Chapter 24
Mathematical Models, Program Software, Technical and Technological Solutions for Measurement of Displacements of the Control Object Surfaces by Laser Interferometer

I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov and S.-H. Chang

Abstract The chapter presents results of development and scientific (calculations and experiments) grounds of perspective methods and means of contactless measurement of displacements of the control object surfaces, directed to creation of novel high-accuracy optic measurement technologies and corresponding technical means for state diagnostics of construction materials and goods during all stages of their lifetime (in manufacture and operation) by acoustic methods of non-destructive testing based on the modern methods of laser interferometry.

24.1 Introduction

In present, one of the actual and most perspective directions for solution of scientific and applied problems of state diagnostics of construction materials and goods during their lifetime is the laser interferometry. Its methods allow one to study damage processes in novel materials and composites and register displacements of the control object surfaces by using high-accuracy contactless measurement means. This approach increase significantly a quality (accuracy) and information of analysis of the elastic wave fields at ultrasound defectoscopy, state

I.P. Miroshnichenko (✉)
Don State Technical University, Rostov-on-Don, Russia
e-mail: ipmir@rambler.ru

I.A. Parinov · E.V. Rozhkov
Vorovich Mathematics, Mechanics and Computer Science Institute, Southern Federal University, Rostov-on-Don, Russia

S.-H. Chang
Department of Microelectronic Engineering, National Kaohsiung Marine University, Kaohsiung, Taiwan

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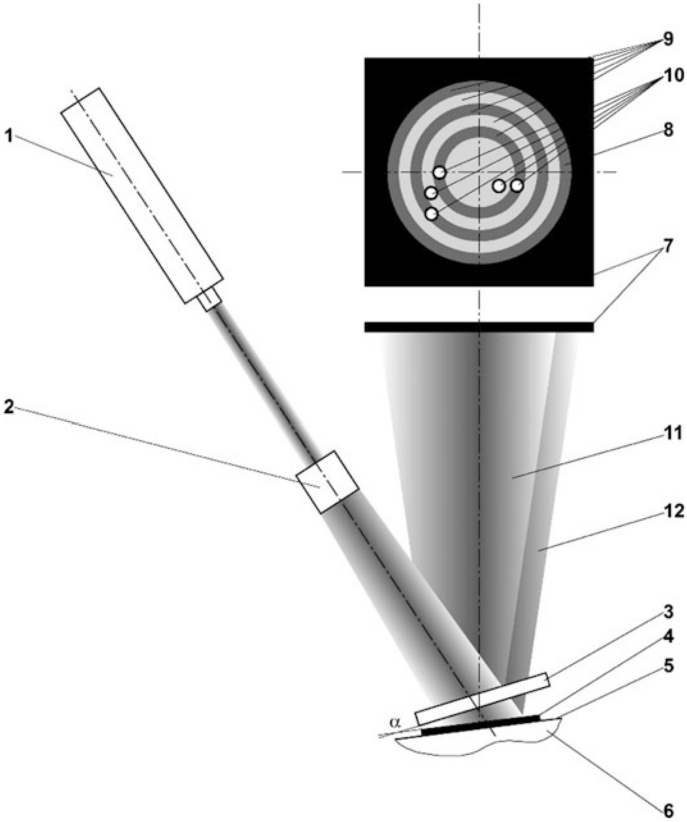


Fig. 24.1 Typical schematic of two-way laser interferometer with combined branches

diagnostics of materials and goods by using acoustic emission methods, etc., that is improve a quality and reliability of different machines and equipment.

The aim of this chapter is the development and scientific (calculations and experiments) grounds of perspective methods and means of contactless measurement of displacements of the control object surfaces. The results are directed to R&D of novel high-accuracy optic measurement technologies and corresponding technical means for state diagnostics of construction materials and goods during all stages of their lifetime (in manufacture and operation). These results are reached by using active and passive methods of non-destructive testing on the base of modern methods of the laser interferometry.

As a base device for solution the pointed problems, we select the two-way laser interferometer with combined branches (see Fig. 24.1). This interferometer includes optically coupled and consecutively located source 1 of coherent optical radiation, optical system 2, beam-splitter 3, reflector 4 fastened at surface 5 of a control object 6, and screen 7 on which are stated photo-detectors 10. The beam-splitter 3 and reflector 4 are situated one from other under angle α. Obtained in combination of reference beam 11 and object beam 12 the interference picture 8 presenting itself the set of rings 9 with various intensities projects on the screen 7, and the photodetectors 10 are located into rings 9 of interference picture 8.

The main directions for improvement of above two-way laser interferometer with combined branches were extension of its functional possibilities and using for solution of applied problems in the structure of mobile diagnostic systems.

24.2 Models, Methods and Measurement Means

24.2.1 Modeling Intensity of Optic Radiation in Interference Pictures

We have developed new mathematical models and program software for modeling intensity of optic radiation in interference pictures. These pictures are created by optic meter of displacements on the base of two-way laser interferometer with combined branches. In this case, it takes into account features of an optic measurement scheme and kind of beam-splitter, and also a technical solution (measurement device), ensuring the meter application at solution of scientific-technical problems.

