Scientific Ground of a New Optical Device for Contactless Measurement of the Small Spatial Displacements of Control Object Surfaces

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Abstract. It is proposed the computational-experimental ground of newly developed optical device for contactless measurement of small spatial displacements of control object surfaces based on the use of new methods of laser interferometry. The proposed device allows one to register linear and angular components of the small displacements of control object surfaces during the diagnosis of the condition of structural materials for forced elements of goods under exploring by using acoustic non-destructive testing methods. The described results are the most suitable for application in the process of high-precision measurements of small linear and angular displacements of control object surfaces during experimental research, the evaluation and diagnosis of the state of construction materials for forced elements of goods, the study of fast wave propagation in layered constructions of complex shape, manufactured of anisotropic composite materials, the study of damage processes in modern construction materials in mechanical engineering, shipbuilding, aviation, instrumentation, power engineering, etc.

1. Introduction

At present, the development and use of high-precision contactless measuring devices based on modern laser technologies and new methods of optical interferometry are very actual for solution different scientific and applied problems. It allows one to significantly improve the accuracy, quality and informative of the measurement results of the small displacements of control object surfaces [1–9].

Optical devices for measuring small linear and angular displacements of control surfaces are known and already used, representing various modifications of a two-way laser interferometer with combined branches [1-11].

The functional capabilities of the known devices can be significantly expanded for account of providing simultaneous measurement of linear and all angular components of the small displacements of control objects surfaces. The need for this is caused by that during the testing of real control objects the small displacements of their surfaces have both linear and angular components. At the same time, the impossibility of their simultaneous registration reduces the informative and accuracy of the measurement results, requires the installation of additional measuring devices, complicating the design and operation of the experimental-measuring setup.

The aim of the study was the development and calculation-experimental ground of an optical device for the contactless measurement of small spatial displacements of control object surfaces based on the use of new methods of laser interferometry.
2. Numerical study and analysis of its results
To prepare the calculation-experimental ground, a numerical study was performed of the intensity distributions in the interference patterns produced by a two-way laser interferometer with aligned branches, using new mathematical models and original software. The effect of different types of beam splitters and various cases of polarization on the optical fields of the intensity of interference patterns was investigated.

The obtained results are shown in illustrations. Figure 1 shows the intensity distribution $I(\Theta)$ in the horizontal section of the interference pattern along the coordinate $\Theta$ in the observation region of the interference pattern for the case of parallel polarization, when in the considered interferometer the amplitude sinusoidal grating is used as the beam splitter.

![Figure 1. Intensity distribution in horizontal section of interference patterns.](image1)

Figure 2 presents a similar distribution for the case when the beam splitter is an amplitude sinusoidal lattice with perpendicular polarization.

![Figure 2. Intensity distribution in horizontal section of interference patterns.](image2)

Figure 3 shows an intensity distribution for the case when the beam splitter is a phase sinusoidal lattice with perpendicular polarization.

Figures 1-3 present the following notations: 1 - the dependence is obtained for linear displacement $\Delta h = 0$ and angular displacement $\Delta \alpha = 0^\circ$; 2 - the dependence is obtained for $\Delta h = \lambda/4$ and $\Delta \alpha = 0^\circ$ (where $\lambda$ is the wavelength of the optical radiation of the source).

An analysis of the results of numerical studies, obtained for different types of beam splitters, makes it possible to note the following. If we compare the parallel and perpendicular polarization, then in the latter case, when the electric field strength vector is in a plane perpendicular to the plane of incidence,
it is possible in greater degree to study the effect of the diffraction properties of beam splitters on the parameters of the interference pattern formed.

Figure 3. Intensity distribution in horizontal section of interference patterns.

Analysis of the results also showed that when using the amplitude gratings as the beam splitters, the diffraction peaks of $-1$ and $+1$ orders are formed (see Figure 2), and when using phase gratings, higher-order peaks are present in addition to them (see Figure 3).

The use of phase gratings in solving measurement problems is quite promising, since it allows one to obtain approximately the same amplitudes of intensity variation at peaks of $-1$, 0 and $+1$ orders. In this case, the intensity amplitude at the peaks of $-1$ and $+1$ orders is higher than in the corresponding peaks, formed by using an amplitude grating.

The results of the numerical study described above made it possible to develop a method for measuring the linear $\Delta h$ and angular $\Delta \alpha$ components of the small displacements of control object surfaces. This method consists in analyzing the intensity distributions at the peaks of $-1$ and $+1$ orders of the interference pattern.

In the case of the carrying out the matching condition, the intensities $I^{-1}$ and $I^{+1}$, respectively, at the peaks of $-1$ and $+1$ orders of the interference pattern varies identically, otherwise the nature of the intensity variation at the peaks of the pointed orders is different.

