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IMPROVING THE MATHEMATICAL MODEL OF A FIBER-OPTIC INCLINOMETER FOR VIBRATION DIAGNOSTICS OF ELEMENTS IN THE PROPULSION SYSTEM WITH SLIDING BEARINGS

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The operational capacity of a vessel's propulsion system (VPS) has an exceptionally large impact on the safety of the ship and shipping as a whole. This requires constant long-term technical diagnostics of VPS elements in order to determine their real resource. First of all, this refers to the bearing units of VPS. The practical use of the concept of continuous diagnostics requires the introduction of the latest means of monitoring the technical condition of VPS, which can significantly increase the reliability of the measurement results. That is why solving the scientific problem of creating diagnostic tools invariant to operating conditions and adapted for continuous, long-term, and reliable monitoring, namely fiber-optic inclinometers (FOI), is relevant. In order to solve the problem, the object of research has been determined – fiber-optic measuring devices for monitoring changes in the geometric position or damping conditions of oscillations in bearing units of VPS elements. The task to improve fiber-optic means was to increase the accuracy of measurement results.

The results are in the form of an improved mathematical model of FOI. The difference of the model is the calculation of actual properties of each material layer of the multilayer structure of real fiber-optic waveguides. A distinctive feature of the proposed solution is that the description of the optical-mechanical process in FOI using an improved mathematical model is more accurate and closer to the parameters of the actual process, which are determined experimentally.

The results of the research belong to the field of systems and means of technical diagnosis of VPS elements and can be applied primarily on ships, submarines, and vessels of large displacement

Keywords: fiber-optic inclinometer, propulsion system, layered structure, refractive index, mathematical model

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1. Introduction

The dominant aspect related to ensuring the long-term operability of elements of a vessel's propulsion system (VPS) is the need to increase their reliability while reducing the cost. In ship power engineering, the fulfillment of these conditions is associated with an increase in the power of the main engines and an increase in the forces and amplitudes of oscillations acting in the bearing supports and transmitted to the ship's hull. In the existing realities, decision-making about the resource of VPS elements is made exclusively on the basis of the results of technical diagnostics. Underlying the concept of operation to the pre-failure condition is the methods for predicting the technical condition, which are focused on the identification of defects and damage at the stage of their occurrence.

The practical use of this concept requires the introduction of the latest means of technical diagnosis and forecasting of the technical condition of VPS, which are able to significantly increase the probability of results of measurements of the controlled parameters.

Modern systems for diagnosing and forecasting the technical condition of VPS are operated under conditions of concentrated influence of powerful electromagnetic, vibrational, and thermal fields created by the ship's power equipment. Disturbances initiated by external influences significantly reduce the effectiveness of the process of diagnosing and forecasting the technical condition of bearing units of VPS. That is why solving the scientific and technical problem of improving diagnostic tools, invariant to operational conditions and adapted for continuous, long-term, and reliable monitoring, is relevant and in demand by shipowners.

Its solution and practical use significantly improve the level of navigation safety.

2. Literature review and problem statement

In works [1, 2] it was determined that the «shaft – sliding bearing» system is a single dynamic system that combines mechanical and hydromechanical subsystems. The basis of the mechanical subsystem is a shaft with attached masses. The influence of variable external loads on the shaft generates transverse, torsional, and axial vibrations in it. Sliding bearings, which form the basis of the hydromechanical system, are the source of more complex processes in the dynamics of the rotor system. The damping properties of lubricants make it possible to effectively reduce shaft vibrations. At the same time, when lubrication conditions are violated, the hydraulic layer can initiate high-amplitude self-excited shaft vibrations. In a VPS shaft line, the vibrations caused by the reactions of the lubricant layer in the sliding bearings are not uniform. Periodic forces from the propeller, due to the uneven and non-stationary flow, are transmitted to all elements of VPS. As a result, structural vibrations and radiated noises are generated. During the translation of the vibration of the helical disturbance, VPS acts as a low-pass filter, which amplifies the reactions of the structural vibration, at its resonances, and the radiated noises [3].

