Development of a New Optical Measuring Set-Up

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Abstract. The paper proposes a description of the developed optical measuring set-up for the contactless recording and processing of measurement results for small spatial (linear and angular) displacements of control surfaces based on the use of laser technologies and optical interference methods. The proposed set-up is designed to solve all the arising measurement tasks in the study of the physical and mechanical properties of new materials and in the process of diagnosing the state of structural materials by acoustic active methods of nondestructive testing. The structure of the set-up, its constituent parts are described, and the features of construction and functioning during measurements are discussed. New technical solutions for the implementation of the components of the set-up under consideration are obtained. The purpose and description of the original specialized software, used to perform a priori analysis of measurement results, are present, while performing measurements, for a posteriori analysis of measurement results. Moreover, the influences of internal and external disturbance effects on the measurement results and correcting measurement results directly in their implementation are determined. The technical solutions, used in the set-up, are protected by the patents of the Russian Federation for inventions, and software is protected by the certificates of state registration of computer programs. The proposed set-up is intended for use in instrumentation, mechanical engineering, shipbuilding, aviation, energy sector, etc.

1. Introduction
At the present time, the appearance of a significant number of new materials and their wide use in various fields of technology leads to the need to develop and use new high-precision measuring instruments that allow solving scientific and production problems. In particular, it is related to the study of the physico-mechanical properties of these materials and the process of diagnosing the state of construction materials under their production and operation by using acoustic active methods of nondestructive testing.

One of the actual and promising directions for the creation of new high-precision measuring instruments is the development of contactless optical measuring devices based on modern laser technologies and new methods of optical interferometry, as well as systems, devices and software that support their operation in solving various measurement problems, accuracy, quality and informative of measurement results [1-3].

The aim of the research is the development of an optical measuring set-up for recording and processing the results of measurements of small spatial displacements of the surfaces of control objects. It allows one to solve all the arising measurement problems by studying the physical and mechanical properties of new materials and during the diagnostics of the state of construction materials by acoustic active methods of nondestructive testing.
2. Structure and components of the proposed optical measuring set-up

The structure and components of the proposed optical measuring set-up are schematically shown in Figure 1.

The optical measuring set-up includes the following components:

1. control system for the optical measuring set-up;
2. optical interference device for contactless measurement of small spatial displacements of control object surfaces;
3. device for protection against the influence of internal disturbing (destabilizing) effects and correction of measurement results;
4. device for protection against the influence of external disturbing (destabilizing) effects and correction of measurement results;
5. system of a priori analysis and preparation for conducting measurements;
6. system for recording measurement results;
7. system for processing and a posteriori analysis of measurement results.

3. Brief description of the set-up components

The control system of the optical measuring set-up is designed to control and provide preparation for the measurement, registration and correction of measurement results during measurements and processing of the obtained measurement results after their completion.

The pointed system is implemented on the base of modern personal computer technology using the original specialized software, developed for the proposed measuring set-up by solving various problems arising in the measurement process.

Optical interference device for contactless measurement of small spatial displacements of control object surfaces is intended for contactless measurement of small spatial (linear and angular) displacements of these surfaces by measuring the intensity of the optical field uniquely associated with the pointed small displacements in a given region of the interference pattern, produced by the laser interferometer. This device is developed on the base of a laser two-way interferometer with combined branches, modified to solve measurement problems.

The appearance of typical interference patterns, generated by the laser interferometer in the measurement of small linear displacements for their different values, is shown in Figure 2. Figure 3 shows the appearance of a typical interference pattern by measuring small spatial (linear and angular) displacements of the control object surfaces.

For the proposed set-up, a number of devices have been developed that make it possible to measure small linear displacement [4], small linear and angular displacements [5], small linear and all angular (spatial) displacements [6] of the control object surface. It can be used as part of both the stationary and mobile diagnostic stations [7]. By this, they use acoustically active methods of monitoring and diagnosing the state of materials, applied in instrument engineering, mechanical engineering, shipbuilding, aircraft building, fuel and energy industry, etc. Devices [4-7] are grounded scientifically in the process of carrying out theoretical calculations and experimental studies of their functional characteristics, as well as in experimental operation (the reasoning is given in [8-11]).

