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OPTICAL INFORMATION TECHNOLOGIES

Determination of Deformation Fields of Diffuse Objects by Phase-Shifting Digital Holographic Interferometry

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Abstract—A modification of the method of digital holographic interferometry for the determination of deformations of an object with a diffuse surface by comparing two complex wavefronts reflected from the object at its two different states is considered. The difference of the proposed method with classical digital holography methods is that digital holograms by which the images are reconstructed have complex values determined by the phase shift method ("complex" hologram), while classical digital holograms have only real values. Besides, digital holograms are reconstructed with allowance for inhomogeneity of the reference beam, which improves the reconstruction quality. For this purpose, a tunable neutral optical filter is introduced into the reference arm of the optical scheme of the interferometer. The method is verified experimentally.

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1. INTRODUCTION

Holographic interferometry is a contactless nondestructive method of measurements with sensitivity on the order of one hundredth of the wavelength. This is an effective method for the determination of the stress-strain state of a solid body [1]. Holographic methods of studying shears and surface relief are used for nondestructive testing and diagnostics of the state of different details and mechanisms [2, 3]. In connection with the development of digital tools for recording optical wave fields, with an increase in computation capacities, appearance of new methods of obtaining and decoding of holograms, classical holography changes to digital holography. In digital holography, the interference pattern of the object diffraction field and reference wave is recorded as a digital hologram which is represented as intensity of the interference pattern in a digital form. The development of digital holography methods revives interest in holographic measurement systems. The aim of this work is to modify the digital holography method for the possibility of determining deformations of an object with a diffuse surface.

2. FORMULATION AND SOLUTION OF THE PROBLEM

Present-day methods of digital holography are based on recording the intensity of the optical interference pattern by use of matrix photoreceivers. In [4], the digital method of image reconstruction was proposed for the first time. Digital holography was further developed after the discovery of direct hologram recording in the digital form [5]. Russian scientists also made a major contribution to this research area [5–7].

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To reconstruct the complex wavefront field reflected from the object, it is necessary to perform the discrete Fresnel transform on the digital hologram:

$$\Gamma(r,s) = -\exp\left\{i\frac{\pi}{\lambda d}\left[\left(\Delta\xi\left(r-\frac{N_x}{2}\right)\right)^2+\left(\Delta\eta\left(s-\frac{N_y}{2}\right)\right)^2\right]\right\}$$
$$\times\,\Im\left(I(k,l)\exp\left\{i\frac{\pi}{\lambda d}\left[\left(\Delta\xi\left(k-\frac{N_x}{2}\right)\right)^2+\left(\Delta\eta\left(l-\frac{N_y}{2}\right)\right)^2\right]\right\}\right), \qquad (1)$$

where λ is the coherent source wavelength used for the illumination, d is the distance at which we find the complex distribution of the wave field scattered from the holographic plane, $I(k,l)$ are samples of the recorded digital hologram with sampling intervals $\Delta\xi = \lambda d/(N_x\Delta x)$ and $\Delta\eta = \lambda d/(N_y\Delta y)$, Δx and Δy are the pixel sizes, N_x and N_y are the numbers of pixels, and $\Im(\cdot)$ is the symbol representing the Fourier transform.

The distance d can be estimated from the following condition: $d \geqslant N\Delta x/\lambda$. If d coincides with the distance from the object to the hologram, the image will be focused. The exact value of the distance d is usually unknown. To refine it, it is necessary to obtain a series of images at different distances and to determine the exact distance after several iterations.

In digital holography, the reconstructed image is a set of complex numbers the intensity and phase of which is obtained using the well-known formulas

$$I(r,s) = |\Gamma(r,s)|^2 \quad \text{and} \quad \varphi(r,s) = \arctan\left[\frac{\mathrm{Im}(\Gamma(r,s))}{\mathrm{Re}(\Gamma(r,s))}\right]. \qquad (2)$$

