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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DYNAMİC PARAMETERS OF MOVİNG OBJECTS MEASUREMENT METHOD AND TOOLS

Speciality: 3337.01 – Information-measurement and managment systems (measurement technology)

Field of science: Technical sciences

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INTRODUCTION

Relevance of the topic and degree of development. The constant increase in the variety and number of objects in motion highlights the need to develop information-measuring systems (IMS) used to measure the dynamic parameters of these objects. IMSs consist of main and auxiliary nodes interconnected by digital or optical communication channels that provide reception, conversion, processing, storage, transmission, acceptance by the operator and (or) input into the control system of information about the measurement results of the dynamic parameters of various types of objects in motion, that is, linear acceleration and velocity in the considered case. Therefore, IMS is a complex measuring complex, and modern computer technologies are widely used to control the nodes included in it.

The relevance of studying vibration processes in moving objects is mainly associated with the development, testing and operation of technical and technological measuring devices with the widespread use of vibrometry. Along with this, IMS is also widely used, which allows achieving high technical and economic efficiency, automatically controlling complex technical systems and technological processes, performing vibration control, monitoring and diagnostic processes. The main node of these systems are dynamic parameter transmitters of vibrations and shocks, which, when placed directly on the measuring object, convert the resulting mechanical vibrations into electrical signals and transmit them to the recording device. Among all types of transmitters, the most widely used are accelerometers measuring piezoelectric vibrations, which, being generator-type transmitters, directly convert the speeds of vibration or shocks into electrical signals proportional to them. Therefore, another component of accelerometers is a displacement detector, which allows them to measure very small amplitudes of oscillatory processes caused by vibration.

In this regard, the development of a dynamic motion sensor that allows receiving information about the measurement results of dynamic parameters of moving objects, accelerometers that measure linear acceleration and velocities of moving objects, a mathematical model of the working body, and a method for analytical reporting of their parameters are of theoretical and practical relevance.

The degree of development of the topic. Currently, the scientific works of domestic and foreign scientists, such as G. Chilikin, B. Ibobotenko, Y. Gadimov, A. Panich, G. Rannev, N. Rubichev, Y. Iorish, A. Dmitriev, A. Yurin, G. Zlodeev, Y. Koptev, V. Klyuyev, Y. Iorish, S. Bazikin, V. Klyuyev, N. Novukov, V. Yanchich, M. Narayana, U. Lindemann, A. Hockin, M Stuber, W. Keck, C. Becker, S. Lakshminaryan, V. Sharapov, T. Gurbanov, T. Mansurov and others, are devoted to solving issues related to the development and study of accelerometers used in measuring dynamic parameters of moving objects.

In most of these works, only the momentum and only the inertia, which vary within a small range, are measured, since the direction of the sensitivity vector is opposite to the direction of the measured inertial forces.

Object and subject of research. The object of research of the dissertation work is accelerometers that measure the dynamic parameters of objects in motion in real time, and the subject of research is mathematical models of the methods and devices for measuring the dynamic parameters of these objects.

Goals and objectives of the research. The goal of the work is to develop a method and means for measuring linear accelerations and velocities, that is, a method for reporting the parameters of accelerometers, their working bodies, and a mathematical model.

In order to achieve the goal set in the dissertation work, the following issues were formulated and solved:

1. Justification of the relevance of the topic based on the analysis of the current state of the problem, analysis of the degree of development;

2. Development of a mathematical model of piezoelectric vibration and three-coordinate accelerometers measuring dynamic parameters;

3. Development of a precision positioning device that provides increased energy efficiency and reduced loss of piezoelectric vibration and three-coordinate accelerometers measuring dynamic parameters, optical beam;

4. Development of a method for reporting the parameters of the working body of accelerometers measuring the dynamic parameters of moving objects;

5. Experimental study of the working body of the accelerometer and precision positioning device.

Research methods. Measurement theory, mathematical modeling, error theory and experimental research methods were used as research methods when solving the problems posed in the dissertation.

The main provisions put forward for defense:

- mathematical model of piezoelectric vibration and three-coordinate accelerometers measuring dynamic parameters of moving objects;
- piezoelectric vibration and three-coordinate accelerometers measuring linear acceleration and velocity in automatic mode, developed on the basis of a mathematical model;
- precision positioning device ensuring increased energy efficiency and reduced loss of optical beam;
- analytical method of reporting parameters of piezoelectric vibration and three-coordinate accelerometers;
- results of experimental research of the working body of piezoelectric vibration and three-coordinate accelerometers.

The scientific novelty of the research consists of the following:

- a mathematical model of a piezoelectric vibration and three-coordinate accelerometer measuring dynamic parameters of moving objects has been developed;
- based on the formulated mathematical model, piezoelectric vibration and three-coordinate accelerometers measuring dynamic parameters in automatic mode have been developed;
- a method for reporting the parameters of the proposed accelerometers and their working body has been developed;
- a precision positioning device has been developed that allows increasing the energy efficiency of the optical beam and reducing losses;
- an experimental study of the working body of accelerometers

measuring dynamic parameters has been conducted and an analysis of the results obtained has been provided.

Theoretical and practical significance of the research.

The theoretical dependencies, mathematical model and reporting method obtained in the dissertation work allow to increase the measurement accuracy and functional capabilities of IOS when measuring the dynamic parameters of moving objects, which determines the theoretical significance of the research.

As a practical significance of the research, the results of the experimental research conducted in the dissertation work can be used in the development of new accelerometers and IMS when measuring the dynamic parameters of objects.

The theoretical and practical results of the dissertation work can be used by scientific research, production and operation enterprises in the improvement of existing IMS, the development and application of new IMS.

Approval and application.

The main provisions and results of the dissertation work were reported and discussed:

- at the 10th International Field ETC on the topic "Technologies of Modern Society" dedicated to the 95th anniversary of the Moscow Technical University of Communications and Informatics (Moscow, 2016) - 1 item;
- at the International ETC on the topic "Modern State and Development Prospects of Information and Communication Technologies" (Baku, 2016) - 1 item;
- at the XX, XXI and XXII International ETC on the topic "Modern Communication Systems" (Minsk, 2015, 2016 -2 items, 2017) - 4 items;
- at the IEEE EPK "Problems of Infocommunications. Science and Technology" (PIC S&T) (Kharkov, 2018, 2021, 2022) - 3 pieces;
- At the International ETC on the topic "Innovative Technologies in Telecommunications" (Baku, 2019) - 1 items;
- At the II International ETC on the topic "Modern Information, Measurement and Control Systems: Problems and Prospects (MIMS'2019)" (Baku, 2020) - 1 items.

The name of the organization where the dissertation work was performed.

The dissertation work was performed at the Institute of Space Research of Natural Resources of the Azerbaijan National Aerospace Agency.

The total volume of the dissertation in characters, indicating the separate volumes of the structural sections of the dissertation.

The dissertation work consists of an introduction, four sections, a conclusion, a list of used literature, a list of abbreviations and conventional symbols.

The separate volumes of the structural sections of the dissertation in characters are as follows:

The introduction of the dissertation consists of 14887 characters, Chapter I consists of 31148 characters, Chapter II consists of 60435 characters, Chapter III consists of 52396 characters, Chapter IV consists of 20837 characters, the conclusion consists of 1057 characters, and the total volume of the dissertation is 201830 characters.

The justification of **the results of the dissertation** work is confirmed by the correct formulation of the mathematical apparatus of the results obtained in the dissertation work using accepted scientific provisions and approved research methods, their application, and the correspondence of the results with known theoretical results.

