm{O}1})\,\mathrm{Re}\,(I_{\mathrm{O}2}) - \mathrm{Im}\,(I_{\mathrm{O}2})\,\mathrm{Re}\,(I_{\mathrm{O}1})}{\mathrm{Im}\,(I_{\mathrm{O}1})\,\mathrm{Im}\,(I_{\mathrm{O}2}) + \mathrm{Re}\,(I_{\mathrm{O}1})\,\mathrm{Re}\,(I_{\mathrm{O}2})}, \tag{2}$$

which describes a change in the object state [5]. Here, $\varphi_{\mathrm{O}1}$ is the object-wave phase in the first state, φ_{O_2} is the object-wave phase in the second (subsequent) state, $I_{\mathrm{O}1} = E_{\mathrm{O}} \exp[-i\varphi_{\mathrm{O}1}(x, y)]$, and $I_{\mathrm{O}2} = E_{\mathrm{O}} \exp[-i\varphi_{\mathrm{O}2}(x, y)]$. To study the dynamic processes, the time variation of the phase is reconstructed as follows. The k holograms of the studied object are recorded in the process of the object-state change. The intensity of the kth hologram, which is recorded with the object wave of the form

$$U(x, y, t) = |U_k(x, y, t)| \exp[i\varphi_k(x, y, t)], \tag{3}$$

is determined as

$$I_k = \frac{1}{\Delta} \int\limits_{(k-1)\,\Delta}^{k\,\Delta} I_k(t)\,\mathrm{d}t, \tag{4}$$

where Δ is the exposure time. Using intensity (4), we can reconstruct the phase $\varphi_k(x, y, t)$ of each point of the studied object for its kth state. In this case, the kth state is related to a certain time instant of the recorded physical process.

The phase variation (difference) in holographic interferometry is determined by the relationship [6]

$$\Delta\varphi = \frac{2\pi}{\lambda}\mathbf{KA}, \tag{5}$$

where $\mathbf{K} = \mathbf{k}_1 - \mathbf{k}_2$ is the sensitivity vector, $\mathbf{k}_1$ and $\mathbf{k}_2$ are the unit vectors in the directions of the object illumination and observation, respectively, and $\mathbf{A}$ is the displacement vector. The sensitivity vector is determined by the spatial geometry of the recording system, i.e., varying the recording-system geometry, we can change the interferometer sensitivity. Variation in the sensitivity vector with the corresponding variation in the recording-system configuration allows one, e.g., to record the displacement only in the observation direction and rule out observation of the displacement of points in the object plane. The influence of the point motion in the observer direction can also be reduced with increasing sensitivity for the points moving in the object plane [7]. According to Eq. (5), the method sensitivity is also a function of the wavelength of radiation, which is used for recording of holograms, namely, the phase variation during the object-point displacement decreases with increasing wavelength. When passing from the visible to long-wavelength infrared (9–10 μm) range, the sensitivity can be reduced 20 times [8]. Figure 1 shows the scheme of the primary-hologram recording by a digital detector for the further analysis by the Fourier method.

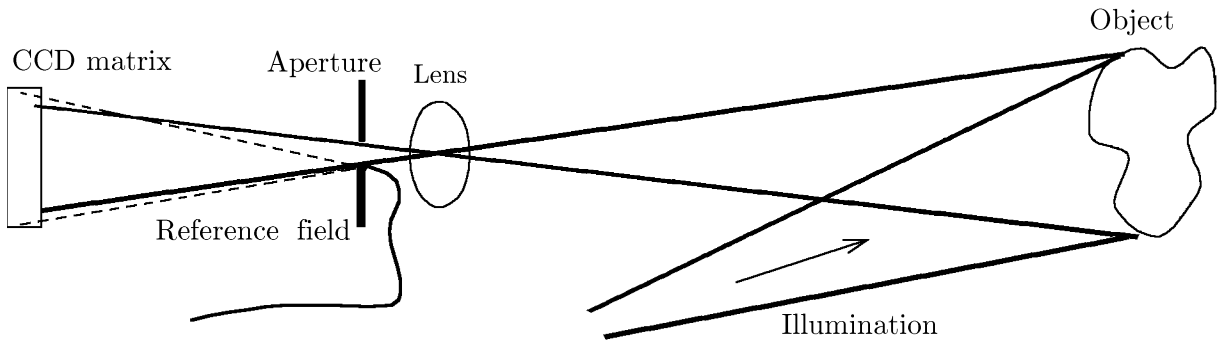

Fig. 1. General layout of the digital-hologram recording.