Vibration processes occurring beyond the nominal indicators are associated with the loss by the entire VPS of work capacity.

For effective monitoring of processes in the «shaft-sliding bearing» system, two stable directions have been formed in theoretical research. The first is focused on the study of the dynamics of shafts, namely the control of their movement and stability. The model of the sliding shaft-bearing system is based on the assumption that the shaft is a deformable rigid body with elastic and inertial properties. The influence of bearing supports is taken into account as linearized reactions of layers of lubricants.

The second direction is based on the hydrodynamic theory of lubrication, which examines the dynamics of changes in the properties of the lubricating layer directly. In this case, a detailed analysis of the lubricant flow is performed, taking into account such factors as:

- viscosity;
- compressibility of the environment;
- possibility of violation of the laminar flow regime;
- influence of the imperfection of the shape of the support surfaces and violation of the geometry of the lubricating layer.

In this case, the shaft model is greatly simplified and reduced to the scheme of a single-mass rotor. In both cases, VPS is considered as a complex active-dissipative system. To ensure the vibration stability of the shaft in such a system, it is necessary to solve a set of tasks. The main one is the identification of parametric, self-excited, and chaotic vibration processes in the dynamics of the “shaft-sliding bearing” node [4].

In order to effectively control vibration processes in bearing assemblies, the following assumption was made in work [5]. A change in the geometry or vibration damping conditions in the bearing units of VPS elements is reflected in the overall mechanical load on the ship’s hull. But the issues related to the reliability of the received information regarding the change in geometry or damping conditions of oscillations remained unresolved. The reason for this is objective reasons related to the fact that the research used measurement results obtained with the help of traditional means of technical diagnostics. The degree of influence on diagnostic tools of operational factors was not taken into account.

In work [6] it is stated that the translation of the load occurs at vertical points above the bearing units. It was also determined that the most expedient is the use of digital inclinometry methods in the technical diagnosis of bearings. But the issues of specifying the mathematical description of the process of interaction between the inclinometer and the object of control and, directly in the device itself, remained unresolved.

In [7], the application of the principle of automated measurement based on a probabilistic approach is proposed and substantiated. A new sensor scheme based on fiber-optic elements is proposed to register the deviation of parameters outside the range of operating values. But the questions related to taking into account the real properties of materials in the description of the sensor remained unresolved. The objective shortcomings are related to the fact that in the work the sensor elements were considered to be made of isotropic glass materials.

In work [8], it was assumed that the change in geometry or the reduction of oscillations by the supports of the azimuth propulsion device should be reflected in the total load transmitted by the propeller and the electric propulsion motor to the hull of the vessel. Therefore, it is advisable to use the results of the inclinometry of the supports of rowing electric motors as additional information on the stress and deformation of the hull. But the work did not cover the technical and mathematical support of the inclinometry process.

In work [9], a mathematical model of the temperature transient response of an elliptical cylindrical coil of a fiber-optic gyroscope (FOG), which is used as an inclinometer, is given. But the issues related to the fundamental shortcomings that significantly limit the possibilities of using fiber-optic gyroscopes (FOG) for monitoring VPS remained unsolved. Objective difficulties are associated with the limited sensitivity of FOG due to fractional noise, which depends on the amount of optical power.

In [10], a new model of fiber-optic gyroscopic inclinometer is proposed to increase the accuracy and efficiency of measurements. But the issues related to the fundamental shortcomings that significantly limit the possibilities of using FOG for the monitoring of VPS remained unsolved. Objective difficulties are associated with the failure to take into account in the model a significant longitudinal temperature gradient in the optical fiber, which causes false phase shifts. The process is caused by the dependence of the refractive index on the ambient temperature. To counteract this phenomenon, appropriate corrections based on information about the real properties of the optical fiber material should be noted. Another way is to use special heat-resistant optical fibers.

Paper [11] proposed the use of distributed fiber optic systems with fiber inclinometers. But the issues related to the effect on the index of refraction of the optical fiber of electric fields, spread in opposite directions, remained unsolved. Objective difficulties are associated with the application of the ideal image of an optical fiber in the device model.

