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USE OF THE SPECKLE HOLOGRAPHY TECHNIQUE IN EXPERIMENTAL MECHANICS

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A new mathematical model for holographic and speckle interferometry is proposed which combines the existing theories of geometric and diffraction optics. New capabilities for solving a wide range of problems in applied optoelectronics and experimental mechanics for measuring the deformation of full-scale structures are examined.

Keywords: *speckle holography, speckle structure, diffraction and computer optics, diffraction gratings, diffraction halo, Fourier transform.*

The technology for speckle interferometry has been developed relatively recently and there is no generally accepted theory for it yet. This technology is, however, used in electron speckle interferometry as an alternative to the contactless holographic process [1–3]. Use of the author's method for analyzing deformations in diffusely reflecting full-scale constructions will make it possible to determine the components of the spatial displacement and deformation tensor.

Physics of speckle structure formation. When illuminated by coherent light from a laser, each point on the diffuse surface of an object scatters a complicated coherent light wave into the surrounding space that is unique to the object. This wave contains information on the structure of the material of the object, the working of its surface, its roughness, and other properties. Because of interference addition of the waves from all points on the illuminated surface, a complicated, coherent speckle field forms in space and carries information on the surface. A set of bright speckles is seen on the surface of the object (the surface "sparkles"). When an optical instrument is used, an image of individual speckles can be obtained which is determined by the aperture of the objective. When the aperture is larger, the structure of the speckles will be finer, since the diameter of the diffraction pattern created by the objective becomes smaller when its aperture is increased. In order to obtain speckles, however, it is not necessary to have an image of the object. A diffuse object illuminated by a laser creates a speckle structure in all the space surrounding it. If a photographic plate is placed at any distance from the object, speckles from the object will be recorded on it. By analogy with the phenomenon of diffraction, these speckles in the near field can be referred to as Fresnel speckles and those in the far field with a focussed image, as Fraunhofer or individual speckles. Speckles are present during the recording of holograms and in the recovered image, although the quality of the image deteriorates. These speckles can be used in experimental mechanics for measuring spatial displacements and deformation of the surface of an object, but also in electronics, radar, space studies, and other applications of coherent optics.

Speckle structures are formed in different ways, for example, with geometric or diffraction optics [2–7]. The author's ideas [3, 5–10] are based on the following facts: First, diffraction of coherent illumination on a regular diffraction grating has a strictly defined spatial frequency that is given by the Bragg formula,

$$\sin\alpha = \lambda/d,$$

where α is the diffraction angle, λ is the laser wavelength, and d is the grating period.

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During diffraction on roughness of a diffuse surface, a spectrum of spatial frequencies is formed which carries information on the object. The speckle field can be regarded as the result of diffraction on a set of gratings of different types with variable spatial frequencies (periods) and spatial orientations. Thus, speckle fields can be analyzed with optical filtration using the Fourier transform, which has the mathematical completeness of functional analysis and is simple to perform in optics.

Second, in the case of the optical configurations described in [5, 11] with detection of speckle holograms "without a reference" of the focussed image by a double aperture, the beams of rays emerging from the apertures are references for one another and create a carrier spatial frequency over the entire image against the background of the speckles. After optical filtration of the diffraction orders of speckle holograms of this type in accordance with a classical scheme against the background of the speckles, a regular grating with the parameters of the apertures is observed.

When the entire aperture of the imaging system or a set of holes within this aperture are used, it is possible to obtain a speckle image and record a speckle hologram with a set of spatial frequency spectra. Thus, for interference with the intensity, at each point of the holographic image, information exists on the spatial frequencies over the entire field of the object, and at each point of the geometric image, there is a set of reference spatial frequencies. This explains the continuous spectrum in the diffraction halo in the frequency plane with filtration of speckle holograms.

When an additional reference beam is used, a regular carrier grating develops over the field of the speckle hologram, is determined by the diffraction angle between the reference and object beams, and is observed against the speckle background. An additional reference beam increases the sensitivity to vibrations, so when speckle holography is done off the test stand under vibration conditions, the grating fringes are smeared out and the recording quality of the holograms deteriorates. Similar processes occur in sandwich holography (an analog of binocular vision) [11]. They are used in optoelectronics and radio astronomy for fabrication of synthesized apertures.

