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IMPROVING TOOLS FOR DIAGNOSING TECHNICAL CONDITION OF SHIP ELECTRIC POWER INSTALLATIONS

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Existing information-measuring systems (IMS) do not fully correspond to the tasks of monitoring electric power installations (EPI) in terms of their characteristics. The capabilities of IMS have certain limitations regarding the probability of measurement results and the degree of invariance to the influence of operational factors. This proves that for modern failure-free EPI technical operation, new diagnostic tools are in demand. Such means should be seamlessly integrated in IMS to enable high operational efficiency and performance reliability. Therefore, it is of particular relevance to tackle the scientific and technical issue of rational combination of protection and preservation of the characteristics of fiber-optic sensors of relative humidity control systems in ship EPI. To solve the problem, the chosen object of this study is the processes of formation and transformation of the diagnostic signal in the means of humidity control. It has been established that the improvement of the characteristics of the control means can be achieved through the synthesis of known optical circuits and the latest materials. To register the parameters of relative humidity, a new circuitry solution was proposed for the sensor based on fiber-optic and elements made of nanomaterials. The main feature of the proposed monitoring tool is invariance to operational destabilizing factors. The scope of application of the obtained research results involves distributed fiber-optic systems for monitoring the technical condition of ship electric power systems. The introduction of a new means for measuring humidity will make it possible to achieve an increase in the efficiency of use and reliability of EPI by reducing the accident rate by 6...11 %, as well as a decrease in operating costs by USD 8...10 per 1 kWh of generated power per year of operation with an average load

Keywords: electric power installations, relative humidity, optical fiber, refractive index, layered structure

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1. Introduction

Innovative means of diagnosing and controlling the parameters of EPI, taking into account all modern challenges, are a prerequisite for reliable safety and stability. According to shipping safety and operational requirements, human errors result in 75...96 % of accidents. On the other hand, the paradigm of today's industry involves significant technological innovations that are expected to have a devastating impact on all shipbuilding industries in the near future. The new design criteria and operational requirements will lead to the replacement of traditional vessels with vessels with increased efficiency and sustainability. This approach will include real-time monitoring of EPI parameters and data mining in order to increase the overall level of efficiency in the updated management approach and introduce predictive models. Experimental studies have shown that optimizing ship control in general and EPI in particular can lead to significant resource savings, which in some cases can reach 15 % reduction in costs.

In the ship's electric power systems, one of the actual scientific and technical tasks is the implementation of maintenance and repair of EPI based on the analysis of data obtained from the results of preventive technical diagnostics. The greatest potential possibilities are inherent in the methods of technical diagnostics, which make it possible to identify defects at the stages of origin, and means that carry out continuous diagnosis and monitoring, over a long time, of partial discharges (PD) on high-voltage EPI. In many cases, PD are associated with the emergence and development of local defects, primarily in insulating elements. It should be taken into account that the level of relative humidity in vessel EPI is one of the dominant external parameters that have a significant impact on the conditions of origin and intensity of PD. Control of environmental parameters in the immediate vicinity of the high-voltage parts of EPI makes it possible to identify and predict the development of PD.

The practical use of methods for detecting defects in the elements of ship EPI requires the introduction of the latest, more efficient, easy-to-use, automated means of technical diagnostics and forecasting of technical condition while significantly complicates the diagnostic processes. Trends in the development of modern methods of operation confirm that it is the use of reliable, verified, invariant to perturbations diagnostic tools that is able to provide high operational efficiency and functional reliability of EPI [1, 2].

Processing the results of measuring the parameters of the EPI is used to perform the task of reconstruction of the time series of calculation laid down in mathematical models. Algorithms for finding diagnostic errors in combination with *k*-fold cross-checking are implemented according to the algorithm for optimizing hyperparameters. The error indicator is considered to compare the results of each analyzed combination. Choosing the length of the sequence of an individual check is critical for adequate model performance since the greater the length of the sequence, the greater the error. This may indicate that the model cannot properly cover the long dependences during the time series. For example, the analysis of the obtained results of EPI check with 18 controlled parameters consists of 1 layer (129 units) and the function of activating the re-check if the value of at least one controlled parameter goes beyond the established critical limits. Moreover, the number of discarded values that go beyond the established limits is 6 while the length of the measurement sequence is 3. In addition, the verification coefficient is set to 0.20. To compile such a model, optimization is used with the number of successive iterations of 100 and the number of controlled parameters in the "control branch" of 5.

According to this approach, operational efficiency as one of the criteria for the expediency of applying the principles of information-measuring management is the primary reason for the use of such diagnostic tools that avoid uncertainty of errors [3]. Information and measurement management technology has long been introduced and used in mobile automatic systems based on unmanned vehicles to support improved control [4].

