HOLOGRAPHIC INTERFEROMETRY

PACS numbers: 42.87.Bg; 42.40.Kw
DOI: 10.1070/QE2008v038n10ABEH013519

Increase in the sensitivity of holographic reversible shearing interferometry by turning around an object

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***Abstract*. It is shown that a turn of an object in holographic reversible shearing interferometry in the case of objects with linear dimensions not exceeding half the diameter of a probe light beam allows the doubling of the sensitivity of interferograms mapping changes in a wavefront caused by the object. The interference patterns of a glass test plate with the doubled sensitivity of inhomogeneity mapping obtained by this method are presented.**

Keywords: *phase object, hologram, reversible shear, interference pattern, measurement sensitivity enhancement.*

1. Introduction

Shearing interferometry differs from two-beam reference-wave interferometry in that in the former case an interference pattern is formed by two waves transmitted through an object [1, 2]. The methods of shearing interferometry use simple optical schemes and shearing interferometers themselves have a higher vibration resistance compared to that of two-beam interferometers. Various methods of shearing interferometry have found wide applications in a variety of fields in science and technology [3 – 9].

Apart from the most widespread lateral shearing interferometry, rotational and reversible shearing interferometry has been applied in a number of cases [3, 10]. The use of holographic principles for obtaining interferograms with different shear types provided the compensation of aberrations of optical systems in real-time measurements [11, 12]. The reversible shear can be obtained both in longitudinal and radial directions [13 – 15]. In radial shearing holographic interferometry, this is achieved by using a Gabor zone plate [16, 17].

An important feature of shearing interferometry is the dependence of the behaviour of interference fringes both on the shear type of interfering wavefronts and its value. If a phase object under study occupies only a part of the working field, interference patterns produced in shearing interferometry can be similar to interferograms obtained in two-beam reference-wave interferometers [18]. This particular case of shearing interferometry is of special interest because it combines all the advantages of the two methods and excludes a complicated interpretation of interference patterns inherent in shearing interferometry. In the above-mentioned particular case of shearing interferometry, the behaviour of interference fringes directly represents the change in the wave phase caused by the object. To increase the sensitivity of mapping these variations, it was proposed in [19, 20] to use either the double lateral shear of wavefronts [19] or combine the lateral shears of wavefronts and interferograms during their optical processing [20]. However, as shown in [21], reversible or rotational shearing interferometry with the rotation of one of the beams through 180° offers, in the case of compensation of aberrations, a number of advantages compared to lateral shearing interferometry. In the method of reversible shearing interferometry proposed in [21], a pair of aberration-free interferograms of the object was observed simultaneously, the behaviour of interference fringes being identical to that in two-beam reference-wave interferometry. The interpretation of such a pair of interferograms and averaging of the result reduces, unlike the case of one interference pattern obtained in the classical scheme of a two-beam reference-wave interferometer, the measurement error.

It is shown in this paper that the turn of the object in holographic reversible shearing interferometry [21] allows the doubling of the sensitivity of this method. Compared to two-beam reference-wave interferometry, this not only reduces the measurement error in the interpretation of a pair of such interferograms but also reduces by half the threshold of optical inhomogeneities being measured.

2. Optical scheme of the method

Figure 1 presents the optical scheme used for increasing the measurement sensitivity of holographic reversible shearing interferometry. Note that this method can be used if the maximum linear dimensions of a phase object under study in the direction perpendicular to the reversible shear axis do not exceed half the diameter of the probe beam.

The coordinate system is chosen so that a light beam transmitted through an object propagated along the z axis coinciding with the principal optical axis of the system forming the probe beam and the reversible shear was performed in reversible shearing interferometer (*3*) by changing the direction of only the x axis of one of the light beams to the opposite one, i.e. by turning the wavefront through 180° with respect to the y axis (Fig. 1). The

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Received 11 January 2007; revision received 6 July 2007
Kvantovaya Elektronika **38** (10) 976 – 980 (2008)
Translated by M.N. Sapozhnikov

