Deformation measurement by digital holographic interferometry

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Abstract. Nondestructive testing (NDT) methods and techniques play a vital role in enhancing product quality across various industries. Among these methods, the optical approach stands out, relying on the analysis of how optical radiation interacts with the test object. The key information parameters for optical testing of objects encompass their spectral and integral photometric characteristics. These characteristics are influenced by factors such as the substance's structure, temperature, physical state, microrelief, angle of incident radiation, polarization degree, and wavelength. By leveraging optical methods, defects within materials can be detected without causing damage to the object. These defects encompass voids (discontinuities), delaminations, pores, cracks, inclusions of foreign bodies, internal stresses, alterations in material structure, and variations in physical and chemical properties, as well as deviations from specified geometric shapes. It's important to note that optical methods are limited to detecting internal defects only in products made of materials that are transparent within the optical spectrum's region. By harnessing the power of nondestructive optical testing, industries can ensure the integrity and quality of their products, detect potential flaws, and maintain stringent quality standards without causing any harm to the tested objects. The method with use of transformation of Fourier over sequence of the holograms, which are written down in various time points, is described. Possibility of measurement of deformations of composite material when heating is shown by low-power laser radiation.

1. Introduction

An important role in improving the quality of products is played by methods and means of nondestructive testing. The optical method of non-destructive testing is based on the analysis of the interaction of optical radiation with the test object [1-3].

The main information parameters of objects of optical control are their spectral and integral photometric characteristics, which generally depend on the structure of the substance, its temperature, physical (aggregate) state, microrelief, angle of incidence of radiation, degree of its polarization, wavelength. Defects detected by non-destructive optical methods include voids (discontinuities), delaminations, pores, cracks, inclusions of foreign bodies, internal stresses, changes in the structure of materials and their physical and chemical properties, deviations from a given geometric shape, etc [4, 5]. Using optical methods, internal defects are found only in products made of materials that are transparent in the optical region of the spectrum.

The use of optical radiation as an information carrier is promising. The electromagnetic field is multidimensional in nature, which allows for multichannel (multidimensional) information processing by one device at a high speed, determined by the speed of light in a given medium [6-10].

In microelectronics, to control the quality of printed circuit boards, control of the geometry of photomasks, control of the refractive index and other characteristics of semiconductor materials, control of the geometry of semiconductor structures (ellipsometry), etc. are used. The use of lasers creates fundamentally new methods of optical non-destructive testing.

The high monochromaticity (narrow frequency spectrum) of laser radiation makes it possible to widely use the methods of spectral selection of objects, and the directivity of the radiation ensures the efficiency of scanning systems for observing remote objects.

The high power of laser radiation makes it possible to use nonlinear optical phenomena in optical non-destructive testing, including parametric tuning of the radiation frequency, self-focusing of light, active coherent scattering

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spectroscopy, etc. Active optical control becomes possible when defective parts of the object (defects in the IC topology, etc.) can be locally removed by evaporation under the action of a laser beam.

2. Methods and approaches

The utility model relates to the field of remote measurement of the dynamics of deformation of the surface of structures and parts in mechanical engineering, construction, oil and gas industry and can be used both for flaw detection of structures, assemblies and parts by local distortions of the pattern of interference fringes during non-destructive tests, and for determining deformation parameters surfaces of parts and structures during operation. The most promising method for measuring strains and visualizing residual stresses is the method of 2x exposure digital holographic interferometry [1].

For this, the method of holographic interferometry is used, which makes it possible to compare the wave fronts of the incident and reflected light beams recorded at different times.

