Development and justification of optical device for contactless measurement of the displacements of control object surfaces

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Abstract. The results of the development and computational-experimental justification of optical device for contactless measurement of the displacements of control object surfaces by using a laser interferometer are described. The proposed device allows solving actual measurement problems by diagnosing the state of structural materials and researching the strength properties of structures in mechanical engineering, aircraft building, shipbuilding, etc.

1. Introduction
At present, the development of diagnostic complexes is relevant for ensuring trouble-free operation and prevention of catastrophes of vehicles, aviation equipment, etc. in operation. The noted complexes using methods of non-destructive testing should provide for the diagnosis of the state of structural materials of power elements of machines and equipment directly at the place of their operation. Diagnostic results are needed to make a decision about the possibility of their further operation and to assess the residual service life.

One of the most important directions of improving the instrumental database of complexes is the development of contactless means of measuring the displacements of control object surfaces for recording information about the state of the machines and equipment in question, for example, using acoustic methods of non-destructive testing.

In [1-5], contactless means of measuring the displacements of control object surfaces, based on a two-way laser interferometer with combined branches, are described. They are based on the use of modern laser technology and new methods of optical interferometry. The devices [1-5] were grounded in the process of carrying out computations and experimental studies, the results of which were presented in [6–13], tested and used in solving actual scientific and industrial problems (see, for example, [14]).

This paper is devoted to the development and justification of a new optical interference device for measuring displacements of control object surfaces, which allows extending the functionality of technical solutions [1-5] by changing the range of measured values of displacements in the process of measuring.

2. Description of measurement method
The proposed device implements a new method for measuring displacements of control object surfaces, namely a method of highlighting the surface of an object of control by a laser interferometer. The essence of the noted method is illustrated by the scheme (see, Figure 1) and lies in the fact that the
laser 1 with the help of the optical system 2 illuminates the surface of the test object 3, which is a point source of reflected radiation.

![Figure 1. Scheme of device that implements method of highlighting.](image)

This radiation comes on interferometer containing a beam splitter 4 and a reflector 5, rigidly fixed relative to each other. The radiation source 1, the interferometer, and the photodetector 6 are fixedly mounted on one base. The displacement of the control object surface 3 in space is determined by the change in the parameters of the interference field formed in the Fresnel zone and recorded by the photodetector 6.

This method is proposed, described and grounded in [15 – 17].

For the theoretical justification of the developed method for measuring displacements, a mathematical model of the measurement process is used, based on the application of a rigorous electromagnetic theory for analyzing laser displacement meters and allowing for one to take into account the complex diffraction, interference and polarization phenomena of laser radiation in computer simulation.

In the course of computer simulation, constitutive relations were obtained that determine the interference field in the observation zone for a given polarization of the source radiation. In these relations, the quantities $x_0$, $y_0$, $\alpha$, $h$ are included as the parameters that determine the coordinates of the point of highlighting $O'$ of the control object surface 3 and the position of the interferometer reflector 5 in space. Based on the analysis of the interference field in the observation zone, the displacement of the control object surface 3 in space can be determined.

The theoretical grounding of this method is described in detail in [15–17], where a feature is noted that must be taken into account when implementing the method. It lies in the fact that the sensitivity of the device depends on the curvature of the wave front of the radiation, reflected from the surface of the test object 3, and is inversely proportional to the distance from the surface of the test object 3 to the beam splitter 4 of the interferometer.

3. Description of the design of proposed device
The essence of the proposed device is illustrated by the scheme shown in Figure 2.
Figure 2. Scheme of device.

The device contains optically coupled and sequentially placed source 1 of coherent optical radiation, the optical system 2, the test object 3 with the surface 4, the common base 5 on which the beam splitter 6, the reflector 7, and the photoreceiver 8 are rigidly fixed, and also the transducer 9. The base 5 is equipped with a mechanism 10 for moving it along the optical axis between the surface 4 of the test object 3 and the outer surface of the beam splitter 6. The optical system 2 focuses the radiation on the surface 4 of the test object 3 in the form of a luminous point 11. The beam splitter 6, the reflector 7 and the photodetector 8 are rigidly fixed to the base 5 in fixed positions relative to each other. The transducer 9 is electrically connected with the photoreceiver device 8 and is designed to determine the displacements of the surface 4 of the test object 3 according to the results of measuring the intensity of the optical field in a given region of the interference pattern of the photoreceiver device 8, as well as to register the received results of displacements measurements.

The device operates as follows.