In work [12], a promising procedure of optical fiber identification using high-order directional modes of visible light radiation is proposed. Owing to the method, it is possible to increase the range of application of fibers that work for bending in measuring devices. However, issues related to taking into account the real properties of fiber optic cables remained unresolved.

In [13], the above listed shortcomings of FOG, which can be used as inclinometers, are confirmed. But among the proposed ways of development of meters of this class, only solutions based on general principles of constructive and technological improvement are proposed. Improving metrological characteristics and ensuring invariance to operational factors by improving mathematical modeling was not considered at all.

Work [14] contains a more detailed version of the structural and technological improvement of FOI to ensure invariance to operational factors. But the work, in view of the fact that it is a patent, does not contain any information about the mathematical description of the measuring device.

In [15], a mathematical model of FOI proposed in the previous work is given. The model describes the processes of conversion of optical power in the sensitive element of the measuring device in sufficient detail. But the questions related to the imagination of OH, which is used, remained unresolved. Objective difficulties are connected with the fact that the model was created as a first approximation, therefore it was mainly of an evaluative nature. The reason for this may be objective difficulties associated with the imperfection of the mathematical model of the measuring transducer and a certain discrepancy between theoretical and laboratory data.

Paper [16] provides information detailing and supplementing the mathematical and optical-mechanical imagination of OH, which can potentially be used in FOI.

The materials of [17] significantly supplement the results of the research reported in the previous paper. But the questions related to taking into account the properties of the optical material for the entire volume of OH remain unsolved. An option to overcome the relevant difficulties can be the application of a mathematical model based on a discrete image of an optical waveguide (OW).

This allows us to state that it is appropriate to conduct a scientific study aimed at improving the mathematical model of FOI for constant and long-term diagnosis and forecasting of the technical condition of the bearing units in VPS.

3. The aim and objectives of the study

The purpose of this study is to improve the accuracy of results of measurements of changes in the geometric position or damping conditions of oscillations in the bearing units of VPS elements using FOI. This will make it possible to obtain reliable information about the technical condition of controlled elements.

To achieve the goal, the following tasks must be solved:

– to define a model of representation of OW as an optical-mechanical system, in which deformations are created under the action of operational factors;

– to synthesize an improved mathematical model of optical power conversion processes in FOI, by calculating the actual properties of each material layer of the multilayer structure of real OWs.

4. The study materials and methods

The object of our research is fiber-optic measuring devices for controlling the bearing units of VPS.

The subject of the study is a mathematical model of the process of forming and converting optical power in fiber-optic measuring devices for controlling the geometric position or damping conditions of oscillations in bearing units of VPS elements.

The main hypothesis of the study assumes the possibility of using a turret-type OW to convert the value of mechanical processes in sliding bearings into changes in the power of optical radiation.

The theoretical part of the work was performed using:

a) system analysis – when determining the connections between elements in structural FOIs and decomposition of the subject of research;

b) the modified theory of coupled modes in the optical fiber – when determining the optical power transmission coefficients and the optical connection between the layers of the optical fiber during its deformation;

c) methods of analytical research of the process of excitation of the fields of a layered OW – when studying the processes of transmission of optical radiation in OW under the influence of deformations initiated by mechanical processes;

d) mathematical modeling – when constructing an improved mathematical model of the optical-mechanical system of FOI.

In order to determine the optical-mechanical properties of FOI, it was important to test them under real mechanical loads. In particular, it was necessary to test a mock-up sample of the measuring device in the range of the bending radius, which is greater than the operational one.

A high-performance optical tester and commercially available optical fibers were used to evaluate the measurement results during the tests. Testing of the optical waveguide for resistance to cyclic bending was carried out in accordance with the recommendations of the International Electrotechnical Commission 60794-1-2, method E6 or DSTU IES 60794-1-2-2002 [18, 19].

The experimental setup included a Wavetek optical reflectometer, two coils of single-mode fiber with a total length of 2200 m, and a deformation bench. Fiber welding was carried out by the Fujikura system. The length of the active fiber was in the range of 5...200 mm.