The main indicator reflecting a decrease in reliability is the measurement of delay time with simultaneous unidirectional stretching of the check vector. For example, for a software algorithm for controlling EPI's two synchronized diesel generators (DG) with a recording time of unsuccessful synchronizations for 100 s to "cover" the maximum stroke of the regulator, the delay is 1.5 s. At a constant speed of the regulator of 50 mm/min, for each DG the number of measurement errors is 3.

Such methods are used on the basis of the study of the internal properties of elements of complex systems and assemblies and take into account the peculiarities of constructing equations that characterize various processes in specific operational modes of a particular system [5]. In turn, the development of principles for constructing regression models according to experimental studies are determined by the principle of combining input on the basis of experiment data with a certain number of joint observations of input and output parameters [6].

Prediction of data on output parameters of DG is carried out by modeling method with a three-level structure of the DG model: one input level with four neural connections (NC), one hidden level (7 NC for predicting torque, 9 NC for predicting CO, 13 NC for predicting NOx), and one output level. The logistic linear data transfer function was used at the hidden and output levels as an activation function, respectively.

To predict each parameter, rotations per minute, cetane number (CN), calorific value (LHV), and specific density of fuel were used as the input parameter. In the reference model, the values were 0.726, 0.898, and 0.919 for torque, CO, and NOx, respectively. Using the properties of the fuel and DG revolutions as predictive parameters, it is possible to evaluate the experimental results. But the performance of models can be improved by providing more accurate data. With greater data accuracy, the ability of models to generalize will increase. In the end, this will make it possible to use the simulation to predict the performance and characteristics of DG operating on different types of fuel.

Existing means of monitoring the technical condition of EPI elements are operated under conditions of intense influence of destabilizing factors – powerful electromagnetic, thermal and vibration fields. It is these perturbations that impede the implementation of effective, corresponding to modern operational requirements, diagnosis and forecasting of the technical condition of the elements of EPI. This proves that for modern failure-free technical operation of EPI, new diagnostic tools are in demand. Namely, insensitive to most operational destabilizing factors (DF), built on the latest fiber-optic technologies and materials.

2. Literature review and problem statement

The results of studies of fiber-optic sensors of relative humidity (RH FOS) in EPI monitoring systems are reported in [7]. It is shown that among RH FOS, the most advanced metrological characteristics are demonstrated by sensors based on fiber Bragg gratings (FBG) with a hygroscopic coating applied to the fiber instead of the traditional silicon shell [8]. But issues related to fundamental and technical shortcomings remained unresolved, which significantly limit the possibilities the use of fiber optic interferometer for monitoring EPI. The reason for this may be objective difficulties associated with:

– FBG generated by the radiation of an excimer laser using phase masks have a temperature range limitation due to the high-temperature degradation of the spectrum of recorded FBG;

– optical fibers used for recording FBG are much more expensive to produce compared to standard ones. The need for long-term exposure of optical fiber to hydrogen to improve the quality of heterostructure formation requires a significant time reserve from the manufacturer for the preparation of optical fibers. The presence of additional costs and areas for the purchase, installation, and operation of special technological equipment;

– the ability of one mask to form a certain period of FBG limits the possible range of wavelengths of the reflected signal of the FBG sensor. As a result, there is a need to manufacture a significant number of phase masks or the formation of only typical sensors for operation in a limited spectral range without taking into account the characteristics and individual technical requirements of EPI [9–11];

– technological operations to remove the recovery of the protective coating of optical fiber not only significantly complicate the production process of FBG but also are associated with the risk of fiber destruction. In addition to the threat of mechanical damage, optical fiber without a protective coating is destroyed by environmental moisture.

The main factor is the threat of destruction of FBG in the interaction of optical fiber with a hygroscopic shell saturated with moisture. This is due to the process of stimulated hydrolysis. During hydrolysis, the water molecule is embedded in a tense Si-O-Si bond, destroys it, and creates new bonds with hydrogen. Within the surface layer of the fiber material, the bridge bond between silicon ions is broken, and two unstable «radicals» are formed. Due to the fact that «radicals» have a significant reactivity to environmental molecules, there is a combination of the silicon atom with the OH group and the creation of the Si-OH silanol grouping.

With further contact of moisture with optical fiber, the area and porosity of the surface of the hydrated surface layer gradually increases. The newly formed layer is able to adsorb water as a result of the action of capillary forces, which contributes to an increase in leached surface layers and the formation of a gel-like layer of silica acid up to 100...200 nm. With further growth of thickness and porosity of the layer, destruction can approach the core of the fiber, which will cause its gradual destruction [12].

An option to overcome the corresponding difficulties may be to increase the thickness of the hydrophilic coating. This approach is used in [13–15].

But the issue remained unresolved related to a significant deterioration in the performance indicator with an increase in the thickness of the hydrophilic coating. A thicker polyimide layer can effectively create larger stresses affecting the FBG to increase the magnitude of the Bragg wavelength shift. However, this, in turn, inevitably impairs the time characteristic of the sensor and increases its sensitivity to changes in ambient temperature. The deterioration is due to the fact that the polyimide coating on the optical fiber with FBG is not uniform throughout the intersection of the site with FBG while the adhesion of the coating to the fiber decreases at elevated temperatures. As a result, the FBG humidity sensor will receive complex humidity measurement characteristics.

