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MEASURING SYSTEMS

FIBER-OPTIC INCLINOMETER FOR DIAGNOSING ELEMENTS OF THE PROPULSION COMPLEX OF AUTONOMOUS VESSELS

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Abstract

The capabilities of the modern technical diagnostics system (TDS) are somewhat limited in terms of the probability of control results and the degree of invariance to the influence of destabilizing operational factors. This shows that within the modern concept of the technical operation of autonomous vessels (AVs) to the pre-failure state, new means of diagnosis are in demand. Such means should be organically implemented to TDS, ensure high operational efficiency and reliability of functioning, be economically expedient. Therefore, the solution to the scientific and technical problem of optimal combination of protection and preservation of the characteristics of fiber-optic inclinometers for monitoring the bearing supports of the ship's propulsive complex is of particular relevance. It was determined that the improvement of the characteristics of the control means can be achieved due to the synthesis of known optical circuits and the latest materials and types of light guides. To register the parameters of mechanical impact and deformations, a new schematic solution of the sensor based on light guides of the revolver type and elements made of nanomaterials is proposed.

Keywords: propulsion system, autonomous vessel, optical fiber, inclinometer.

I. INTRODUCTION

The analysis of damage to ship propulsion systems shows that among the various reasons that can lead to loss of operational capacity, as well as to accidents with catastrophic consequences and significant losses, one of the dominant places is occupied by the failure of the elements of the shafts as a result of the spatial shift of the axes and the increase in the amplitudes of shaft vibrations. The existing procedure for ensuring the operational efficiency of ship rotor systems by further increasing the reliability and redundancy of their elements is associated with significant material and economic costs and does not always provide effective constructive solutions. In the current situation, it is most expedient to separate from the hierarchy of functional subsystems of the propulsive complex of systems of retention and stabilization of shafts and to identify potential reserves for increasing the efficiency of their functioning.

The long-term performance of such complexes is primarily determined by the mode of operation of the tribocombination in the suspensions. Under the influence of operating factors, tribomechanical and rheological processes are activated in the bearing units, which contribute to the dissipation of the supplied mechanical energy both by destructuring mechanisms that cause nutation of the rotor and wear of the supporting bearing units, and by damping elements.

However, the known circuit-technical solutions for supporting the shafts of the propulsive complex are limited by the specifics of the functioning of shipboard energy-intensive objects, and their implementation makes it possible to reduce the intensity of the influence of a limited range of operational factors. Under these conditions, technical diagnosis of the state of the position of the axes and the stabilization of the vibrations of the engine rotors and shaft lines is one of the priority tasks in the formation of a comprehensive approach to increasing the operational reliability of the operation of unmanned vessels.

The solution to the problem of increasing the efficiency of technical diagnostics of the state of the position of the shafts of the propulsive complex throughout the life cycle of the USVs requires the implementation of the concept of using the latest, more efficient and economically feasible, automated means of technical diagnostics and forecasting of the technical condition and significantly complicates the diagnostic processes. The trends in the development of modern technical operation methods confirm that the use of reliable, verified, invariant to disturbances diagnostic tools is able to ensure high operational efficiency and reliability of the functioning of marine unmanned vehicles [1, 6].

According to this concept, operational efficiency, as one of the criteria for the expediency of applying the principles of information and measurement management, is the primary reason for the use of such diagnostic tools that allow preventing the uncertainty of errors [18]. Information and measurement management technology has long been implemented and used in mobile automatic systems based on unmanned vessels to support improved management [12].

Similar methods are applied based on the study of the internal properties of elements of complex systems and complexes and take into account the peculiarities of creating a mathematical apparatus that comprehensively characterizes various processes in specific operating modes of a specific system. In turn, the development of the principles of building regression models based on the data of experimental studies is determined by the principle of connecting inputs based on experimental data with a certain number of joint observations of input and output parameters [3].