3. THE RESULTS OF USING DIGITAL HOLOGRAPHIC INTERFEROMETRY OF INFRARED RADIATION

The methods of digital holographic interferometry for infrared radiation (wavelengths of 9–12 μm) have been developed. A high-resolution thermographic camera by the "INFRATEC" Company (Germany) with a resolution of 640×480 pixels was used as the infrared-signal detector. A CO_2 laser with a wavelength of 9.3 μm and a power of 8 W was used in the holographic interferometer. The Kevlar- and aluminum-based composite materials, which are used in aircraft engineering, were used as the study objects. The test-object dimensions were 360×360 mm and the deformation displacements were 16 μm. The test objects were considered with allowance for the structural defects, which were simulated by the different-density segments. The measurement results (an interferogram with localized defects and a three-dimensional representation of deformations) are shown in Fig. 2.

Recording of the hologram series allows one not only to reveal the defects, but also estimate dynamic deformation in time in the region of localization of the problem zone during the object loading [7, 8]. A combination of two methods of optical nondestructive testing, i.e., active thermography and holographic interferometry, is also of interest. It becomes possible to simultaneously record two different-nature signals (thermal and coherent) with their subsequent separation. Therefore, the observation time can be reduced.

4. A HOLOGRAPHIC METHOD FOR TESTING OF MOBILE ELEMENTS IN MICROELECTROMECHANICAL SYSTEMS

Modern microelectronic technologies are used for creating microelectromechanical systems. Such structures and devices are used in miniature control and detection systems [9]. However, testing and calibration of such systems have just started to develop. In this work, digital holographic interferometry is used for estimating mechanical characteristics of such structures and measuring the displacements of their mobile parts. In the optical scheme, a helium-neon laser (with a wavelength of 632 nm) was used. A typical microelectromechanical structure and the value of the mobile-surface displacement as a function of time are shown in Fig. 3. The geometric dimensions of the structure are 5×5 mm. The maximum value of the surface motion is 1.5 μm. One can see the surface deviation from the strictly horizontal position, which allows us to conclude on the possibility of observing and measuring nanometer displacements. Using the holographic methods, we can also simultaneously obtain information from all surface points. Using the methods of estimating the displacements through the point measurers, the above-mentioned deviation from the strictly horizontal location cannot be determined during one measuring session. We should emphasize the main advantage of the holographic-interferometry method, namely, complete reconstruction of the phase and intensity of the object-field radiation. This allows us to estimate variation in the motion of all object-surface points without using point detectors.

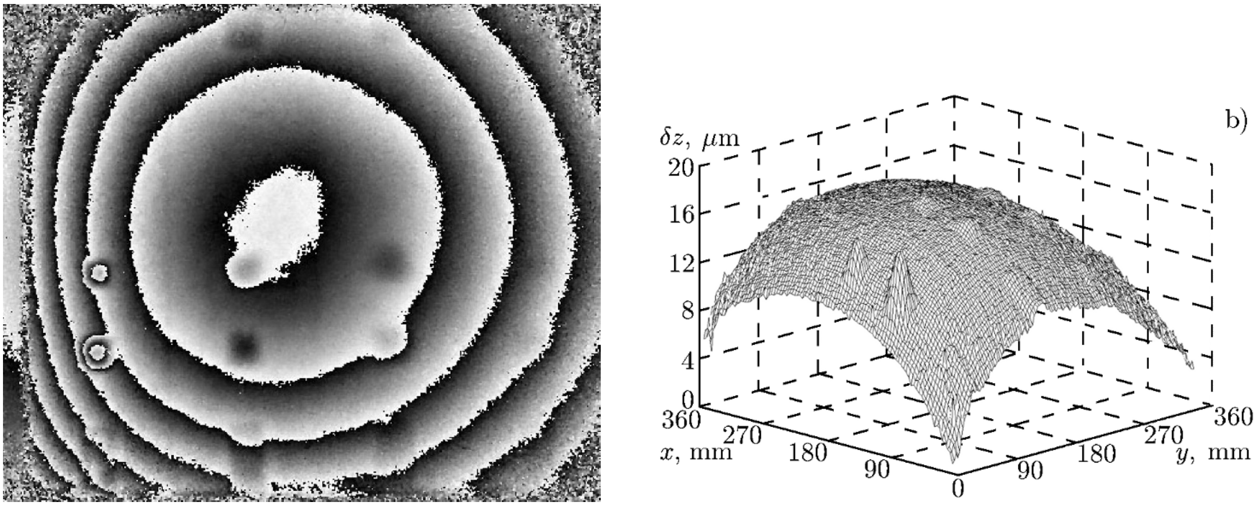

Fig. 2. Deformed state of the object (Kevlar) with pronounced defects: interferogram with localized defects (*a*) and three-dimensional representation of deformations (*b*).