We shall treat the speckle hologram *Sg* as the convolution © of the instrument function *A* of the detection and recording apparatus, such as a photodetector and CCD array, with an object wave *S*, i.e., *Sg*=*S*©*A*. The speckle hologram can be represented as the convolution of different kinds of signals in the recording field with its instrument function. Note that when the spatial angle θ of the scattering indicatrices of the incident illuminator coherent source wave with diffuse reflection from the surface of the object of the front of this wave is greater, more spatial frequencies can be written in the speckle hologram. Thus, with optical differentiation with respect to the spatial frequency using optical filtering, it is possible to record a larger range of plane components of the spatial deformations of the surface of the object.

In the holography plane, a stationary field of the superposition of waves with a distribution of amplitudes corresponding to the spatial structure of the diffuse scattering of the object is detected. Usually, it is assumed that after photochemical processing, the transmission amplitude $\tau(x)$ of the speckle hologram is proportional to its recorded intensity. In the plane of the hologram, the object beam interferes with every spatial component of the waves and all these components interfere with one another. Thus, we shall assume that a corresponding set of interference gratings is recorded on the speckle hologram with periods which are determined by the interference angles. To simplify the expressions for the amplitude transmission of a linearly recorded speckle hologram, including the sum of the spatial components of the frequencies of the field of the speckle structure, in terms of one component $T(x)$ [4], we write:

$$\tau(x) = T_0 - K|t(x)|^2 - k\sum_{n,m}|t(x)|^2 \exp\left(\frac{\mathrm{i}2\pi x}{d_{nm}}\right) - k\sum_{n,m}|t(x)|^2 \exp\left(\frac{-\mathrm{i}2\pi x}{d_{nm}}\right),$$

where T_0 is the zero component; K and k are constants of the recording process; d_{nm} is the step size of the interference fringes for components n and m.

The distribution of the amplitudes in the Fourier plane with filtering is given by

$$U(\xi) = F[\tau(x)] = T_0\delta(\xi) - KF[|t(x)|^2] - k\sum_{n,m}T(\xi)\oplus T^*(\xi+\xi_{nm}) - k\sum_{n,m}T(\xi)\oplus T^*(\xi-\xi_{nm}),$$

where F, $\oplus$ are, respectively, the Fourier transform and autocorrelation operators; δ is the delta function; $T(\xi)$ is the Fourier transform of the function $t(x)$; $\xi_{nm} = 1/d_{nm}$ is the spatial frequency of the speckle structure of the *n*th and *m*th emitters, used to

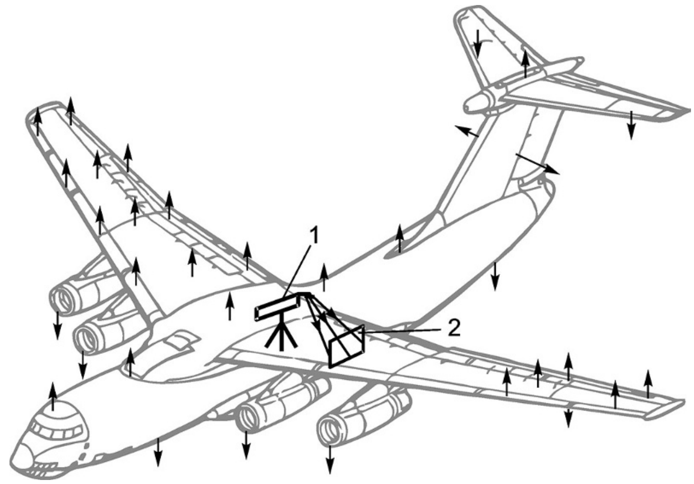


Fig. 1. Configuration for testing of a full scale aircraft using a recording holograph system: *1*) laser; *2*) speckle hologram; the directions of the loads on the structure are indicated by arrows.

determine the scale of the fringes in the speckle interferogram of the field of the derivative of the displacements with respect to the field of the speckle-hologram; and * denotes the complex conjugate of a function.