The magnitude of the load and the range of the bending radius corresponded to data from the technical documentation for the optical fiber. On the bench, the fiber was bent at an angle of up to ±30° on both sides from the vertical. For a full cycle, the bending of the fiber is taken from the vertical position to the extreme right position, then to the extreme left. After bending, the sample returned to a vertical position. The time of one cycle is 2 seconds.

The analysis of reflectograms made it possible to estimate the dependence of the attenuation value and the optical power transmission coefficient on the fiber bending value.

To avoid the problem of sensitivity to uncontrolled operational factors, the relative humidity was kept constant at the level of 10 %±1 % *RH*, and the temperature at the level of 25±1 °C.

To prevent the effect of the protective package, only the primary sheath remained on the fiber.

5. Results of investigating the fiber-optic inclinometer model for monitoring the condition of bearing assemblies

5. 1. Definition of the model of the representation of an optical waveguide as an optical-mechanical system

It is known that the solution to the problem of significantly increasing the level of probability of measurement results relies on the rational synthesis of the measuring device. This means the optimization of a set of design parameters and a combination of materials that differ in invariance to external uncontrolled influences, based on an adequate mathematical model.

In contrast to the approaches that were used in the previously built model, a different way is proposed for consideration of OW, which is a sensitive element of FOI.

In accordance with the method of stratification of the known distribution of the refractive index, the known distribution of the refractive index of OW is approximated by a multilayer structure. In a multilayer structure, the refractive index and width of each layer are chosen to match the original profile as closely as possible. When dividing the optical waveguide (OW) into N layers, the refractive index is taken equal to n_j $(j=1–N)$.

It is known from [20] that in a straight optical waveguide, the mode field at each point of the cross section is directed parallel to the OW axis. A field with the same phase velocity propagates in such a way that the constant phase plane is orthogonal to it. In the case of OW bending, the fields and phase fronts begin to rotate around the center of the bending arc with a constant angular velocity. As a result, there is a linear increase in the phase speed, parallel to the OW axis. The increase is proportional to the distance from the center of the bending arc.

Therefore, the existence of a critical radius in the bending plane is assumed. Exceeding this radius creates conditions for stopping the direction of the OW field and turning it into a radiating one.

To determine the amount of optical power emitted during bending, it is advisable to use the antenna model of OW. Such a model is a curved OW as a current antenna of infinitesimal thickness. Such an antenna radiates into an unrestricted environment with the index of refraction of the general shell OW of the turret type.

According to the model, the current in the antenna is determined step by step. At the first stage, the «OW – mode fields» system is replaced by the corresponding current density distribution in a homogeneous medium. This makes it possible to obtain the distribution law of the current density. The value of the current density is not equal to zero only in the region of the axial line of the OW core.

The next step is to consider OW as a layered structure.

Conditions of a large ratio of bending radii and core are applied to such a structure.

The modified theory of coupled modes considers the connection of the entire continuum of modes of the layered structure of OW, which form a complete orthogonal system. It is believed that the OW layers in the system are located close to each other. And the total field of a complex waveguide will be a superposition of undisturbed fields of each layer. Optical mutual communication consists in interference between mode fields corresponding to scalar solutions.

To estimate the connection of modes in the layered structure of OW, it is sufficient to apply the two-wave approximation. As part of the approximation, only those modes are considered that satisfy the condition of phase synchronism and their connection provides a significant exchange of optical power.

For the case of bending deformations, the perturbation of OW parameters is considered a distributed source of polarization of the medium. And the process of optical communication between modes is a result of the interaction of surface waves with polarization waves.

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5. 2. Synthesis of the improved mathematical model of optical power conversion processes in FOI

For the case of bending deformations, the perturbation of OW parameters is considered a distributed source of polarization of the medium. And the process of optical communication between modes is a result of the interaction of surface waves with polarization waves.