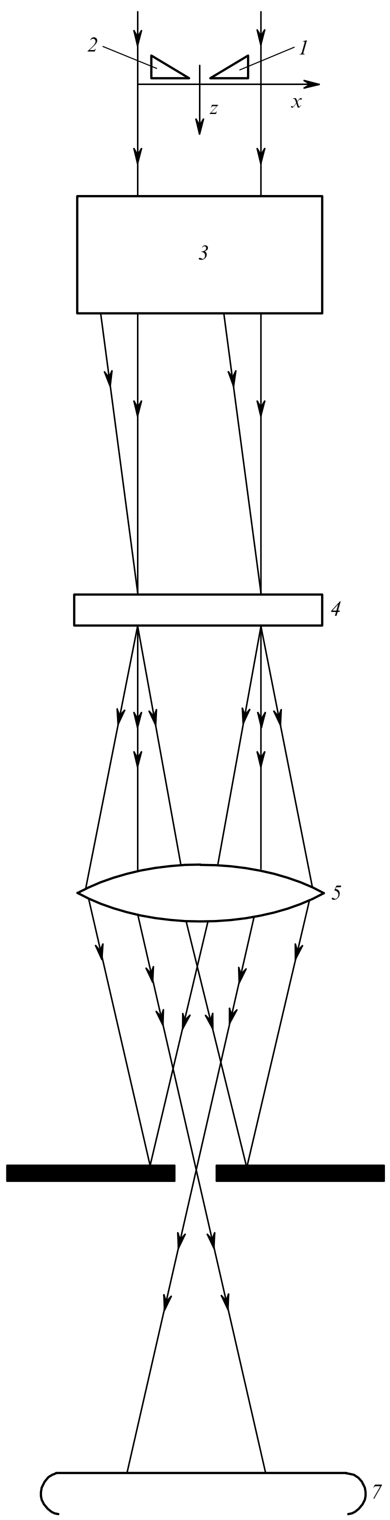


Figure 1. Optical scheme for increasing the sensitivity of holographic reversible shearing interferometry: (*1*, *2*) positions of a phase object; (*3*) reversible shearing interferometer; (*4*) reference holographic interferogram; (*5*) objective; (*6*) aperture; (*7*) interference pattern plane.

coordinate system xy is located in the object plane, as shown in Figs 1 and 2.

The reference holographic interferogram was recorded by placing a phase object in one of the halves of the probe beam, for example, in position (*1*) (Fig. 1) so that it occupies less than half the light beam field. Figure 2 shows

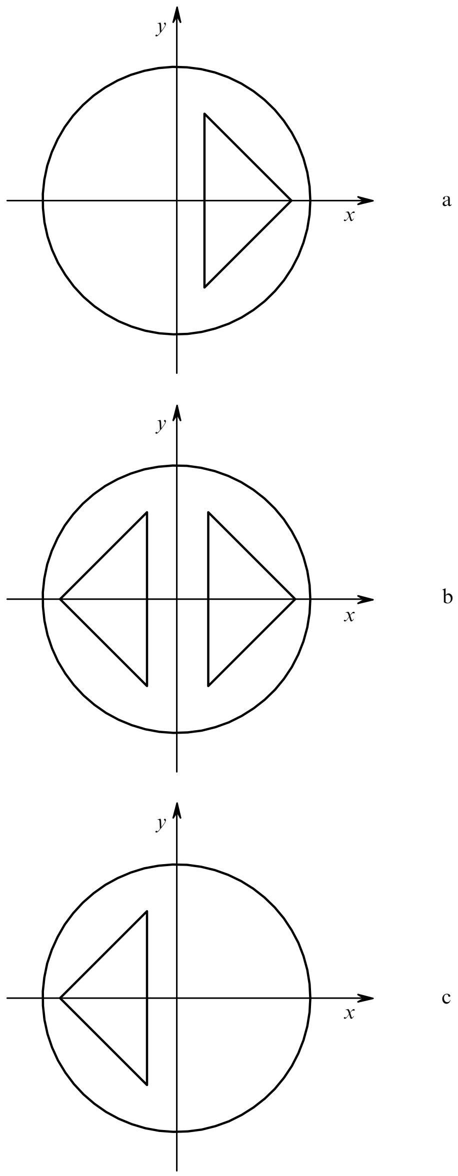


Figure 2. Schematic light beam contour (circle) and contours of the object and its image (triangles) in different planes of the optical scheme (Fig. 1): in the object plane before the object turn (a), in the plane of the reference holographic interferogram (b), and in the object plane after its turn (c).

schematically the contours of light beams, the object under study, and its image in different planes of the optical scheme (Fig. 1).