An option to overcome the corresponding difficulties may be the use of optical fibers covered with a layer of agar and agarose. This solution is proposed in [16]. But, since agarose is a linear polysaccharide, issues related to the resistance of these materials to the concentrated effects of DF in real operating conditions remained unresolved.

It is proposed in [17] to completely isolate optical fiber from moisture and DF exposure to a thin layer of nanomaterial and apply hair of biological origin to convert humidity parameters into changes in optical radiation. The use of a protective nanolayer demonstrated not only the powerful protection of optical fiber but also had a positive effect on its physical and mechanical properties [18].

At the same time, the issue related to the long-term stability of hair of biological origin under the influence of operational factors remained unresolved. The reason for this may be objective difficulties associated with changes in the physical and mechanical characteristics of the fiber in real operating conditions.

An option to overcome the corresponding difficulties may be the use of synthetic analogs of biological hair. This approach is used in [19], where the potential possibilities of synthetic polyamide materials were evaluated.

All this suggests that it is expedient to conduct a study on the replacement of biological materials with artificial fibers made of hygroscopic polyimide.

So, in this situation, it is of particular relevance to tackle the scientific and technical problem of rational combination of protection and preservation of metrological and technological-economic characteristics of RH FOS systems for monitoring the intensity of PD and the level of humidity in ship EPI [20–22].

3. The aim and objectives of the study

The aim of this study is to develop a technology for measuring humidity using a fiber-optic sensor. The introduction of the results of the study will make it possible to significantly reduce the probability of error when assessing the value of relative humidity during the operation of EPI.

To accomplish the aim, the following tasks have been set:

– to determine the circuitry solution for RH FOS, which is noise-resistant to the effects of operational DF in the implementation of constant and long-term diagnosis and forecasting of the technical condition of EPI elements;

– to synthesize a mathematical model for estimating the influence of controlled parameters on the metrological characteristics of invariant fiber humidity sensors.

4. The study materials and methods

The object of this study is the processes of formation and transformation of optical power in the sensitive optical fiber of the moisture control tool during EPI operation.

The subject of our study is fiber-optic means of humidity control, operating under difficult o conditions.

The main hypothesis of the study assumes the possibility of using the combination of optical fiber with a depressed core and polyimide fiber to convert the value of humidity into changes in the power of optical radiation.

The theoretical part of the work is done using:

a) system analysis – in determining the structural relationships between the elements of the measuring means of humidity control and decomposition of the object of our study;

b) the theory of optical waveguides – in determining the coefficients of optical communication of the cores of optical fiber;

c) methods of analytical study of the processes of interaction of fields of optical waveguides – investigating the processes of transformation of light radiation in optical fiber under the influence of deformations initiated by changes in humidity;

d) mathematical modeling – when obtaining an approximate assessment of the functioning of the optomechanical system FOS.

To characterize the thermohygrometric properties of fiber-optic sensors, it was important to check them in an environment with precise temperature and humidity settings. In particular, it was necessary to work at very low levels of relative humidity (less than 10 % relative humidity), controlling relative humidity with a resolution of 0.1 % RH in the range from 0 % RH to 90 % RH, and temperature fluctuations from −20 °C to 50 °C. To assess the measurement error, a highly efficient dew point hygrometer with a cooled mirror was used as a reference sensor for measuring moisture. To average the result, three additional industrial electronic hygrometers were used along with three calibrated resistive thermometers (PT100) to measure temperature. These sensors were connected to the outer measurement circuit through sealed connectors. The experimental installation software is implemented in MATLAB Simulink.

Interaction with EPI DG was implemented on sixteen channels of FC/APC adapters. Sensors are connected to an optical scanner with a resolution of 1 pm and a working range of wavelengths from 1460 nm to 1620 *nm*.

The reference sensors were calibrated in the range of temperature changes of −5 °C to 25 °C and relative humidity in the range of 0...25 %.

To parameterize all DG for temperature, relative humidity was maintained constant at 10 1±% % RH to avoid cross-sensitivity problems. To calibrate all devices, several temperature tests were carried out, during which the temperature changed in the range of −5...25 °C. The fiber-optical sensors showed unexpected spectral changes for temperatures below 0 °C. This behavior is probably due to the bending of the fiber. Therefore, calibration points at negative temperatures were not taken into account. This behavior can be explained by the effect of the package. The package not only protects the fiber but also keeps it even in a state of constant tension. However, with relatively large temperature changes, the difference in the coefficients of thermal expansion of different materials (copper and ceramics packaging, fiberglass) does not guarantee such a deformed state.