When studying deformation of objects with a diffuse surface, the large number of phase transitions does not allow one to use expression (2) for its direct determination. To solve this problem, it is proposed to use the "mathematical" hologram in (1) as the digital hologram $I(k,l)$

$$G(k,l) = a_p(k,l)\mathrm{e}^{-i\varphi(k,l)}, \qquad (3)$$

where $a_p(k,l)$ is the amplitude and $\varphi(k,l)$ is the phase of the mathematical hologram. Formula (1) takes the form

$$\Gamma(r,s) = -\exp\left\{i\frac{\pi}{\lambda d}\left[\left(\Delta\xi\left(r-\frac{N_x}{2}\right)\right)^2+\left(\Delta\eta\left(s-\frac{N_y}{2}\right)\right)^2\right]\right\}$$
$$\times\,\Im\left(G(k,l)\exp\left\{i\frac{\pi}{\lambda d}\left[\left(\Delta\xi\left(k-\frac{N_x}{2}\right)\right)^2+\left(\Delta\eta\left(l-\frac{N_y}{2}\right)\right)^2\right]\right\}\right). \qquad (4)$$

The amplitude and phase of the mathematical hologram are found using the method of stepwise phase shifts. In this method, a series of digital holograms $\mathbf{I}$ is recorded by introducing different phase shifts into the reference beam. In addition, using stepwise phase shift methods in obtaining digital holograms allows one to avoid problems related to elimination of the zero diffraction order and double image [8]. Using expressions from [9], we obtain

$$\varphi = \arctan\left(\frac{\mathbf{I}\cdot\mathbf{C}^{\perp}}{\mathbf{I}\cdot\mathbf{S}^{\perp}}\right) \quad \text{and} \quad a = \frac{1}{\mathbf{C}\cdot\mathbf{S}^{\perp}}\left[(\mathbf{I}\cdot\mathbf{C}^{\perp})^2+(\mathbf{I}\cdot\mathbf{C}^{\perp})^2\right]^{1/2}, \qquad (5)$$

where $\mathbf{C} = (\cos\delta_0,\ldots,\cos\delta_{m-1})^{\top}$, $\mathbf{S} = (\sin\delta_0,\ldots,\sin\delta_{m-1})^{\top}$ is a collection of sines and cosines of known phase shifts δ, $\mathbf{C}^{\perp}$ is a vector orthogonal to the vector $\mathbf{C}$, and $\mathbf{S}^{\perp}$ is a vector orthogonal to the vector $\mathbf{S}$; and

$$\varphi = \varphi_p - \varphi_r; \quad a = 2a_pa_r. \qquad (6)$$

It follows from expressions (3)–(6) that a correct reconstruction of the image from a digital hologram requires knowing the real value of amplitudes of the object and reference beams. As shown in [11],

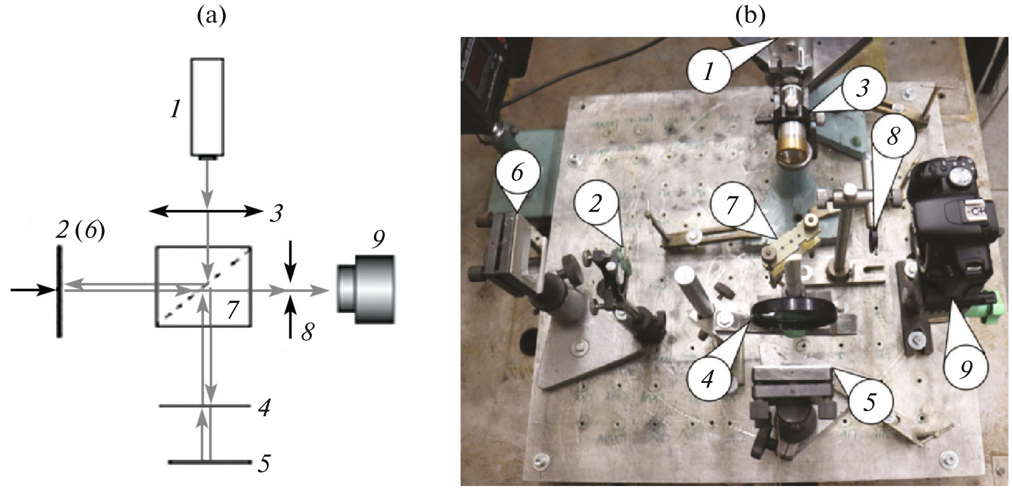

Fig. 1. Scheme of hologram recording: (a) scheme of the holographic setup and (b) photograph of the optical setup. Notation: (*1*) laser, (*2*) object, (*3*) beam expander, (*4*) tunable neutral filter for varying the level of the reference beam intensity, (*5*) reference mirror, (*6*) mirror for adjusting the setup, (*7*) light beam divider, (*8*) diaphragm, and (*9*) video camera.