A device [2] is known, in which a continuous Nd:YAG laser is used as a light source, the radiation of which is divided into two beams - a reference and an object, using a beam splitter (wedge - splitter). The object beam is expanded by a negative lens and illuminates the object. The image of the object with the help of a positive lens is built on the plane of the light amplifier (based on a microchannel plate). The reference beam is also fed through a light guide to the input plane of the light amplifier with the help of a positive lens. The interferogram is obtained by interference between the reference and reflected object beams on the input plane of the light amplifier. The aperture diaphragm limits the spatial frequencies of the reflected object beam to match the spatial resolution of the receiving system and the distance between the fringes of the interference pattern. With the help of an optical image transmission system, the interferogram is transferred to the input of the SSD camera. From the SSD camera, through the image digitization board, the information enters the computer, where it is stored and processed. The phase fronts of two successively received interferograms in different periods of time are processed by the digital Fourier transform method. From the comparison of the two obtained phases, it is possible to calculate the amount of deformation or change in the relief of the surface of the object in a short period of time between the acquisition of two successive interferograms. Thus, in the device described in [2], it is possible to obtain non-contact, remote interferograms with their subsequent introduction into a computer and digital processing. However, the disadvantage of the device is that a light guide with a fixed length is used to match the reference and reflected by the object beam. When changing the distance to the object, it will be difficult to combine the optical paths of the reference and object beams. This imposes a limitation on the type of lasers used, it is necessary to use solid-state lasers only with a large coherence length (of the order of several meters), for example, Nd:YAG. And their use immediately increases the size of the structure and increases its cost. Since the device is intended for recording fast changes in the surface topography in a short period of time, this requires either illuminating the object with intense light, or using light amplification systems, in particular, reflected ones. Therefore, the authors introduced a light amplifier based on an MCP board into the reception scheme of the radiation reflected by the object, which made it possible to obtain two successive interferograms with a 700-microsecond interval between them and with exposure times of about 100 microseconds for each of them. However, the use of a light amplifier based on the MCP board for recording relatively slow processes with exposure times of the order of 10-1000 milliseconds leads to the presence of a large noise component in the recorded video signals, which reduces the measurement accuracy.

The prototype of our utility model is a device [3] in which the radiation of a semiconductor laser is divided into a reference beam (reflected from the wedge) and an object beam (passed through the wedge). Object beam, evenly illuminates the object. The radiation scattered by the object is collected by an optical system consisting of a diaphragm and a lens, which transmits images of the object under study to the plane of the receiving matrix of the SSD camera. The reference beam also falls on the plane of the receiving matrix of the SSD camera. Combining the length of the reference and object arm of the interferometer to obtain an interferogram when the distance to the object changes, is achieved by smoothly moving the wedge in the optical delay line. Light filters located in the reference arm serve to match the intensity level of the reference and object beams. When the object and reference beams are superimposed in the plane of the receiving matrix of the SSD camera, an interferogram appears, which is recorded by the receiving matrix of the SSD camera. The registered signal is digitized by the digitization board and enters the computer, where it is processed by a special program.

The disadvantage of the above device is that when the distance to the object changes, the intensity of the object beam may change, which will lead to a deterioration in the quality of the digital hologram. The selection of the required ratio of the intensity of the reference and object beams by using a set of light filters is carried out manually, and this, firstly, takes time, which prevents automation of the measurement process, and secondly, when adding a light filter to an existing one, or changing it, the total transmission at the laser wavelength does not change smoothly, but abruptly, because the transmission of light filters has a stepped character. And this complicates the process of selecting the necessary light filters to obtain the required ratio of the intensity of the reference and object beams.

The task of creating a utility model is to create a device for continuous automated remote measurement of the dynamics of surface deformation of objects during operation by digital interferometry.

The solution to this problem is a device based on a digital holographic interferometer, consisting of a laser, a beam-splitting element (glass wedge) that provides the formation of reference and object beams at the input of laser radiation to the interferometer, plane-parallel plates that guide the reference and object beams into photodiodes, photodiodes that record the intensity reference and object beams, a polarization modulator of light intensity, consisting of a polarizer - a Glan prism and a Pockels cell, an automatic control unit for the ratio of the intensity of the reference and object beams and a negative lens-expander of the object laser beam, matching optics - a positive lens, which ensures focusing of the image of the object under study on input of a SSD camera, an adjustable aperture diaphragm and a matching element, which ensure the superposition of the object and reference beams in the plane of the receiving matrix of the SSD camera and adjustment of the beam convergence angle, SSD camera, reference beam delay line, consisting of a wedge and a mirror, which provides adjustment of the path length reference beam within any required limits, a lens - a reference beam expander that provides adjustment of the divergence and intensity of the reference beam, a digitization board and a computer.

