Fiber-optic rudder position sensor for unmanned vessels

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Abstract. The paper presents the results of a study on the design of the rudder position sensor of a steering vessel, in which an optic fiber is a sensitive element and a data transmission line. A design of a sensitive element based on the effect of bending modulation of light transmission of an optic fiber is proposed, and a mathematical expression is obtained in ray equivalence, which describes the behavior of the sensitive element. The prototypes of the sensitive element and the laboratory setup have been developed, numerical modeling has been carried out, and experimental results have been obtained showing the potential use of the proposed approach for this class of problems.

1. Introduction

The steering device is designed to change the turn of the vessel (including unmanned) and keep it on course by turning the rudder at a certain angle or keeping it in the center plane of the vessel. The rudder is the main body that ensures the operation of the device; it is designed to perceive the water pressure and turn the vessel; the steering drive is designed to communicate with the steering gear and transfer torque to the stock; steering gear - to ensure the operation of the steering gear, and finally, teledynamic transmission is needed to connect the steering gear with the vessel control posts. To control the position of the rudder of the vessel, an axiometer is used - a vessel measuring device, which is a part of the steering device, and indicates in degrees the deviation of the rudder from the centerline of the vessel at each moment of time. The axiometer is installed, as a rule, in front of the helm and is connected by an electrical circuit with the rudder stock. The sensitive element of the axiometer is traditionally a resistive rudder position sensor, the signal from which is also used in the feedback system of automatic steering devices. Such a sensor must have a shockproof, waterproof housing that provides vibration resistance and high operational reliability.

At present, a significant number of fiber-optic sensitive elements of various types have been developed [1]. One of the promising types of sensors for controlling the position of the rudder blade are amplitude fiber-optic sensors based on total internal reflection diffraction, in which the transmission of optical radiation of a fiber-optic guide (FG) changes when its geometry changes. Ample opportunities for creating on their basis a rudder position sensor open up such their properties as the continuity of the design of the sensitive element and the ease of control of its geometry. A study on the principles of amplitude microbending sensors operation and designs can be found in the works [2-8].
In [2], a study on the design and analysis of the experimental results of a sensitive element based on a plastic optical fiber with a NiTi alloy deposited on the surface with a shape memory effect is presented. On the basis of microbending of an optical fiber using a micro-deformer, a load sensor with good sensitivity and a wide measurement range (declared up to 30,000 Newtons) is described in [3]. The work [4] considers a fiber-optic textile heart rate sensor. The described design involves squeezing a multimode (MM) optical fiber with two parallel stripes in an elastic substrate. Approaches based on micro-bending “sensing” of optical fibers in three-dimensional carbon or epoxy composites are also successfully used to measure internal deformations [5].

In [6], a new approach to the formation of a microbend in the sensitive element of an optical fiber based on photocurable technology is described. The photocurable material is injected into a flexible hollow center fiber containing an optical fiber. When such a structure is bent, a part of the optical power is “emitted” from the fiber and causes the photopolymerization of the photocurable material.

A theoretical study on the bending loss of a single-mode fiber in mode equivalence is presented in [7]. The authors have developed a loss modulator that provides losses of 0-25dB in the offset range of 0-25μm.

The authors of the current article propose a design of a sensitive element based on a fiber-optic element base, as an alternative to a traditional resistive rudder position sensor. This solution is most relevant for unmanned vessels, since the sensitive elements based on fiber optics have all their advantages - they are able to operate in places with increased requirements for explosion and fire safety, have high corrosion resistance, are insensitive to the influence of electromagnetic interference, and the use of a light carrier provides the minimum time for transformation and transfer of information to the processing system. Also, amplitude fiber-optic sensors do not impose high requirements on optical radiation sources, which determine the low cost of measuring systems based on them.

2. Theoretical calculation and design of the sensor

The fiber-optic angle sensor under development is based on the effect of changing the transmission of an optical channel by controlling its geometry. In this case, the transmission of the optical channel changes due to the formation of a given number of microbends in the optical fiber.

