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Principles of Building Information Measuring Systems of Linear Displacement

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***Abstract* — The article dwells on principles of building and conditions of production of information measuring systems of linear displacement. A possible generalized scheme of the optometrist-electronic systems is presented. It is shown that action of optometrist-electronic information measuring systems is based on acceptance and transformation of the electromagnetic radiation in different ranges of the optical area of the spectrum. The modern laser interferometers organically fit in complex technical systems, for instance, in information measuring systems of coordinate tool and measuring machines, and realize not only measuring functions, but also solve the problems of control and checking during processing the product, thus guaranteeing quality to finished products. It is shown that increasing of the accuracy of information measuring systems is aimed at compensations of inaccuracy when processing result measurements, meets the certain difficulties connected with determination of inaccuracy in the worker technical system. Use of modern information measuring systems based on the laser interferometer allows one to define separate forming total inaccuracy in a chosen point worker space of the technical system and solve this problem.**

Keywords* — *information measuring system, laser interferometer, optics.

I. Introduction

Currently, optoelectronic devices are used in solving a wide variety of problems: linear and angular measurements, automatic tracking and control of moving objects, the study of natural resources and the environment, processing of optical images. The complexity of the problems, solved by optoelectronic information-measuring systems, encourages us to consider them as part of the overall information processing system, the latter may consist of a large number of systems, different by the physical principle of element.

The structure of many modern optoelectronic information-measuring systems is quite complex [4,6]. It includes a large number of links-analog and digital converters of electrical signals, microprocessors, mechanical and electronic-mechanical components, etc. different by its physical nature and principle of operation.

One of the possible generalized schemes of optoelectronic information-measuring systems is presented in figure 1.

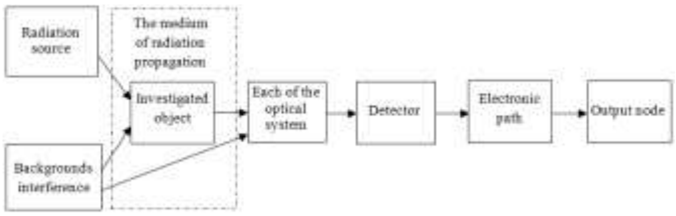

Fig 1. Generalized scheme of optoelectronic information-measuring systems

The action of optoelectronic information-measuring systems is based on the reception and conversion of electromagnetic radiation in different ranges of the optical spectrum: ultraviolet, visible and infrared.

The radiation source creates a material carrier of useful information stream of radiation. Often, the radiation source is supplemented by a transmitting optical system that directs the flow to the object under study or directly to the receiving optical system. The receiving optical system collects the flux emitted by the observed object or reflected from it, forms this flux and directs it to the radiation receiver [5,11]. As a result of moving the object, a low frequency signal is generated. This signal, superimposed on the radiation flux, forms a modulated measurement signal, carrying useful information about the measured physical quantity.

The radiation receiver converts the optical signal into an electrical signal. The output unit generates a signal that meets the requirements of the information recipient.

The first optoelectronic information-measuring systems appeared in connection with the desire to automate optical measurements. Their predecessors are visual optical devices for which the human eye serves as a radiation receiver. Visual optical devices are still widely used in various fields of science and technology. However, the failure of the spectral sensitivity range of the human eye, limited by the speed of the senses and the "executive" organs of the human body, led first to the creation of relatively simple automated optical information-measuring systems, for example, with the photoelectric registration of measurement results, and then completely automated optoelectronic information-measuring systems and complexes.

The development of lasers in front of optoelectronic information and measuring systems has revealed opportunities. The advantage of lasers is that they have high spatial and temporal coherence. The spatial and temporal parameters of laser radiation are determined by the phase state of the active medium (solid, liquid, gaseous), by various resonator designs and by the laser pumping regime [4,10].

Lasers are classified according to the wavelength of radiation: x-ray, ultraviolet, visible range, near and far infrared radiation.

In interferometry, helium-neon lasers stabilized by radiation wavelength are most widely used.