Continuity and automation of the process of remote determination of the dynamics of surface deformation during operation is achieved by using a polarization light intensity modulator, consisting of a Glan prism polarizer and a Pockels cell and an automatic control unit for combining the intensity of the reference and object beams.

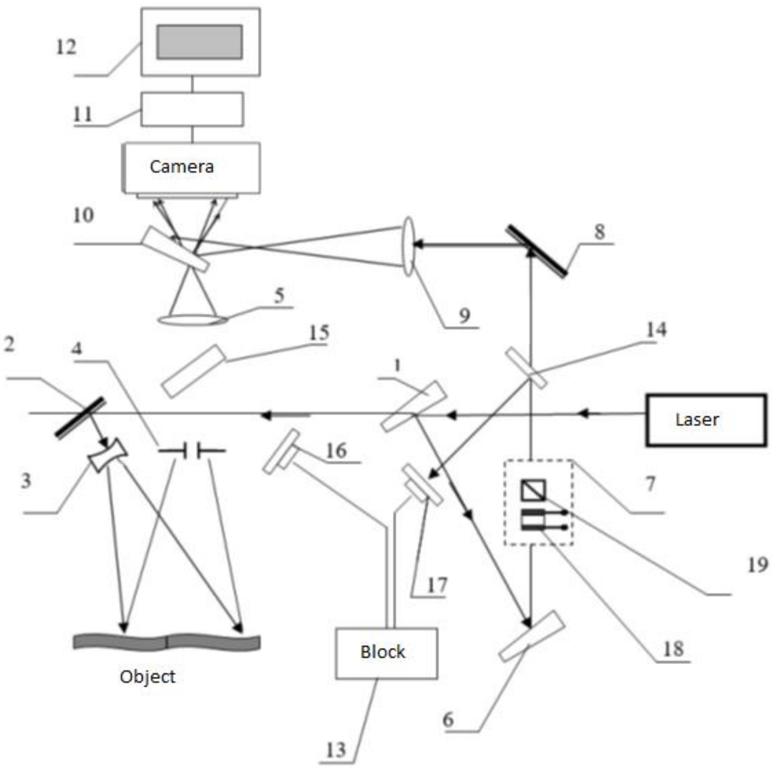


Fig. 1. Optical layout of the device for measuring strain dynamics

The drawing (Figure 1) shows the optical diagram of the device for measuring strain dynamics. The device consists of the following main elements: a light source (laser), a beam-splitting element (glass wedge) 1, a mirror 2, a negative expander lens 3 of the object laser beam, which provides uniform illumination of the objects under study; adjustable aperture diaphragm 4 of rectangular section, matching optics (positive lens) 5, reference beam delay line consisting of wedge 6 and mirror 8, light intensity polarizing modulator 7 with Pockels cell 18 and Glan prism 19, lens 9, matching element (glass wedge) 10, digitization board 11 and computer 12, plane-parallel plates 14, 15, photodiodes 16, 17 and block 13 for automatic control of the intensity ratio of the reference and object beams.

The design works as follows. On the block 13 automatic control of the ratio of the intensity of the reference and subject beams, the ratio of the intensities of the subject and reference beams is programmatically set.