Above results allow us to numerically model different optical schemes (defined by specific problem) of interference meters for contactless measurement of small displacements of the control object surfaces by using two-way laser interferometer with combined branches. This technical solution increases an accuracy of the measurement results during diagnostics of construction materials by acoustic non-destructive testing methods up to 30 % in dependence on used method of processing information, obtained from interference picture. It attains taking into account heterogeneities of distribution of the interference picture optical field.

Based on the proposed models and program software, we performed numerical modeling of intensity distributions of the interference picture optical fields. These results (see Figs. 24.2, 24.3, 24.4 and 24.5) have been obtained at registration of small displacements of the control object surfaces for various versions of optical

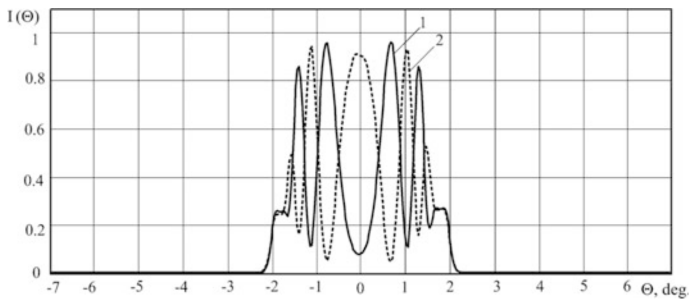


Fig. 24.2 Distribution of intensity in horizontal section of interference picture (beam-splitter is the amplitude sinusoidal grid with parallel polarization)

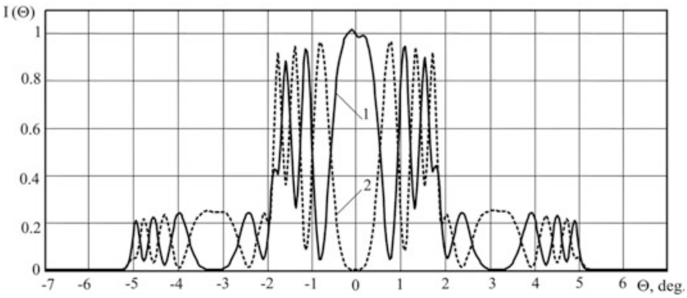


Fig. 24.3 Distribution of intensity in horizontal section of interference picture (beam-splitter is the amplitude sinusoidal grid with perpendicular polarization)

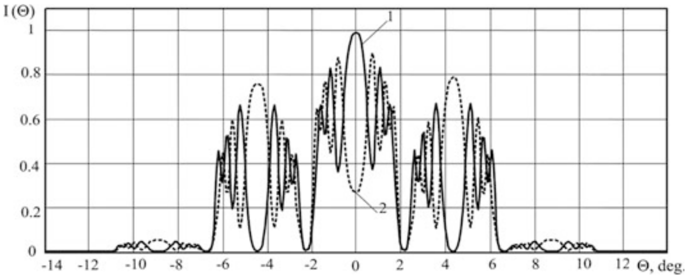


Fig. 24.4 Distribution of intensity in horizontal section of interference picture (beam-splitter is the phase sinusoidal grid)

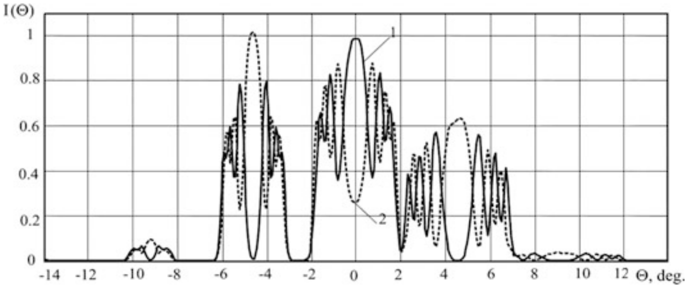
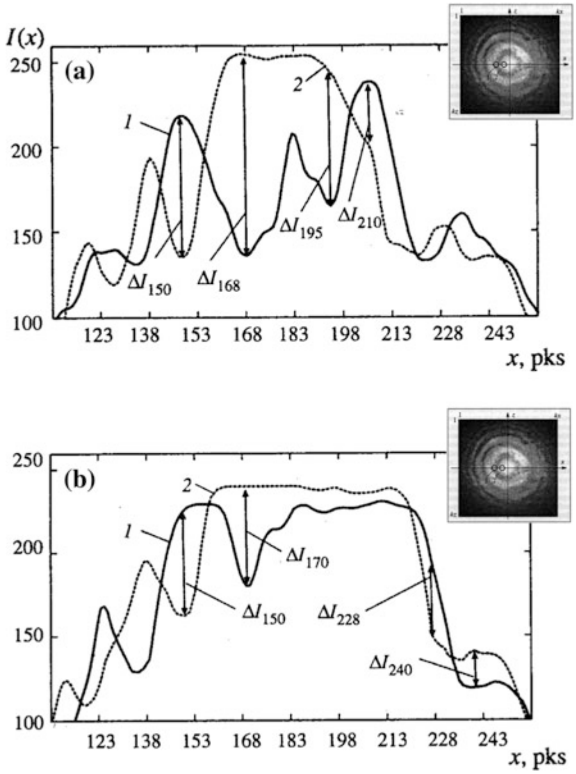


Fig. 24.5 Distribution of intensity in horizontal section of interference picture (beam-splitter is the phase zone plate)

measurement schemes and kinds of beam-splitters. As the beam-splitters, we considered a semitransparent mirror, amplitude sinusoidal grid, amplitude zone plate, phase sinusoidal grid, phase zone plate and amplitude holographic diffraction grid.