The existing means of monitoring the technical condition of the elements of the propulsive complex of unmanned vessels are operated under the conditions of intense influence of destabilizing factors - powerful electromagnetic, thermal and vibrational fields. It is these disturbances that prevent effective diagnosis and forecasting of the technical condition of elements of the propulsive complex in accordance with modern operational requirements. This proves that the latest diagnostic tools are in demand for the modern technical operation of unmanned vessels to the pre-failure state. Namely, they are insensitive to most operational destabilizing factors (DF), built on the latest fiber-optic technologies and materials [17].

This process is accompanied by a change in the parameters of the trajectories of the moving balance of the shaft axes in the space of the gaps, which are located in the area of the areas of application of dynamic loads of the support nodes, and which in the initial state were dynamically more stable.

In addition to the vibrations created by the reactions of the lubricating layer in the bearing assemblies, there is another powerful source that creates mechanical oscillations in the shaft line. The pulsating force of the propeller, induced by the uneven and unsteady flow, is transmitted by the propeller shaft system, causing structural vibrations and radiated noise. The dynamic characteristics of the propeller shaft coupling system are indispensable for the transmission of the vibration of the stern disturbance, where the coupling system acts as a low-pass filter that amplifies the vibrational reactions at its resonances [20].

The research hypothesis formulated in this way was based on the assumption that the change in the geometry or the conditions of vibration damping by the engine supports and shaft elements should affect the overall mechanical load transmitted by the power unit to the ship's hull at vertical points above the bearing assemblies. And precisely the control of the spatial state of the engine supports and the shaft line can provide the necessary diagnostic information about the state of the propulsive complex [13].

In [5, 26], the results of research of fiber-optic inclinometers (FOI) based on fiber-optic gyroscopes in technical monitoring systems are given.

However, issues related to fundamental and technical deficiencies that significantly limit the possibilities of using FOI for monitoring the elements of the propulsive complex of unmanned vessels remained unresolved. The reason for this may be objective difficulties associated with:

- the need to implement measures to ensure high stability of FOI parameters. This mainly concerns the optical fiber and the wavelength of the radiation source. The stability of the wavelength of the radiation source and the associated power input into the optical circuit determine the accuracy of the device. The permissible level of fluctuations of the output signal (noise) is limited by the sensitivity of the photodetector;

- the need to compensate for the influence of such physical phenomena as: polarization effects, thermo-optical, magneto-optical, non-linear Kerr effect, etc. The zero drift caused by them can significantly exceed the useful signal;

- the difficulty of application, from the point of view of working in conditions of high temperatures, low-temperature solders used in the production of superluminescent diodes, as well as when connecting an optical fiber to a radiation source. This is also due to the fact that temperature effects, in addition to directly influencing the characteristics of the elements of the FOI, also affect the manifestation of various physical effects, and because of them, the accuracy of the device.

An option to overcome the relevant difficulties can be the approach used in [23], which consists in:

- changes in the production technology of FOI (working out issues of optical fiber soldering);

- use of radiation sources with a larger range of operating temperatures;

- application of the thermoregulation system and circuit-algorithmic compensation of temperature dependence.

But the issue related to the essential indicators of accuracy, reliability and economic feasibility of the implementation of the specified measures remained unresolved.

An option to overcome the relevant difficulties can be the use of the FOI proposed in [8, 11].

The inclinometer consists of a 2000-mm-long PVC pipe that acts as a housing, a fiber-optic light guide, and a strain-measuring device. In each quadrant of the pipe section at 0, 90, 180 and 270° there are grooves along the pipe axis. Four short metal guide tubes are attached to the pipe in the middle and at the end of the pipe. A section of optical fiber is pulled along the grooves through the guide tubes to form two loops. The part of the light guide inside the guide tubes is firmly glued to the inner surface of the tube. To prevent the fiber optic cable from slipping around the circumference during bending, the fiber optic cable is glued to the PVC pipe inside the surface of the groove. The guide tubes and fiber optic cable configurations are secured by clamping the guide tubes. The two free ends of the optical fiber are connected to a device for measuring deformation.

However, since the open optical fibers are in the zone of influence of destabilizing factors, the issues related to the stability of the materials of the FOI elements in real operating conditions remained unresolved.