3. Results and discussion

The radiation of a semiconductor laser with a wavelength of 0.67 μm and a power of P=75mW falls on the beam-splitting element 1, which is a glass wedge. After hitting the wedge, the beam is divided into a reference beam (reflected from the wedge) and an object beam (passed through the wedge). The object beam reflected from the mirror 2 passes through the negative beam expander lens 3 and uniformly illuminates the object. The object beam scattered by the object and passing through the plane-parallel plate 15 is collected by an optical system consisting of a diaphragm 4 and a lens 5, which ensures focusing of the image of the object under study on the plane of the receiving matrix of the SSD camera. The part of the object beam reflected from the plane-parallel plate 15 enters the photodiode 16, the signal from which is fed to block 13.

The reference beam, using wedge 1, wedge 6, mirror 8, lens 9, and matching element (wedge) 10, also enters the plane of the receiving matrix SSD cameras. The intensity of the reference beam reflected from the plane-parallel plate 14 is recorded by a photodiode 17, the signal from which is also fed to the automatic control unit 13 for combining the intensity of the reference and object beams. The automatic control unit 13 for combining the intensity of the reference and object beams compares the intensity levels of the reference and object beams and, if the intensity levels of the reference and object beams do not match, applies voltage U to the Pockels cell 18 of the polarization light intensity modulator 7, consisting of the Pockels cell 18 and the Glan prism 19.

Lens 5 sets the angle of convergence of the object beam, and lens 9 of the reference beam to obtain a high-quality interferogram. A matching element (glass wedge) 10 ensures the superposition of the object and reference beams in the plane of the receiving matrix of the SSD camera.

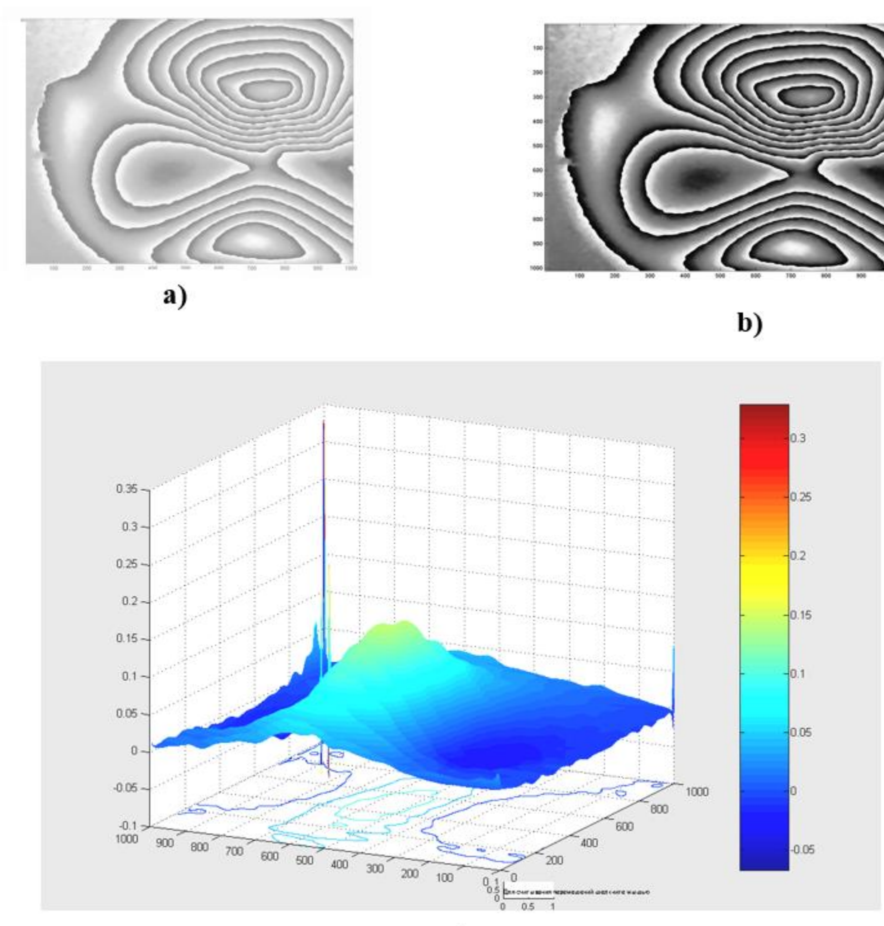


Figure 2. Stages of calculating surface deformation dynamics from interferograms.