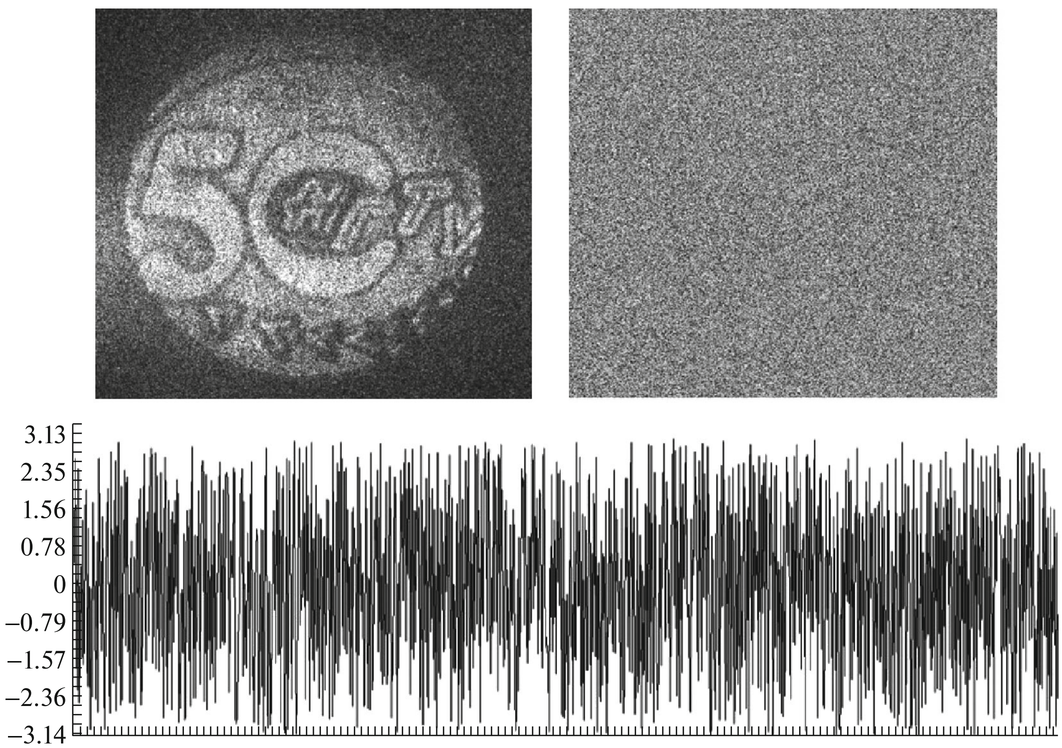

Fig. 2. Object's (a) amplitude and (b) phase reconstructed by a digital hologram and (c) plot of the phase by the central row.

changing the intensity of the reference beam by the known value k, one can obtain the system of equations

$$\begin{cases} I = a_r^2 + a_p^2 + 2a_r a_p \cos\varphi, \\ I(k) = (ka_r)^2 + a_p^2 + 2ka_r a_p \cos\varphi \end{cases} \quad \text{and} \quad \begin{cases} a = 2a_r a_p, \\ a(k) = 2ka_r a_p, \end{cases} \tag{7}$$

from which real values of the amplitudes a_p and a_r are found. The coefficient of variation in the reference beam intensity k also can be determined directly from the set of digital holograms $\mathbf{I}$ [10].

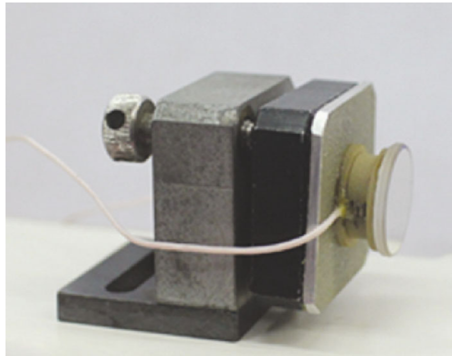

Fig. 3. Reference mirror on piezoceramics.