The main factor is the threat of destruction of the FOI elements when the optical fiber interacts with the hygroscopic sheath saturated with moisture. This is due to the process of stimulated hydrolysis. During hydrolysis, a water molecule is embedded in a strained Si-O-Si bond, breaks it and creates new bonds with hydrogen. Within the surface layer of the fiber material, the bridging bond between the silicon ions is broken, and two unstable "radicals" are formed. Due to the fact that "radicals" have a significant reactivity to environmental molecules. The combination of the silicon atom with the OH group and the creation of a layer of the Si-OH silanol group takes place. With further growth of the thickness and porosity of the layer, destruction may approach the core of the fiber, which will cause its gradual destruction [18].

An option to overcome the relevant difficulties can be the complete isolation of sensitive optical fibers from the influence of moisture and operational factors with a thin layer of nanomaterial. The use of a protective nanolayer demonstrated not only powerful protection of the optical fiber, but also positively influenced its physical and mechanical properties. This is the approach used in [15, 24].

At the same time, the issue related to the exact identification of mechanical influences on bearing supports in different directions remained unresolved.

An option to overcome the relevant difficulties can be the use of revolving light guides. This is the approach used in work [4, 14], where the potential capabilities of light guides of this class were evaluated.

Therefore, in this way, the solution of the scientific and technical problem of a rational combination of protection and preservation of metrological and technological and economic characteristics of the FOI for technical diagnosis of the state of the elements of the propulsive complex [2, 7, 27] becomes particularly relevant.

II. PURPOSE OF WORK

The purpose of the study is to develop a technology for measuring mechanical load and corresponding deformations of bearing supports of the shaft line using a fiber-optic multivector inclinometer. The implementation of the research results will make it possible to significantly reduce the probability of an error during the assessment of the technical condition of the elements of the ship's propulsion complex.

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

- to determine the scheme and technical solution of the FOI, which is resistant to the influence of operational factors during the implementation of constant and long-term diagnostics and forecasting of the technical condition of the elements of the ship's propulsion complex;
- synthesize a mathematical model for evaluating the influence of controlled parameters on the metrological characteristics of invariant fiber optic inclinometers.

III. CONTENTS AND RESULTS OF THE RESEARCH

The object of research is the processes of formation and transformation of optical power in a sensitive optical fiber of the revolver type.

The subject of research is fiber-optic means of controlling mechanical deformations that function in difficult operating conditions.

The main hypothesis of the study is the assumption of the possibility of using a revolving optical fiber to convert the amount of deformation in different directions into changes in the power of optical radiation.

The theoretical part of the work is performed using:

a) system analysis - when determining the structural connections between the elements of the measuring tool for controlling the deformation and decomposition of the research object;

b) the theory of optical waveguides of equal volume - when determining the distribution of optical power in each branch of a revolving optical fiber;

c) methods of analytical research of processes of interaction of fields of optical waveguides - when studying the processes of transformation of light radiation in an optical fiber under the influence of deformations initiated by external mechanical influence;

d) mathematical modeling - when obtaining an approximate assessment of the operation of the optomechanical system of the FOI.

It is known that the task of significantly increasing the level of stability of characteristics and reliability of the results of FOI measurements, in most existing applications, is solved on the basis of the synthesis of the measuring tool. Such a tool is designed on the basis of optimizing the combination of structural parameters and the combination of materials. The optimization criterion is the degree of invariance to the influence of external operating and destabilizing factors (DF).

In order to achieve more perfect physical and mechanical characteristics of the sensitive element of the FOI, it is proposed to use light guides made of artificial sapphire as the material of the optical channel. The use of artificial sapphire, which has almost no mechanical hysteresis, will allow to ensure the required level of sensitivity and, at the same time, the resistance of the light guide surface to the influence of DF [16].

The general protective shell is a clip consisting of carbon nanotubes, in which sensitive optical fibers are located radially. The use of such a general clip will ensure an increase in moisture resistance of the fiber, leveling of the phase interface: solid base-coating, increase in homogeneity, mechanical and laser strength, decrease in surface roughness of the optical fiber (Fig. 1) [9].