5. Results of investigating a fiber-optic relative humidity sensor for monitoring electric power installations

5. 1. Determining a circuitry solution for the fiber-optic sensor of relative humidity

It is known that the problem of a significant increase in the level of stability and reliability of sensor measurements is solved in most practical applications on the basis of synthesis of the measuring instrument. Such a tool is built on the basis of optimizing the combination of design parameters and a combination of materials that are invariant to external uncontrolled influences.

In RH FOS, either directly or after a preliminary transformation, the measuring physical quantity affects the parameters of the optical channel of the sensor through which optical radiation propagates.

Therefore, it is advisable at the first stage of designing a circuitry solution to determine the parameters of the sensitive optical fiber of the sensor.

From the standpoint of providing more advanced physical and mechanical characteristics of the sensor sensing element, it is proposed to use optical fibers created on the basis of artificial sapphire as the material of the optical channel. The use of artificial sapphire in which there is almost no mechanical hysteresis will provide the necessary level of sensitivity, resistance of the fiber surface to DF, and the necessary and sufficient increase in the geometric dimensions of the fibers [23].

To overcome the limitation in fibers of increased diameter due to the multimode mode coupled to the phenomenon and problems caused by intermodal dispersion, the following is proposed.

Choose the implementation of a single-mode mode at the sensitive optical fiber of the sensor of increased diameter by increasing the working wavelength and using fiber with a depressed core [24].

As for the protection of the surface of the sensitive optical fiber of the sensor, we consider it appropriate to completely eliminate any contact of the surface with the environment using a protective coating.

A protective coating is a system consisting of a single layer of carbon nanotubes with a thickness of ≤100 nm, applied in vacuum when using laser radiation and when orienting carbon nanotubes in an electric field. The use of a protective coating will provide an increase in moisture-resistant fibers, leveling the phase separation limit: solid base-coating, increased uniformity, mechanical and laser strength, reducing the surface roughness of the optical fiber [25].

One of the most promising replacement materials is polyimide fiber. Among the most important qualities of polyimides, which determine their importance in various applications, is high heat resistance. The strength of polyimide fibers with hinged fragments in the dianhydride fragment can reach 400 MPa, and the relative elongation at stretching is 30 % [26]. As in the nearest analog, polyimide fiber will come into contact with moist air, and by changing its geometry during moisture adsorption, cause fluctuations in compression voltage to optical fiber covered with a protective layer. Thus, the circuitry solution for RH FOS will take the form shown in Fig. 1.

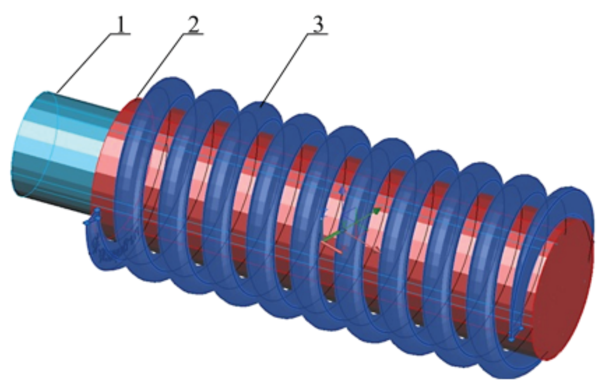

Fig. 1. Schematic of the proposed fiber-optic humidity sensor: 1 – optical fiber made of sapphire glass; 2 – protective coating; 3 – coil made of hygroscopic polyimide fiber

The fiber superimposed on the light guide creates a preliminary voltage in it. The fiber is fixed on the protective sheath with a preliminary tension. As a result, a stress is formed in the light conductor, which initiates a change in the refractive profile index (RPI) of the optical fiber material. From the standpoint of the method of equal volumes, the combination of the stressed and free parts of the optical fiber is analogous to the combination of light conductors with different apertures. After moistening the fiber, its length increases, which initiates a decrease in tension in the optical fiber. That is, conditions are created for equalizing the apertures of two areas of sensitive fiber.

5. 2. Synthesis of mathematical model of invariant fiber humidity sensor

The first assumption is due to the technology of creating optical fiber. The latter was considered as a layered structure of a homogeneous core with a radius ρ of material with a refractive index n_{co}, and concentric layers with refractive indices n_{co1}, n_{co2}, etc. At the boundary of the layer section, the parameter of the relative dielectric constant ε is changed by an abrupt jump. In this case, the full field can be evaluated as the superposition of the fields of each layer. In such a structure, the voltage within each layer is considered constant. Each layer has its own mechanical characteristics. The fiber material is considered absolutely elastic, the deformations do not lead to destruction. The assumption allows us to apply in the calculations of the model of classical mechanics of continuous media obeying Hooke's law for an anisotropic body.

To analyze the multilayer optical structure, wave analysis based on Maxwell's equations was used, which makes it possible to consider the processes of light propagation at any ratio between the size of the system forming the light beam and the wavelength.