Before testing the test object 3, and, respectively, measurements of the movements of its surface 4, a range of possible values of displacements occurring during the tests is known a priori. Therefore the base 5 with the beam splitter 6, reflector 7 and photoreceiver 8 fixed to it are placed using mechanism 10 at a certain distance between the surface 4 of the test object 3 and the outer surface of the beam splitter 6, corresponding to a given range of displacements changes. It can be performed by using the dependence of the change in sensitivity on the distance between the surface 4 of the test object 3 and the outer surface of the beam splitter 6, obtained experimentally with metrological services.

As the range of measured displacements increases, this distance is increased, while when the range of measured movements decreases, this distance is decreased by a corresponding change in the position of the base 5.
The optical system 2 focuses the radiation from the source 1 on the surface 4 of the test object 3 in the form of a luminous point 11, which in turn is a point source of radiation located on the surface 4 of the test object 3. Further, the radiation from the luminous point 11 comes the beam splitter 6, which divides it into two beams: one beam is reflected from the surface of the beam splitter 6, and the other is reflected from the surface of the reflector 7. The spatial combination of these rays occurs in the area of disposition of the photoreceiver 8, namely in the region of observation of the interference pattern. The photoreceiver device 8 records the intensity of the optical field in a given area of the interference pattern, and the transducer 9 associated with it determines the displacement of the surface 4 of the test object 3 according to the results of measuring the intensity of the optical field by the photoreceiver 8, and also records the results of displacement measurements.

The device is protected by a patent of the Russian Federation for invention [18].

The device described above is intended for use in the laboratory and is not applicable for solving practical problems as part of mobile diagnostic systems due to the high labor intensity of preparation for conducting measurements and reducing the accuracy of the results when conducting measurements in "field" conditions.

The high labor intensity of preparation for the measurement is due to the fact that before starting the measurements, each optical element is individually installed and adjusted to obtain an interference pattern in the field of information recording. The decrease in the accuracy of the results is due to the influence of external sources of optical radiation that distort the measurement results.

To eliminate these drawbacks, which restrain the use of the device [18] as part of mobile diagnostic systems, a modified device has been developed, the scheme of which is shown in Figure 3.

![Figure 3. Scheme of modified device.](image)

The modified device includes a base 1, a device 2 for adjusting and fixing the position, bonded to the base 1 and the end 3 of the cylindrical body 4, in the internal cavity 5 of which the source 6 of coherent optical radiation is placed with the device 7 for adjusting and fixing its position and the optical system 8 with device 9 for adjusting and fixing its position. The modified device also contains a pivot hinge 10 mounted on the end 11 of the cylindrical body 4 faced to the surface 12 of the test object 13, connecting the cylindrical body 4 with the support beam 14, the movable support 15 with the device 16 for adjusting and fixing its position placed on the surface 17 of the support beam 14, the
support plate 18, rigidly mounted on the movable support 15, light-proof protective housing 19 with a window 20. In the internal cavity 21 of the window 20 are rigidly fastened together in a fixed position the beam splitter 22 and the reflector 23 with a device 24 for adjusting and fixing their position and the screen 25 with a device 26 for adjusting and fixing its position.

The photoreceivers 27 are installed on the screen 25 in the specified areas of the interference pattern. The support beam 14 is made integral in the form of the same type of cylindrical elements 28, connected by a detachable connection, for example, using a threaded connection 29. The cylindrical body 4 and the support beam 14 are interconnected by means of the device 30 for changing and fixing the position (angle) between them using the pivot hinge 10.

The modified device also contains a transducer that is electrically connected to the photoreceiver devices 27 and is designed to determine the displacements of the surface 12 of the test object 13 from the results of optical field intensity measurements in specified areas of the interference pattern by the photoreceiver devices 27, as well as to register the received results of movement measurements. The optical system 8 focuses the radiation 31 from the source 6 onto the surface 12 of the test object 13 in the form of a luminous point 32, which in turn is a point source of radiation located on the surface 12 of the test object 13.

The window 20 of the opaque protective housing 19 provides the optical contact of the radiation 33 from the luminous point 32 with the beam splitter 22 and the reflector 23. Further, the radiation 33 from the luminous point 32 falls on the beam splitter 22, which divides it into two beams: one beam 34 reflects from the surface of the beam splitter 22, and the other beam 35 reflects from the surface of the reflector 23. The spatial combination of these rays occurs in the area of the screen 25, namely in the field of observation of the interference pattern.

The device is protected by a patent of the Russian Federation for invention [19].