The revolving optical fiber contains 32 optical fibers in a protective shell 8 to cover all possible azimuthal deformations of the bearing supports. To accurately identify the azimuth, the revolving light guide 2 is connected to the radiation source through a multibranch splitter 3. Each branch of the splitter contains optical filters 4.

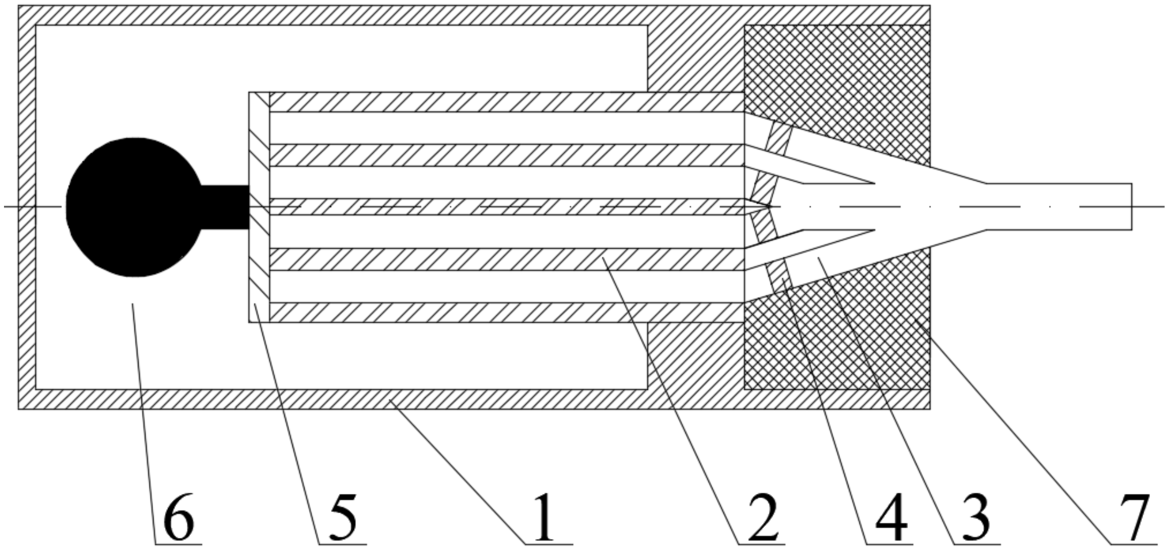

Fig. 1. Fiber-optic inclinometer: 1 – body; 2 – light guide of the revolver type; 3 – multi-branch splitter; 4 – optical filters; 5 – reflective layer; 6 – inertial mass; 7 – vibration-absorbing protective gasket; 8 – general protective sheath of the light guide of the turret type

Optical filters form optical radiation with its own wavelength for each optical fiber. After passing through the optical fibers, the radiation is reflected from the reflective layer 5 and returns to the splitter. When deviated from the vertical, the inertial mass 6 deflects the fibers and causes bending deformations in them, which are the largest in the azimuth of the inclination. In fibers maximally coinciding with the tilt azimuth, the conditions of complete internal reflection of light are violated to the greatest extent. Such fibers, namely, the angle and azimuth of the inclination, is determined by the loss of optical power at its own wavelength of radiation, which is assigned to this optical fiber. The hull 1 is connected to the ship's structures through a vibration-absorbing protective gasket 7 [19].

The first assumption is due to the technology of creating an optical fiber. The latter was considered as a layered structure consisting of a homogeneous core with a radius ρ of material with a refractive index n_{co}, and shells with a refractive index n_{co1}, n_{co2}, etc. At the interface between the core and the shell, the relative dielectric constant parameter ε changes with a jump. Each layer has its own physical and mechanical characteristics. The fiber material is considered absolutely elastic, the deformations are such that they do not lead to destruction. The assumption allows the use of models of classical mechanics of continuous media obeying Hooke's law for an anisotropic body in calculations.