The computer simulation results agree well with the test results and operation data.

Fig. 24.6 Distribution of intensity in horizontal section of interference picture (beam-splitter is the phase zone plate)



As an example, Fig. 24.6 presents the computer simulation results of dependencies of variation of the optic field intensity for interference picture in horizontal section for displacements $h = 0$ (curve 1) and $h = \lambda/4$ (curve 2) (where λ is the wavelength of optical radiation of the used laser) for beam-splitter in the form of diffraction grid displayed in contrary beams (a), and for beam-splitter in the form of semitransparent mirror (b). Figure 24.7 presents a scheme of meter of the small displacements with pointed area 11 for registration of optic field intensity of the interference picture.

Above results have been published in necessary details in [1–17].

24.2.2 Method of Contactless Measurement of Small Linear and Angular Displacements

We have developed a novel method of contactless measurement of small linear and angular displacements of the control object surfaces, its theoretical and experimental grounds (mathematical model, program software, results of computer simulation,

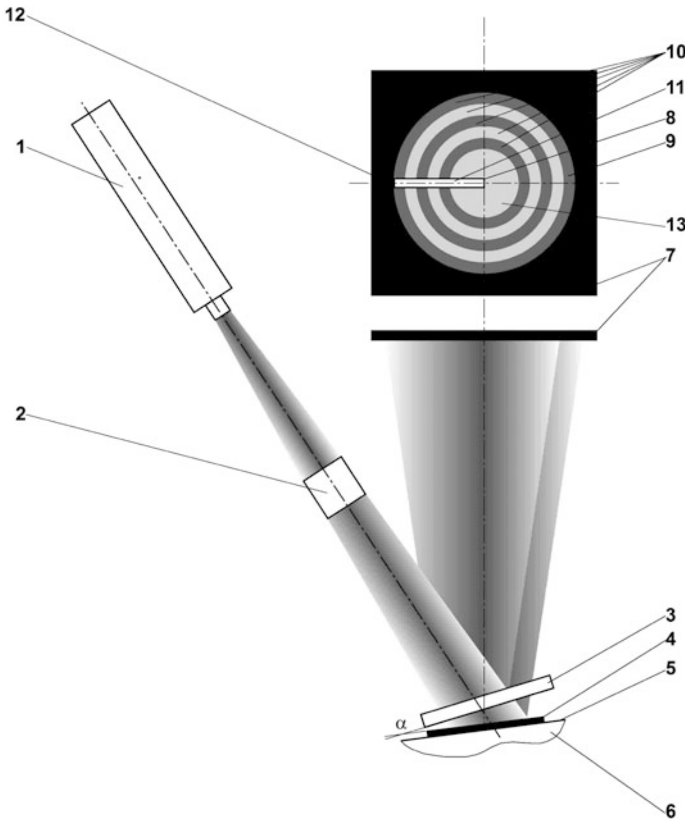


Fig. 24.7 Scheme of meter of small displacements

experimental means, test results, etc.) and technological solution (measurement method), ensuring its realization in solution of scientific-technical problems.

Essence of the proposed solutions consists in that as beam-splitter, it is used sinusoidal diffraction grid; maxima of +1 and −1 orders of interference picture are projected at the screen; the photo-detectors are divided into two groups and placed in areas of the maxima of +1 and −1 orders of the interference picture. The components of small displacement are defined on the base of two values of intensity, measured by using the photo-detector groups, applying dependencies known for each of the maximum. These dependencies couple the intensity with linear and angular displacements. As a result, there are used the values of linear and angular components of displacement, which satisfy simultaneously to the measured intensity at the maxima of +1 and −1 orders.

Significant difference of the technological solution, compared with known analogues, consists in ensuring of possibility of the simultaneous contactless registration of small linear and angular displacements of the control object surface by using only one optical meter. This allows one to extend considerably its functional possibilities.

Figure 24.8 presents optical scheme of the proposed technological solution, and Fig. 24.9 shows dependencies of intensity on linear and angular displacements of the control object surface at −1 (a) and +1 (b) maxima of interference picture (solid lines correspond to results of computer simulation and dotted lines show experimental results).

Above results have been published in necessary details in [1, 13, 14, 16–22].