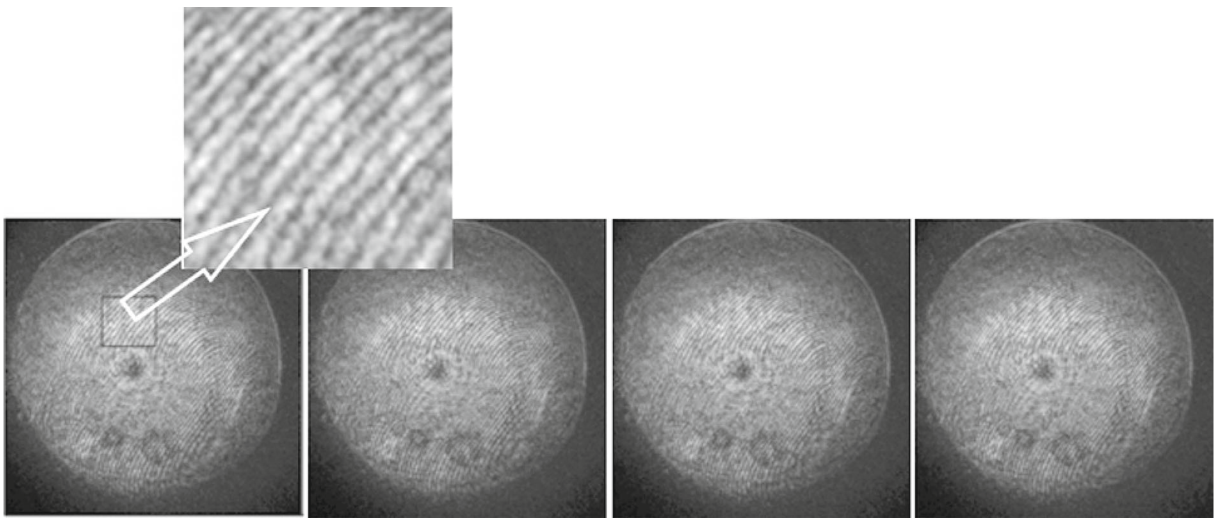

Fig. 4. Interference patterns under changes of the phase shift angle: $\delta_1 = 0°$, $\delta_2 = 90°$, $\delta_3 = 180°$, and $\delta_4 = 270°$.

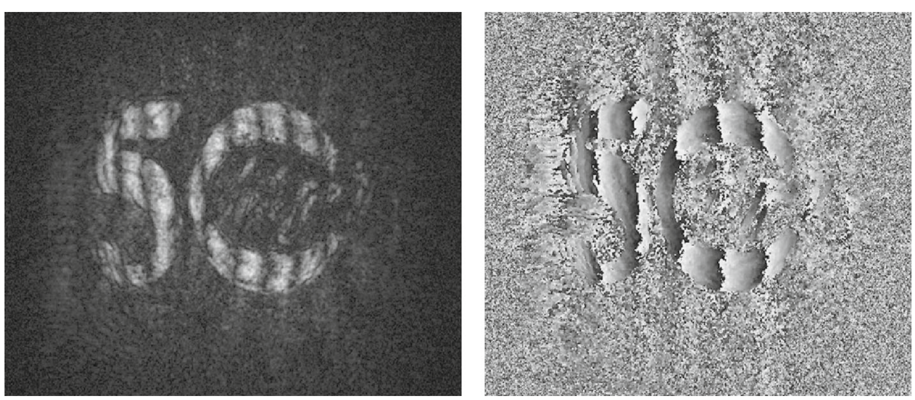

Fig. 5. Amplitude and phase of interference fringes.

3. EXPERIMENTAL VERIFICATION

Reconstruction of the complex wavefront reflected from the surface of a diffuse object was verified experimentally using a simple optical scheme [11] shown in Fig. 1. A series-production Canon EOS M50 camera with the maximum resolution of 6000×4000 pixels was used as the input device. The photoreceiver matrix has dimensions 22.3×14.9 mm, the pixel size is 3.7 μm. The digital hologram is recorded by the camera without a lens. For the illumination, an LS-1-SLM-532-100 green