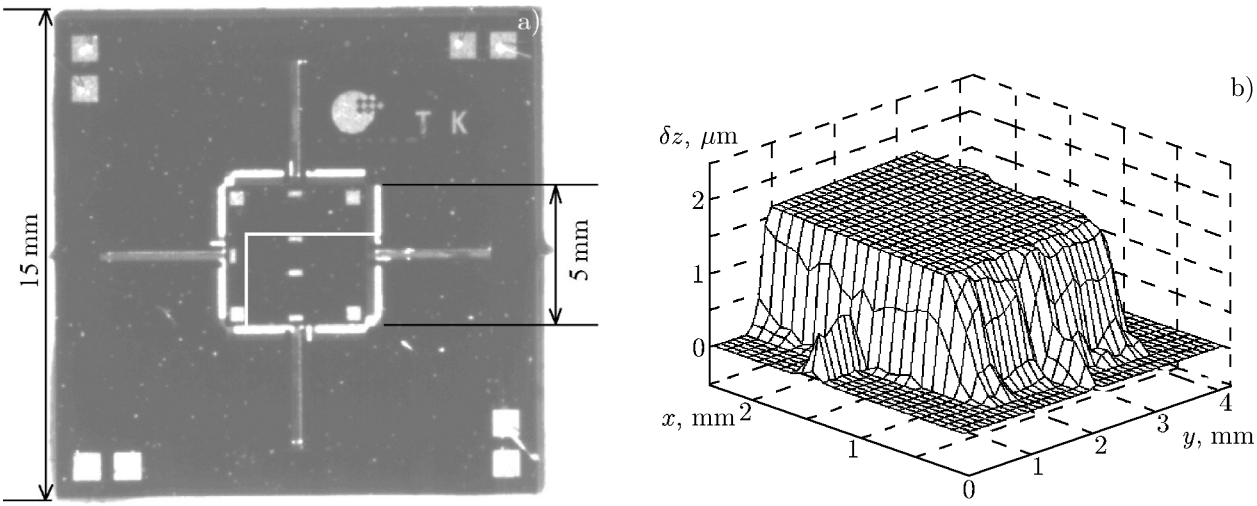

Fig. 3. The study of microdisplacements of the microelectromechanical structure: image of the structure whose 5×5 mm central part moves in the direction perpendicular to the structure plane (*a*) and the result of measuring the structure-part motion by the method of digital holographic interferometry (*b*). The 2.5×4 mm surface part, which is shown in Fig. 3*b*, is marked white in Fig. 3*a*.

5. DIGITAL HOLOGRAPHIC MICROSCOPY IN THE STUDIES OF BIOLOGICAL OBJECTS

The method for measuring parameters of the processes related to variation in the inner structure of biological objects has been developed. The microscope employs the methods of digital holography and holographic interferometry in real time to reconstruct images including their three-dimensional representation from the refractive-index distribution. The microscope comprises a high-resolution digital camera, precision optomechanical components, and an Nd-YaG laser with the radiation wavelength $\lambda = 532$ nm.

The onion cells were used as the object. The experiment demonstrated the possibility to combine the method of visualization of biological microstructures and the method of digital holographic interferometry, which allows one to estimate the relative variation in the refractive index of the cell medium, in one hardware/software complex [10]. The technology has future-development prospects due to improvement of the system resolution with the transition to the UV range and use of new algorithms for optical-information processing.

6. CONCLUSIONS

The proposed methods of digital holographic interferometry use an extended spectral range from the near infrared to visible, which allows us to flexibly vary the method sensitivity. The complex approach to dynamic measurement and visualization of the states of both macroscopic and microscopic of objects study has been implemented. The use of modern methods of recording optical signals and optimization of the holographic interferometers along with the modern algorithms for the data processing substantially extend the class of studied objects and the physical processes in them.

REFERENCES

1. A. Faridian, D. Hopp, G. Pedrini, et al., *Opt. Express*, **18**, No. 13, 14159 (2010).
2. B. Freque, P. Robert, C. Minassian, et al., *Proc. SPIE*, **6940**, 69401X (2008).
3. L. Onural, *Appl. Opt.*, **39**, 5929 (2000).
4. M. Takeda, I. Hideki, and S. Kobayashi, *J. Opt. Soc. Am. A*, **72**, 156 (2082).
5. G. Pedrini, H. J. Tiziani, and Y. Zou, *J. Mod. Opt.*, **42**, 367 (1995).
6. C. M. Vest, *Holographic Interferometry*, Wiley, New York (1979).
7. I. Alexeenko, J.-F. Vandenrijt, M. Georges, et al., *Appl. Mech. Mater.*, **24–25**, 147 (2010).
8. I. Alexeenko, J.-F. Vandenrijt, G. Pedrini, et al., *Appl. Opt.*, **52**, No. 1, 56 (2013).
9. G. Pedrini, J. Gaspar, M. E. Schmidt, et al., *Opt. Eng.*, **50**, No. 10, 101504 (2011).
10. M. Wilke, I. Alekseenko, G. Situ, et al., *Proc. SPIE*, **8082**, 80820D1 (2011).