Such information-measuring system with high resolution (0.01 μm) has small periodic and occasional technical mistakes that are typical of conventional measuring means (error type inconsistencies of scale lines, changes of scale due to the heat and dirt, the beating of the measuring screws, etc.).

Modern laser interferometers organically fit into complex technical systems, for example, in information-measuring systems of multi-axis machines and measuring machines. They have a non-contact principle of interference measurements, modularity of design, the ability to build multi-coordinate information and measurement systems, the presence of communication with the computer. Therefore they can carry out not only measurement functions, but also solve the problem of control and monitoring during processing, thereby ensuring the quality of the finished product.

The information-measuring system based on laser interferometers can compete with traditional measuring tools if you measure ranges with an upper limit of measurement up to 1 m [6,11]. If the upper limit of the measurement range exceeds 1 m, the information-measuring system is based on acousto-optic laser interferometers performance, metrological and economic criteria superior to a traditional measuring system. This conclusion is confirmed by the practice of industrial production of metal-cutting machines and measuring machines equipped with information-measuring systems based on laser interferometers. Currently, there are more than a dozen machines of this type, including precision machines for diamond processing, lathes, milling, grinding machines, measuring machines for the control of propellers, bar scales, gears, etc.

Equipping the machines with control computers allows you to record the results of the certification of the machine interferometer and in combination with the correction program, used for operational control of the coordinate of the moved executive body.

Improving the accuracy of information and measurement systems by compensating errors in the processing of measurement results is not new, but its implementation to date has encountered some difficulties associated with the determination of errors in the working volume of the technical system, for example, the machine. Expansion of functionality of modern information-measuring systems based on laser interferometers for measuring straightness of displacements, flatness, parallelism of mating planes and angular displacement of objects allows determining the individual components of the total error in the selected points of the working space of the technical system [2,3]. These errors are then summed to determine the error at a given point. Correction of results in the entire working area is carried out according to the obtained error values.

Thus, the practical use of laser interferometers and laser information-measuring systems by domestic and foreign companies shows that they are superior to traditional optoelectronic information-measuring systems in terms of metrological parameters.

II. Principle of operation of information measuring systems

With the wide development of nanotechnology, especially in the machine tool industry for diamond turning and milling information and measurement systems with a small step of the sample size of the order of 0.01 μm or less should be used as feedback sensors. Therefore, laser interference systems should be further developed.

The use of gas lasers in information-measuring systems of displacements as light sources, which have a large spatial and temporal coherence, allows covering the necessary ranges of measurement for a machine-tool construction.

The most promising one is the phase measurement transformation at the carrier frequency. Information-measuring systems based on laser interference interferometers due to the small value of the measure interval must have a high carrier frequency of the order of units-tens of megahertz [1,9].

Construction of information-measuring systems on the basis of phase interference interferometers of movements with high carrier frequency is possible on the principles of heterodyne laser interferometry.

Heterodyne methods of laser interferometry are based on photoelectric registration of the interference field of two coherent light waves having a certain frequency shift. The measured value (displacement, optical refractive index), which causes a change in the optical path length of one of the light waves - the signal, is converted into a proportional change in the phase value of the electric signal, the carrier frequency of which is equal to the difference in the frequencies of interfering waves. Compared to homodyne methods, heterodyne methods have higher sensitivity and noise immunity, and the high carrier frequency of the signal provides detection of the measured values in a wider range of frequencies and rates of their change in time and space.

The scheme of the information-measuring system on the basis of the heterodyne interferometer is determined by the method of coherent frequency shift of interfering waves. Various methods of frequency conversion of light waves are known: mechanical and optoelectronic. Mechanical methods are based on Doppler frequency shift during reflection or passage through moving optical elements (mirrors, gratings, etc.) and are characterized by low speed (about tens of kilohertz) [1]. Optoelectronic methods using the interaction of optical radiation with fields of different physical nature (electric, magnetic) have high speed (up to hundreds of megahertz), broadband and the ability to control the electrical parameters of radiation.