The distribution of the amplitudes for the image of the speckle field after filtration and taking the inverse Fourier transform in the photoimage, is given [3, 4] by

$$U(x') = k\sum_{n,m}\left|t(x')\right|^2 \exp[\mathrm{i}(2\pi/\lambda)x'\sin\theta_{nm}] + k\sum_{n,m}\left|t(x')\right|^2 \exp[-\mathrm{i}(2\pi/\lambda)x'\sin\theta_{nm}], \tag{1}$$

where $\sin\theta_{nm} = \lambda\xi_{nm}$.

Equation (1) for the spatial frequencies with filtration in the frequency plane is used to interpret speckle holograms when plane components of the deformation of the object are isolated. An analysis of transmission of speckle holograms in a double exposure with deformation and displacement of the object as a rigid whole is given in [3, 5–10].

The speckle interferogram is a result of the superposition of two correlated light speckle fields of a double exposure diffusely scattered speckle hologram. A displacement in the image plane corresponds to a change in the spatial frequency in the Fourier plane and a nonuniform displacement; in the case of the derivative of the displacements – deformations, a distinct spectrum of the spatial frequencies is formed which corresponds to the deformations. Filtering in the frequency plane is related to the isolation of individual regions of this spectrum. Optical differentiation of the double-exposure speckle holograms involves optical filtration of these holograms in the frequency plane, where individual spatial frequencies of the optical fields are isolated and an optical image (the interferogram corresponding to the derivative with respect to the displacement field, i.e., the deformation component) is constructed:

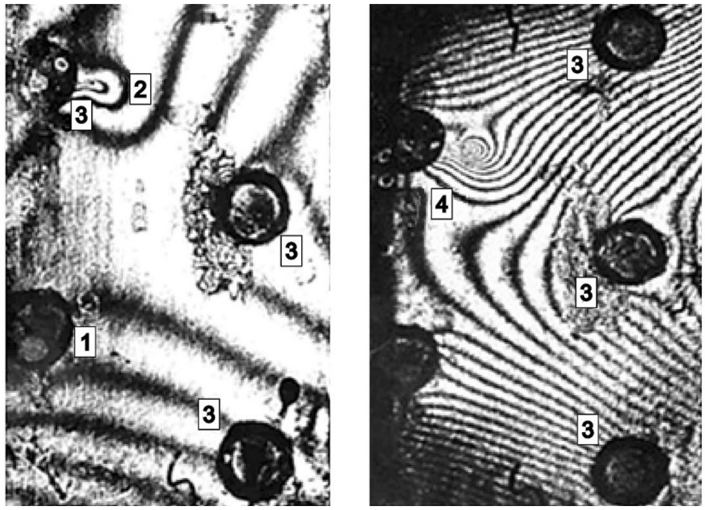
$$\varepsilon_\psi = \partial\mathbf{U}/\partial u_\psi,$$

where ψ is defined by the azimuth of the filtration angle for the spatial displacement field $\mathbf{U}$ with respect to the direction of the plane component u_ψ.

In other words, with optical filtration along the direction ψ, quasi-irregular structures are isolated which correspond to the carrier spatial frequency (the analog of the step size of a diffraction grating along the azimuth), which defines the scale for the derivative of the displacements in this direction:

$$u_\psi^\lambda = \lambda/\sin\alpha_\mathrm{f},$$

where α_f is the spatial filtration angle, which for small angles (up to 10°) is given by $\alpha_\mathrm{f} = a/f$; a is the distance of the center *a*



b

Fig. 2. Identifying crack formation zones in a part of a wing spar using interferograms taken before and after (frames *a* and *b*, respectively) the cracks emerge at the surface of the spar: *1*) corrosion damage zone; *2*) subsurface crack; *3*) bolt connection to the wing spar; *4*) emergence of the subsurface crack at the wing spar surface.

of the filtering aperture from the optical axis of the lens used to form the Fourier transform of the double-exposure speckle hologram field; and f is the focal distance of the lens.