The correctness of the results is confirmed by the complete correspondence between the theoretical results obtained with the help of mathematical modeling and conducted experimental studies and the scientific and practical results.

Personal contribution. The theoretical and practical results in the dissertation work and published materials were obtained by the author independently and under the guidance of a scientific supervisor.

Publications. 30 scientific and educational-methodological works have been published based on the results obtained in the dissertation work, of which 11 are articles, 2 are in Thomson Reuters and 3 are in periodical scientific publications included in the international summarization and indexing databases Scopus, 11 are International and 1 are Republican ETC materials, 1 is Eurasian, 2 are patents of the Republic of Azerbaijan, and 1 is a textbook entitled "Electrical

Measurements and Instruments" published under the seal of the Ministry of Education, which is taught at the bachelor's level of higher education institutions and is included in the main subject block.

Brief summary of the work

In the introduction, the relevance of the topic of the dissertation is justified, the degree of development is analyzed, the object and subject of the research are determined, the goals and objectives of the research are formulated, research methods, the main provisions put forward for defense, the scientific novelty of the research, the theoretical and practical significance of the research, the approval of the results of the work, the name of the organization where the dissertation work was performed, and brief characteristics of the structural units of the dissertation are given.

In the first chapter, an analysis of the characteristics and development stages of IMSs, a classification of accelerometers and measurement and operating characteristics of dynamic parameters of moving objects are given, the objective function of the research and the statement of the problem are formulated.

It should be noted that the analysis of the stages of development of IOS shows that the use of multi-channel and multiprocessor systems in IOS allows, on the one hand, to separate the processing and control functions from each other, to significantly increase its speed due to the parallelization of these processes, and on the other hand, to conduct large-scale and highly reliable measurements in real time, to reduce the influence of subjective factors in the measurement process, to take into account the characteristics of the technical measuring instruments used, and to meet the requirements for the development and design of systems. When measuring the dynamic parameters of moving objects, piezoelectric, piezoresistive, capacitive, Hall effect, magnetoresistive, heat transfer and MEMS (Micro Electromechanical Systems) technologies of accelerometers are used. Among the analyzed technologies of accelerometers, piezoelectric accelerometers have high accuracy, so these types of accelerometers are widely used when measuring the dynamic parameters of moving objects. Based on the above principles, the following objective function of the study was formulated to evaluate the operating mode of accelerometers:

$$f(x)=\{\min[\delta_{mp},P_m],\max[\tau_{aa},A_{as},D_{dr}]\}, \tag{1}$$

where δ_{mp} – relative errors arising in the measurement process; P_m – the obstacle level created on the coordinate axis of the coordinate system, which is not measured; τ_{aa} – accelerometer acceleration; A_{as} – accelerometer sensitivity; D_{dr} – is the dynamic range that can be recorded by the accelerometer and is determined by the upper and lower levels of oscillations located in a narrow frequency band.

Thus, the objective function formed on the basis of the selected criteria allows us to assess the optimal operating mode of accelerometers used to automatically measure the dynamic parameters of moving objects. In this regard, the development of piezoelectric accelerometers, their mathematical model and a method for reporting parameters, which allow measuring the dynamic parameters of objects and directing the linear acceleration vector of the piezoelectric element in the direction of the accelerometer's sensitivity axis, is an urgent issue.

The second chapter deals with the development of the IOS, piezoelectric vibration and three-coordinate accelerometers and optical beam precision positioning devices used to measure the dynamic parameters of moving objects.

The complex structure of moving objects (aviation and space technology) makes it necessary to measure a large number of physical quantities during their testing. These quantities can be either homogeneous (for example, temperature fields or stress-strain states of the structural elements of the object) or heterogeneous (a set of the above-mentioned physical quantities, deviation of moving objects from a certain course, pressure in fuel tanks, etc.).

The use of individual measuring instruments when measuring physical quantities is limited for the following reasons:

- since there are serious restrictions on the dimensions and weight of measuring instruments, it is not always possible to place measuring instruments on controlled and moving objects (for example, on an airplane);

- to use the indications of measuring instruments, obtaining the full range of measurement results must be accomplished within a limited time, and this process creates difficulties due to the limited physiological capabilities of the operator.

Modern measuring instruments intended for use in the above cases, in addition to measurements, must also provide a certain information service for the object under study. Information services include automatic collection, presentation, delivery, storage, registration, reflection, processing and analysis of measurement results obtained as a result of individual measurements.

The need to solve these problems requires the development of a new class of measuring instruments intended for automatic collection and processing of measurement data - multichannel information-measuring systems (MIMS) [1].

In a number of cases, for example, during aircraft flight tests or space exploration, the distance between the object under study and the equipment processing the measurement results is large.

A multichannel IMS has been developed, which differs from the existing IMS by the inclusion of a multichannel interface, a multichannel optical switch and a precision positioning device that allows increasing energy efficiency and reducing losses by increasing positioning accuracy, the structural scheme of which is given in Figure 1 [72, p. 23-27].

Information about the measurement result can be transmitted from the multichannel IMS to the operator and / or to the computer. The operator and the computer system can influence the control device by changing the operating program. When a computer is included in the multichannel IMS, information can enter this computer directly from the processing or memory device.

Thus, the proposed multi-channel IMS performs the processes of receiving, processing, storing, transmitting to the operator or computer, and forming control effects on the objects being measured, through a multi-channel interface, information about the dynamic parameters measured from moving objects.

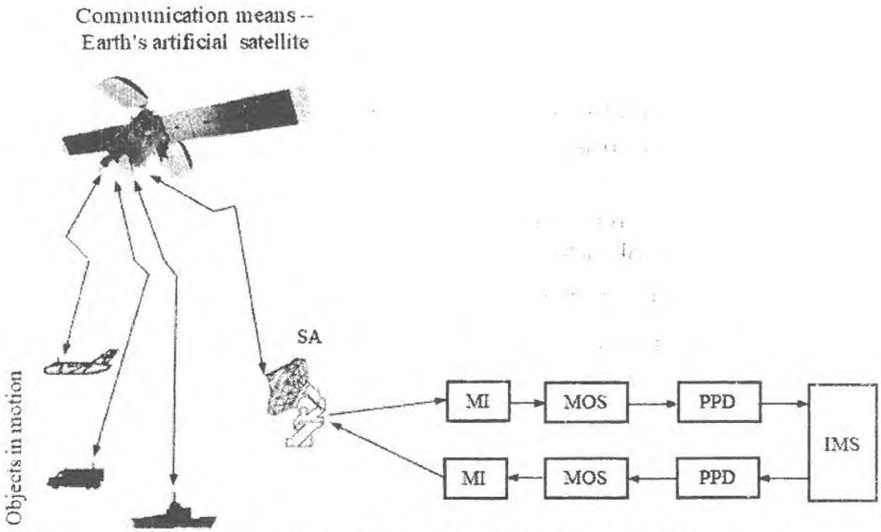

Figure 1. Structural diagram of a multichannel information-measuring system

SA-satellite antenna; MI-multichannel interface; MOS-multichannel optical switch; PPD-precision positioning device

The conducted analyses show that the existing accelerometers do not allow measuring the movement speeds of moving objects, mainly by measuring the accelerations resulting from vibration and impact. On the other hand, since the direction of the accelerometer sensitivity vector is directed in the opposite direction to the measured inertial force, the measurement of speed is not provided by measuring linear inertias that vary within a small range and only the acceleration.

A mathematical model of piezoelectric vibration and three-coordinate accelerometers measuring the dynamic parameters of moving objects and a piezoelectric vibration and three-coordinate accelerometer based on this model were developed.