Maxwell's equations in differential form are suitable for linear structures whose parameter ε either does not depend on coordinates or is a continuous coordinate function.

To fully determine the field of such a structure, the boundary conditions are determined in Maxwell's equations, 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 is the Bessel function of the first kind; K_0 – modified Bessel function of the second kind; U and W are the scalar parameters of the mode for the core and shell related to the optical fiber parameters thru the ratios $V^2=U^2+W^2$;

$$V=k\rho\left(n_{co}^2-n_{cl}^2\right)^{1/2}.$$

Parameter U is associated with a constant propagation of mode β via the relation

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

The second assumption is due to the nature of the perturbation of parameters under the action of a controlled value.

In the case of homogeneous changes in the refractive indices of the core and the shell, when the refractive index of the core differs everywhere from the refractive index of the unperturbed fiber by Δn_{co}, then one can take $\overline{\eta}_p=\overline{\eta}$, $\Delta n=\Delta n_{co}$, where $\overline{\eta}$ is the share of mode power spreading through the core. The proportion of power in the shell is equal to $1-\overline{\eta}$, if the refractive index of the shell differs by Δn_{cl} from the corresponding parameter of the unperturbed fiber, the constant propagation in the perturbed fiber is defined as

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

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

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

where K_1 is the modified Bessel function of the second kind.

The third assumption is due to the dependence of the intensity distribution of the main mode over the cross-section of single-mode fibers with stepped RPIs and the value of the waveguide parameter V on the "volume" of the refractive index profile. This gives reason to consider the interaction of perturbed layers of fiber from the standpoint of the method of refractive index of equal volume [27].

For a more significant analysis, it is accepted that the sensor sensing element is a composite rod, which consists of an elastic three-component core, a protective coating (index 4), and an elastic shell. A three-component is understood as a complex core of the primary depressed (index 1) and two secondary (index 2, 3) (Fig. 2).

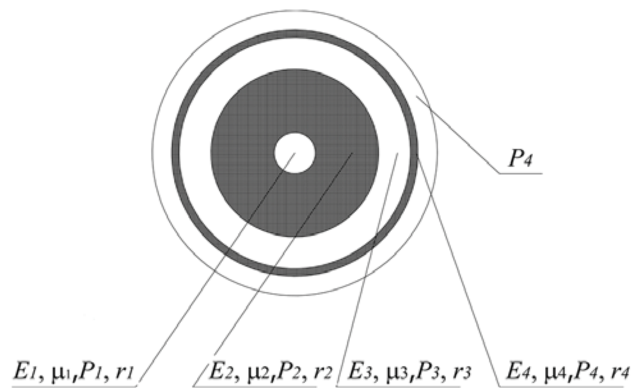

Fig. 2. Structure of the sensing element of the fiber-optic humidity sensor

The interrelation of processes in the multilayer structure of the optical fiber allows any arbitrary deformation of the boundary of the separation of layers to be approximated by a sequence of small jumps. The transformation of mode radiation by many jumps is a superposition of the fields generated by each individual jump. Such a simple and rational model can be applied to any complex optical fiber field. Approximation of optical fiber with a multilayer structure allows us to create and apply a discrete design scheme. According to this scheme, the task of coordinating two waveguide structures is considered as the excitation of the field of the receiving antenna by some field of the emitting antenna. Within each layer, the effective volume of the profile is defined as the volume of the body given by the rotation of the profile curve around the fiber axis. The approximation of a deformed multilayer fiber by a coaxial structure allows us to consider the processes of optical radiation conversion within the framework of the theory of connected modes, namely fiber as a set of tunnel-connected waveguides in which optical radiation tunneling (ORT) occurs. Optical cross-connection implies interference between the fields of each waveguide.

It is advisable to accept that the radiation enters the first secondary core and, under the influence of mechanical loads, is partially tunneled to the second secondary core. Then, to determine the constant of propagation β in perturbed cores, it is necessary to determine the corresponding stresses and additions to the magnitude of the refractive indices in these layers Δn.

For the structure of the sensing element in the cylindrical coordinate system r, ψ, z (the z axis coincides with the axis of the rod), from the solution to the Lame problem, at r=0 voltage

$$\sigma_r^{(1)} = \sigma_\psi^{(1)} = -P_1, \tag{5}$$

where P_1 is the pressure from the outer layer to the primary core [28].

Then, taking into account the boundary conditions $\sigma_r^{(2)} = -P_1$ at $r=r_1$ and $\sigma_r^{(2)} = -P_2$

$$\sigma_{r,\varphi}^{(2)} = \frac{P_1 r_1^2 - P_2 r_2^2}{r_2^2 - r_2^2} \pm \frac{r_1^2 r_2^2}{r^2} \cdot \frac{P_1 - P_2}{r_2^2 - r_1^1}. \tag{6}$$

The expression $\sigma_r^{(2)}$ corresponds to a minus sign, $\sigma_\psi^{(2)}$ – a plus sign.