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In the case of unidirectional coupling of modes for the boundary conditions when the complex amplitudes of modes $A_{1m}(0)=1$, $A_{2n}(0)=0$ the power transfer coefficient is defined as:

$$\eta=\frac{\sin^2\left(CL\left(1+(Q/C)^2\right)^{0.5}\right)}{1+(Q/C)^2}, \tag{1}$$

where C is the coupling coefficient; L is the length of the optical communication section; $Q=0.5(B_{2k}-B_{2n})$ – phase mismatch of coupled modes; B – mode spread constant.

But, if we consider the OW layers from the point of view of the effective refractive index method, then each layer can be represented as rectangular. In the case of connection of OW layers, the connection coefficient C will be determined as:

$$C=\frac{2h_{nm}^2 s_4 \exp(-s_i d)}{BW\left(h_{nm}^2-s_i^2\right)\left(1+\frac{1}{s_{i-1}W}+\frac{1}{s_{i+1}}W\right)}, \tag{2}$$

Where $h_{nm}=k\left(n_1^2-n_{nm}^2\right)^{0.5}$; $s=k\left(n_{nm}^2-n_i^2\right)^{0.5}$; W is the thickness of the OW layer.

In the approximation, for symmetric coupled weakly directional OW (2) is transformed to the form:

$$C=\frac{2(1-b_{nm})(b_{nm}\Delta n)^{0.5}}{n^{0.5}W}\exp\left(-k\left(2nQnb_{nm}\right)^{0.5}\right), \tag{3}$$

where $b=\frac{\left(n^{*2}-n_{nm}^{*2}\right)}{\left(n_1^{*2}-n_{nm}^{*2}\right)}$, $V=kW\left(n_1^{*2}-n_{nm}^{*2}\right)^{0.5}$ are the normalized parameters; k – wave number; $Qn=n_1-n_2$; n_1 – the maximum value of the refractive index; n_0 – index of refraction of the OW shell; n^* – effective index of refraction of the equivalent OW.

The total stress in the cross-section of OW consists of stresses that are uniformly distributed over the thickness. Namely, tensile and bending stresses, which are distributed according to the linear law [21, 22]:

$$Sig_z=Sig_p+Sig_{bend}. \tag{4}$$

If we add the tensile and bending stress values to (4), the expression takes the form:

$$Sig_z = \frac{T}{h} + \frac{M_x}{J}, \tag{5}$$

where $J = h^3/12$ is the moment of inertia; $M = DO^*$ – bending moment per unit width of OW; x – geometric parameter.

Taking into account the fact that the largest stresses are formed in the outermost layers at $x = \pm h/2$, (6) due to double differentiation is transformed into the form:

$$Sig_z = \frac{T}{h} + \frac{1}{h^2} \frac{24p/k\pi}{\left(\frac{k\pi}{l}\right)^2 + \frac{T}{D}}. \tag{6}$$

Then the addition to the refractive value of the layer when bending:

$$n_{1z} = n_1 + C_1 S_z, \tag{7}$$

where C_1 is the light elastic constant; S_z – mechanical stress.

Taking into account (7), expression (3) for determining the coupling coefficient is transformed into the form:

$$C = \frac{2\left(1 - \left(b_{nm} + n_z\right)\right)\left(\left(b_{nm} + n_z\right)\left(Qn + n_z\right)\right)^{0.5}}{\left(n + n_z\right)^{0.5} W} \times$$

$$\times \exp\left(-k\left(2n\left(b_{nm} + n_z\right)\left(Qn + n_z\right)\right)^{0.5}\right). \tag{8}$$

But experimental studies showed a certain discrepancy in the loss of optical power, calculated according to (8) and that obtained when testing a real OW (Fig. 1).

To analyze the discrepancy, the features of creating optical fibers by various methods were analyzed [23]. The results are given in Table 1.