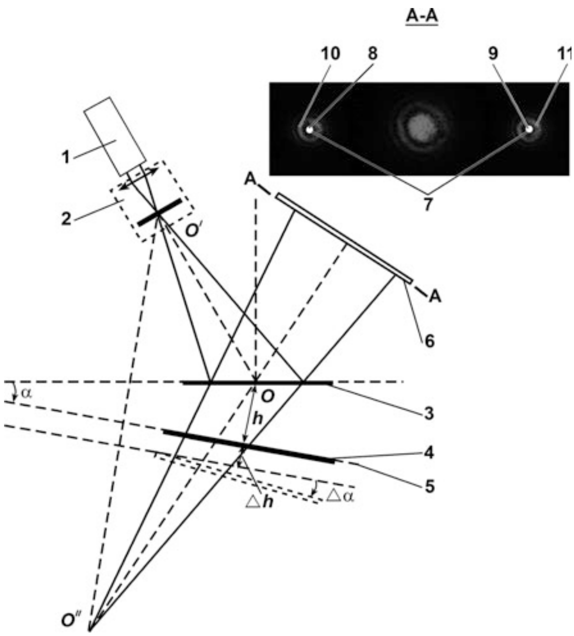


Fig. 24.8 Optical scheme of the proposed technological solution

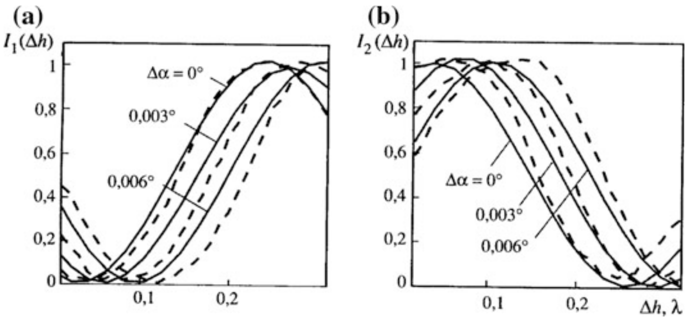


Fig. 24.9 Dependencies of intensity on linear and angular displacements of the control object surface at −1 (a) and +1 (b) maxima of interference picture (*solid lines* correspond to results of computer simulation and *dotted lines* show experimental results)

24.2.3 Under-Shining Method of Control Object Surface by Laser Interferometer

We have developed a novel method of contactless measurement of displacements of the control object surfaces, consisting in under-shining these surfaces by laser interferometer, its scientific theoretical and experimental grounds (mathematical model, program software, results of computer simulation, experimental means, test results, etc.) and technical solution (measurement device), ensuring its realization in solution of scientific-technical problems.

Essence of the proposed results consists in that the control object is placed after optical scheme, focusing optical radiation on the object surface in the form of a lighting point; beam-splitter, reflector and photo-detector are rigidly fasten on common base, supplied by the displacement mechanism. This mechanism is made with a possibility to increase (decrease) distance between the control object surface and external surface of beam-splitter at increasing (decreasing) a range of measured displacements.

Significant difference of the proposed solution from known analogues is a possibility to change a range of measured values of displacements of the control object surface during experiment without change a measurement scheme by way of alteration of the wave front curvature of the optical radiation reflected from the control object surface. This allows one to extend functional possibilities of the optical interference meter of displacements.

Figure 24.10 presents scheme of the proposed measurement device, and Fig. 24.11 demonstrate the obtained experimental dependence of sensitivity alteration on distance between surfaces of the control object and beam-splitter.

Above results have been published in necessary details in [1, 23–28].

24.2.4 Method of Complex Correction of the Measurement Results of Displacements

We have developed a novel method of complex correction of the measurement results of displacements by using optical interference means, its scientific theoretical and experimental grounds (mathematical model, program software, results of computer simulation, experimental means, test results, etc.) and technical solution (measurement method), ensuring its realization in solution of scientific-technical problems.

The proposed results differ from known analogues that during measurement of displacements of the control object surface, it is registered simultaneously and continuously a summary intensity of optical field by using a square of interference picture, value of which introduces a correction to the measurement results. This allows one to carry out a correction of the measurement results, immediately during

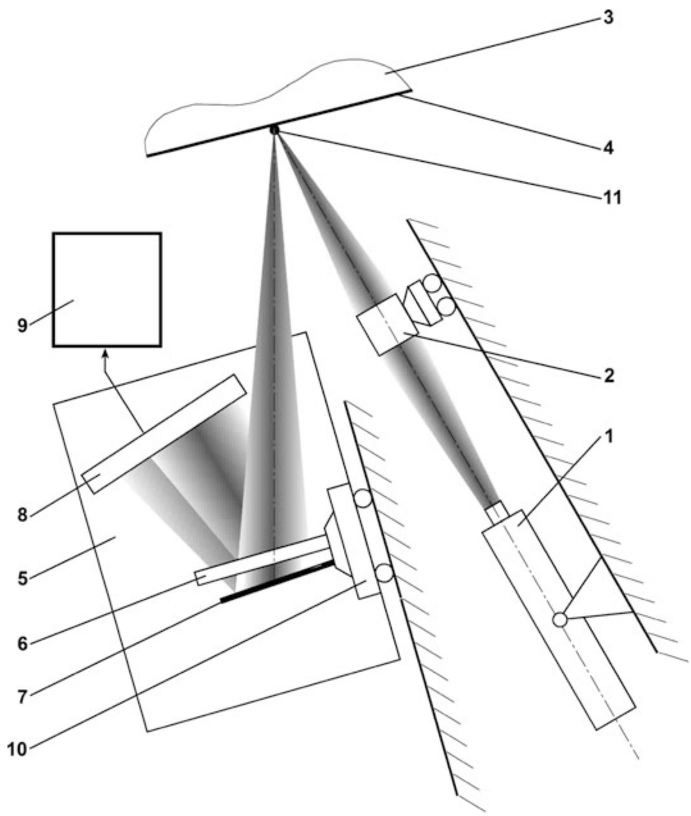
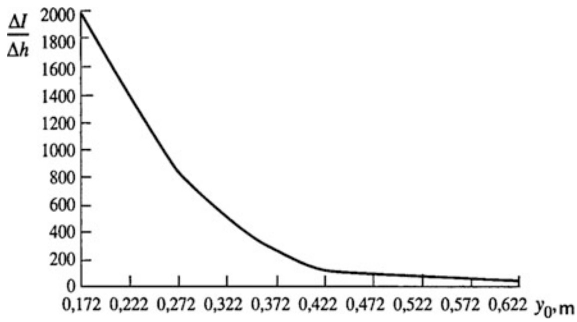