At any instant of time, the acceleration vector can be determined by differentiating the velocity vector of the free end of the piezoelectric element as a working body with respect to the time vector as follows:

$$\vec{i} = \frac{d\vec{v}}{dt} = \frac{d^2 r}{dt}, \tag{2}$$

where $\vec{i}$ – is the acceleration (m/s^2), $\vec{v}$ – is speed (m/s), t – is time (s), r – is the movement trajectory of the free end of the piezoelectric bimorph element.

If we consider the movement trajectory of the free end of the piezoelectric bimorph element and the time dependence of the momentum $\vec{i} = (t)$ – at time instants $\vec{r}(t) = \vec{r}_0$ and i_0 – then by integrating equation (4), each t – time coordinate and $\vec{v}$ – velocity of the free end can be determined as follows:

$$\vec{v}(t) = \vec{v}_0 + \int_{t_0}^{t} (t)dt, \tag{3}$$

$$\vec{r}(t) = \vec{r}_0 + (t - t_0)\vec{v}_0 + \int_{t_0}^{t}\int_{t_0}^{t} \vec{i}\,dt^2. \tag{4}$$

In the general case, if the vector $\vec{i}$ is constant with respect to time, then this motion is considered uniform motion, and taking this into account, simplifying expressions (3) and (4), we obtain the following mathematical dependences:

$$\vec{v}(t) = \vec{v}_0 + (t - t_0) \cdot \vec{i}, \tag{5}$$

$$\vec{r}(t) = \vec{r} + (t - t_0) \cdot \vec{v}_0 + \frac{(t - t_0)^2}{2} \cdot \vec{i}. \tag{6}$$

The proposed mathematical model forms the basis for the development of a piezoelectric vibrating and three-coordinate accelerometer. The increase in the effect of inertia during movement and the fact that the piezoelectric vibrating accelerometer provides measurement of both the momentum during movement and the velocity by integrating the signal through an integrator expand its functional capabilities.

The structural diagram of the proposed piezoelectric vibration accelerometer is given in Figure 2.

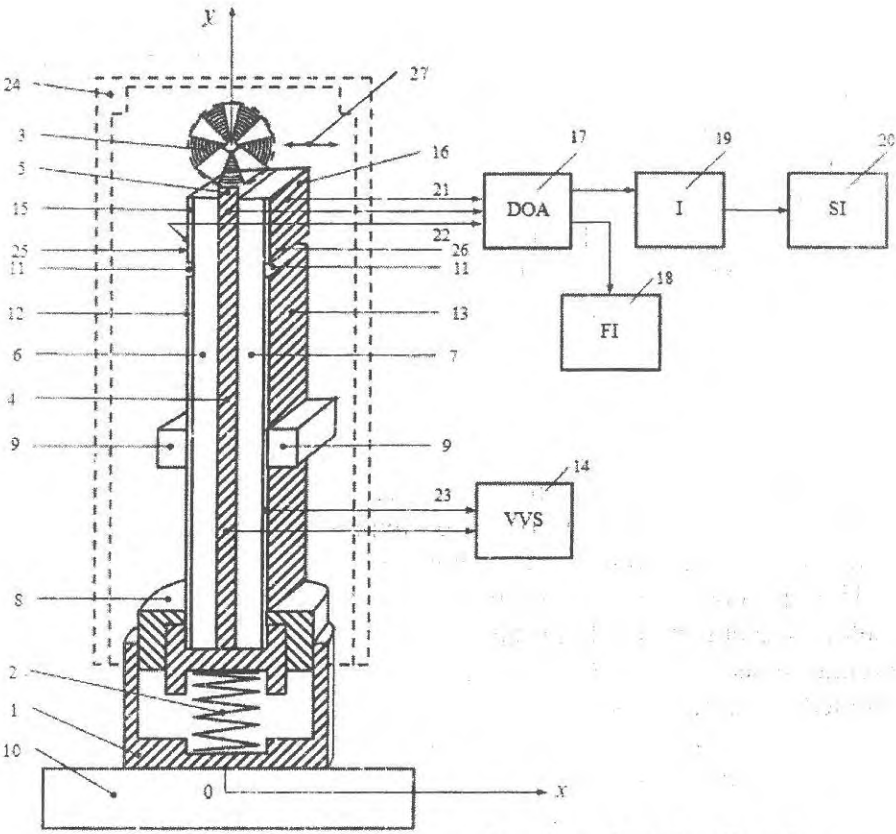

Figure 2. Structural diagram of a piezoelectric vibration accelerometer

DOA-differential operational amplifier; FI-first indicator, I-integrator, SI- second indicator; VVS-variable voltage source

The proposed piezoelectric vibration accelerometer consists of a body -1, a piezoelectric element with tensile-compression mechanical deformation compressed by a screw spring -2, an inertial mass fixed on it -3, a flat metal plate -4, a protrusion -5, piezoelectric plates forming a multilayer piezoelectric bimorph vibrator fixed by welding -6,7, a fastening mold -8, a metal cube firmly fixed on both sides of the wide surfaces of the piezoelectric bimorph vibrator -9, a measuring object -10, an excitation section separated by insulating strips -11 -12,13, from a variable voltage source -14, sections of the piezoelectric element -15,16, a differential operational amplifier -17, a first indicator -18, an integrator -19, a second indicator -20, electrical connection clamps of the piezoelectric element -21,22, electrical connection clamps of the excitation section -23, the accelerometer consists of a fixed cover -24 to protect it from external mechanical influences, and a truncated spherical cavity -25 in the middle of the upper part of the fixed cover to ensure free movement of the inertial mass.Figure 3 shows the structural diagram of the three-coordinate accelerometer that measures the linear acceleration and speed of the measurement object in automatic mode alongside the piezoelectric vibration accelerometer.

The structural diagram of a three-coordinate accelerometer that automatically measures the linear acceleration and velocity of a measurement object based on the expressions (2-6) of the mathematical model given above is shown in Figure 3.

The proposed three-coordinate accelerometer consists of piezoelectric elements made in the form of two-layer flat plates with an excitation section -1,2,3, a sensitive element section -4,5,6, glued or welded together, insulated from each other channels -7,8,9, damped "P"-shaped flat springs -10,11,12, a measuring object -13, from three-coordinate position transmitters -14, electrodes of three-coordinate position transmitters -15, a first differential operational amplifier -16, a block for selecting the axes of the "XYZ" rectangular coordinate system -17, outputs of the differential operational amplifier on the three coordinate axes -18,19,20, a channel detection block -21, a detection block -22, a barrier device -23, a control code transmitter -24, a control block -25, triggers -26,27,28, electronic switches -29,30,31, variable voltage sources -32,33,34, differential operational amplifiers of the “XYZ” coordinate axes -35,36,37, pulse shapers -38,39,40, first-digit indicators -41,42,43, pulse shapers -44,45,46, integrators connected to the “XYZ” coordinate axes -47,48,49, second-digit indicators 50,51,52, a protective cover in which all elements of the accelerometer are placed -56,57,58.