After the passage through the phase object (Fig. 2a), the object light beam is directed to reversible shearing interferometer (*3*). As the reversible shearing interferometer, a two-beam Mach–Zehnder interferometer rotating the wavefront of one of the interfering beams by 180° can be used. The scheme and operation principle of this interferometer are described in detail in [21]. A specific feature of the interferometer is that the wavefront of one of the interfering light beams is turned around the axis through 180°. Figure 2b shows the contours of interfering combined light beams and images of the object in the plane of formation of the reference reversible shearing holographic interferogram (*4*). The optical scheme for filtering spatial frequencies is formed by aperture (*6*) mounted in the image focal plane of objective (*5*) and is used for separating the corresponding diffraction orders of light on reference holographic interferogram (*4*). To obtain interference patterns with the enhanced sensitivity in plane (*7*), the object was turned around the axis by 180°. This turn leads to the displacement of the object to position (*2*) in the second half of the object probe beam (Figs 1 and 2c). The observation plane of interference pattern (*7*), which maps with the doubled sensitivity the changes of the wavefront caused by the object, is optically conjugated with reference hologram (*4*) and object (*1*).

3. Recording of a reference holographic interferogram

At the first stage of the method of increasing the sensitivity of holographic reversible shearing interferometry, the object under study is placed in position (*1*) and a reference holographic interferogram is recorded in plane (*4*).

Let us assume that the optical scheme of reversible shearing interferometer (*3*) is adjusted so that the first light beam is inclined in the xz plane to the axis at an angle α_0, while the second beam, experiencing a reversible shift, propagates along the z axis. In this case, the complex amplitudes A_1 and A_2 of light waves at the interferometer output in the plane of recording reference holographic interferogram (*4*) can be written in the form

$$A_1(x,y) = a_1 \exp\{\mathrm{i}[2\pi\xi x + \varphi(x,y) + \varepsilon_0(x,y) + \varepsilon_1(x,y)]\}, \quad (1)$$

$$A_2(x,y) = a_2 \exp\{\mathrm{i}[\varphi(-x,y) + \varepsilon_0(-x,y) + \varepsilon_2(x,y)]\}, \quad (2)$$

where a_1 and a_2 are real amplitudes; $\xi = \lambda^{-1}\cos\alpha_0$ is the spatial frequency of the light wave; λ is the wavelength; $\varphi(x,y)$ and $\varepsilon_0(x,y)$ are phase distortions caused by the phase object and aberrations of the object arm of the optical system for formation of the probe light beam; $\varepsilon_1(x,y)$ and $\varepsilon_2(x,y)$ are phase distortions caused by aberrations of the first and second arms of reversible shearing interferometer (*3*). If linear recording conditions are fulfilled [22] and $a_1 = a_2$, then the amplitude transmission of the reference holographic interferogram can be written in the form

$$\tau(x,y) = 1 + \cos[2\pi\xi x + \varphi(x,y) - \varphi(-x,y) + \varepsilon_0(x,y) - \varepsilon_0(-x,y) + \varepsilon_1(x,y) - \varepsilon_2(x,y)]. \quad (3)$$

After chemical processing of reference holographic interferogram (3), it is placed in the same position (*4*) (Fig. 1). The accuracy of positioning can be controlled visually by making the contour of object (*1*) coincident with the contours of its images recorded on the reference holographic interferogram (*4*). A more precise positioning of the reference holographic interferogram is achieved when an infinitely broad moire fringe is observed on reference holographic interferogram (*4*). When the uniform illumination of the moire picture is achieved over the entire visualised field, which corresponds to an infinitely broad moire fringe, we can assert that no bending of the fringes due to inaccurate positioning of the object will be observed visually. Usually, the bending of interference fringes in this case does not exceed 0.1 of the fringe width [22, 23].