Fig. 24.10 Scheme of the proposed measurement device

Fig. 24.11 Dependence of sensitivity on distance between surfaces of control object and beam-splitter



controlling process (in the same time scale) and increase an accuracy of the measurement results up to 20 % in dependence on excitation amplitude.

Figure 24.12 shows a device scheme realizing the proposed technological solution. Figure 24.13 demonstrates an experimental dependence of summary intensity of optical field of the interference picture during measurement of displacement of the control object surface (a) and results of direct measurement of displacement of the control object surface (b). The dotted line shows measurement results, and solid line corresponds to measurements after introducing the correction.

Above results have been published in necessary details in [1, 29, 30].

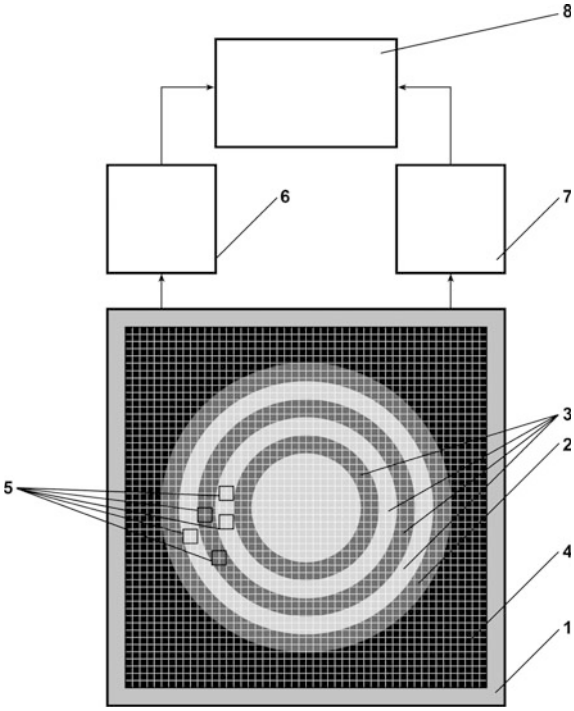


Fig. 24.12 Scheme of device realizing the proposed method

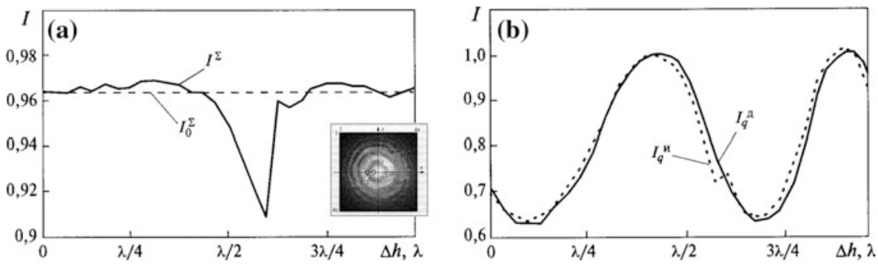


Fig. 24.13 Results of measurements and processing

24.2.5 Method of Increasing Vibro-stability of the Optical Interference Meter

We have developed a novel method of increasing vibro-stability of the optical interference meter based on using its own measurement possibilities, its scientific theoretical and experimental grounds (experimental means, test results, etc.) and technical solution (measurement device), ensuring its realization in solution of scientific-technical problems.

The proposed results differ from known analogues by continuous during measurement of displacements of the control object surface, the registration and compensation of influence of the external destabilizing effect (vibrations, impacts, etc.) on the measurement results. They allow increasing an accuracy of the measurement results up to 40 % in dependence of kind of the destabilizing influence.

Figure 24.14 presents a scheme of the proposed technical solution.

Above results have been published in necessary details in [1, 31–33].