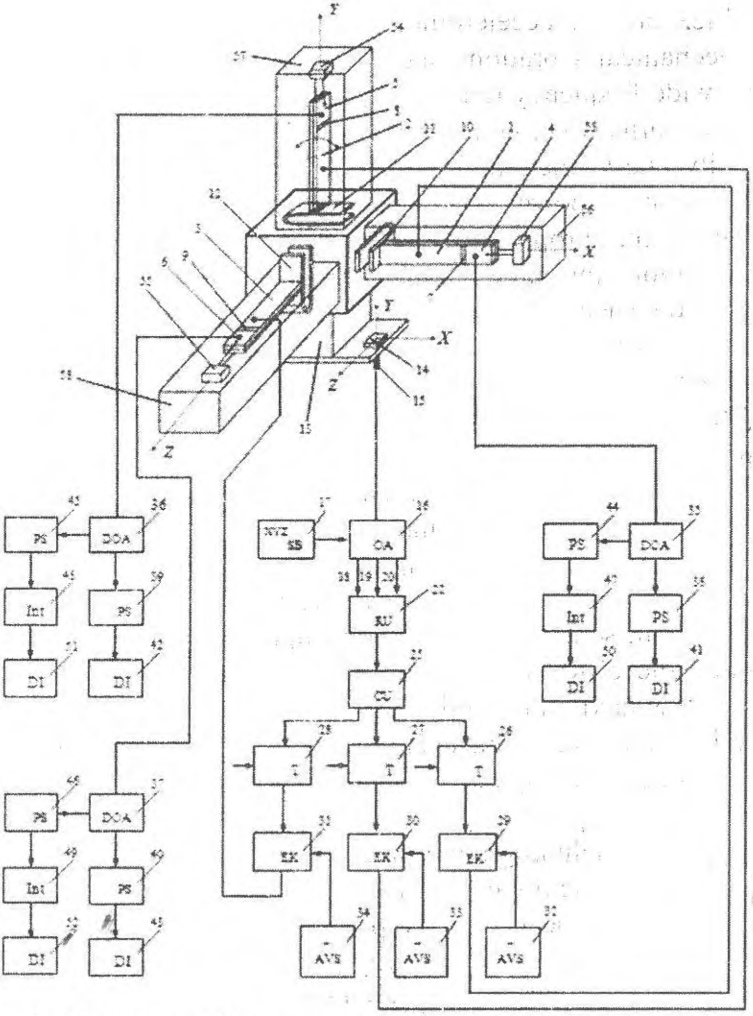

Figure 3. Structural diagram of a three-coordinate accelerometer

At this time, the use of a piezoelectric element as a working body in the proposed piezoelectric vibration and three-coordinate accelerometers is due to high temperature stability, high quality of the signal on thermal gradients, high durability and reliability, internal insulation of the body and its design for long-term use in harsh conditions.

Piezoelectric accelerometers provide high accuracy in measuring mechanical vibrations and, from a metrological point of view, have a wide frequency range, high resistance to environmental influences, linearity of characteristics in a wide dynamic range, high durability due to the small number of moving parts, no need for an active converter power source, and the ability to convert the output electrical signal proportional to the acceleration caused by mechanical oscillations into a signal proportional to the vibration velocity or vibration displacement.

The proposed piezoelectric vibration and three-coordinate accelerometer can be used to measure linear accelerations and velocities of moving objects, to measure the movement of objects along the three-coordinate axis in a rectangular coordinate system in automatic mode, and to measure the angle of inclination and displacement during the drilling of oil wells.

The accuracy of the input of measurement results into the optical fiber by means of an optical beam is the main indicator of the "optical beam source - optical fiber - optical beam receiver" system, in which the efficiency of the positioning process depends on the value of the maximum possible energy of the optical beam input into the optical fiber, that is, its energy efficiency.

Among the components of the optical beam positioning system, the optical beam precision positioning device (PPD) is determined by many criteria, including increasing the energy potential of the optical beam input into the optical fiber, studying the basic regularities of the use of the optical beam and the positioning process of optical fibers, and inputting the maximum energy potential of the optical beam into the optical fiber. Taking into account the above, the efficiency of the precision positioning device proposed as the objective function of the study can be expressed by the following dependence:

$$E_p = \left\{ \min[t_{tp}, a_{oi}, A_0, A_{ri}, \Delta_{ep}], \max[\nu_{ps}, \eta = P_{po} / P_{out}] \right\}, \quad (7)$$

where t_{tp} – is the time spent on the positioning process; a_{oi} – offset introduced by the optical beam precision positioner (PPD) during the positioning process; A_0 – optical signal reflection loss; A_{rl} – radiation losses; Δ_{ep} – errors in the positioning process; v_{ps} – positioning speeds; $\eta = P_{po} / P_{out}$ – coefficient of insertion of the power of the optical beam into the optical fiber; P_{po} – the power of the optical beam inserted into the optical fiber; P_{oup} – is the output power of the optical beam source.

Based on the objective function, the PPD of the optical beam is developed, which provides an increase in the positioning accuracy of the optical beam, which leads to a reduction in the energy loss of the transmitted optical beam, and the resulting losses in this case are 0.8...3.0 dB.

A precision positioning device for the optical beam with a control unit is proposed, and its structural diagram is given in Figure 4.

The PPD consists of a stepper motor -1, an operational amplifier -2, a calculating device -3, a comparison circuit -4, a selection block -5, a logic switch -6, an alternating current generator -7, a first electronic switch -8, a first trigger -9, a photodiode -10, a cylindrical shaft fixed on a rotating axis with a piezoelectric element of the stepper motor clamped at an angle of 45° -11, an optical beam reflector -12, a focusing lens -13, electrical clamps of the photodiode -14, electrodes of the piezoelectric element of the stepper motor -15, a piezoelectric brake element -16, a first phase shift circuit -17, a second trigger -18, a second electronic switch -19, a constant current generator -20, electrodes of the piezoelectric brake element -21, optical fibers of the optical beam transmission cables -22, sections in the device body -24 -25, a cylindrical shaft of the piezoelectric brake element the mechanical effect consists of a tip made of friction-resistant material -26 and an optical fiber cable for transmitting the optical beam -27 and an optical beam source -28, a second phase shift circuit -29, a pulse shaper -30, a comparison block -31, a reference voltage block -32, a third trigger -33, a control input, a feedback automatic regulator block -34, a constant current generator -35, a third electronic switch -36, a signal input, and a signal output -37 electrodes of a piezoelectric element additionally included in the device -38, a mechanical contact tip of the piezoelectric element with a cylindrical shaft of a stepper motor -39. New elements included in the proposed device are shown by dashed lines, conditionally marked with the position -40. The device is started by means of a start switch -41.