The functional diagram of the simplest interferometer is shown in figure 2. Laser radiation 1 is split by the beam splitter 2 in the direction of reflectors 3 and 4. The movement of the reflector 4 is measured. When it moves, the path difference of interfering rays is measured, which is recorded by a photo detector 5 with a diaphragm 6 and counted by a counting device 7. The latter includes a frequency meter, operating in pulse counting mode, and an analog device for measuring the fractional part of the interference.

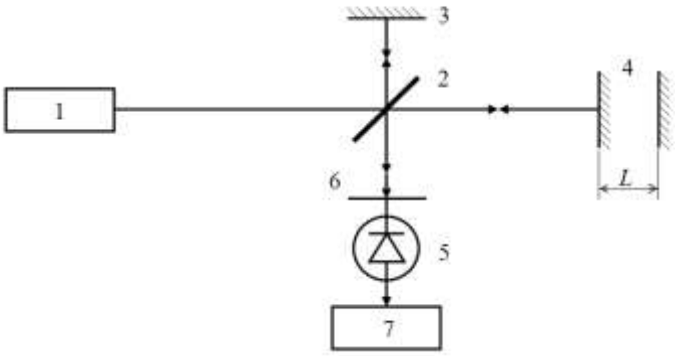

Fig 2. A functional diagram of a simple laser interferometer

Information-measuring systems based on heterodyne laser interferometers are the most widely used in industry. Representatives of this class of information-measuring systems with the highest metrological characteristics are information-measuring systems of the company "Hewlett-Packard", domestic systems IPL-30K, IPL-MP.

Information-measuring systems based on the Michelson interferometer are the most widely used in linear measurements. The measure of the value of the movement is compared with the value of the frequency (wavelength) of the laser. Measurement of linear motion in information-measuring systems based on laser interferometer is carried out by the indirect method. The value of the displacement:

$$L = \Delta\varphi\lambda_a = m_k\lambda_a\int_0^t v(t)dt, \quad (1)$$

where $\Delta\varphi$ – phase difference of the path of interfering optical beams accumulated during measurement (motion); λ_a – the actual wavelength of optical radiation; $v(t)$ – the value of the change in the frequency of the measuring optical wave when the object moves due to the Doppler effect; m_k – coefficient depending on the type of the optical scheme and determined by the number of optical radiation passes along the measurement path.

The actual value of the displacement is represented as the product of the sum of the accumulated electrical pulses by the numerical value of the radiation wavelength λ_a for these measurement conditions. The number of pulses accumulated during the motion is determined by the sensitivity coefficient and depends on the time quantization condition.

Thus, the prospects of information-measuring systems on the basis of 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 on the numerical value of the wavelength of radiation for these conditions of measurement, are determined.

III. Measurement Error Analysis

The accuracy of the measurement of the physical parameter by laser interferometers depends on the determination of the actual wavelength of the laser radiation in the air λ_a. The determination λ_a is made by measuring the refractive index of air n_a and at a known value of the wavelength of laser radiation in vacuum. The calculated value λ_a is determined by the formula:

$$\lambda_a = \frac{\lambda_v}{n_a}, \quad (2)$$

where λ_v – the value of the wavelength of optical radiation in vacuum.

The refractive index of dry air under normal conditions at the wavelength of a helium-neon laser of 0.63299138 μm is $n_н$ = 1.0002765 [2, 10]. Changes in temperature, pressure and humidity are taken into account using the formula:

$$\Delta n = [-93(t-20) + 36(P-760) - 5.6(p-10)]\cdot 10^{-8}, \quad (3)$$

where t – temperature; P – air pressure; p – the partial pressure of water vapor.

P, t, p values are determined by temperature, pressure and humidity sensors with unified output signals. Then the value of Δn is calculated. If the value of the wavelength of optical radiation for normal air conditions λ is recorded as the scale conversion coefficient in the display unit of information-measuring systems, the deviation is promptly introduced as corrections to the measurement result.

The disadvantage of this method of determining the value λ_a is that the refractive index of air n_a is determined at local points of space, often remote from the measurement route [7]. The uncertainty of the distribution law of the refractive index of air along the route along, which the object moves, leads to uncertainty of the average real wavelength of optical radiation in the entire measurement area.