If one summarizes the features of the production process, one can define a common stage for all methods. OW is created due to the layer-by-layer deposition of the forming materials on the primary workpiece under conditions of high temperatures. A micro deviation of the flame temperature can be a source of permissible deviation of the optical parameters of each layer of OW. For each wavelength of optical radiation in a vacuum and profile of the refractive index, only certain values of the propagation constant β are possible. The directed radiation mode in the non-absorbing layer of OW propagates without attenuation, so the propagation constant β is a real value. The profile of the refractive index corresponds to the condition $n_{co} \geq n(x, y) \geq n_{cl}$, where n_{co} and n_{cl} are the maximum and minimum values of the refractive index. Therefore, the minimum phase velocity of the wave is equal to the minimum phase velocity of radiation in OW. Otherwise, there will be a loss of power due to radiation in the shell. That is, independent of cross-sectional geometry and refractive index profile. In view of this, there was a need to introduce the correction factor Δβ into (8). The coefficient can be determined on the basis of precise measurements of the refractive indices of OW as:

$$n_{cl} k < B \leq n_{co} k. \tag{9}$$

The calculation of the modified expression (8) and its approximation by the corresponding reflectogram are shown in Fig. 2.

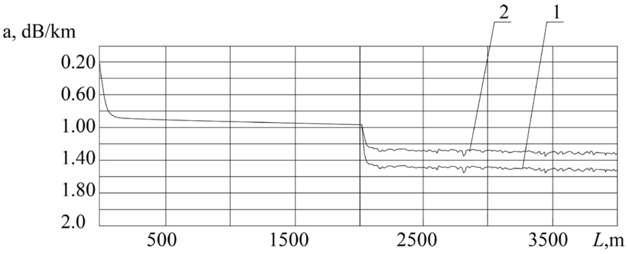

Fig. 1. Reflectogram of OW bending tests: 1 – experiment; 2 – based on a known model

Table 1

Features of creating optical fibers using different methods

Method	Features
Production of the blank by deposition of glass from the vapor phase	Layer-by-layer deposition of glass can be performed on the inner surface of the rotating support quartz tube, on the outer surface of the rotating seed rod or on the end surface of the workpiece. Glass deposition occurs under the influence of the decomposition reaction of compounds of a high degree of purity and volatility in a plasma flame. As a result, microparticles of powdered silicon dioxide condense from the vapor and settle on the workpiece
Modified chemical vapor phase deposition method (MCVD)	In the MCVD method, high-purity silicon dioxide is deposited on the inside of the supporting quartz tube, which is then heat treated. The precipitation process is based on high-temperature oxidation of $SiCl_4$, and oxidation of alloying impurities. In the MCVD process, a significant temperature gradient occurs between the inner surface of the supporting quartz pipe at the reaction site and the outer surface
Plasma method of chemical vapor phase deposition (PCVD)	In the process of manufacturing OW by the PCVD method, the resulting powdery particles at a temperature of the order of 1300 K are deposited in the form of a glass layer. The high speed of movement of the plasma flame along the tube in two directions makes it possible to produce more than 1000 thin layers
External vapor phase deposition method (OVD)	During the production process, a hot stream of silicon dioxide particles passes over the surface of a thin rod. Some of the particles from them stick to the rod, which rotates around its axis along the plasma torch. Layer by layer is created on the porous rod. At the same time, some particles are sintered. Next, the necessary components are added to the flame of the burner and converted into the corresponding oxides. Microparticles of oxides, when deposited on a rotating rod, form a multilayer structure. It is possible to individually alloy each layer
Axial vapor phase deposition method (VAD)	During the production process, powdered microparticles are created in the flame of an oxygen-hydrogen burner. Then there is a deposition on the end surface of the rotating workpiece. On the workpiece rod, it is preliminarily created by spraying, which is the basis for building up the workpiece. Layer-by-layer deposition occurs in the axial direction

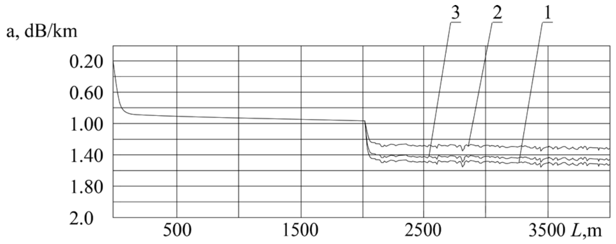

Fig. 2. Reflectogram of OW bending tests: 1 – experiment; 2 – calculation based on a known model; 3 – calculation based on the improved model

The patterns of reflectograms indicate that the description of the optical-mechanical process in FOI using the improved mathematical model is more accurate and closer to what is actually recorded on the test bench.