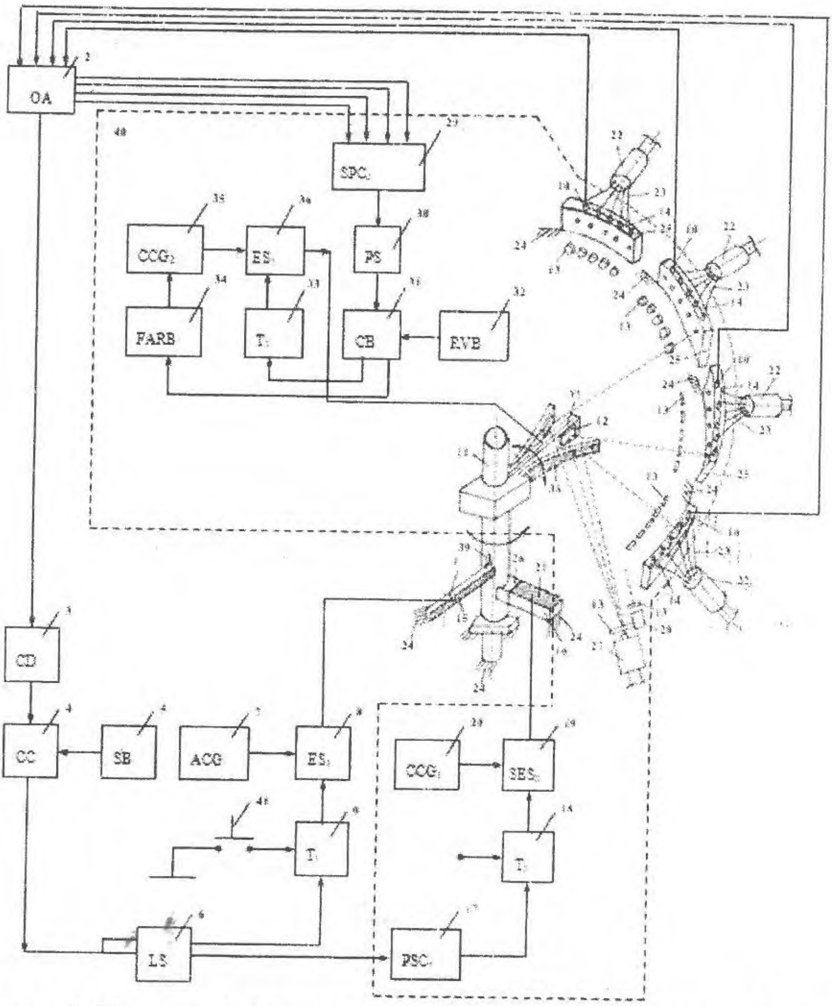

Figure 4. Structural diagram of the precision positioning device

Thus, the proposed optical beam precision positioning device provides an increase in the positioning accuracy of the optical beam, which leads to a reduction in the energy loss of the transmitted optical beam. The losses during the positioned insertion of the optical beam -1 into the optical fiber -2 of the fiber-optic communication line are 0.8...3.0 dB, which is 40...55% less than the values of the losses in existing devices, and in this case the positioning error is 0.17...0.65%.

The third chapter discusses the multichannel optical switch (MOS), optical beam source (OBS), optical beam receiver (OBR), analytical method of reporting the parameters of the working body of the MOK, the mathematical model of the PMD and the analytical method of reporting the amplitudes of mechanical oscillations of the piezoelement of the three-coordinate accelerometer used in the transmission of measurement results of dynamic parameters of moving objects.

The optical system (OS) should ensure the transmission of the maximum possible energy potential of the optical beam at the output of the MOC to the optical fiber and from the output of the optical fiber to the OS. The complexity of the design of the MOC during the transmission of information about the measurement results is determined by the characteristics of the OS. The switching process requires automatic control of the propagation direction of the optical beam in horizontal and vertical directions relative to the cross-sectional area of the optical fiber in case of an accident or other necessary circumstances.

To achieve this goal, a piezoelectric element and its control scheme were developed, which ensures the high-precision matching of the output of the optical fiber with the input of the optical fiber and the output of the optical fiber with the input of the optical beam receiver.

In order to more accurately assess the technological, mechanical and operational characteristics of the optical fiber in connection with the requirements for ensuring high accuracy of the optical switching process and automatic control of the direction of the optical signal by means of the optical fiber, an analytical method of calculating the parameters of the optical fiber was developed.

When voltage is applied from the power source, bending oscillations of the core of the piezoelectric element (PE), which is used as the working body of the optical fiber, occur, which is expressed by the differential equation given below:

$$E \cdot I \frac{d^4\eta}{dx^4} - \rho \cdot S \frac{d^2\eta}{dt^2} = 0.$$

The amplitude of the deformation of the free (unfixed) end of the PE is determined as follows:

$$\Delta_{ey.PE} = \frac{F_{\mathrm{PE}}\, l_1^3}{3E_y J} = \frac{F_{\mathrm{PE}}}{\mathrm{K}_{\mathrm{m}\Sigma}},$$

where F_{PE} – is the force acting on the PE (plane spring) of the OKD (N); l_1 – is the length of the PE; E_y – is the Young's modulus (modulus of rigidity) of the piezoceramic; J – is the moment of inertia (m4); $K_{m\Sigma}$ – is the total stiffness of the plates forming the rectangular cross-section core of the PE.

The total strength of the plates forming the rectangular cross-sectional core of the PE of the OKD is determined as follows:

$$K_{m\Sigma} = \frac{E_y \cdot l_2 \cdot l_3^3}{4 \cdot l_1^3},\ N/m.$$

where l_2, l_3 – is the length, width and thickness of the hollow piezoelectric cylinder.

Thus, the values of the errors in the results obtained using the above theoretical analytical dependencies for calculating the main parameters of the OKG, as well as the results obtained as a result of experimental measurements, are satisfactory, and the difference between them is 1-3%.

If we do not take into account the constructive losses, we obtain the following expression to calculate the maximum permissible linear displacement velocity of the free end of the piezoelectric element:

$$V_{mr} = \frac{4F_{sr} \cdot V_{lw}}{\pi \cdot l_1 \cdot l_2 \cos\alpha \cdot E_y} = \frac{4F_{sr}}{\pi \cos\alpha \cdot Z_0} = \frac{4F_{sr} V_{lw}}{\pi \cos\alpha \cdot E_y},\ m/s \quad (9)$$

where $Z_0 = l_1 l_2 \sqrt{\rho E_y}$ – is the wave resistance; ρ – is the density of the ZTBL-3 (zirconate-titanate barium lead compound piezoceramic) type piezoelectric element.

The resonant frequency of a piezoelectric element is determined as follows:

$$f_r = V_{lw} / 2l,\ \mathrm{kHs} \quad (10)$$

where $V_{lw} = 3{,}5 \cdot 10^3$ m/s is the propagation speed of the longitudinal wave.

The speed of the working end of a loaded piezoelectric element is determined as follows:

$$V_{lp} = \frac{U_h \cdot l_2 \cdot d_{31} \cdot E_y}{R_{ml} \cdot \cos\alpha}, m/\text{s}, \tag{11}$$

where $\alpha = 45^0 \ (\approx 0,73 rad)$ – is the inclination angle of the piezo element with respect to the working body; R_{ml} – is the mechanical loss resistance.

Experiments were conducted to determine the accuracy of the optical switching process of the working body. During the experimental experiments, the control-measuring head is attached to the free end of the working body and when the supply voltage is applied to the piezoelectric element, the working body performs a linear displacement movement. When the perforation holes of the light-emitting diode and the photoreceptor coincide, the movement of the working body is stopped by cutting off the supply voltage to the piezoelectric element, and in this case the accuracy of the optical switching process is recorded by the control-measuring head. The results of the experiments are given in Tables 1 and 2.

Table 1. Numerical values of errors arising in the process of optical switching depending on the compression force of the piezo element to the working body

№	The experiment was carried out in a field 100 mm long					
1	The piezo element is compressed into the working body, F_c (N)	4,1	3,6	3,3	2,9	1,2
2	An error in the optical switching process, δ,%	0,0013	0,0031	0,0054	0,0067	0,0071

Table 2. Numerical values of the linear displacement speed of the working body depending on the compression force of the piezo element to the working body

№	The experiment was carried out in a field 100 mm long					
1	The piezo element is compressed into the working body, F_c (N)	2,0	2,5	3,0	3,5	4,0
2	The speed of linear displacement of the working body, $V_{wb} \cdot 10^{-3}$, m/s	10	15	18,5	20,7	20,7

Based on the experimental results obtained, in order to determine the accuracy of the optical switching process of the working body, the dependence of the relative error of the optical switching process on the compression force of the piezoelectric element on the working body (Figure 5), as well as the dependence of the linear displacement speed of the working body along its axes on the compression force of the piezoelectric element on the working body (Figure 6) were derived.

