Laser technology in high-tech instrumentation

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Abstract. The main task of modern high-tech instrumentation is to increase the accuracy of devices for determining the position of the object in space. A promising direction of improvement of devices for determining the position of an object in space is the use of devices operating on the principles of laser interferometry. A method for determining the absolute position of an object in space is described. The prospects of using measuring devices based on optoelectronic devices with the use of phase methods of measuring information processing are shown. The structure of the phase measuring device based on optoelectronic devices with spatial reference points is proposed. This makes improving the accuracy of measurement by dividing into sub-bands possible.

1. Introduction

One of the main tasks of modern high-tech instrumentation is to improve the accuracy of devices for determining the position of an object in space.

The device for determining the position of an object in space is based on different physical nature of the effects: electric, magnetic, optical, acoustic, etc. Current information is formed during execution of the measurement process in strictly defined points in time with different physical nature of measuring instruments. Metrological characteristics of such devices are determined by the type of measuring devices, algorithms for obtaining and processing of primary measuring information and operating conditions of the environment.

A promising direction of improvement of devices for determining the position of an object in space is the use of devices operating on the principles of laser interferometry [1, 2].

An example of modern devices for determining the position of an object in space are the control devices of various machines with numerical control. Advances in nanotechnology and optoelectronics make it possible to create devices for determining the position of an object in space with a small step of readability (about 0.01 µm or less). At the same time, the use of lasers with high spatial and temporal coherence as sources of the reference action makes it possible to provide the necessary measurement error.

In Russia, fundamentals of the theory and principles of construction of laser interferometers with external modulation were developed by a group of specialists at the Moscow State Technological University STANKIN under the guidance of professor V.I. Teleshevsky and at the Novosibirsk Institute of Automation and Electrometry under the guidance of professor V.P. Koronkevich. As a result of these works, the production of industrial samples of laser interferometers IPL-30K and IPL-MP was carried out. In other countries, the development and production of laser interferometers are conducted in the companies “Hewlett-Packard” (USA), “Renishaw” (England), “Carl Zeiss” (Germany), etc.
2. Tasks of science-intensive instrument making
When using optoelectronic devices to form several measuring channels in conditions of limited power of the optical radiation source due to the decrease in the intensity of the optical signal along the measurement path, there is a problem of limiting the functionality of devices to determine the position of an object in space due to the decrease in the signal/noise ratio of the measuring signal. This problem arises because of the limited power of the laser and can be solved by improving existing devices and creating new ones to determine the position of an object in space [3, 4].

The actual task of high-tech instrumentation is the development and research of a complex of scientific and hardware solutions that provide the creation of new devices based on optoelectronic devices to determine the position of an object in space. To achieve this goal, it is necessary to perform the following activities:

- analysis of the subject area and the definition of prospects for the development of measuring devices based on optoelectronic devices to determine the position of an object in space;
- study of the structures of measuring devices in which the accuracy of the physical parameter is determined by the actual value of the wavelength of optical radiation in the measuring medium;
- derivation of mathematical dependences of the signal-to-noise ratio value depending on the number of measuring channels with simultaneous frequency and spatial filtering prior to the modulation process;
- development of methods for the formation of spatial reference points in the optical path of measuring devices, which allows one to determine the position of an object in space, and the creation of a measuring device based on optoelectronic devices with high accuracy and reliability of measurement results;
- development of a measuring device based on optoelectronic devices with an absolute readout of the result of measuring movements with an increased value of the spatial period of unambiguity of the signal corresponding to the range of the movement of the controlled object.

3. Block diagrams of measuring devices
The typical structure of multichannel measuring devices based on optoelectronic devices consists of an optical radiation source, the object of the study, and other devices. The radiation source directs the radiation flow to the objects of study which receive signals and input control actions. Next, the flow of radiation is supplied to the multiplexer through the nodes of the primary transmitters. The entire process of transmission and conversion of the input signal is controlled by a microcontroller which controls the processing of data in a particular channel. In case of simultaneous requests from two or more channels on the priority system, the connection with the device with the highest priority will be established [5].

The block diagram of a single-channel interference measuring device is based on the primary converter, consisting of two delay lines: the measuring and reference ones. The optical signal from the source of optical radiation is supplied to the acousto-optic modulator, the second input of which is supplied with an electric signal from the source of the electrical signal. After the acousto-optic interaction, optical signals passing optical delay lines are fed to the photoelectric converter. As a result of changes in the state of the measuring optical line under the influence of the input action on it, a measuring signal is formed. This signal, connecting with the radiation flux in the measuring optical line, forms a modulated measuring signal, carrying useful information about the measured physical quantity. The effect on the measuring optical line changes the phase value of the output signal. The change in the phase value of the output electrical signal from the differential photovoltaic converter carries information about the measured value and is fixed by the integrated phase meter.