4. Justification of proposed device

In order to justify the functional characteristics of the proposed devices, experimental studies were carried out, in the course of which the linear displacements of the surface of the test object were measured. The scheme of experimental setup is shown in Figure 4.

![Figure 4. Scheme of experimental setup.](image)

The setup consisted of a radiation source 1 (He-Ne laser, wavelength 0.63 μm), an optical system 2, a reflector 3, an interferometer consisting of a beam splitter 4 and a reflector 5; photoreceiver 6, a device for recording and processing measurement results 7. The control object was modeled by the reflector 3, which was installed in the device for reproducing displacements 8 on the guides 9.

The principle of the operation of setup was as follows.
The laser radiation 1, transformed by the optical system 2, was focused on the surface of the test object 3 in the form of a luminous point. The radiation, reflected from the control object (reflector 3) with a spherical wave front, falls on the interferometer beam splitter 4, which divides it by amplitude, with one part (beam) reflected from the surface of the beam splitter 4, and the other from the surface of the interferometer reflector 5. The formation of the interference pattern was achieved by spatial alignment of the two marked rays in the plane of the arrangement of the photoreceiver 6. The image of the interference pattern was recorded by a digital photodetector device 6 and processed by a device for recording and processing measurement results 7 (PC). The test object 3 was displaced linearly along the guides 9 with the help of the micrometric screw 10 installed in the device for reproducing displacements 8.

The experimental procedure consisted in the step-by-step setting the linear displacements of the reflector 3 in the direction of the interferometer beam splitter 4, while the signal of the photoreceiver 6 was recorded at each step of displacement. The sensitivity of the method of highlighting the surface of the test object, and accordingly the devices under study, depends on the distance $y_0$ from the surface of the test object 3 to the beam splitter 4 of the interferometer.

During the experimental study, 10 experiments were carried out according to the developed method for 10 initial values of the distance $y_0$, which were set in the range from 0.17 m to 0.62 m with a step of 0.05 m. At each of the specified initial distances $y_0$, linear displacements of the surface of the test object in the direction of the interferometer were carried out step by step.

For each of the initial distances $y_0$, the sensitivity of the device was determined, defined as the ratio of the intensity change $\Delta I$ in a given region of the interference picture during the transition from the light to the dark strip to the corresponding displacement of the surface of the test object $\Delta y_0$. A plot based on the results of an experimental study characterizing the dependence of the sensitivity of the device on the magnitude of the initial distance is shown in Figure 5.

The experimental results shown in fig. 5 are in good agreement with the results obtained in numerical simulation and correspond to the physical representations of the interference processes occurring in the measurements when radiation with a spherical front is used.

![Figure 5. Dependence of the sensitivity of device on the magnitude of initial distance $y_0$.](image-url)

Experimental studies were performed at different angles of incidence of the laser optical radiation on the surface of the test object ($\alpha_0 = 5^\circ, 25^\circ, 45^\circ$). Analysis of these results makes it possible to note that the sensitivity of the device does not depend on the angle $\alpha_0$, if the distance from the point of illumination of the surface of test object to the beam splitter remains constant.
5. Conclusions
A new optical interference device has been developed for measuring the displacements of control object surfaces, which makes it possible to expand the functionality of the known technical solutions by providing the possibility of changing the range of measured displacements during the measurement process. The proposed device implements a new method for measuring displacements of control object surfaces, namely a method of highlighting the surface of a control object by a laser interferometer.

An experimental justification of the proposed device is carried out, confirming its main functional characteristics with various parameters and geometrical characteristics of the optical scheme. We obtained experimentally dependence of the sensitivity of the proposed device, which allows us to uniquely associate the displacement of the surface of the test object in a given range with changes in the interference pattern. The results of experimental studies confirm the validity of the application of the proposed device for solving practical measurement problems in the production, testing, operation, metrological support and diagnostics of the state of structural materials of power elements of machines and equipment.

The results of the test exploring the model of the proposed device showed that its structural-layout scheme allows one to preserve the capabilities of known devices and ensure the use of both stationary and mobile diagnostic systems. Its design provides a reduction in labor-intensity and time-consuming for preparation and measurement to 40%.

The described technical solution can also be successfully applied in the process of high-precision measurements of the linear and angular displacements of control object surfaces by conducting experimental studies of promising structures, buildings, structures, etc., evaluating their technical condition and diagnosing the state of both stationary and mobile diagnostic complexes, in the study of defect formation processes in new structural materials, the study of wave processes in layered structures and constructions made of anisotropic structural materials in mechanical engineering, aircraft building, shipbuilding, etc.

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