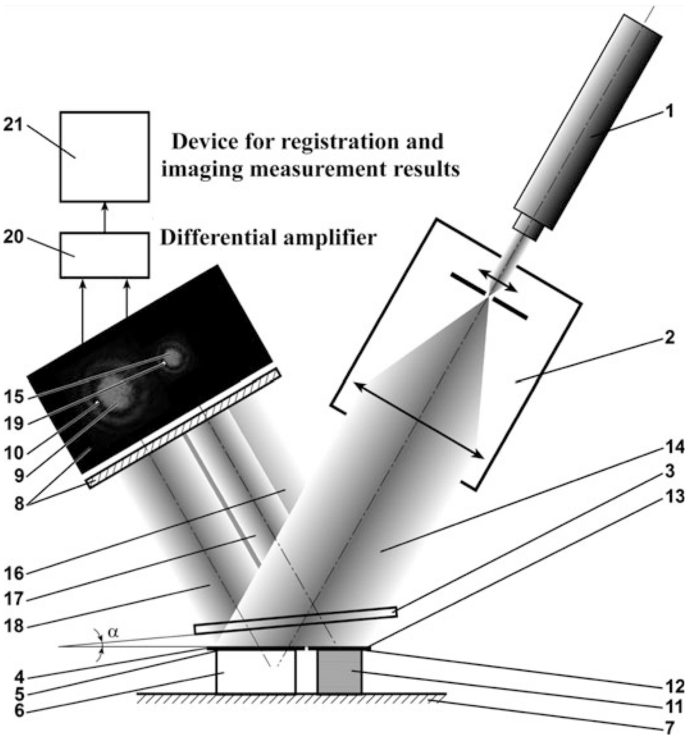


Fig. 24.14 Scheme of device for measurement of small displacements of the control object surfaces, protected of external destabilizing influences

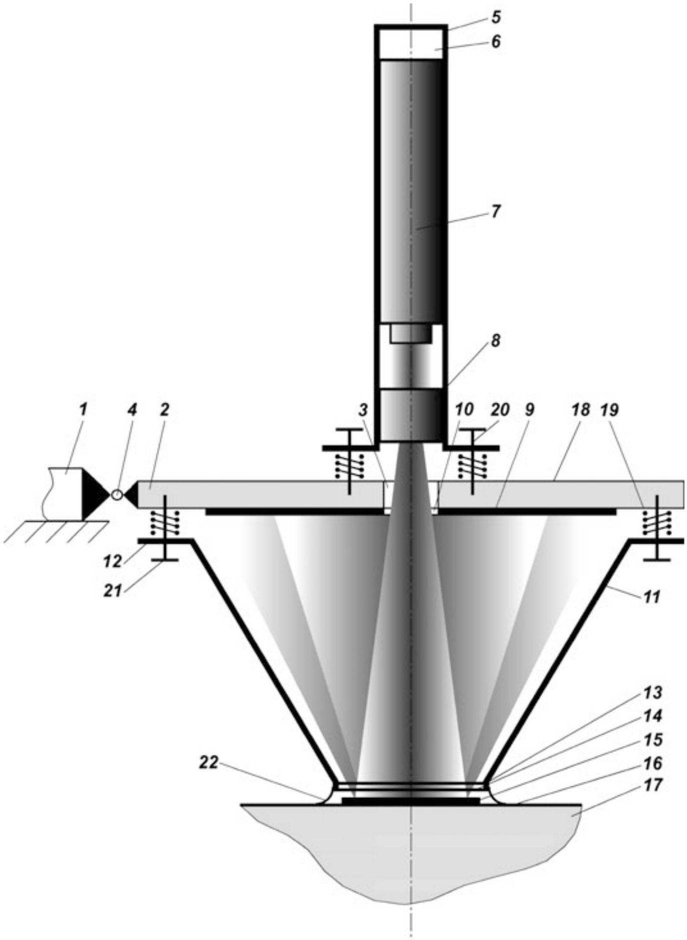


Fig. 24.15 Scheme of device for measurement of small displacements of the control object surfaces for mobile diagnostic complexes

24.2.6 Measurement Devices Realizing the Optical Interference Measurement Methods

We have developed new scientific-grounded technical solutions (measurement devices), realizing the optical interference measurement methods of displacements of the control object surfaces (see Sects. 24.2.1–24.2.5), adapted for using in the structure of stationary and mobile diagnostic complexes.

These measurement devices allow us to ensure solution of measurement problems both as in laboratory conditions, as in "wild" conditions (mobile diagnostic complexes). By this, we reach complete preservation of functional possibilities of the methods, presented in Sects. 24.2.1–24.2.5, decreasing labor and time expenses on mounting and tuning at preparation of measurements and also during testing.

Figure 24.15 presents scheme of device for measurement of small displacements of the control object surfaces for mobile diagnostic complexes. Figure 24.16 shows