Provided that the displacements in the tangential direction are equal to $u_1=u_2$ at $r=r_1$, the internal pressure P_1 is defined as

$$P_1 = \frac{E_2\left(r_2^2 - r_1^2\right)}{(1-\mu_2) r_1^2 + (1+\mu_2) r_2^2}\left[\frac{2 r_2^2 P_2}{E_2\left(r_2^2 - r_1^2\right)} - 1\right], \tag{7}$$

where E_2 is the Young modulus of the first secondary core;

μ_2 – Poisson coefficient;

r_1 – radius of the primary depressed core;

r_2 – radius of the first secondary core.

Taking into account the boundary conditions $\sigma_r^{(3)} = -P_3$ at $r=r_3$ $\sigma_r^{(3)} = -P_2$ at $r=r_2$

$$\sigma_{r,\psi}^{(3)} = \frac{r_2^2 r_3^2}{r_3^2 - r_2^2}\left(\frac{P_2 r_2^2 - P_3 r_3^2}{r_2^2 r_3^2} \pm \frac{P_2 - P_3}{r^2}\right). \tag{8}$$

Provided that the displacements in the tangential direction $u_2=u_3$ at $r=r_2$ are equal, the pressure in the first secondary core P_2 will be defined as

$$P_2 = \left[\frac{4}{3} \cdot \frac{1+\upsilon_3}{E_3} \cdot \frac{r_3^2 P_3}{r_3^2 - r_2^2} + \frac{2 P_1 r_1^2}{E_2\left(r_2^2 - r_1^2\right)}\right] \times \left[\frac{1+\mu_3}{3E_3} \cdot \frac{3r_3^2 + r_2^2}{r_3^2 - r_2^2} + \frac{r_2^2(1-\mu_2) + r_1^2(1+\mu_2)}{E_2\left(r_2^2 - r_1^2\right)}\right]^{-1}, \tag{9}$$

where E_3 is the Young modulus of the second secondary core;

r_3 – radius of the second secondary core.

By analogy with above calculations

$$\sigma_{r,\psi}^{(4)} = \frac{r_3^2 r_4^2}{r_4^2 - r_3^2}\left(\frac{P_3 r_3^2 - P_4 r_4^2}{r_3^2 r_4^2} \pm \frac{P_3 - P_4}{r^2}\right). \tag{10}$$

Provided $r=r_3$

$$P_3 = 4\left[\frac{1+\mu_4}{E_4} \cdot \frac{r_4^2 P_4}{\left(r_4^2 - r_3^2\right)} + \frac{1+\mu_3}{E_3} \cdot \frac{2 P_2 r_2^2}{\left(r_3^2 - r_2^2\right)}\right] \times \left[\frac{1+\mu_4}{3E_4} \cdot \frac{3r_3^2 + r_4^2}{r_4^2 - r_3^2} + \frac{(1+\mu_3) + \left(r_3^2 + 3r_2^2\right)}{E_3\left(r_3^2 - r_2^2\right)}\right]^{-1}, \tag{11}$$

where E_4 is the Young modulus of the protective shell;

μ_3 – Poisson coefficient of the second secondary core;

r_4 – radius of the protective shell.

The main stress in the material of the optical fiber covered with a protective sheath is the compression stress P_4, resulting from the winding of polyimide fiber with a diameter of d_{pf} with tension $S_{\max}$ on it. The wound polyimide fiber creates a uniformly distributed surface load. Regardless of the shape of the surface, the projection of an equivalent force from this load onto a given axis is equal to the product of this distributed load on the projection area of this surface on a plane perpendicular to a given axis. Then the radial pressure between polyimide and optical fiber, when the polyimide fiber stretches under the influence of moisture, can be defined as

$$P_4 = \frac{k\Delta l}{r_4 d_{pf}}, \tag{12}$$

where k and Δl are the rigidity and elongation of polyimide fiber.

The relationship between the components of stress tensors and the refractive index in the radial compression of the optical fiber in cylindrical coordinates is defined as

$$n_r = n + C_1 + \sigma_r; \quad n_\psi = n + C_1\sigma_\psi + C_2\sigma_r;$$

$$n_z = n + C_2\left(\sigma_r + \sigma_\psi\right). \tag{13}$$

where n is the refractive index of the unperturbed layer;

n_r, n_ψ, n_z are the diagonal components of the tensor of the refractive index**;**

C_1, C_2 – light-elastic constants.