Therefore, it is necessary to develop such method for determining the actual wavelength of optical radiation for interference measurements, which leads to a decrease in the measurement error from the uncertainty of the refractive index of air at various points along the entire route.

IV. Analysis of Immunity of Information Measuring Systems

The problem of noise immunity of information-measuring systems is one of the most important problems of the modern theory of information transmission. This problem arises in the design and operation of information-measuring systems with limited energy potential. This primarily applies to information and measurement technology, which uses optical radiation as a carrier of information. Optoelectronic information-measuring systems of information transmission work effectively provided that the signal-to-noise ratio at the input of the radiation receiver exceeds a certain threshold.

Taking into account the numerical value of the threshold, signal-to-noise ratio is absolutely necessary in the design and operation of optoelectronic information-measuring systems. A decrease in the signal-to-noise ratio at the input of the radiation receiver, when operating in the threshold area, leads to a rapid increase in the measurement error and to a sharp deterioration in the measurement quality.

Operation information-measuring systems occurs while the threshold regimes are poorly understood. Until now, there are no uniform and clear definitions for threshold mode, threshold signal and threshold signal-to-noise ratio. The design of information-measuring systems indicates the total permissible error of the system, which is the sum of the dependent and independent errors.

It is only known that together with the useful signal through the elements of optoelectronic information-measuring system there is almost always noise, which can be generated in the elements of the system. Superimposed on a useful signal, these disturbances distort its parameters, which inevitably leads to measurement errors. In most cases, these disturbances are random, statistical characteristics of which depend on the nature of the problem, the structure and composition of the elements of the optoelectronic information-measuring system. To reduce the inertia of the optoelectronic information-measuring system and reduce the value of its dynamic errors, bandwidth frequency response of the system is expanded, which leads to an increase in the level of noise and distortion of the parameters of the useful signal from them. Thus, the trends in dynamic errors and errors from noise while reducing the inertia of information-measuring systems are opposite, and there are such parameters of the system that determine its frequency transfer function, in which the sum of the dynamic error and error from noise will be minimal for the specified operating conditions.

The intensity of optical radiation for information-measuring systems decreases with the increase of the measured distance. Therefore, to measure long distances, as well as to measure several coordinates using one optical source, the task of increasing the signal-to-noise ratio of the measuring signal is relevant.

Noise immunity of optoelectronic information-measuring systems depends on many reasons: the characteristics of the radiation source, the parameters of the transmitting optical system, the properties of the radiation propagation medium, the parameters of the receiving optical system and the radiation receiver. If the transmitting and receiving optical systems are combined, the noise immunity will be inversely proportional to the power of the glare (optical beams) arising from the reflection of the transmitted radiation from the optical surfaces. The reflection coefficient of optical elements depends on the angle of incidence and the polarization state of the incident radiation.

In interferometers of the type Michelson interferometer with the addition of two interfering beams occur loss of radiation power. In the case of diffraction of light by ultrasound in the acousto-optic modulator the decomposition of the light beam on the diffraction orders that in the future in some optical systems are used inefficiently. Inefficient use of laser power in optical circuits leads to a decrease in the signal-to-noise ratio. With a sufficient degree of accuracy, the signal-to-noise ratio in heterodyne laser information-measuring systems is determined by the formula [6,7]:

$$\frac{P_{\mathrm{m}}}{P_{\mathrm{r}}} = \sqrt{\frac{\eta\lambda}{hc\Delta f}\frac{P_{\mathrm{m}}P_{\mathrm{r}}}{P_{\mathrm{m}}+P_{\mathrm{r}}}}\,, \qquad (4)$$

where c – the speed of light in a vacuum; h – Planck constant; η – the quantum efficiency of the photo detector; Δf – the bandwidth of the selective amplifier; P_{m}, P_{r} – respectively, the power of the measuring and reference light waves.

The formula shows that the signal-to-noise ratio depends on the power ratio P_{m}, P_{r}. The signal-to-noise ratio at the receiver input must be at least the specified threshold. The signal-to-noise ratio below the threshold leads to a disproportionately rapid increase in error and an increase in the probability of anomalous phenomena in the electronic unit.