4. Obtaining of interference patterns with the enhanced sensitivity

At the second stage of the method of increasing the sensitivity of holographic reversible shearing interferometry, phase object (*1*) is turned by 180° with respect to the y axis and occupies position (*2*), which is symmetrical (with respect to the y axis) to its initial position. Figure 2c shows schematically the contours of the probe light beam and phase object in the new position after the turn. The accuracy of the turn of the phase object can be controlled by making the contour of the object image coincident with the contours of images recorded on the reference holographic interferogram (Fig. 2b). These contours should exactly coincide. In this case, the complex amplitudes of light waves at the interferometer output in the plane of reference holographic interferogram (*4*), taking into account the turn of the phase object, are transformed from (1) and (2) to expressions

$$A_1'(x,y) = a_1 \exp\{\mathrm{i}[2\pi\xi x + \varphi(-x,y) + \varepsilon_0(x,y) + \varepsilon_1(x,y)]\}, \quad (4)$$

$$A_2'(x,y) = a_2 \exp\{\mathrm{i}[\varphi(x,y) + \varepsilon_0(-x,y) + \varepsilon_2(x,y)]\}. \quad (5)$$

The distribution $B(x,y)$ of the complex amplitudes of light waves at the output of reference holographic interferogram (*4*) is described by the expression

$$B(x,y) = [A_1'(x,y) + A_2'(x,y)]\tau(x,y). \quad (6)$$

To obtain interference patterns of the enhanced sensitivity, the waves propagating along the principal optical axis of objective (*5*) are separated with the help of aperture (*6*) placed in the image focal plane of objective (*5*). These waves have the complex amplitudes

$$B_1(x,y) = b_1 \exp\{\mathrm{i}[2\varphi(-x,y) - \varphi(x,y) + \varepsilon_0(-x,y) + \varepsilon_2(x,y)]\}, \quad (7)$$

$$B_2(x,y) = b_2 \exp\{\mathrm{i}[\varphi(x,y) + \varepsilon_0(-x,y) + \varepsilon_2(x,y)]\}, \quad (8)$$

where b_1 and b_2 are real amplitudes. Waves (7) and (8) are separated by the aperture from other waves and produce the infinite-fringe-width interference pattern

$$I(x,y) = b_1^2 + b_2^2 + 2b_1b_2\cos[2\varphi(-x,y) + 2\varphi(x,y)]. \quad (9)$$

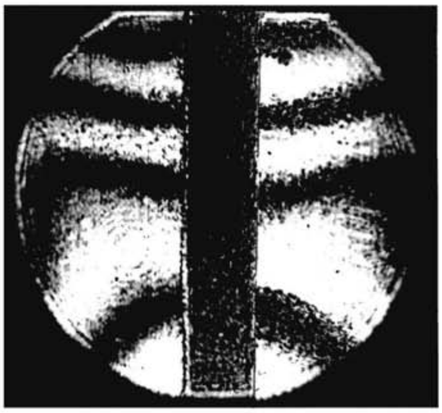
As follows from (9), aberrations of the system forming the probe beam and of the reversible shearing interferometer are completely compensated. Such an interference pattern, as in the case of the method of aberration-free holographic reversible shearing interferometry [21], represents two interferograms located symmetrically with respect to the y axis (Fig. 2b), but mapping a change in the phase by the object with the doubled sensitivity compared to that of two-beam reference-wave interferometry.

Finite-fringe-width interference patterns could be obtained, as in the case [21], due to a small change (compared to $\pi/2 - \alpha_0$) in the propagation direction of one of the light beams illuminating the reference holographic interferogram. If $\Delta\alpha$ and $\Delta\beta$ are the angles determining the change in the propagation direction of light beams (4) and (5), respectively, in planes xz and yz, the interference pattern (9) can be written in the form

$$I(x,y) = b_1^2 + b_2^2 + 2b_1 b_2 \cos[2\pi\xi_0 x + 2\pi\eta_0 y + 2\varphi(-x,y) + 2\varphi(x,y)], \tag{9a}$$

where $\xi_0 \approx \lambda^{-1}\Delta\alpha\sin\alpha$ and $\eta_0 \approx \lambda^{-1}\Delta\beta$ are parameters determining the width and orientation of interference fringes in the region of the interference pattern unperturbed by the object.

It is obvious that the symmetry of interference fringes in the left and right interferograms with respect to the y axis takes place when the conditions $\xi_0 = \eta_0 = 0$, corresponding to an infinitely broad fringe, and $\eta_0 = 0$, corresponding to vertical finite-width fringes, are fulfilled in (9a). Only in these two cases, interference fringes are symmetric with respect to the y axis.