It is known that a decrease in the output optical power upon application of a force to an optical fiber occurs due to the microbending-induced mode conversion and the subsequent release of higher-order modes into the cladding and the environment. In this case, an increase in the amplitude sensitivity of the sensor is achieved through the use of additional mechanical elements - specially profiled plates. When a fiber is compressed between two profiled plates, a predetermined number of microbends appear, affecting the output value of the optical signal much more than a single macroscopic bend. For example, when an optical fiber is compressed between two specially shaped plates, a given number of microbends appear which affect the output value of the optical signal much more strongly than a single macroscopic bend [8].

The authors obtained the main dependences in the ray equivalence, which describe the effect of a profiled plate on a fiber: the dependence of the grating constant of the shaped plate on the mechanical and optical parameters of the fiber and the dependence of the optical power attenuation coefficient on the pressing force of the shaped plate. Thus, in [8], the calculation of the lattice constant of a profiled plate is presented, the optimal value of which corresponds to the maximum loss of power of optical radiation in a fiber, provided that its elastic properties are preserved. The dependence of the radiation power loss at the output of the optical fiber on the force acting on the profiled plate $F_d$ is described as

$$P(F_d) = P_0 \exp(-\varphi(F_d) \cdot \gamma(R(F_d);F_d))$$

where $\varphi(F_d) = \pi \cdot \Lambda / 180R(F_d)$ - the bending angle of the fiber as a function of the force in radians, the attenuation coefficient $\gamma = \gamma(R(F_d);F_d)$ on the force and the microbending radius of the optical fiber, $\Lambda$ – the lattice constant of the profiled plate. The obtained dependences confirm the tendency of monotonic
disturbance of the light transmission of an optic fiber bent onto a profiled plate and make it possible to theoretically calculate the insertion loss of microbends in the production of the sensor.

To measure physical quantities, it is necessary to introduce an element into the sensor design that converts the measured physical effect into a force between the profiled plates of such a fiber-optic sensor, for example, in the production of a temperature sensor; a thermodynamic converter with a liquid working fluid can be used [8]. A threaded screw of a given pitch can serve as such a transducer for measuring the angle of rotation, as shown in figure 1.

![Figure 1. Design of fiber-optic rudder position sensor:](image)

- 1 – profiled plates;
- 2 – optical fiber;
- 3 – mechanical stop;
- 4 – screw;
- 5 – mechanical propulsion for rudder stock connection;
- \( \Lambda \) – lattice constant of the profiled plate.

The design also assumes a mechanical connection with the rudder stock of the vessel. The screw is located over the top profiled plate and is rigidly fixed relative to the bottom plate. When the screw turns between the profiled plate, a force is generated that is proportional to the angle of its rotation. In this case, the dependence of the radiation power loss at the fiber output can be expressed as

\[
P(k\alpha) = R_0 \exp(-\varphi(k\alpha) \cdot \gamma(R(k\alpha);k\alpha))
\]

where \( \alpha \) – the screw rotation angle, \( k \) – the proportionality coefficient depending on the screw pitch and the lattice constant of the profiled plate.

To develop the design of the sensor, the main dependence in the ray approximation was obtained, which describes the attenuation of the optical radiation power at the output of the optical fiber when it is exposed to profiled plates with the number of bends \( N \), depending on the applied force \( F \):

\[
P(F) = R_0 \left[ \frac{R(F) + \rho \theta_{\ell}(r)}{R(F) - \rho - \theta_{\ell}(r)} \right] \exp \left( -\frac{\pi \cdot N^3 F^2 NA}{101 d_e^2 E^2 N^2 \varepsilon} \cdot \exp \left( -\frac{4FAKL}{\rho(1 - \beta A)4FA + 3d_e^4 EN} \right) \right) d\theta
\]