Given the scale u_ψ^λ for the fringe, it is possible to calculate the deformation with respect to the interferogram field by dividing the scale by the step size of the fringes. When the step size of the fringes is smaller, the deformation is greater, and so is the stress level. It is, therefore, easy to calculate the deformation concentration coefficient and, thereby, the stresses.

A practical application of speckle holography. The choice of optical recording system is especially relevant for a determination of deformations of an object. This choice depends on the specific conditions for recording the speckle holograms and the scattering properties of the surface. Figure 1 shows the configuration for tests of a full-scale aircraft with a recording holographic system installed on it, including a laser *1* and the resulting speckle hologram display *2*. The directions of the arrows indicate the loading of the structure during testing. The simplest scheme involves recording the holograms in counterpropagating beams [12]. Illumination is by an expanded laser beam propagating through an almost transparent photographic plate located immediately at the object or near its surface. Two states of the object are recorded on the same photographic plate (without shifting the plate); one with intermediate loading P_1 and the other with loading $P_2 = P_1 + \Delta P$, where ΔP is 5–10% of P_1; this yields a double-exposure speckle hologram. When the image is recovered, the two states of the object are compared on the basis of the observed fringes, i.e., the interferogram. The pattern of the fringes can be interpreted using the Aleksandrov–Bonch-Bruevich equation [13]

$$\mathbf{u}(\rho_{il} + \rho_{ob}) = \lambda n, \tag{2}$$

where $\mathbf{u}$ is the displacement vector for points in the object; ρ_{il} and ρ_{ob} are the illumination and observation vectors of the object, which determine the sensitivity λn; and n is the order of the fringes.

Equation (2) is the projection of the displacement of points on the surface on the sensitivity vector $\rho_{il} + \rho_{ob}$. When the object is illuminated and observed near the normal to the surface, the bending component of the surface deformation is observed with a sensitivity of $\lambda/2$. For a He–Ne laser ($\lambda = 0.6328$ μm), the sensitivity is about 0.3 μm per fringe. This method of interpreting holograms has a number of shortcomings. A method of recording speckle holograms in counterpropagating beams has been developed to counterbalance them [13]. The theoretical basis of the interpretation of the speckle holograms is discussed in [3, 8], and a device for interferometric measurement of displacements and deformations of objects is described in [10]. The author has estimated the errors in recording and interpreting double exposure speckle holograms. The test object was taken to be a flat sample with an aperture under tension. The configurations of the fringes for three orthogonal components of the displacements of the sample under tension in the interferogram are entirely the same as the maps of the fringes when moire and holographic moire are used for two-dimensional components. The fringe pattern for the normal component is the same as the contours obtained near the aperture by photoelastic and classical holography and is indicative of transverse deformation of the plane in the region of the aperture (the narrowing is a consequence of the Poisson effect) [3].

Figure 2 shows some interferograms recorded during a study of the effect of corrosion damage in used samples of aluminum alloy cut from the wing spar of an aircraft wing that is stretched during the stages of loading and cyclical testing of the component. A subsurface crack *2* (Fig. 2*a*) at a bolt junction *3* can be identified from the characteristic anomaly in the fringe pattern in a crack formation zone which is indicative of local flexure. The emergence *4* (Fig. 2*b*) of the crack at the surface of the wing spar shows up as a convergence of fringes of different orders which illustrate the opening of the crack boundaries. When the fringe pattern is decorrelated, it is possible to observe the corrosion damage zone *1* (Fig. 2*c*).

Conclusions. An analysis of speckle-field formation and of the theoretical basis of speckle interferometry shows that speckle holograms can be used in experimental mechanics for measurement of spatial displacements and deformations of the surface of full-scale objects. This opens up new prospects for studies of the operation of full-scale objects and a new way of looking at the physical essence of the interferometry of diffusely reflecting objects. The common physical mechanism of classical holography and speckle optics is pointed out in a description of the foundations of holography and the processes for recording information on diffuse objects employed, in particular, in interferometry. This supplements and expands the geometrical and diffraction analysis of optical fields. Speckle holography can be used to overcome the shortcomings of classical holographic interferometry during measurement of the plane components of deformations and under the conditions of heightened sensitivity to vibrations associated with the geometrical concepts of holography and an off-axis reference beam.

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