The analysis of the two-layer optical structure was performed on the basis of Maxwell's equations. The equations make it possible to consider the processes of light propagation at any ratio between the dimensions of the system forming the light beam and the wavelength.

To fully define the field of such a structure in Maxwell's equations, boundary conditions are defined, on the basis of which the characteristic equation is obtained

$$U\frac{J_1(UR)}{J_0}=W\frac{K_1(WR)}{K_0(W)}, \tag{1}$$

where J_0 – Bessel function of the first kind; K0 – modified Bessel function of the second kind; U and W – scalar mode parameters for the core and shell are related to the parameters of the optical fiber by ratios

$$V^2=U^2+W^2;\quad U=\rho\left(k^2n_{co}^2-\beta^2\right)^{0,5};$$

$$W=\rho\left(\beta^2-k^2n_{cl}^2\right)^{0,5};\ V=k\rho(n_{co}^2-n_{cl}^2)^{0,5}.$$

The parameter U is related to the mode propagation constant β ratio

$$\beta\frac{V}{\rho\sqrt{2\Delta}}\left(1-2\Delta\frac{U^2}{V^2}\right)^{1/2}. \tag{2}$$

The second assumption is due to the nature of the perturbation of the parameters of the optical fiber under the influence of the controlled quantity.

In the case of homogeneous changes in the refractive indices of the core and shell, when the refractive index of the core differs everywhere from the refractive index of the undisturbed fiber by Δn_{co},, then it is possible $\bar{\eta}_p=\bar{\eta}$, $\Delta n=\Delta n_{co}$, $\bar{\eta}$ – a fraction of the power of fashion spreading through the core. The share of power in the envelope is equal to $1-\bar{\eta}$. Therefore, if the index of refraction of the shell differs by Δn_{cl} from the corresponding parameter of the undisturbed fiber, then the propagation constant in the disturbed fiber is determined as

$$\beta=\bar{\beta}+k\left[\bar{\eta}\Delta n_{co}+(1-\bar{\eta})\Delta n_{cl}\right], \tag{3}$$

where $k=\pi/\lambda$ and λ – wavelength in vacuum. In this case, the propagation constant does not depend either on the shape of the cross-section or on the profile of the refractive index. Since $\Delta n = n_0 - n_{cl}$, then for the main modes of fibers with a stepped profile of the refractive index (RI)

$$\beta = \beta + 2\left(n_{co} - n_{cl}\right)k\,\frac{\Delta\rho}{\rho}\left[\frac{UK_0W}{K_1W}\right]^2, \qquad (4)$$

where K_1 – modified Bessel function of the second kind.

The third assumption is connected with the dependence of the intensity distribution of the main mode on the cross-section of single-mode fibers with a stepped RI and the value of the waveguide parameter V on the "volume" of the refractive index profile. This gives reason to apply the equal-volume refractive index method for evaluating the interaction of disturbed fiber layers from positions [25].

In a straight optical fiber, the mode field at each cross-section point propagates parallel to the fiber axis. Propagation occurs with the same phase velocity, so that the constant phase plane is orthogonal to it. In the case of bending the fiber into a flat arc with a constant field radius and the phase fronts rotate around the center of curvature of the bend with a constant angular velocity. At the same time, the profile of the refractive index of the optical fiber changes (Fig. 2).

For a weakly strained fiber, there must be a certain radius in the plane of bending, exceeding which the field must already turn into a radiating one. To calculate the optical power emitted during bending, it is advisable to use an approximate fiber model. The antenna radiates into an unlimited medium with a refractive index equal to the refractive index of the shell n_{c1}. Therefore, the formulas of antenna theory for the far field can be used in the calculations of the radiation field.