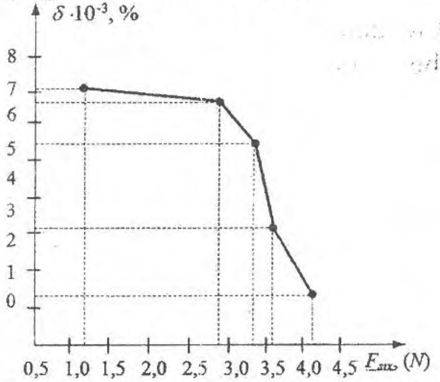

Figure 5. Dependence of the error in the optical switching process on the compression force of the piezoelectric element on the working body

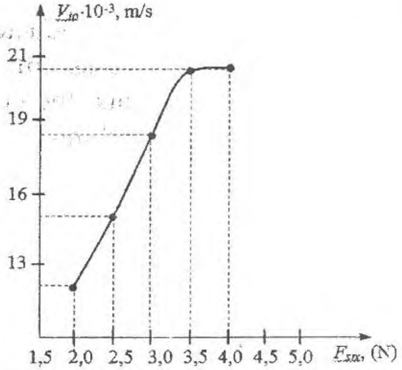

Figure 6. Dependence of the linear displacement velocity of the working body on the compression force of the piezoelectric element on the working body

The amplitude of the bending deformation of the working body in the form of a hollow piezoelectric cylinder of a precision positioning device is determined as follows:

$$\Delta = \frac{F_{sf}}{E_y \cdot J}\left(\frac{R^3 a}{2} - \frac{R^3}{4}\sin 2\alpha\right), \ (m) \tag{12}$$

where F_{sf} – is the statistical force of bending of a hollow piezoelectric cylinder (N); moment of inertia of J – hollow piezoelectric cylinders (m^4); R – is the radius of the hollow piezoelectric cylinder.

In this case, the statistical power generated during the bending of the hollow piezoelectric cylinder is determined as follows:

$$F_{sf} = K_{\Sigma s} \cdot \Delta, \quad (N) \tag{13}$$

where, $K_{\Sigma ts}$ – is the total strength of the hollow piezoelectric cylinder (N/m).

The total stiffness of a hollow piezoelectric cylinder is related to the stiffness of the piezoelectric element and the metal plate and is determined as follows:

$$K_{\Sigma ts} = K_{sps} + K_{smp}, \quad (N/m) \tag{14}$$

where K_{sps} – is the strength of the hollow piezoelectric cylinder (N/m); K_{smp} – is the strength of the metal plate (N/m).

The moment of inertia of a hollow piezoelectric cylinder is determined by the following expression:

$$J = \frac{l_2 \cdot l_3^3}{12}, \quad (m^4) \tag{15}$$

where l_2, l_3 – is the arc width of the piezoelectric element plate and is the thickness (m).

An analytical method for calculating the value of mechanical oscillations of the working body of a three-coordinate accelerometer has been developed.

As is known from the theory of bending elastic deformation of a spring of a rectangular plate fixed on one side, the maximum stress in the cross section of the plate is

$$\sigma_{ms} = \frac{3Fl_1}{2l_2 \cdot l_3^2}, \tag{16}$$

and the amplitude value of the bending deformation

$$\Delta = \frac{A \cdot l_1^3}{3 \cdot I} = \frac{F}{K_m E}, \tag{17}$$

mechanical quality indicator

$$Q_{mec} = \frac{f_r}{\Delta f} \tag{18}$$

defined as, where also f_r – resonance frequency; Δf – frequency change; A – cross-sectional area of the sample; F – force acting on the spring of the plate (N); l_1 – arc length of piezo element plate (m); I – is the moment of inertia (m^4).

Conducted studies show that at the above-obtained value of the amplitude of the bending deformation of the hollow piezoelectric cylinder, when the radiation of the optical beam source is introduced into the optical fiber, the device introduces an attenuation of 0.8…3.0 dB, which is 45…50% less than the attenuation created by known devices, and in this case the insertion error is 0.17…0.65%.

In general, piezoelectric transducers (PT) belong to the class of piezoelectric transducers with small mechanical oscillations. In the considered piezoelectric element (PE), energy is transferred from one system to another through an electric field connection, in this case, the voltage at the input terminals is in electrical form, and at the output terminals in mechanical form. Taking into account the above, the generalized scheme of the PE-PT is given in Fig. 3.9.1 [10, p.49,50]. The method of analytical calculation of the amplitudes of mechanical oscillations of the piezoelectric element of a three-coordinate piezoelectric accelerometer essentially consists of calculating three frequencies, namely the serial resonance frequency, the parallel resonance frequency and the new value of the resonance frequency obtained by connecting the PE and a capacitance of known value in parallel, and based on the three measured resonance frequencies, the equivalent parameters of the three-coordinate piezoelectric accelerometer (TPA) are determined [10, p.49,50].

In the fourth chapter, the issues of mathematical modeling of the working body of a precision positioning device in the single- and multimode transmission of optical beams during the transmission of measurement results to the IOS, experimental research of the accelerometer and the working body of the precision positioning device, and evaluation of metrological characteristics are solved, and the results of the experimental research are given.

Despite the rapid development and improvement of technologies and equipment designed for multi-channel IOSs, there is no scientifically substantiated and accepted unified methodology for modeling the process of operation of such devices. Therefore, one of the most urgent issues is the development of a mathematical modeling of the process of operation of a precision positioning device of an optical beam.

In the given devices, a piezoelectric element with a rectangular cross-section, receiving a supply voltage from an external source, undergoes a longitudinal tensile deformation determined according to:

$$\Delta_{ld} = \frac{2T_m \cdot l_1}{\pi E_y}, \tag{19}$$

where T_m – is the mechanical stress in the center of the plate, equal to $19{,}6 \cdot 10^6\ (N/m^2)$; l_1 – is the length of the piezo element and is equal to $5 \cdot 10^{-2}$ (m); E_y – is Young's modulus (modulus of fragility) and equal to $0{,}8 \cdot 10^{11}\ (N/\mathrm{m}^2)$ – for ZTBL-3 piezoelement.

A mathematical model has been developed to determine the performance characteristics of the optical beam precision positioning device. The developed analytical model is implemented in the following sequence.

The power of the optical beam entering the multimode optical fiber depends on the aperture number NA, as well as the angular orientation diagram of the optical beam source. A multimode optical fiber receives optical rays with a refractive index of n_0 – incident on its cross-section at an angle less than $\Theta_{0\,\max}$. This time

$$NA = \sin\Theta_{0\,\max} = \begin{cases} \sqrt{n_1^2 - n_2^2}\,/\,n_0, & \text{for optical fibers with a stepped profile refractive index;} \\ \sqrt{n_1^2 - n_2^2}\,/\,n_0\sqrt{2}, & \text{for optical fibers with a gradient profile refractive index.} \end{cases}$$

Therefore, an appreciable value of the input extinction occurs when the angular distribution of the power of the optical beam exceeds the value of $2 \cdot \Theta_{0\,\max}$ angle.

Based on the mathematical models developed in the dissertation, the reported values of the parameters and characteristics of the optical beam precision positioning device were compared with the experimental values, and an experimental research device was used to assess the degree of difference between the theoretical and experimental results, which is shown in Figure 6.