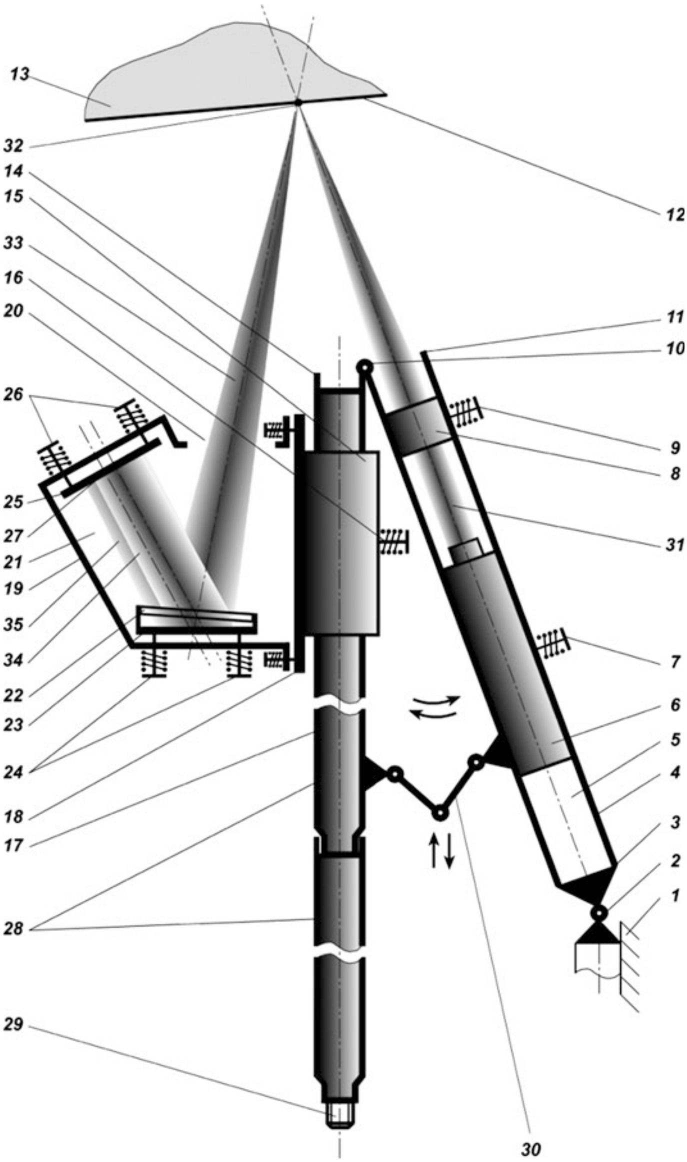


Fig. 24.16 Scheme of device for measurement of small displacements of the control object surfaces for mobile diagnostic complexes with regulated range

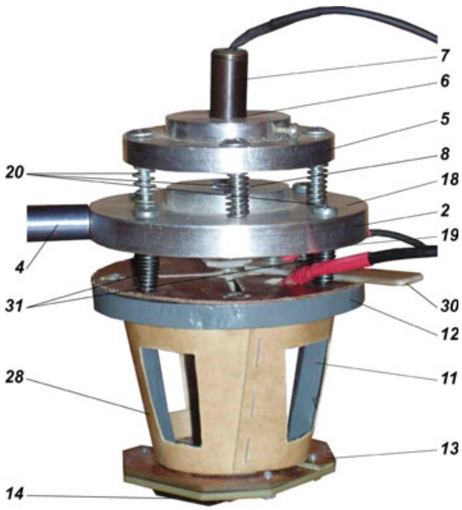


Fig. 24.17 Common form of experimental sample of measurement device

scheme of device for measurement of small displacements of the control object surfaces for mobile diagnostic complexes with regulated range. Figure 24.17 demonstrates common form of experimental sample for measurement of small displacements of the control object surfaces.

Above results have been published in necessary details in [9, 10, 31, 34–37].

24.3 Conclusions

The technical and technological solutions have been manufactured in the form of full-scale measurement means, experimental-measurement laboratory devices, demonstration models and used in solution of actual scientific and industrial problems for study of strength characteristics of construction materials, developments of novel methods for quality control of construction materials and goods. Moreover, the obtained results have been used for study of damage processes in high-temperature superconductive tapes [38–41].

These technical and technological solutions and also program software, presented in the chapter, have been awarded by 13 medals and main prizes of the following international salons and exhibitions: “Concours Lepine International Paris 2014”, “Inventions Geneva—2014”, “INVENTICA 2013–2015”, “TunisInnov—2014”, “Tesla Fest—2014”, “Archemede 2013–2014”.

Scientific novelty and significance of the obtained results are confirmed by the Russian patents and certificates on Russian state registration of programs for computer. Reliability of the obtained results is based on the performed modeling and study of functional characteristics of the technical and technological solutions, compared with known analogues.

The obtained results may be applied in high-accuracy measurements of small linear and angular displacements of the control object surfaces at experimental studies of perspective constructions, estimation of their state and diagnostics, investigation of acoustic-emission processes in solids, research of damage in novel materials, consideration of wave processes in layered constructions and anisotropic materials applied in different branches of industry.

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References

1. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, A.G. Serkin, V.P. Sizov, in *Piezoelectrics and Related Materials: Investigations and Applications*, vol. 238, ed. by Ivan A. Parinov (Nova Science Publishers, New York, 2012)
2. I.P. Miroshnichenko, A.G. Serkin, Meas. Tech. **49**(5), 22 (2006)
3. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, Meas. Tech. **50**(1), 9 (2007)
4. I.P. Miroshnichenko, A.G. Serkin, Russ. J. Nondestr. Test. **43**(4), 234 (2007)
5. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, Izv. VUZov. Priborostroenie **12**, 34 (2007). (In Russian)
6. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, J. Opt. Technol. **75**(7), 437 (2008)
7. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, Nanotekhnika **4**, 56 (2008). (In Russian)
8. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, in *Common Issues of Radio-electronics* (RNIIRS, Rostov-on-Don, 2009), p. 155
9. I.P. Miroshnichenko, Mod. Sci. Res. **2** (2014). http://e-koncept.ru/2014/55188.htm. (In Russian)
10. Miroshnichenko I., DOAJ—Lund University: Concept: Sci. Methodological e-magazine, Lund, **4** (2014). http://www.doaj.net/2846/
11. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, A.G. Serkin, Optical device for measurement of displacements. Russian Patent No. 2373492, 11.20.2009 (In Russian)
12. I.P. Miroshnichenko, A.G. Serkin, Program for calculation of optical field intensity of the interference picture. Certificate on Russian State Registration of Program for Computer No. 2008614831(2008) (In Russian)
13. I.P. Miroshnichenko, Program for Calculation of optical field intensity of the interference picture (Case of Perpendicular Polarization). Certificate on Russian State Registration of Program for Computer No. 2014614501 (2014) (In Russian)
14. I.P. Miroshnichenko, Program for calculation of optical field intensity of the interference picture (Case of Parallel Polarization). Certificate on Russian State Registration of Program for Computer No. 2014614502 (2014) (In Russian)
15. I.P. Miroshnichenko, V.A. Shevtsov, Program for calculation of optical field intensity of the interference picture, created by laser two-way interferometer with combined branches. Certificate on Russian State Registration of Program for Computer No. 2014662261 (2014) (In Russian)
16. I.P. Miroshnichenko, I.A. Parinov, Definition of optical field intensity of interference picture, created by laser interferometer, for beam-splitter in the form of phase sinusoidal grid with uniform period. Certificate on Russian State Registration of Program for Computer No. 2015610921 (2015) (In Russian)

