Development of nanoscale measurement system

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Abstract: The work is devoted to measuring linear displacements in the nanoscale, analysing the features of this kind of work, ensuring the unity of measurements and stability of the measured physical quantity, the reliability of

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the results and their linkage to the State Standard. The criteria must be met by methods and means of precision measurements in the nanoscale, as well as methods and means for acquiring and presenting the information obtained. The analysis of the main sources of errors is made and the results of these studies are presented in Novikov [1]. The features of the construction of measuring systems, as well as the problems of calibration of phase measurements in optics, are considered. The problems of an applied nature are considered: the measurement of real displacement of objects in the nanoscale, their speed and acceleration, as well as the introduction of the developed methods into the field of practical application. The results obtained in solving experimental and applied problems using methods and means of numerical heterodyning are presented. The developed 'interferometer-phase meter' measuring system allows online investigating of complex piezoceramic structures used in various devices as actuators.

Keywords: laser; linear displacement; nanoscale; interferometry; PSA; phase shift angle.

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1 Introduction

A development of science-intensive technologies is impossible without creation of highly sensitive methods and high-precision measurement of linear dimensions and precision movements control of objects in nanoscale. At the same time, the maximum possible degree of accuracy must be achieved and the corresponding metrological level ensured.

A precision measurement of ultra-small displacements is needed for fundamental works, related to creation of a new generation of interrelated standards in the field of mechanical and acoustic quantities, for investigation of quantum-size effects and highly stable sources of coherent radiation, for calibration of micro- and nanorange actuators, and for controlling of dangerous technogenic objects and ensuring an ecological balance of the environment.

An optimal solution of these problems in the future could be the use of linear measurement methods and instruments of optical (laser) interferometry-phaseometry (nanometry), based on fundamental constants and standards of physical quantities [1–3].

The phase (interference) methods in optics are used to measure the space-time variations of the phase difference values – phase shift angle (PSA) in interference field between measurement and reference beams, due to the frequency, spatial or polarisation dispersion of radiation in the phase object [3–8].

Optical (laser) interferometry-phaseometry (nanometry) with highly developed radio range phasometry technique gives an opportunity for creation a high-precision measuring systems and basis for ensuring the uniformity of linear measurements in the micrometer and nanometre ranges, as well as in the radio and optical ranges.

All of this led to the creation a new class of measuring tools and methods, meeting the high metrological requirements of nanotechnology and possessing wide opportunities to satisfy the demands of science and technology in the field of high-precision measurements, i.e., meet a wide range of requirements of high technology, including nanotechnology.

In this work a structural and functional scheme of phase measurement system in nanoscale is considered. The measurement of objects' real displacement in nanoscale was performed and issues of practical application of developed methods were also considered.

2 Experimental setup

On the basis of analysis and recommendations a LMS-01M laser measuring system was developed.

LMS system consists of (Figure 1):

- stabilised helium-neon laser
- interference optical transducer
- photodetector (PD)
- electron-phasometric system (EPS)

- block of high-frequency generators (HFGB)
- communication interface
- personal computer
- software.

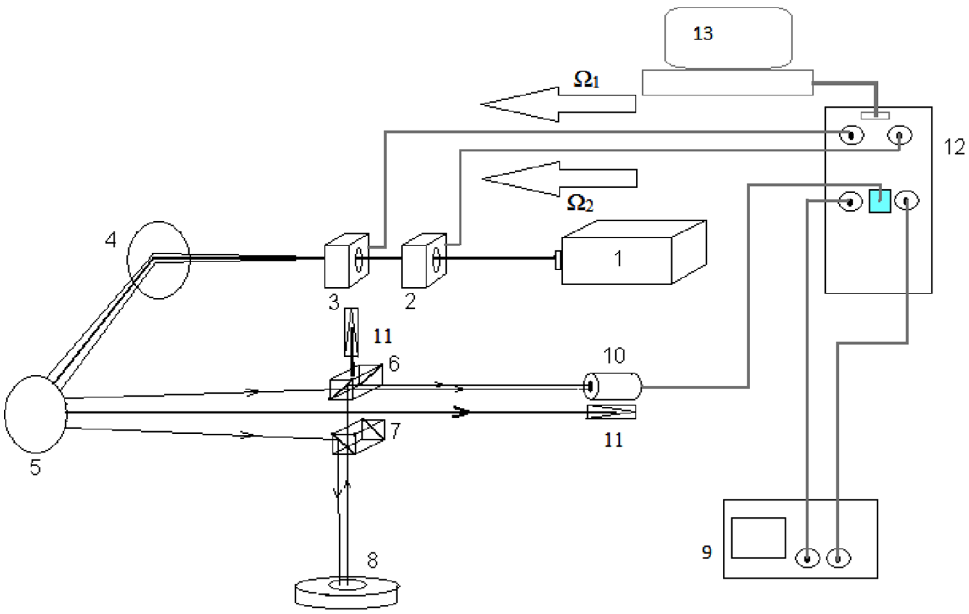
LMS provides online measurement operation of ΔX displacement by counting of phase cycles (PC) and adding of so called $\Delta\varphi$ PSA:

$$\Delta X = \left(N + \frac{\Delta\varphi}{2\pi}\right) \cdot \frac{\lambda}{2n} \tag{2}$$

where N is the phase cycles ($N = 0, 1, 2, 3, \ldots, N$), $\Delta\varphi$ is the phase shift angle, λ is the radiation wavelength of laser, and n is the refractive index.

LMS optical system is a two-beam modified Michelson interferometer. Functional scheme of LMS is shown in Figure 1.

Figure 1 Structural and functional scheme of LMS-01M (see online version for colours)



1 – LHN 302 laser; 2,3 – acoustooptical modulators (AOM); 4,5 – mirrors; 6,7 – beam-splitting elements; 8 – sample with reflective coating; 9 – oscilloscope; 10 –photodetector; 11 – absorber of a non-working beam; 12 – EPS; 13 – laptop.

LMS has a range of linear displacement measurements of 10^{-9}–10^{-2} m with resolution of 0.1 nm and high speed response rate due to the selected frequency difference. The range of absolute measurement error is within the range from 0.5 nm to 3 nm. Such technical characteristics allow solving a wide range of tasks.

3 Experiment and discussion

An optical beam with a frequency ω_0 (zero beam), passing through the first modulator at the Bragg angle, diffracts on a diffraction grating (running with frequency Ω_1), then it is divided into two beams with frequencies ω_0 and $\omega_0 + \Omega_1$ (plus the first beam). Further, the zero beam passes through the second modulator with a frequency Ω_2 at the Bragg angle and it is again divided into two beams with frequencies ω_0 and $\omega_0 - \Omega_2$ (minus the first beam). Thus, there are three beams at AOM output: zero, plus first and minus first. One of the received beams, falling on the sample and being reflected, obtains information about the object's movements as a phase shift angle $\Delta\varphi$ (information beam); another beam passes its optical path without interaction with sample (reference beam). The zero beam is absorbed by absorber of non-working beam (Figure 1). After, the information and reference beams interfere with each other, falling on the photodetector (PD). Futher, the extraction of information signal occurs thru the difference of frequencies $|\Omega_1 - \Omega_2|$ in PD. Analysis of obtained information is carried out in a specialised electronic-phase-measuring system (EPS). EPS is connected to the laptop. The software allows online collecting of measurement data, analysing and presenting output file in an easy-to-use format.

There are data below (Figures 2 and 3), which were obtained by using a heterodyne method of measuring displacements in nanoscale. In particular, there are data of vibrational displacement measurements of the free end of a piezo table when a modulating signal of various frequency and shape is applied to it.