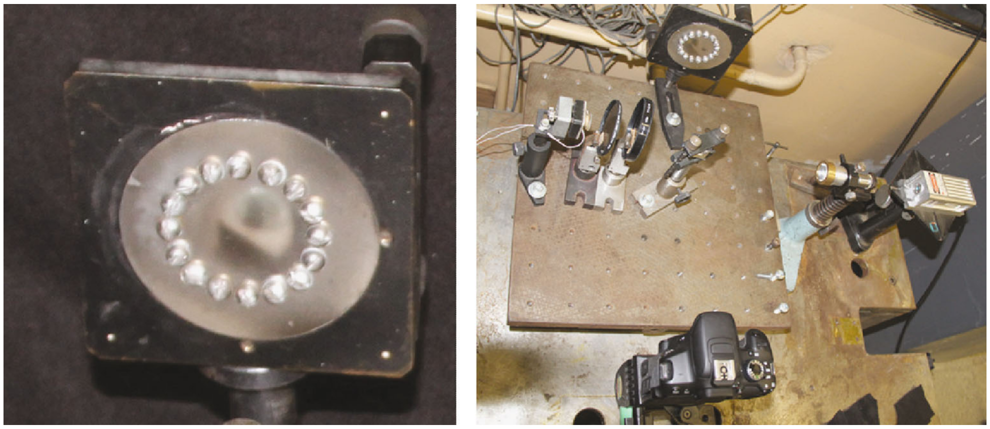

Fig. 6. Photographs of the membrane and optical setup.

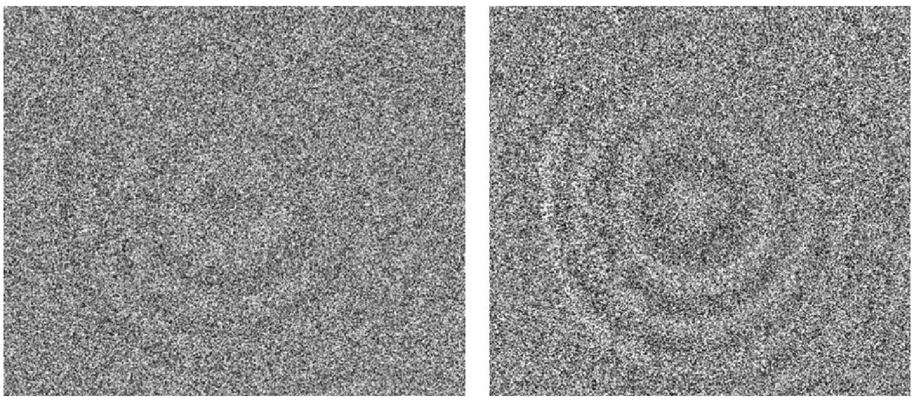

Fig. 7. Digital holographic interference patterns under different loads of the metal membrane.

semiconductor laser with a wavelength of 532 nm, power of up to 100 mW, and coherence length of 15–20 cm was used. To vary the reference beam intensity, a Thorlabs NDC-50C-2-B tunable neutral filter was introduced into the optical scheme.

The anniversary silver badge of the Novosibirsk State Technical University was taken as the object. The object size is 7 mm and the distance from the object is 135 mm. Figure 2a shows the result of reconstruction of a diffuse object by a digital hologram calculated by formula (1).

As seen in Figs. 2b and 2c, the phase of the digital hologram of the diffuse object is of random character and cannot be used for purposes of interferometry. To obtain a mathematical hologram, the optical setup (see Fig. 1) was modernized. The reference mirror *5* (see Fig. 1) was made movable (Fig. 3).

Figure 4 shows results of interference between the reference and object beams under changes of the phase shift angle.

According to algorithm (4)–(7), mathematical hologram (3) was formed. The hologram is represented by a matrix of complex numbers. Then, the complex wavefront was reconstructed by formula (4). To accelerate the computations, a NVIDIA GTX 1070 graphics card [12] was used. The computation time for one image is about 1 min. To tune the focusing of the reconstructed image, the hologram size was reduced to 600×400 pixels. In this regime, the hologram computation time was 30 fps.

To obtain the interference fringes, the object was inclined by motion of micrometer screws by 5 μm. Then, the second series of digital interferograms was recorded. Figure 5 shows the amplitude and phase of interference fringes obtained from mathematical holograms of the object before and after its shift.

For the determination of the deformation field, a metal membrane loaded in the center was chosen as an object. Figure 6 shows the external view of the membrane and optical setup. The optical scheme of the setup is the same as in Fig. 1.

Further, the mathematical hologram of the object without a load was formed. Then, the object was loaded and one could observe in real time holographic interference fringes corresponding to deformation of the disk (Fig. 7).

4. CONCLUSIONS

In this work, the possibility to determine deformations of an object with a diffuse surface by digital holography is considered. For this purpose, two series of digital holograms of the object before and after loading are formed by the stepwise phase shift method. Then, mathematical holograms are generated; using the holograms, complex wave fields reflected from the object surface are reconstructed in software. The deformations are estimated by comparing wave fields of two different states of the object. The method is verified experimentally. Using a graphics accelerator for the computations makes it possible to observe the deformation picture in real time.

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