6. Discussion of results of investigating the improved mathematical model of a fiber-optic inclinometer

A new model of representation of OW in FOI was built, as an optical-mechanical system in which deformations are created under the action of operational factors. It involves the representation of OW as a multilayer structure, each of the layers of which has its own optical and mechanical properties. Our result is explained by the peculiarities of OW production, regardless of the technological method (Table 1).

In contrast to [20], where the OW material is considered as isotropic, the distribution of OW volume by layers allows taking into account the actual mechanical parameters (6) and refractive indices for each layer (2). Owing to the proposed solution, the value of the coefficient of optical communication (3) between the layers during the deformation of real OW is determined with greater accuracy.

Owing to this advantage over the existing solutions [15] (Fig. 1), the amount of change in the geometric position or damping conditions of oscillations in the bearing units of VPS elements can also be determined with greater accuracy.

An improved mathematical model of optical power conversion processes in FOI was synthesized. The calculation of the change in optical power according to the proposed model is closer to the results obtained as a result of experimental tests (Fig. 2). Our results can be explained by the fact that the transmission coefficient of the optical power during deformation of OW is determined by calculating the transmission coefficients between all layers of the waveguide. Owing to the proposed solution, the value of the optical power transmission coefficient between layers (1) when the real OW is deformed is determined with greater and sufficient accuracy.

Increasing the accuracy of measurements is decisive, especially in the area of small deviations of the geometric position or conditions of vibration damping in the bearing assemblies of VPS elements. After all, it is precisely under the conditions of small deviations that the processes of violation of lubrication regimes are activated and manifestations of the adsorption-dissolving effect occur inside the fatigue microcracks of the bearing material. Unlike known solutions, the FOI, which is created on the basis of an improved model, will allow measurements in this area.

The improved model has certain limitations in the area of its application. First of all, such limitations include the need for precise measurements of the index of refraction of OW in certain layers.

A significant limitation can be associated with the influence of an aggressive environment on the elements of FOI. That is, in the model it is desirable to provide compensation for errors in obtaining reliable information under conditions when the destruction of FOI occurs under the influence of DF.

It is possible to consider the lack of a detailed treatment of the issue of the distribution of complex refraction profiles into OW layers as a drawback of the study.

Taking into account the opportunities, limitations, and shortcomings, the development of research should involve:

– further improvement of the mathematical model of FOI, which will allow taking into account a larger range of factors that affect the accuracy of diagnosing VPS bearing units, especially in the area of small deviations of the geometric position or vibration damping conditions;

– searching for ways to increase the accuracy of determining the refractive index for all layers of OW and the general protective shell;

– optimization of the parameters of all elements of FOI according to the criteria of reliability and speed of operation based on the obtained mathematical model.

The proposed mathematical model can be extended to the latest glass materials used in fiber-optic technologies [24].

One of the main advantages of the improved model is the adaptability regarding the selection of local operating points for each remote sensing channel. This allows phase shift configurations to be designed to achieve the target behavior of measurement parameters such as linearity or sensitivity. The further development of this approach consists in the application of virtual devices for the determination of virtual delay measurement lines, self-identification and auto-diagnosis of FOI of the proposed survey topology for a specific VPS [23, 25–29].

7. Conclusions

1. We have proposed a model to represent OW as a multilayer structure, in which each layer of the material is characterized by its specific optical and mechanical properties. This made it possible to more accurately determine the parameters affecting the determination of change in the optical power of FOI under the influence of operational factors.

2. We have improved a mathematical model of FOI, which is based on a multi-layer OW representation. By taking into account the properties of the layers of the structure of OW glass materials, the results of calculations based on the model are closer to the results obtained from experimental tests than in known similar models.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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