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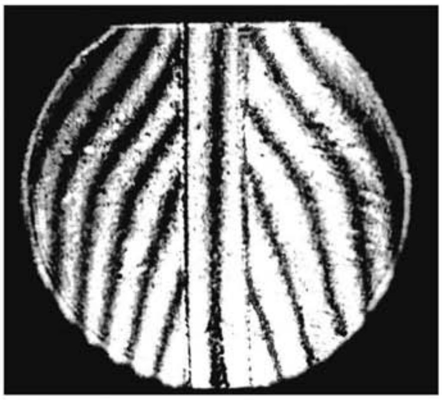

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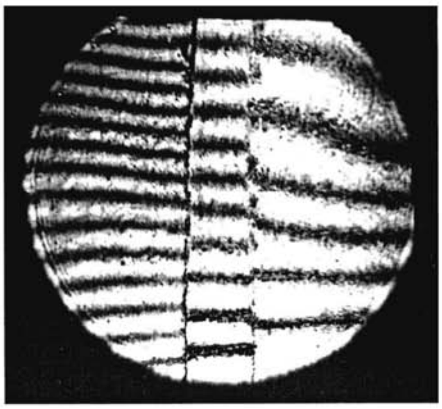

c

Figure 3. Interference patterns of a test glass plate obtained by the proposed method in infinitely broad (a) and finite-width fringes.

Figure 3 presents interferograms of a test glass plate obtained by the method of holographic reversible shearing interferometry with the enhanced sensitivity described above. The vertical edge of the plate is parallel to the y axis. The plate occupies less than half the object beam zone, which provides the production of a region in the form of a vertical strip near the y axis, which is unperturbed by the object and divides the interference pattern into the right and left interferograms. This vertical strip also visualises the adjustment of interference fringes.

One can see from Fig. 3 that the symmetry of interference fringes of the right and left interferograms with respect to the y axis is observed in interference patterns with infinite-width fringes (Fig. 3a) and finite-width fringes oriented in the unperturbed zone (central vertical strip) perpendicular to the x axis. In the case of arbitrarily adjusted interference fringes (Fig. 3b), the symmetry of fringes in the right and left interferograms is violated.

The doubling of the sensitivity of phase mapping by the object (Fig. 3a) is confirmed by the infinite-fringe-width interference pattern (Fig. 4) for the same test plate obtained in the two-beam reference-wave interferometer. To obtain the interference pattern in the Mach–Zehnder interferometer (Fig. 4), the test plate was placed into the right half of the object light beam. A comparison of the interference patterns shows that in the first case (Fig. 3a) the number of interference fringes in the region of the object under study is twice as large as that in the second case (Fig. 4).

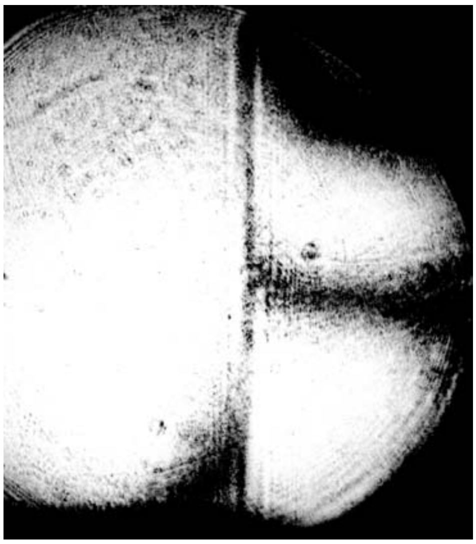

Figure 4. Interference pattern of a test plate in infinitely broad fringes obtained in a two-beam reference-wave interferometer.

5. Conclusions

The turn of an object in holographic reversible shearing interferometry in the case of objects with linear dimensions not exceeding half the diameter of a probe light beam allows the doubling of the sensitivity of interferograms mapping changes in a wavefront caused by the object compared to two-beam reference-wave interferometry and the method of aberration-free holographic reversible shearing interferometry developed earlier [21]. Despite the complication of the measurement process, the doubling of the sensitivity of phase mapping by the object in the developed method of reversible shearing interferometry will allow the investigation of phase objects with optical inhomogeneities smaller by half than those studied by the method of two-beam reference-wave interferometry. In this case, the doubling of the measurement sensitivity is equivalent to the corresponding decrease in the wavelength of a coherent radiation source.

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