The device for protection against the influence of internal disturbing (destabilizing) influences is intended for recording the influence of internal disturbing influences (arising in the measuring device itself, for example, power supply voltage jumps during measurements, etc.) on the measurement results for their correction directly in the process of measurements.

A new technical solution was proposed in [12] providing protection from the influence of internal disturbing influences. It is based on recording the total intensity of the optical field of the interference pattern, which must be unchanged during the measurements, regardless of the values of the recorded small linear and angular displacements. The technical solution [12] is grounded scientifically, and the technical result achieved with its help is confirmed by carrying out a number of test studies of the functional characteristics [13] and by its experimental operation.
Figure 1. Structure and components of the optical measuring set-up.

The device for protection against the influence of external disturbing (destabilizing) effects is intended for recording the external disturbing effects (arising from outside the measuring device, for example, impacts, vibrations, oscillations of a different nature, etc.) on the results of measurements. It allows one to correct the measurement results directly in the process of the fulfillment of experiments.
A new technical solution was proposed in [14] providing protection from the influence of external disturbing influences, based on the use of the measuring capabilities of the optical interference device itself for the contactless measurement of small spatial displacements of the control object surfaces without the use of additional measuring devices.

The technical solution [14] constructively represents two combined single-type laser interferometers. It provides simultaneous recording the intensity of the optical field in a given region of the interference pattern, as well as the registration of the increment of the intensity arising under external disturbing effects. The intensity of the optical field includes the total intensity, corresponding to the resulting small displacement of the surface of the test object, and the intensity increment arising from the influence of external disturbing effects. The result of the measurements is the difference

\[ I_{total} - I_{external} = I_{test} \]

where \( I_{total} \) is the total intensity, \( I_{external} \) is the intensity increment arising from external interfering effects, and \( I_{test} \) is the intensity of the optical field corresponding to the test object surface displacement.
between the pointed intensity values. The technical solution [14] is grounded scientifically, and the technical result achieved with its help is confirmed in the course of experimental studies of the device functional characteristics [15].

The system of a priori analysis and preparation of measurements is intended for preliminary predictive modeling of the small displacements of the control object surfaces by using the active acoustic method of nondestructive testing. Moreover, this system defines the distribution of the optical field intensity of interference patterns during measurements.

The system for recording the results of measurements is designed to record the optical field intensity of the interference pattern in certain areas during measurements.

The system for processing and a posteriori analysis of the measurement results is intended to processing the results of measurements after their completion and recognizing the obtained measurement results. It uses the results of preliminary predictive modeling of the dependencies of small displacements of the control object surfaces for the active acoustic method of nondestructive testing applied in a priori analysis.

4. Description of the software included in the set-up
The software of the proposed optical measuring set-up includes the following:

(i) Computer programs for modeling the intensity distributions of the optical fields of interference patterns, taking into account the geometric characteristics of the measuring system used, longitudinal or transverse polarization and the type of beam splitter (semitransparent mirror, amplitude sinusoidal array, amplitude zone plate, phase sinusoidal grid with uniform period, phase zone plate or amplitude holographic diffraction grating) (preliminary predictive modeling of the measurement process).

(ii) Computer programs for modeling the dependencies of changes in small displacements of control surfaces by using the active acoustic method of nondestructive testing, taking into account the spatial-temporal distribution of the sources of probing, the type of the material of control object (monolayer, layered), its physical-mechanical characteristics (isotropic, transverse-isotropic), types of elastic waves propagating in this material and the features of the arising wave processes (preliminary predictive modeling the control object condition).

(iii) Computer programs for registering and processing the intensity of optical fields, obtained for certain areas of the interference pattern, by recording the intensity by a single photoreceiver with specific geometric characteristics. This photoreceiver is disposed at the selected ring of the interference pattern (see, Figure 4a). By using two photoreceivers with prescribed geometric characteristics, they are installed in adjoining rings of interference pattern with different intensity (Figure 4b). Figure 4c corresponds to vertical and horizontal selected regions of the interference pattern and Figure 4d relates to the selected area of the interference pattern, characterized by the maximum contrast in accordance with the technical solution [4].