Figure 2 Displacement dependence on time of free end of a piezo table when a sinusoidal oscillation (*f* ~ 1 kHz; *U* = 6 V) is applied (see online version for colours)

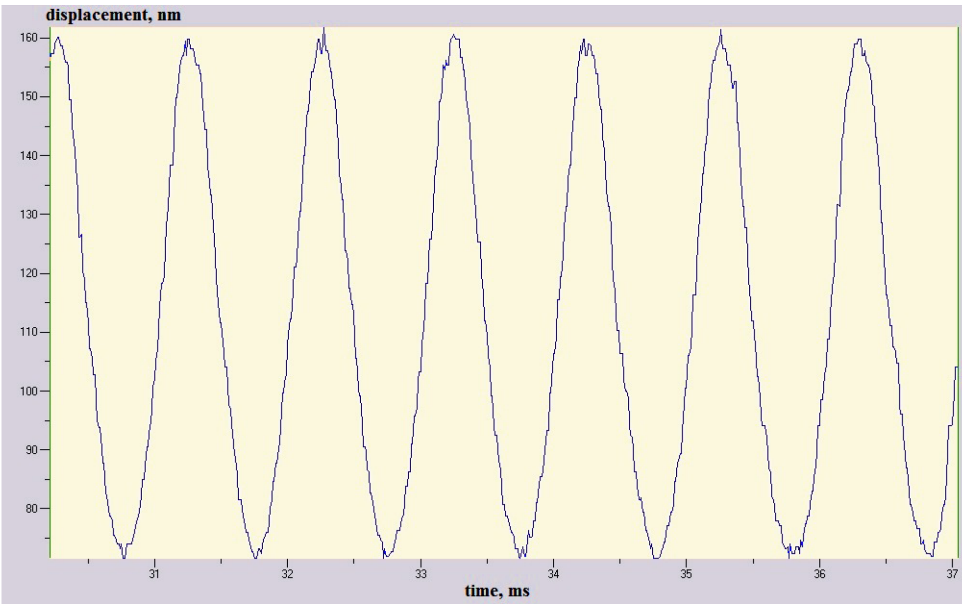
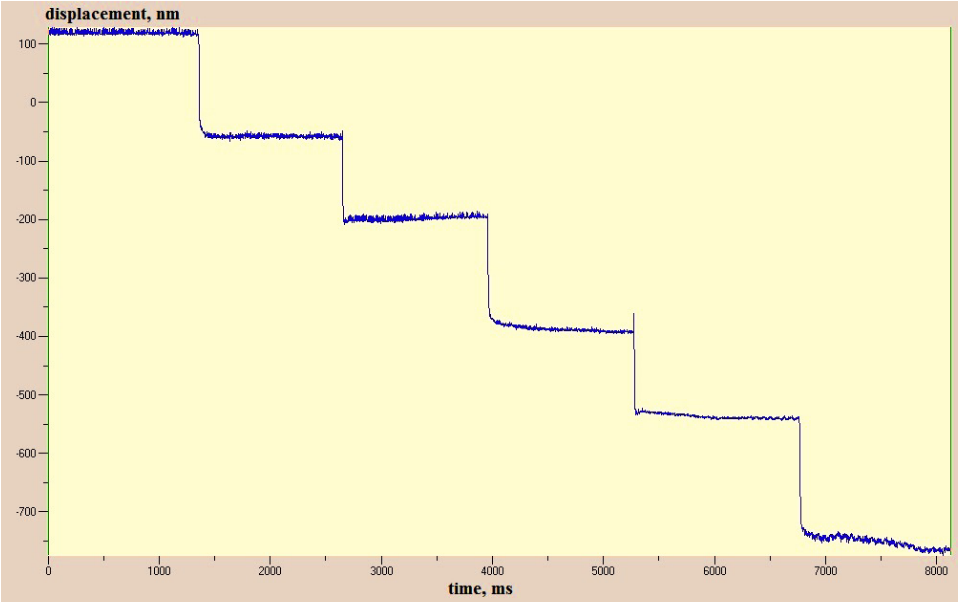


Figure 3 Displacement dependence on time of free end of a piezo table when the voltage is applied in steps of 10 V and in a range '0–50 V' (see online version for colours)



4 Conclusion

A laser digital phase meter operating in a wide spectral range has been developed to calibrate and validate laser linear displacement meters, as well as to measure the amplitudes of the vibrational motion of the solid surface, and to ensure the uniformity of the measurements in nanorange. The presented 'interferometer-phase meter' measuring system allows online investigating of complex piezoceramic structures used in various devices as actuators.

Acknowledgements

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