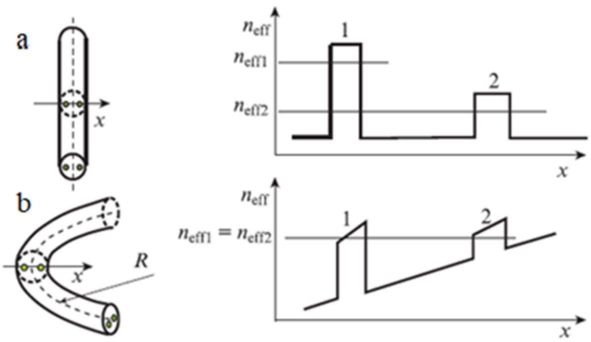

Fig. 2.
Equivalent profiles of the index of refraction of an optical fiber: a – "heterogeneous" straight; b – curved [4]

In a curved antenna, the bending power attenuation coefficient is estimated as

$$\xi = \frac{P_{rad}}{\left[2\pi R_c P(0)\right]}, \qquad (5)$$

where P(0) – the power that is input to the antenna; P_{rad} – power emitted during bending; R_c – bending radius.

For a single-mode optical fiber, taking into account (1), the power attenuation coefficient of the main mode in a curved fiber with a stepped RI will be obtained [25]

$$\xi = \frac{\pi^{0,5}}{2\rho}\left(\frac{\rho}{R_c}\right)^{0,5}\frac{U^2}{V^2W^{1,5}}\frac{1}{K_1^2(W)}\exp\left(-\frac{4R_cW^3\Delta}{3\rho V^2}\right). \qquad (6)$$

For a uniform and thin fiber under certain tension, the modulus of elasticity for stretching (compression) E_χ and torsion E_v can be considered separately constant across the cross section, because the fiber can be considered as a one-dimensional homogeneous medium. Such an assumption does not significantly distort the picture of tension distribution.

Then the diagonal element of the refractive index tensor $n_{33} \equiv n_{zz}$ it is possible to present as

$$n_{zz} = \sqrt{\varepsilon_{zz}} = \sqrt{\varepsilon(r) + g_{zz} - 1} \qquad (7)$$

where $\varepsilon(r)$ – profile of the relative permittivity of an not tense straight fiber.

Tension deformation (compression) along a spirally curved axis ψ $\sigma_{zz} = \sqrt{g_{zz} - 1}$ is equal to the corresponding change in relative permittivity, and the metric factor $\sqrt{g_{zz}}$ the coefficient of change of lines located at the same distance from the axis makes sense Ψ inside the curved fiber and is defined as

$$g_{zz} = \left(1 - \eta r\cos\varphi\right)^2 + \nu^2 r^2 = \left(1 - \eta x\right)^2 + \nu^2\left(x^2 + y^2\right), \qquad (8)$$

where angle φ counted from the axis $\vec{x}(\psi)$. Taking into account (7) and (8) and the fact that $g_{zz} - 1 << 1$ in polar coordinates

$$n_{zz} \approx n(r) + \frac{1}{2n(r)}\left(-2\eta r\cos\phi + \eta^2 r^2\cos^2\phi + \nu^2 r^2\right), \qquad (9)$$

where $n(r) = \sqrt{\varepsilon(r)}$; τ and ν – parameters of curvature and rotation of the axis of a spirally curved fiber, which are equal to

$$\eta=\frac{R}{R^2+\left(p/2\pi\right)^2};\quad \nu=\frac{p}{2\pi}\cdot\frac{1}{R^2+\left(p/2\pi\right)^2}, \tag{10}$$

where R, p – the bending radius of the fiber axis and the spiral pitch, respectively.

Then the changes in the RI during bending and twisting of the fiber can be estimated as

$$n_{zz}\approx n_0+\frac{1}{2n_0}\left(-2\eta r\cos\phi+\eta^2 r^2\cos^2\phi+\nu^2 r^2\right), \tag{11}$$

where n_0 – index of refraction of an undisturbed fiber [10, 21, 22].