Then the dependence of the value of the coefficient of connection between the first and second secondary cores in ORT under a deformation mode will be defined as

$$C = \sqrt{\frac{\pi\Delta_p}{\left(\beta^2 - k^2\left(n_3 + n_{r3}\right)^2\right) d r_3^2}} \times \frac{\sqrt{\left(k^2\left(n_2 + n_{r2}\right)^2 - \beta^2\right)}}{\left(k\rho\left(n_2 + n_{r2}\right)^2 - \left(n_3 + n_{r3}\right)^2\right)^2} \times \frac{\exp\left(-\left(\sqrt{\beta^2 - k^2\left(n_3 + n_{r3}\right)^2}\right) d\right)}{K_1^2\left(\rho\sqrt{\beta^2 - k^2\left(n_3 + n_{r3}\right)^2}\right) d}, \tag{14}$$

where β is the difference in the constants of propagation in the core and shell of optical fiber;

k – wave number;

d – optical fiber diameter;

Δ_p – profile height parameter;

n_{r1}, n_{r2} – addition of the refractive index of the first and second secondary cores;

K_1 is the Bessel function.

From (13) and (14) it follows that the optical power F_Σ in the first secondary core can be defined as

$$F_\Sigma = \left[1 - \frac{\sin^2 C(L+\Delta L)\sqrt{1+\left[\left(\left(\beta_R + \beta_{cs}\right) - \left(\beta_T + \beta_{cs}\right)\right)/2C\right]^2}}{1+\left[\left(\left(\beta_R + \beta_{cs}\right) - \left(\beta_T + \beta_{cs}\right)\right)/2C\right]^2}\right] F_0, \tag{15}$$

where F_0 is the total power injected into the first secondary core;

β_R – distribution constant in the first secondary core;

β_T – distribution constant in the second secondary core;

β_{cs} – increase in propagation constant due to perturbations that violate the circular symmetry of the coaxial structure;

L – length of the optical fiber section with a protective sheath and a coil made of polyimide fiber;

ΔL – elongation of the optical fiber during deformation.

Once we, to determine the value of the optical power recorded at the output of the first secondary core, apply the parameters of real materials, namely [29]:

C_{21}=–2.5·10^{-6} mm^2/N; C_{22}=–3.8·10^{-6} mm^2/N;

E_1=345 GPa; v_1=0.25; r_1=0.025 mm; n_1=1.47;

E_2=345 GPa; v_2=0.25; r_2=0.0625 mm; n_2=1.77;

E_3=345 GPa; v_3=0.25; r_3=0.2 mm; n_3=1.75;

E_4=0.82 GPa; v_4=0.33; r_4=0.35 mm;

E_{PF}=4 GPa; v_{PF}=0.3; d_{PF}=0.35 mm;

Δl=2...10 % (in the RH range of 20...60 %), then the dependence of the value of optical power on RH will take the form given in Fig. 3.

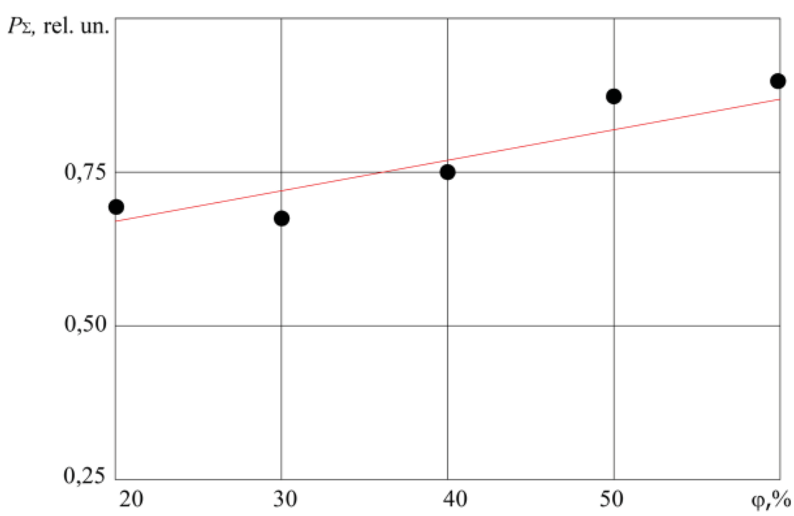

Fig. 3. Dependence of the optical power value F_{Σ}, recorded at the output of the sensing element of the fiber-optic sensor, on the value of relative humidity (• — experimental points obtained from the test results of the model sample)

The nature of the dependence indicates that the refractive coefficients increase with increasing radial compression, respectively, the number of modes, the relative difference between the refractive indices and the intermodal dispersion decrease.

6. Discussion of results of investigating a new circuitry solution for a fiber-optic humidity sensor

The design of RH FOS according to the proposed circuitry solution has made it possible to obtain a measuring instrument that is invariant to the uncontrolled effects of destabilizing factors. The use of such a tool will contribute to the organization of constant and long-term monitoring of the technical condition of EPI elements.

To enable the noise immunity of the proposed RH FOS, advancements in the following areas are involved.