The most important task in the conditions of limited power of optical radiation is to obtain the maximum signal/noise ratio in the optical path of optical-electronic information-measuring and control systems. Increasing the power of optical radiation can increase the power of the radiation source.
However, at low efficiency, an increase in its power leads to excessive thermal output, which worsens the operating conditions and increases the additional measurement error from temperature changes [6].

There are two structures of optoelectronic information-measuring devices. The first structure uses acousto-optic transformation of the measuring signal after modulation by its input signal. The input optical radiation from the optical radiation source is fed to the optical cube which forms two optical channels. Each of the measuring optical channels is a Michelson interferometer, a reference arm of which consists of rigidly connected optical cubes and stationary corner reflectors. Optical wedges deflect optical beams relative to the reference ones, and after the optical lenses, the angle between the measuring and reference beams is equal to the diffraction angle. The acousto-optic modulator receives two light beams at the angle of diffraction to each other, losing part of its power. After the acousto-optic modulator, the zero-order diffraction maximum of the measuring beam interferes with the first-order diffraction maximum of the reference beam. Photovoltaic cells emit an electrical measuring signal of a difference frequency, the modifying of the phase values of which for the period \((2\pi \text{ radian})\) corresponds to the movement of the reflector at half the wavelength.

To obtain the maximum signal-to-noise ratio in the optoelectronic path of optoelectronic devices, a scheme is used where the power losses of optical radiation are minimal.

The power of the input laser radiation from the optical radiation source is fed to the acousto-optic modulator, in which, as a result of interaction with the ultrasonic wave, different frequency optical signals are received from the electric signal source. The ultrasonic wave is obtained as a result of the piezoelectric effect from the electrical signal of the source of the electrical signal. The frequencies of the optical signals will be equal to the sum and the frequency difference of the optical signal of the optical radiation source and the acoustic signal of the electric signal source, respectively. After the acousto-optic modulator, the optical signals pass through the optical lens and enter the Michelson interferometers. The Michelson interferometers consist of optical cubes, fixed and movable angle reflectors. Then, these optical signals interfere on a beam-splitting faces of the optical cubes and are fed to the photoelectric transducers, where the signal of the difference frequency is allocated. This signal is due to the Doppler effect in the motion of the movable corner-cube reflectors. The change in the phase of the electric signal on the photovoltaic converters, relative to the value of the reference phase, determines the value of the measured parameter [7, 8].

Optoelectronic devices are considered to be a class of phase measuring devices. In phase measuring devices, the change of measurement information occurs during the movement of the moving object. The effect of electromagnetic interference leads to the distortion of the measuring signals. Protection against such interference is carried out by electrical filtering of measuring signals. The disadvantage of phase optoelectronic devices with phase accumulation is the possible ambiguity of reference and the probability of measurement information loss at random interruptions of optical communication or failures in the network supply system of devices [4, 9]. To reduce the error of measurement of physical parameters and improve the reliability of the measurement information, it is necessary to organize reference points along the measured path of movement, which provide the ability to restore information about the movement by counting the whole number of periods of optical radiation.

4. Description of the method for determining the absolute position of an object in space

In phase optoelectronic measuring devices, the value of the phase difference between two optical waves is used as a spatial reference point. These are the waves that are simultaneously propagating along the measured path and formed by two orthogonally polarized spectral lines of a laser operating in a two-mode mode.

Optical radiation from the source of optical radiation is directed to the acousto-optic modulator through a rotary mirror. Optical beams are directed to a moveable corner reflector installed on the node motion and, using a turning mirror, on the optical cube. Optical beams on a beamsplitter of the optical faces of the cube interfere and are directed to a polarization cube via a rotating mirror. An optical signal comes to the cube. This signal consists of two orthogonally polarized components of emission lines from the optical source that have different wavelengths. As a result of the separation of
this signal on the polarization cube by polarization, its separation also occurs in frequency. The photovoltaic converters receive optical signals with different wavelengths of optical radiation.

Electrical signals from the photovoltaic converters are fed to the processing unit, the electrical signal from which will appear only if the absolute values of the phases of the electrical signals from the photovoltaic converters are equal. With the further movement of the movable angle reflector, due to different wavelengths of optical radiation, absolute values of the phases of the two electrical measuring signals will be different [3, 10].

The use of the reference points located on the measured track reduces the error of measurement of physical parameters of optical-electronic information-measuring and control systems by dividing the measurement range into sub-bands. It also increases the reliability of the result in case of accidental interruptions of optical communication or failures in the network supply system of devices.