When the object and reference beams are superimposed in the plane of the receiving matrix of the SSD camera, an interferogram appears, which is recorded by the receiving matrix of the SSD camera. The registered signal is digitized by the digitization board 11 and enters the computer 12, where it is processed by a special program.

For the reconstruction (reconstruction of the image of the object) of a digital interferogram, which is a three-dimensional data array, computer processing is used. Data processing uses the LabVIEW Full Development System Win 2000/NT/9X program developed by National Instruments. The program makes it possible to calculate, from the resulting interferogram, the magnitude of the surface deformation during the time between two exposures. And since the time between exposures when illuminating an object with a continuous laser is set programmatically, then on the computer display you can observe the dynamics of deformation of the surface of parts and structures during operation almost in real time.

An example of the results of calculating the dynamics of deformation of the surface of a test steel plate in the form of a three-dimensional picture is shown in the figure (Figure 2). The operability of the device was checked by obtaining a series of digital interferograms. The test steel plate was remotely irradiated with a laser during the deformation process. Figure 2a shows the interferogram before turning on the polarization intensity modulator and feeding a signal from it to the automatic control unit for combining the intensity of the reference and object beams; By combining the intensities of the reference and object beams, the intensities of the reference and object beams became equal. As can be seen from Figure 2b, the contrast of the interferogram has improved significantly. Figure 2c shows the three-dimensional patterns of deformation of the surface of a steel plate calculated on the basis of the interferogram under pressure on it with a sharp object.

Thus, using the device, it is possible to remotely control the amount of surface deformation due to various processes - loading, bending. Moreover, the device allows such continuous remote monitoring, for example, of the surfaces of gas tanks, welding joints of gas pipes or steam boilers under pressure throughout the entire operation process. And such automatic control of the state of the surface, upon reaching the limiting value of the deformation of the surface of the structure, gives reason to stop the technological process and prevent the destruction of the structure (Figure 3).

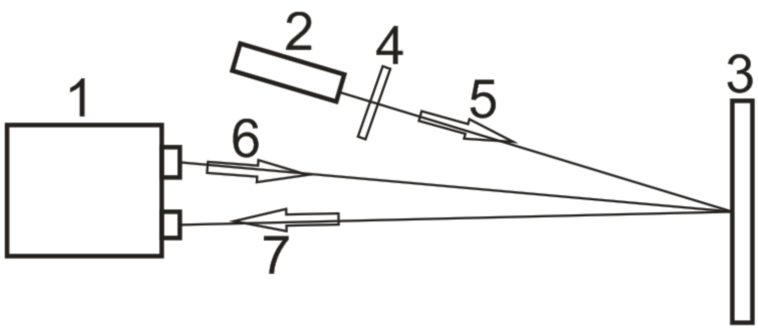


Fig. 3. Measurement scheme: 1 - interferometer. 2 - heating laser. 3 - object. 4 - light filter. 5 - heating radiation. 6- illumination of the object. 7 - radiation reflected from the object.