Heat resistance and moisture protection of the sensor sensing element was enabled by a combination of the latest materials (artificial sapphire and nanotubes) and technological features of production (the method of precipitation from the vapor phase). Owing to this technological process, it is possible to achieve a strong combination of optical fiber and protective shell. To build a coil of polyimide fiber, technologies for creating similar coils for fiber-optic gyroscopes can be well mastered by industry. Polyimide fiber itself has properties that allow its use under conditions of concentrated exposure to DF.

Unlike [1], where direct contact of polyimide and glass materials is applied, the use of ultra-thin protective nano-shell prevents the destruction of optical fiber without compromising the sensitivity of RH FOS.

The proposed tool has certain limitations of its application. First of all, such restrictions include levels of mechanical and temperature exposure. A significant limitation can be associated with the influence of an aggressive environment on the elements of RH FOS. That is, the humidity sensor can provide degenerate information under conditions when the destruction of its elements occurs under the influence of DF. Taking into account the peculiarities of RH FOS layout, it can be noted that the most vulnerable is a coil made of polyimide fiber. Another element that significantly affects the characteristics of RH FOS is an adhesive material that fixes the ends of the polyimide fiber on the protective sheath.

The improved mathematical model (15) allows synthesizing a fiber sensor invariant to the effects of DF, with any variation of the initial information and structural elements of the sensing element.

Analyzing Fig. 3, we can conclude that by using this approach, the survey of 16 sensors at a remote location of engine room occurred with losses in optical fiber of 0.2·10^{-3} dB/m with a reflectivity of 99 %. With a channel power of –10 dB/m, assuming the worst-case scenario with the highest vibration coefficient near the main engine, such losses are not significant and lie within the measurement error [30–35].

Given the possibilities, limitations, and disadvantages, the development of the study should involve:

– further improved mathematical model of RH FOS, which will make it possible to take into account more factors affecting the ability to carry out continuous monitoring of ship EPI for long periods of time;

– search for ways to increase the physical and mechanical properties of polyimide fiber, materials for its combination with a protective sheath;

– optimization of parameters of all elements of RH FOS according to the criteria of reliability and speed.

7. Conclusions

1. The circuit design solution of RH FOS has been determined, which meets, first of all, the criteria for noise immunity to the effects of operational DF in the implementation of constant and long-term diagnosis and forecasting of the technical condition of EPI elements. Unlike many well-known ones, the proposed RH FOS, due to the higher resolution has made it possible to improve the accuracy of measurement and, due to the design characteristics, to reduce dependence on temperature and humidity. The performance of the sensor has been experimentally confirmed and characterized in terms of amplitude-frequency characteristic, sensitivity, and dependence on humidity and temperature. In addition, experimental tests were carried out in the RH range of 20...60 % for further verification of the effectiveness of the combination of the proposed sensor with similar ones. The deviation of the optical power value outside the specified static pressure is insignificant and is within the statistical error.

This result was achieved due to the fact that the proposed sensor had a linear response to static pressure and high resolution to dynamic pressure. Several resonant frequencies that could affect the humidity measurement indicators lie within the highest odd harmonic components, and the favorable detection range did not reach 300 Hz, that is, 6 harmonics of the DG output voltage. The temperature dependence of the sensor was less than 0.5 mV to change in the temperature of 14 °C, which is impossible under the conditions of the machine-boiler room (MBR) of the vessel. The dependence of the output signal on the distance to DG is not significant in terms of the possibility of increasing the value of the structural coefficient of energy efficiency (Energy Efficiency Design Index – EEDI) and the operational coefficient of energy efficiency (EKEE) of modern vessels through the use of high-voltage technologies.

2. The synthesized mathematical model has made it possible to prove that the change in the deformation of the detection of optical fiber at a key level corresponds to the change in pressure in the fiber-optic sensor, and the trend of 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 optical source, as well as undesirable losses at any point in fiber-optic communication. This has made it possible to minimize the level of required signal power at the output of FOS without losing the accuracy of RH measurement, assuming that the communication length can be halved for the worst adapter channel.

Thus, the proposed modeling approach avoids an unnecessary increase in the number of adapter channels, thereby scaling the proposed network of sensors but not by reducing or increasing the distance of the remote location in MBR and increasing the number of elements.

Also, unlike other existing models, the proposed model allows us to assess the level of cross disturbances when two sensors operating in the same channel are interrogated simultaneously. The implementation of scalability to any networks based on FOS to increase the number of addressed sensors is not by reducing or increasing the distance to the location of DG but by the possibility of calibrating the signal strength.

One of the main advantages of the synthesized model is the flexibility to select specific MBR operating points for each remote sensing point, which allows the development of phase shift configurations to achieve the target behavior of the measurement parameter, such as linearity or sensitivity. It is possible to expand the implementation of this approach in order to use virtual devices to determine virtual delay lines and self-identify sensors of the proposed survey topology for specific MBR.

The mathematical model of optical radiation conversion in RH FOS is universal and can be used to build a wide range of noise-resistant diagnostic tools for ship electric power systems.

Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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