Measurement of the intensities $I^{-1}$ and $I^{+1}$ at the peaks of $-1$ and $+1$ orders of the interference pattern allows us to obtain, instead of an equation with two unknowns, a set of equations for $\Delta h$ and $\Delta \alpha$ (respectively, the linear and angular components of the small displacement of control object surface):

$$\begin{cases} 
I^{-1} = f_1(\Delta h, \Delta \alpha) \\
I^{+1} = f_2(\Delta h, \Delta \alpha)
\end{cases}$$

where $f_1(\Delta h, \Delta \alpha)$, $f_2(\Delta h, \Delta \alpha)$ are the known dependences for the peaks of $-1$ and $+1$ orders, respectively, linking the corresponding intensities with linear $\Delta h$ and angular $\Delta \alpha$ components of the small displacement of the control object surface.

The values of $\Delta h$ and $\Delta \alpha$, satisfying Equation set (1), will correspond to the actual displacement of the object.

3. Description of the proposed optical device and the principle of its operation

The proposed technical solution is a further development of the method described above. The scheme of the proposed optical device for measuring small spatial displacements is shown in figure 4.

The proposed device consists of the following elements: a source of coherent optical radiation (laser) (1); an optical system (2) that converts the radiation of source (1) into a divergent beam; a beam
splitter (3) made in the form of a phase grating; a reflector (4) rigidly fixed on the surface (5) of the control object; screen (6), in the plane of which photodetector devices (7) (for example, photodiodes) are installed, divided into three groups (8, 9, 10), each of which is located in the corresponding regions of peaks: of $-1$ order (11), of 0 order (12) and of $+1$ order (13) of the interference pattern (14) (see figure 5).

Figure 4. Scheme of the proposed optical device for measuring small spatial displacements of control object surfaces.

The photodetectors (7) are connected to a system for recording, processing and displaying measurement results. The reflector (4) and beam splitter (3) are disposed to each other at an angle $\alpha$, while the reflector 4 is removed from the inner surface of the beam splitter (3) by a distance $h$. The reflector (4) can absent, in this case, its functions are performed by the reflecting surface (5) of the control object. The peaks of $-1$ order (11), of 0 order (12) and of $+1$ order (13) of the interference pattern (14) are projected onto the screen (6).

The principle of operating the device is as follows. In the process of testing, when linear $\Delta h$ and (or) angular components $\Delta \alpha$ and $\Delta \beta$ of a small displacement of the control object surface (5) arise, it is occurred a change in the intensity of the optical field at the peaks of $-1$ order (11), of 0 order (12) and of $+1$ order (13) of the interference pattern (14). This change takes place also in their corresponding areas at the installation sites of the allocated groups (8), (9) and (10) of the photodetector devices (7).
Figure 5. Appearance of the interference pattern in the screen area.

The photodetectors (7) detect the intensity of the optical field, and the intensities, obtained from each of the groups (8), (9), and (10) of the photodetectors (7), are the measurement results. The system for recording, processing and displaying the measurement results provides the recording of the intensity values from each of the groups (8), (9) and (10) of the photoreceptors (7) and performs their processing.

One of possible options of the processing is, for example, the solution of the following equations set:

\[
\begin{align*}
I_1^{-1} &= f_1(\Delta h, \Delta \alpha, \Delta \beta) \\
I_0 &= f_2(\Delta h, \Delta \alpha, \Delta \beta) \\
I_1^+ &= f_3(\Delta h, \Delta \alpha, \Delta \beta)
\end{align*}
\]

where \( f_1(\Delta h, \Delta \alpha, \Delta \beta) \), \( f_2(\Delta h, \Delta \alpha, \Delta \beta) \), and \( f_3(\Delta h, \Delta \alpha, \Delta \beta) \) are the known dependences for the peaks of \(-1\) order (11), of \(0\) order (12) and of \(+1\) order (13), respectively; they link the intensities with linear \( \Delta h \) and angular \( \Delta \alpha \) and \( \Delta \beta \) components of the displacement of the control object surface (5), respectively; \( I_1^{-1}, I_0 \) and \( I_1^+ \) are the intensities, measured by each of the groups (8), (9) and (10) of the photodetectors (7), installed in the respective regions of the peaks of \(-1\) order (11), of \(0\) order (12) and of \(+1\) order (13) of the interference pattern (14).

The results of the processing are the values of the linear \( \Delta h \) and angular \( \Delta \alpha \) and \( \Delta \beta \) components of the displacement of the control object surface (5) that simultaneously satisfy the intensity values \( I_1^{-1}, I_0 \) and \( I_1^+ \).