17. I.P. Miroshnichenko, I.A. Parinov, Definition of optical field intensity of interference picture, created by laser interferometer, for beam-splitter in the form of phase zone plate. Certificate on Russian State Registration of Program for Computer No. 2015611078 (2015) (In Russian)
18. I.P. Miroshnichenko, A.G. Serkin, Russ. J. Nondestr. Test. **44**(5), 318 (2008)
19. I.P. Miroshnichenko, Control. Diagnostics **1**, 45 (2010). (In Russian)
20. I.P. Miroshnichenko, A.G. Serkin, Control. Diagnostics **7**, 46 (2011). (In Russian)
21. I.P. Miroshnichenko, South-Siberian Scientific Vestnik **2**, 149 (2014). (In Russian)
22. I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, Method of measurement of the linear and angle displacements. Russian Patent No. 2388994, 05.10.2010 (In Russian)
23. I.P. Miroshnichenko, I.A. Parinov, S.H. Chang, in *Advanced Materials—Studies and Applications*, vol. 437, ed. by Ivan A. Parinov, Chang Shun-Hsyung, Somnuk Theerakulpisut (Nova Science Publisher, New York, 2015)
24. V.E. Alekhin, I.P. Miroshnichenko, V.P. Sizov, Russ. J. Nondestr. Test. **43**(2), 113 (2007)
25. V.E. Alekhin, I.P. Miroshnichenko, V.A. Nesterov, V.P. Sizov, Russ. J. Nondestr. Test. **43**(9), 592 (2007)
26. V.E. Alekhin, I.P. Miroshnichenko, A.G. Serkin, Meas. Tech. **51**(10), 26 (2008)
27. I.P. Miroshnichenko, Control. Diagnostics **2**, 34 (2010). (In Russian)
28. V.E. Alekhin, I.P. Miroshnichenko, A.G. Serkin, V.P. Sizov, Optical device for measurement of displacements of the control object surfaces. Russian Patent No. 2343402, 01.10.2009 (In Russian)
29. I.P. Miroshnichenko, A.G. Serkin, Sens. Syst. **3**, 28 (2008). (In Russian)
30. V.E. Alekhin V. E., Miroshnichenko I. P., Serkin A. G., Sizov V. P., *Registration Method of Displacements by Optical Transducers*. Russian Patent No. 2343403, 01.10.2009 (In Russian)
31. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, V.P. Sizov, V.A. Shevtsov, in *Physics and Mechanics of New Materials and Their Applications*, vol. 145, ed. by Ivan A. Parinov, Chang Shun-Hsyung (Nova Science Publishers, New York, 2013)
32. I.P. Miroshnichenko, V.A. Shevtsov, Polzunov Vestnik **2**, 66 (2014). (In Russian)
33. I.P. Miroshnichenko, V.A. Nesterov, A.G. Serkin, V.P. Sizov, V.A. Shevtsov, Interference meter of small displacements. Russian Patent No. 2410642, 01.27.2011
34. I.P. Miroshnichenko, Polzunov Vestnik **2**, 95 (2014). (In Russian)
35. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, A.G. Serkin, Device for testing thin specimens on bending. Russian Patent No. 2376567, 12.20.2009 (In Russian)
36. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, A.G. Serkin, Device for measurement of displacements. Russian Patent No. 2407988, 2010 (In Russian)
37. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, Optical interference device for measurement of displacements of control object surfaces. Russian Patent No. 2512697 (2014) (In Russian)
38. I.P. Miroshnichenko, I.A. Parinov, E.V. Rozhkov, A.G. Serkin, Metallurgist **50**(7–8), 408 (2006)
39. I.P. Miroshnichenko, A.G. Serkin, Metallurgist **54**(3–4), 189 (2010)
40. I.P. Miroshnichenko, Mod. Sci. Res. **3** (2015). http://e-koncept.ru/2015/85842.htm. (In Russian)
41. I.P. Miroshnichenko, DOAJ—Lund University: Concept: Scientific and Methodological e-magazine, Lund, **7** (2015). http://www.doaj.net/5062/