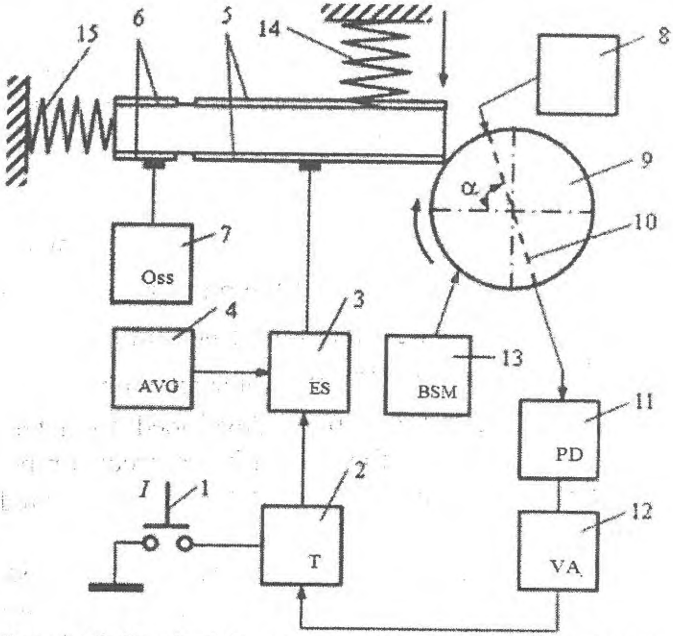

Figure 6. Optical beam precision positioner device experimental research design

The piezoelectric motor is activated by means of the "Ignition" (*I*) - 1 button, as a result of which the trigger (*T*) -2 moves to another steady state and the electronic switch (ES) -3 opens. In this case, from the output of the alternating voltage generator (AVG) -4, an alternating voltage with a f_r resonant frequency is supplied to the first section of the excitation electrodes -5. After the piezoelectric motor is turned on for $t_{i_i}, i = \overline{1,5}$ time, the mechanical oscillations of the first section -5 are transmitted to the second section of electrodes -6. As a result of the influence of those mechanical oscillations, the second section of electrodes -6 switches to the transmitting source mode and forms signals, which are transferred to the input of the oscillograph (Oss) -7 and recorded.

The shaft -9 of the piezoelectric motor rotates until the optical beam from the output of the light diode (LD) -8 falls on the photodiode (PD) -11 through the radial holes -10 on the shaft -9. As soon as this state is obtained, the electric signal from the output of the photodiode (PD)-11 enters the control input of the trigger -2 through the voltage amplifier (VA) -12 and returns it to the initial state, and the electronic switch -3 opens, and the power from the output of the alternating voltage generator (AVG)-4 stops supplying the voltage and the first section of the excitation electrodes -5 is de-energized. In this case, the exact stopping of the shaft is recorded by means of a binocular stereoscopic microscope -13 (BSM-2).

During experimental studies, the dependence of the supply voltage of the piezoelectric stepper motor shaft on the start-up and braking time was established by varying the shaft rotation speed in the range of $5\cdot10^{-3}...88\cdot10^{-3}$ m/s and the clamping force on the working body in the range of 1.3…4.1N (correspondingly, the clamping torque in the range of 0.248…0.288N/m). In this case, the exact stopping of the shaft was recorded using a binocular stereoscopic microscope (BSM-2).

According to the results of the conducted experiment, the deviation after stopping the piezoelectric stepper motor was 1...3 μm, and the resulting error was 0.13...0.71%. Since the diameter of the single-mode optical fiber is 8...10 μm, it covers 70...80% of the scanned signal reflected from the mirror, which ensures the required stopping accuracy of the piezoelectric stepper motor shaft, which is achieved by the absence of a gap, as well as by adjusting the clamping force of the spring and the tension of the piezoelectric element.

The losses associated with the hysteresis of the piezoelectric element are imperceptibly small, and the operation of the piezoelectric stepper motor is carried out in the step mode with stopping at the minimum displacement speed. According to the results of the conducted experiments, the numerical values of the studied parameters of the piezoelectric stepper motor were obtained and are given in table 3.

Table 3. Parameters and numerical values of the piezoelectric stepper motor

№	Characteristics	Numerical values				
1.	Compression force of the piezoelectric element on the working body of the piezoelectric stepper motor, F_{cf} (N)	1,3	2,7	3,3	3,7	4,1
2.	Moment generated by tangential force, M_1 $(N{\cdot}m)$	0,23				
3.	The moment created by the compressive force of the spring, M_2 $(N{\cdot}m)$	0,018	0,038	0,046	0,052	0,058
4.	The total torque generated by the tangential force acting on the shaft of the piezoelectric stepper motor and the compressive force of the spring, M_{tg} $(N{\cdot}m)$	0,248	0,268	0,276	0,282	0,288
5.	Turn-on time of the piezoelectric stepper motor, $t_{tt}\cdot10^{-3}$ (s)	1,4				
6.	Braking time of piezoelectric stepper motor, $t_{br}\cdot10^{-3}$ (s)	18	8	1,2	0,5	0,07

According to the results of experimental studies, the dependence of the change in the supply voltage of the piezoelectric stepper motor shaft on the start-up and braking time of the shaft at different values of the compression moment of the piezoelectric element on the working body has been established.

Conclusion

The results of theoretical analyses, experimental studies and proposals made in the dissertation are dedicated to the solution of an independent scientific and technical problem related to the development of a precision positioning device for IOS, accelerometers and optical beam used to measure dynamic parameters of moving objects in automatic mode in real time and combine the following:

1. Based on the analysis of the current state of the problem, a mathematical model of a piezoelectric vibration and three-coordinate accelerometer measuring dynamic parameters of moving objects in automatic mode in real time was developed;

2. Based on the formulated mathematical model, piezoelectric

vibration and three-coordinate accelerometers measuring dynamic parameters in automatic mode were developed;

3. A method for reporting the parameters of the proposed accelerometers and their working body was developed;

4. A precision positioning device was developed that allows increasing the energy efficiency of the optical beam and reducing losses;

5. An experimental study of the working body of accelerometers measuring dynamic parameters was conducted and an analysis of the results obtained was provided.

The results obtained in the dissertation were reflected in the following scientific works:

1. Mansurov T.M., Huseynov B.I., Aliyev Ch.P. Analysis of the parameters of optoelectronic switches of optical systems of telecommunications // Materials of the XX-th International National Technical Committee "Sovremennye means of communication". - Minsk: Belarusian State Academy of Communications, 2015. - p. 28-31.
2. Mansurov T.M., Aliev Ch.P., Dzhebrailova S.A. Tasks of development and modeling of a device for positioning multimode optical fibers of a communication cable // Materials X of the International Industry National Technical Committee "Technology of the Information Society", dedicated to the 95th anniversary of the Moscow Technical University of Communications and Informatics. -M., MTUSI, 2016. p. 45,46.
3. Mansurov T.M., Aliyev Ch.P., Accelerometer for measurement of acceleration and speed of moving objects // Materials of XXI International National Technical Committee «Sovremennye media svazija». - Minsk: УО БГАС, 2016. p. 22-25.
4. Mansurov T.M., Aliev Ch.P., Dzhebrailova S.A. The device of precision positioning of the direction of optical radiation // Materials of the XXI International National Technical Research Center «Modern means of communication». - Minsk: Belarusian State Academy of Communications, 2016. p. 27-30.
5. Mansurov T.M., Aliyev Ch.P. Classification of accelerometers for the measurement of speed and acceleration of moving objects in

automatic mode // Materials of the International ETK "Modern state and development prospects of information and communication technologies". - Baku, AzTU, 2016. p. 38-41.