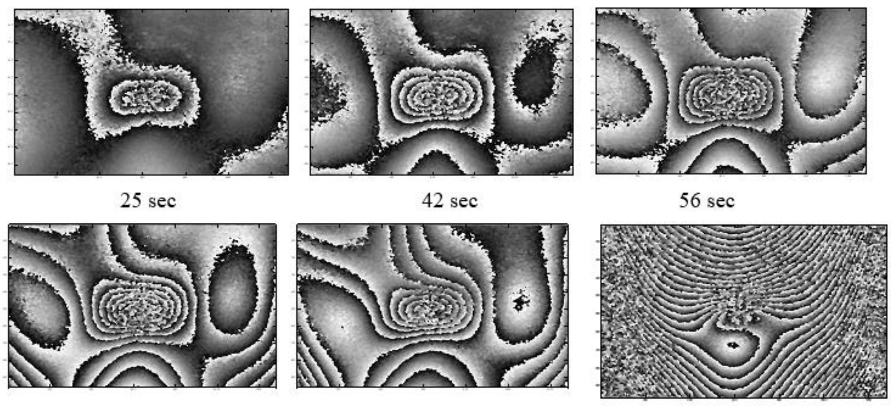
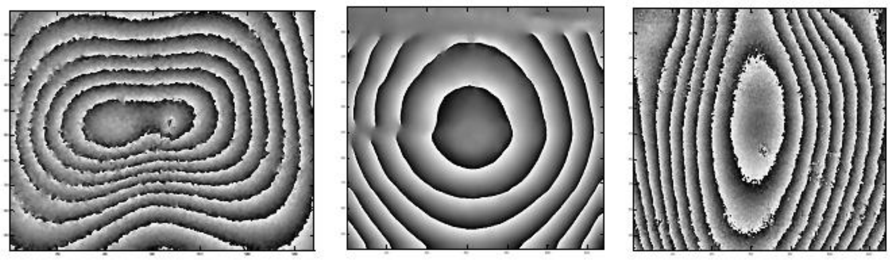


Fig. 4. Interferograms of deformations due to heating of the residual stress pattern, at the bottom of the heating time

A hologram of an unperturbed object was taken to measure thermal deformations using the method of double-exposure digital holographic interferometry. Holograms were captured at various time intervals subsequent to the activation of the heating laser. The digital holograms obtained using the double Fourier transform were compared with the hologram of an unperturbed object. Interferograms were obtained from which it is possible to construct the field of normal displacements of the object surface using the phase unfolding program.
Figure 4 shows interferograms reflecting the heating dynamics of the object surface after turning on the heating laser. Under each interferogram, the heating time is indicated. Preliminary measurements showed that the heating is performed mainly by radiation with $\lambda 2$=0.53 microns, and $\lambda 1$=1.06 microns is not absorbed by the composite.
Then the plate was pierced to form a defect (3 mm long slit) and heating was performed on the side edge of the slit. The plate was moved to the interferometer and the visible area was 5x3.5 cm. Holograms were taken at different angles of illumination. Figure 5A shows an interferogram of deformations in the defect area when the object is illuminated at an angle of 45°. The presence of the defect causes a distortion in the interference fringes, as illustrated in Figure 5A.



A B C

Fig. 5. Interferograms of thermal deformations: A - the fiberglass plate with the defect. B - the glass-reinforced plastic heated from the photoimulsion side. C - metal plate.

To compare the deformation patterns due to heating under the same experimental conditions, interferograms of deformations of the lighted photoplastic plate Figure 5B and interferograms of deformations of the heating area of the metal plate Figure 5C, as well as interferograms of deformations during heating of the white plastic plate Figure 6 obtained at different times after the beginning of heating. The thickness of the plate is 3 mm.

A B

Fig. 6. Interferograms of deformations during the heating of a white plastic plate obtained at different times after the start of heating: A - interferogram of deformations of the plate made of white plastic, heating time 1 min; B - interferogram of deformations after 4 min of heating.

4 Conclusions

The proposed structure requires a number of discussions in comparison with analogues:
1. The use of polarization of a light intensity modulator with an automatic control unit for the frequency ratio of the reference and object beams requires a given value of the density of the reference and object beams, the measurement time, and automates the process of recording a digital hologram.
2. Continuous, non-stepping process of adjustment of the reference and object beams improves the quality of recording digital holograms.
Thus, results arise that allow remote measurements of the dynamics of the surface of structures and parts in industry.

The possibility of measuring deformations of a composite material when heated by low-power laser radiation is shown. The stress area is deformed at the same time on the peripheral manifestations, associated with internal stresses in the individual material.

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