There are two main schemes of phase interference information-measuring systems of displacements: with acoustic-optical frequency conversion at the input of the interference scheme and with frequency conversion at the output of the interference scheme.

When calculating the ratio of the intensities of interfering light waves in acoustic-optical schemes, it is assumed that the light wave, passing the acoustic-optical modulator, decomposes into diffraction orders without absorbing their intensities in the modulator and the power of the diffraction orders above the "1" - th is negligible.

The comparative analysis of two-coordinate optical schemes of heterodyne laser interferometers with acoustic-optical conversion before and after modulation of measuring signals by a moving controlled object shows that the relative signal-to-noise ratio at the output of the schemes will be greater in the optical scheme with acoustic-optical conversion of measuring signals before modulation by their moving controlled object [6,8]. This is because the losses of light energy in the node for separation and displacement of the reference and measuring light beams in the acousto-optic modulator are reduced. At the same time, the new mutual arrangement of the elements made it possible to more fully use the properties of light diffraction on ultrasound in the acousto-optic modulator, namely:

- combining the formation of coherent frequency-shifted optical beams with their simultaneous spatial separation (i.e., combining the functions of the frequency conversion of light with their division in space);
- more rational use of the diffraction spectrum at the output of the acousto-optic modulator in the interference scheme: all orders of diffraction are involved in the measurement transformation ("0", "+1", "-1"), moreover, "0" and "+1" propagate in the first interference channel, "0" and "-1" – in the second interference channel, and a more energetically powerful "0" order is involved in the formation of the measuring signal;
- interference beams in each channel are formed at one point of acousto-optic interaction, which allows one to increase the stability of the information-measuring system.

Increasing the signal-to-noise ratio of the measuring signal makes it possible to change some parameters of information-measuring systems based on acousto-optic laser interferometers. Most laser interferometers have a measuring range of up to 30 m. Although the coherence length of stabilized lasers can be more than 1 km, Photo detectors detect a signal reflected at this distance at a power of 4 mw optical source, which is achieved by modern stabilized helium-neon lasers [10]. However, due to the radiation divergence, the contrast of interference fringes m generally differs from one. This is due to the fact that the length of the measuring arm is greater than the reference. Therefore, the intensity of the measuring beam reaching the photo detector decreases with the growth of the measuring arm.

The optical scheme with acoustic-optical conversion before signal modulation makes it possible to obtain different-frequency optical beams of different intensity.

Photo detectors capable of taking the optical measuring signal at $m > 0.05$. When using a single-coordinate scheme with acousto-optic transformation at the input, the maximum allowable range of measured displacements, at which $m > 0.05$ will be equal to $L = 50$ m.

V. Conclusion

Comparative analysis of optoelectronic information-measuring systems for noise immunity showed that the most promising is the optical scheme of information-measuring system based on interferometers with acoustic-optical conversion of the optical signal to modulation of its measuring movement.

The practical use of domestic and foreign firms' optoelectronic shows that according to the metrological parameters they are superior to the traditional information-measuring system.

It is determined that the actual value of the displacement is represented as the product of the sum of the accumulated electrical pulses by the numerical value of the radiation wavelength λ_a for these measurement conditions. The number of pulses accumulated during the motion is determined by the sensitivity coefficient and depends on the time quantization condition. It is shown that the accuracy of the physical parameter measurement using optoelectronic information-measuring systems depends on the determination of the actual wavelength of laser radiation in the air.

The choice of the most optimal structure of information-measuring systems based on interferometers by determining the layout of optical elements in order to reduce the loss of intensity of optical signals is justified.

The proposed theoretical development allowed the design stage to determine the design parameters of information-measuring systems based on interferometers with improved performance.

The ways of increasing the signal-to-noise ratio in separate units of the measuring device are realized. They allow one to increase the noise immunity of optical-electronic information-measuring and control systems on the basis of the analysis of mathematical models of information-measuring and control systems in general and its individual units.

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