6. Mansurov T.M., Aliev Ch.P., Dzhebrailova S.A. Tasks of development and modeling of optoelectronic components of optical communication / Collection of scientific papers of the Odessa National Academy of Communication. A.S. Popova. - Odessa, 2016, No. 2. pp. 88-98.
7. Mansurov T.M., Aliev Ch.P., Dzhebrailova S.A. Design and modeling of passive components of linear path of optical communication / Thomson Reuters ENDNOTE. International Journal of Engineering Sciences & Research Technology, Vol. 5, Iss. 11, 6th November 2016. ISSN 2277-9655. p. 226-233.
8. Mansurov T.M., Mamedov I.A., Zenevich A.O., Aliev Ch.P. Mathematical model of direction control system of optical radiation / Thomson Reuters ENDNOTE. International Journal of Application or Innovation in Engineering & Management (IJAIEM), Volume 6, Issue 2, February 2017. pp.20-25.
9. Mansurov T.M., Aliyev Ch.P. Piezoelectric vibration accelerometer for measurement of linear accelerations and speeds of moving objects // Materials of the XXII-oi International National Technical Research Center "Sovremennye means of communication". -Minsk: Belarusian State Academy of Communications, 2017. -p.61-63.
10. Mansurov T.M., Aliyev Ch.P. Accelerometer for measuring the parameters of moving objects / Scientific journal «Problemy infocommunications» of the Belarusian State Academy of Communication. - Minsk, Belarusian State Academy of Communications, 2017, No. 2 (6). p. 37-46.
11. Mansurov T.M., Aliev Ch.P., Guliyeva G.I. Electrical measurements and tools. Textbook for higher schools. -Baku, Khazar University Publishing House, 2018. -332p.
12. Mansurov T.M., Huseynov B.I., Aliyev Ch.P., Jabrayilova S.A. Precision positioning device of an optical beam (in Azerbaijani) // Official bulletin of the Center for Patents and Trademarks of the State Committee for Standardization, Metrology and Patent of the

Republic of Azerbaijan. -Baku, 2018, No. 3, 30.03.2018. -p.9.

13. Mansurov T.M., Huseynov B.I., Aliyev Ch.P., Jabrayilova S.A. Precision positioning device of an optical beam (in Russian) // Official bulletin of the Center for Patents and Trademarks of the State Committee for Standardization, Metrology and Patent of the Republic of Azerbaijan. Physics section. -Baku, 2018, No. 3, 30.03.2018. -p. 16,17.
14. Mansurov T.M., Aliyev Ch.P. Accelerometer for measurement of accelerations and speeds of moving objects in automatic mode / Scientific journal «Vestnik of Khmelnytskyi National University». - Kharkiv, KhNU, No. 5, 2018. p. 78-83.
15. Mansurov T.M., Aliyev Ch.P. Photonic switch for transmitting information and optical noise over a quantum channel of communication / Scientific journal «Bulletin of the Khmelnytskyi National University». - Kharkiv, KhNU, No. 6, 2018. p. 157-165.
16. Mansurov T.M., Aliev Ch.P., Mansurov E.T. Criteria for evaluation of characteristics of photon switchboards of optical signals and optical fibers for the quantum systems of transfer of confidential information // IEEE International Scientific-Practical Conference «Problems of Infocommunications. Science and Technology» (PIC S&T-2018). -Kharkov (Ukraine), 9 - 12 October 2018. p.378-392 (Skopus).
17. Mansurov T.M., Aliyev Ch.P. Piezoelectric vibration accelerometer (in Azerbaijani) / Intellectual Property Agency of the Republic of Azerbaijan. Official Bulletin of the Center for Examination of Patents and Trademarks No. 8. -Baku, 2019, 31.10.2019. -p.11.
18. Mansurov T.M., Aliyev Ch.P. Piezoelectric vibration accelerometer (in Russian) / Intellectual Property Agency of the Republic of Azerbaijan. Official Bulletin of the Center for Examination of Patents and Trademarks No. 8. -Baku, 2019, 31.10.2019. p.44,45.
19. Mansurov T.M., Aliyev Ch.P. Three-coordinate accelerometer for measuring the acceleration and speed of the measurement object in automatic mode // Bulletin of the Eurasian Patent Office of the Eurasian Patent Organization. -M, 2018, No. 9. p. 125.
20. Mansurov T.M., Aliyev Ch.P. Accelerometer for measuring the

acceleration and speed of moving objects in automatic mode // 1st International National Technical Committee «Modern information, measurement and control systems: problems and perspectives (MIMCS-2020)». - Baku, Azerbaijan State University of Oil and Industry, 2019. p. 159.

21. Aliyev Ch.P. Mathematical model of the piezoelectric vibration accelerometer that measures the linear acceleration and speed of objects in motion // Materials of the International ETK on "Innovative technologies in telecommunications". -Baku, AzTU, 2019. pp.163,164.
22. Mansurov T.M., Huseynov B.I., Aliyev Ch.P., Jabrayilova S.A. Precision positioning device of an optical beam // Intellectual Property Agency of the Republic of Azerbaijan. Patent for Invention No. I 2019 0100. -Baku, 2019, 29.12.2019. -13p.
23. Mansurov T.M., Aliyev Ch.P. Piezoelectric vibration accelerometer // Intellectual Property Agency of the Republic of Azerbaijan. Patent for Invention No. I 2020 0027. -Baku, 2020, 15.07.2020. -13p.
24. Mansurov T.M., Aliyev Ch.P. Three-dimensional piezoelectric accelerometer measurement of dynamic parameters of moving objects / Scientific journal "T-Comm-Telecommunications and Transport". -M.: ID "Media Publisher", 2020, Volume 14, No. 7. p. 29-35.
25. Mansurov T.M., Aliyev Ch.P. Three-coordinate accelerometer for measuring the acceleration and speed of the measurement object in automatic mode // Eurasian Patent Office of the Eurasian Patent Organization. European Patent No. 036355. -M, 2020 from 29.10.2020. 8s.
26. Aliyev Ch.P. Evaluation of the effectiveness of the functioning of accelerometer measurement of dynamic parameters of moving objects // Materials of the 2nd International NPK «Modern information, measurement and control systems: problems and prospects (MIMCS-2020)», dedicated to the 100th anniversary of the Azerbaijan State University of Oil and Industry. -Baku, Azerbaijan State University of Oil and Industry, 2020. p.268-270.
27. Mansurov T.M., Aliev Ch.P. Development of an information-

measuring system for measuring the dynamic parameters of moving objects // Proceedings of the IEEE 2020 International Conference "Problems of Infocommunications. Science and Technology" (PIC S&T'2021). -Kharkov, Ukraine, 2021. pp. 23-27 (Scopus).

28. Aliev Ch.P. Method for determining the magnitude of mechanical oscillations of piezoelectric bimorph elements of a three-dimensional piezoelectric accelerometer // IEEE International Scientific-Practical Conference "Problems of Infocommunications. Science and Technology" (PIC S & T ' 2022). -Kharkov, Ukraine, 2022. p.117-122 (Scopus).
29. Aliyev Ch.P. A method for calculating the magnitude of mechanical oscillations of a piezo element of a three-component accelerometer // Materials of the XXII International National Technical Research Institute of Students, Masters and Graduates "New Information Technologies in Telecommunications and Postal Communications". -Minsk, Belarusian State Academy of Communications, 2022. p. 49,50.
30. Mansurov T.M., Aliyev Ch.P. Device for measurement of linear acceleration and speed of moving objects / Scientific journal «Problemy infocommunications» of the Belarusian State Academy of Communications. -Minsk, Belarusian State Academy of Communications, 2024, No. 2 (20). v.5-9.

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