Thus, the linear and all angular components of the small displacement of control object surface can be determined by using the intensity values, measured by groups of photodetectors at the peaks of \(-1\), \(0\) and \(+1\) orders, knowing for each peak the dependences of intensity *versus* linear and angular displacements of the control object surface. In this case, the measurement results are those values of the linear and angular components of displacement, which simultaneously satisfy the measured values of intensity at the peaks of \(-1\), \(0\) and \(+1\) orders of the interference pattern.

The described optical device is protected by the Russian Federation patent for an invention \cite{12}.

4. Experimental research and analysis of its results

The present study was carried out for the experimental confirmation of the method described above, and also for the preparation of an experimental ground for the proposed technical solution. During the research, an experimental setup was used, constructed according to the scheme depicted in figure 4.
and allowing to provide separate and simultaneous reproduction of the given linear $\Delta h$ and angular $\Delta \alpha$ components of small displacements. The source of coherent optical radiation was He-Ne laser (wavelength $\lambda \approx 0.63 \, \mu m$). By creating the simulated linear $\Delta h$ and angular $\Delta \alpha$ components of the small displacements, the disposition of the reflector 4 (see figure 4) was changed by means of piezoelectric transducers linked to it, which were connected electrically with voltage sources. During the investigation, the photodetector devices recorded intensities in the specified regions of the peaks of $-1$ and $+1$ orders of the interference pattern.

Figure 6 shows an image of a typical interference pattern, where the notations: $-1$, $0$, $+1$ correspond to the peaks of $-1$, $0$ and $+1$ orders of the interference pattern, the mutual position of which depends on the grating period and on the distance between the beam splitter (4) and screen (6) (see figure 4).

![Image of typical interference pattern](image)

**Figure 6.** Image of typical interference pattern.

![Graph](graph)

**Figure 7.** Results of experimental study (explanation into text).

![Graph](graph)

**Figure 8.** Comparison of numerical and experimental results (explanation into text).
The experimental procedure consisted of stepwise assignment of the linear component $\Delta h$ of the small displacement of reflector at fixed value of the angular component $\Delta \alpha$, while the recording of the signals of the photodetectors was carried out at each step.

During numerical study, the main parameters of the mathematical model of the proposed optical device were brought into line with the parameters of experimental setup. It allowed one to compare the results of numerical and experimental studies, and to confirm the feasibility of the developed method for measuring small displacements and to ground the proposed technical solution.

The intensities $I^{-1}$ and $I^{+1}$ are obtained at the peaks of $-1$ and $+1$ orders in dependence on the linear component $\Delta h$ of the small displacement of reflector (presented by the voltage $U_1$ on the piezoelectric transducer, modeling the linear component $\Delta h$) (see figures 7a and 7b, respectively) at various values of angular component $\Delta \alpha$ of the small displacement of reflector (presented by the voltage $U_2$ on the piezoelectric transducer, modeling the angular component $\Delta \alpha$).

Figure 8 shows the dependences of the intensities $I^{-1}$ and $I^{+1}$ obtained by comparing the results of numerical experimental studies at the peaks of $-1$ order (Figure 8a) and peaks of $+1$ order (Figure 8b). The solid line corresponds to the results of a numerical study and the dotted line presents the results of an experimental study.

Analysis of the numerical and experimental results allowed one to clearly confirm the described method and ground the proposed technical solution.

At present, the experimental investigation continues in the direction of investigating the features of simultaneous detection of linear ($\Delta h$) and angular ($\Delta \alpha$ and $\Delta \beta$) components of the small displacement of the control object surface.

5. Conclusions
The obtained in the paper results allow us to make the next conclusions:

1. On the basis of the use of new methods of laser interferometry, a new optical device for contactless measurement of small spatial displacements of control object surfaces has been developed. It allows simultaneous registering the linear and all angular components of small displacements without installing additional measuring means.

2. The proposed device is scientifically grounded by carrying out numerical and experimental studies of its functional properties.

3. The described device allows one to expand the functionality of known domestic and foreign small displacement meters, to increase the information content and significantly up to 30% the accuracy of measurement results. Moreover, it also provides the possibility of correction of measurement results, excluding the influence of internal and external destabilizing effects without the use of additional measuring means, which improves the quality of measurement results up to 40%.

4. The obtained results are most expedient for using in the process of high-precision measurements of small linear and angular displacements of the control object surfaces during experimental studies, evaluation and diagnostics of the state of construction materials for the power elements of operating goods, investigation of fast-moving wave processes in layered structures of complex shape made of anisotropic composite materials, the study of the processes of defect formation in new construction materials in engineering, shipbuilding, aircraft building, instrument making, power engineering, etc.

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