Optical fibers in the manufacturing process, due to contact with the spinnerets, acquire a certain ovality [25]. Such a shape can be replaced by such an averaged concept as ovality, where one of the axes of the ellipse is equal to the diameter of the fiber. The increase in constant propagation due to the ellipticity of the coaxial structure, where one of the axes of the ellipse is equal to the diameter of the fiber, is

$$\Delta\beta_e=\frac{2R\pi n_{co}}{r_e\lambda}-\frac{2\pi n_{co}}{\lambda}, \tag{12}$$

where R – semimajor axis of the ellipse; r_e – minor semi-axis of the ellipse and radius of the circle of an ideal fiber; λ – wavelength of radiation.

Then from (6, 11, 12) a mathematical description is obtained for determining the effective optical power at the output of a bent optical fiber

$$P(z)=P(0)\left(\begin{array}{c}\dfrac{\pi^{0,5}}{2\rho}\left(\dfrac{\rho}{R_c}\right)^{0,5}\dfrac{\left(\rho\left(k^2\left(n_{co}+n_{zz}\right)^2-\left(\beta+\beta_e\right)^2\right)\right)^{0,5}}{\left(k\rho\left(\left(n_{co}+n_{zz}\right)^2-\left(n_{cl}+n_{zz}\right)^2\right)\right)^{0,5}\left(\rho\left(\left(\beta+\beta_e\right)^2-k^2\left(n_{cl}+n_{zz}\right)^2\right)\right)^{0.75}}\\ \dfrac{1}{K_1^2\left(\rho\left(\left(\beta+\beta_e\right)^2-k^2\left(n_{cl}+n_{zz}\right)^2\right)^2\right)}\exp\left(-\dfrac{4R_c\left(\rho\left(\left(\beta+\beta_e\right)^2-k^2\left(n_{cl}+n_{zz}\right)^2\right)^3\right)\Delta}{3\rho\left(k\rho\left(\left(n_{co}+n_{zz}\right)^2-\left(n_{cl}+n_{zz}\right)^2\right)\right)}\right)\end{array}\right). \tag{13}$$

IV. CONCLUSIONS AND RECOMMENDATIONS

The implementation of the developed FOI will allow to obtain a means for the organization of permanent and long-term control of the technical condition of the elements of the propulsive complex.

Heat resistance and moisture protection of the sensitive fibers of the inclinometer is ensured by the combination of artificial sapphire and nanotubes and technological features of production. Thanks to the vapor deposition process, it is possible to achieve a strong connection between the optical fiber and the overall protective clip-sheath.

The improved mathematical model (13) makes it possible to synthesize a fiber inclinometer invariant to the influence of DF, with any variation of the initial information and structural elements.

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

- further improvement of the mathematical model of the VOI, which will allow taking into account more factors that affect the possibility of continuous monitoring of elements of ship propulsion systems over long periods of time;

- searching for ways to improve the physical and mechanical properties of the materials of the measuring device;

- optimization of the parameters of all elements of the FOI according to the criteria of long-term reliability and speed of operation.

In accordance with the first task, a scheme and technical solution of the FOI was determined, which first of all satisfies the criteria of immunity to the influence of operational DFs during the implementation of permanent and long-term diagnostics and forecasting of the technical condition of the elements of ship propulsion complexes AVs.

The synthesized mathematical model made it possible to prove that the change in optical fiber deformation detection at the key level corresponds to the change in pressure in the FOI, and the trend of the change is the same.

This result was achieved primarily due to the fact that the model takes into account fluctuations in the power of the modulated radiation source, as well as unproductive losses of optical power at any point of the optical path of the measuring device. This made it possible to minimize the level of the necessary signal power at the FOI output without losing the accuracy of measuring the mechanical deformations of the bearing supports.

Also, unlike other existing models, the proposed one allows to estimate the level of crosstalk when two sensors working in the same channel are interrogated at the same time. The implementation of scalability to any networks based on fiber-optic technologies to increase the number of responding sensors does not occur at the expense of reducing or increasing the distance to the location of the control points, but through the possibility of calibrating the signal strength.

One of the main advantages of the synthesized model is the flexibility to choose specific working points of the shaft line for each remote monitoring point.

The mathematical model of conversion of optical radiation into FOI is universal and can be used to create a wide range of interference-resistant diagnostic tools for ship information and measurement systems [28].

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