In phase measuring devices for measuring sizes within units and tens of meters, the sequential accumulation of the phase in the form of whole and fractional fractions of the phase change period of the optical wave is required, since the wavelength of the optical radiation is fractions and units of micrometers. Overlapping of the optical beam during measurement or random interference leads to the loss of the optical measurement information. In this case, the measurement process has to be repeated again. This reduces the performance and reliability of the measurement. For such cases, it is necessary to use measuring devices based on optoelectronic devices with the absolute readout of measurement. The value of the spatial period of uniqueness of laser measuring devices based on optoelectronic devices is determined by the wavelength of optical radiation. The increase in the wavelength leads to an increase in the spatial period of uniqueness, but shifts the frequency spectrum of optical radiation to the infrared region. This imposes certain difficulties associated with the alignment and control of the optical scheme of the measuring device [3, 4].

The use of the interaction effect of two coherent optical oscillations with different spatial periods leads to an increase in the period of uniqueness of the measuring device. The difference between the absolute instantaneous values of the phases of the two measuring signals from the corresponding photovoltaic converters determines the location of the coordinates of the point within the period of uniqueness. An increase in the period of uniqueness in interference methods can also be obtained by using two optical beams simultaneously propagating in inclined directions with respect to the direction of the measurement line.

The optical signal from the optical radiation source passes through the optical system and is modulated in an acousto-optic modulator. Different frequency optical beams propagating at an angle of diffraction to each other, called “0” and “+1” orders, are used. These optical beams have different frequencies which differ by the value of the excitation signal frequency. The optical beams are directed to a movable angle reflector, reflected from it and subjected to secondary diffraction. After the secondary diffraction, the optical beam “+1” of the diffraction order obtains an angular slope α coinciding with the direction “0” of the optical beam and an additional frequency shift by the value of the excitation signal frequency. These optical beams are directed through an optical diaphragm to a photoelectric transducer.

The proposed method allows one to measure the movement of moving objects in the absolute mode. The spatial position of the point located on the measurement path is found by the absolute value of the phase difference between the two optical beams “0”-th and “+1”-th diffraction orders. The proposed method makes it possible to increase the noise immunity of the measurement process, since the impact of random noise during the measurement is excluded and the spatial position of the point is determined within the spatial period of uniqueness.

5. Conclusion
Thus, as a result of the review of the structures of measuring devices for non-contact measurement of linear and angular displacements, velocities and accelerations, the prospects of using laser interferometry based on the differential method with acousto-optical conversion of the optical signal to modulation by the measured value parameter are revealed.
The developments of domestic and foreign companies have revealed the prospects of building high-precision measuring devices based on the use of optoelectronic devices with high stability parameters.

The prospects are shown of the use of measuring devices based on optoelectronic devices with the use of phase methods of processing of measuring information, in which the actual value of the movement is represented as the product of the sum of the accumulated electrical pulses by the numerical value of the wavelength $\lambda$ for these measurement conditions.

The structures of measuring devices, in which the measurement accuracy of the physical parameter is determined by the actual value of the wavelength of optical radiation in the measuring medium, are presented.

The mathematical dependences of the signal-to-noise ratio depending on the number of measuring channels with simultaneous frequency and spatial filtering before the modulation process are derived.

References

[1] Porfiriev L F 2013 *Fundamentals of the Theory of Signal Transfer in Optical-Electronic Systems* (St. Petersburg: DOE) p 387
[2] Yakushenkov Y G 2013 *Fundamentals of Optical-Electronic Instrumentation* (Moscow: Logos) p 376
[3] Bazykin S N, Bazykina N A and Samohina K S 2017 Problems of systems dataware using optoelectronic measuring means of linear displacement *IOP Conf. Ser. IPDME* (in Russian – Izvestiya Vysshikh Uchebnykh Zavedeniy. Povolzhskiy Region. Estestvennye Nauki) 2 156-161
[4] Murashkina T I, Badeeva E A, Serebrjakov D I, Istomina T V and Shachneva E A 2016 Fluid flow measurement in astronauts’ life support systems *Biomed. Eng.* 5 295–299
[5] Murashkina T I, Motin A V and Badeeva E A 2017 Manufacturing technology of 2-axial fiber-optic accelerometer *J. Phys.: Conf. Ser.* 10(2) 109–132
[6] Murashkina T I, Badeeva E A and Motin A V 2016 Transformation of signals in the optic systems of differenzialtype fiber-optic transducers *J. Eng. Appl. Sci.* 11(13) 2867–72
[7] Murashkina T I and Badeeva E A 1999 Method for increasing the accuracy of fiber-optic sensors *J. Opt. Technol.+* 66(1) 50–52
[8] Bardin V A, Vasiliev V A and Chernov P S 2017 Piezoactuators and piezomotors with nano- and micro-dimensional resolution for test and control equipment *Meas. Tech.+* 60(2) 166-172
[9] Zastrogin J F 1986 *Precision Measurement of Parameters of Motion with the Use of Laser* (Moscow: Mashinostroenie) p 272