(iv) Computer program for determining the total intensity of the optical field of the interference pattern and correcting the results of intensity measurements directly by performing measurements of small linear displacements (Figure 5a) or small linear and angular (spatial) displacements (Figure 5b) of control object surfaces.

(v) Computer program for correcting the results of measurements, obtained from the influence of external disturbing effects. It determines the results of measurements as the difference between the total intensity, corresponding to the arising small displacement of the control object surface, and the intensity increment arising from the influence of external disturbing influences, as well as the intensity increment arising from external disturbing influences. The appearances of interference patterns for this case are shown in Figure 6 by measuring small linear displacements, respectively, for each of the components of the difference from left to right).

The software for modeling the intensity distributions of the optical fields of interference patterns are developed by using new mathematical models, describing the functioning of various versions of the proposed optical interference device for the contactless measurement of the small spatial
displacements of control object surfaces with help of a two-way interferometer with aligned branches (see [16-19]).

The software for modeling the dependencies of the changes in the small displacements of the control object surfaces by using the active acoustic method of non-destructive testing are developed with help of new methods. These methods are based on the tensor relations of the generalized method for the scalarization of dynamic elastic fields in transverse-isotropic media. These constitutive relations allow us to determine displacements, stresses and deformations in certain regions of monolayer and layered, flat, cylindrical and elliptical constructions for isotropic and transverse-isotropic materials of the layers (see [8-9, 11]).

![Figure 4](image1.png)

**Figure 4.** Variants of recording the intensity of optical fields, obtained from certain areas of interference patterns.

![Figure 5](image2.png)

**Figure 5.** Variants of recording the total intensity of the optical field of interference pattern.

![Figure 6](image3.png)

**Figure 6.** Appearance of interference patterns for correction the results of measurements, caused by the influence of external disturbances (measurement of small linear displacements).
5. Conclusions

Based on the above results, we can make the following conclusions:

(i) an optical measuring set-up has been developed that allows solving all arising measurement tasks by studying the physical and mechanical properties of new materials and during diagnosing the state of construction materials by acoustic active methods of nondestructive testing;

(ii) the technical solutions and the original specific software, included in the proposed measuring set-up, are grounded in the process of carrying out theoretical and experimental studies, and they also confirmed the achievement of the expected technical and functional characteristics in the solution of various actual measurement tasks in the test operation;

(iii) by using the developed measuring complex, it is possible to increase the information content and reliability of the measurement results to 20 – 30%, and also to correct the measurement results directly during measurements without using additional measuring instruments (by using their own measuring capabilities), which allows one to improve the quality of measurement results to 20 – 40%;

(iv) the technical solutions, implemented in the proposed measuring set-up, are protected by patents of the Russian Federation for inventions, and software is protected by the certificates of state registration of computer programs;

(v) the proposed optical measuring set-up is intended for using in the composition of both stationary and mobile diagnostic stations in instrument engineering, mechanical engineering, shipbuilding, aircraft building, fuel and energy industry, etc.;

(vi) the results of the paper were presented and approved at the International Conferences on “Physics and Mechanics of New Materials and Their Applications” (PHENMA-2015, Rostov-on-Don, Russia; PHENMA-2016, Surabaya, Indonesia and PHENMA-2017, Jabalpur, India), International Conference on Innovative Research “EUROINVENT ICIR 2017” (Iasi, Romania), etc. Moreover, they were discussed at the 45 International Salon of Inventions “Inventions Geneva-2017” (Geneva, Swiss), the 9-th European Exhibition of Creativity and Innovation “EUROINVENT 2017” (Iasi, Romania), the 31-th World Genius Convention and Education «Expo 2017» (Tokyo, Japan) and the XI International Warsaw Invention Show «IWIS 2017» (Warsaw, Poland), where were awarded gold medals.

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