where \( d_e \) – the effective diameter of the optical fiber; \( \Lambda \) – the lattice constant of the profiled plate, \( E \) – the Young's modulus of the fiber; \( \rho \) – the radius of the fiber core; \( NA \) – its numerical aperture; \( K = 2k/3 \), where \( k \) – the wave vector; \( \beta = \frac{l^2}{n_0^2 \theta_{\ell}^2} \), where \( l = r n(r)/(R + \rho) \) - the invariant of the ray path, which is constant along the path of propagation of the ray and characterizes its direction at any point of the cross section of the fiber, \( \theta_{\ell}(r) = \arcsin(n(r)/n_0) \) - the local critical grazing angle, \( n_0 \) – the refractive index of the fiber core; \( L = \sqrt{(l^2/n_1^2 - 1)^3} \); \( \varepsilon = 2\pi \rho \cdot 1 \).

### 3. Description of the laboratory setup

To check the proposed theoretical principles of the sensor design, an experimental model of the measuring system was made, the diagram of which is illustrated in figure 2.
Figure 2. Diagram of the laboratory layout (a) and the working window of the program (b).

The model consists of an optical radiation input unit, an optical information registration unit and a data processing and visualization system. A personal computer with a specialized software package developed for processing data from the sensor under study was used as a data processing and visualization system. The registration unit is a microcontroller-controlled analog-to-digital converter (ADC), at the input of which there is a photodetector amplification circuit. The registration unit is connected to the computer by a RS-485 data transmission line. The input block implements the key control circuit for the emitter. To ensure high metrological characteristics of the sensor, elements for stabilizing the emitter current are introduced into the circuit. Before the experiment, the radiation registration system was calibrated using an OT-30-1 optical tester. A single-fiber multimode fiber 7 m long with a core/cladding diameter of 50/125 μm and an outer diameter of 3 mm was used as a sensitive element. The optic fiber is passed between the profiled plate and is connected to the optical radiation input unit and the optical information recording system through standard FC/PC fiber-optic connectors.

Profiled plate size 15×27 mm, lattice constant Λ = 5.52 mm.

The work of the layout is carried out as follows. Upon request from the computer, the registration unit generates a pulse of a given duration in the optical radiation input unit. Passing through the optical fiber, the level of the optical signal decreases in proportion to the external influence. This level is measured by the ADC, pre-processed and passed to the computer, which displays the result of external influence.

4. Results and conclusion

Figure 3a shows the result of numerical simulation of expression (3) - a graph of the dependence of the output optical power on the external force P(F) for the PP with Λ = 5.52mm, N = 10 and the radius of bending elements R = 1.5mm. The dependence is continuous and monotonically decreases in the entire domain of definition, which confirms the possibility of modulating the optical radiation power by the compression force of the profiled plates, and, consequently, the possibility of creating a rudder position sensor based on the described design, which uses an optic fiber not only for supplying/removing radiation, but also in as a sensing element.

An experimental study of a laboratory sample of the sensor (figure 3b) generally correlates well with the theoretical relationship. It should be noted that the experimental dependence demonstrates the effect of hysteresis, which goes beyond the instrumental error. In the case under study, the effect consists in the discrepancy between the values of the optical power at the output of the fiber during the fixation of data with increasing and decreasing the angle of rotation, while the maximum value of the difference reaches 5% at significant bends of the fiber. This is due to the fact that the elastic deformation of the optical fiber restores its original value only at insignificant bends, thus requiring additional design solutions for restoring the fiber geometry for deep modulation of light transmission. Also, significant restrictions on the practical application of this type of sensitive elements are introduced by the fact that the fiber under pressure on it with profiled plates simultaneously undergoes both axial and radial deformation, which can complicate its compensation and subsequent restoration of the optical fiber.
Figure 3. a) numerical modeling of expression (3); b) experimental dependence of the normalized output optical power $P(F)$ on the angle of rotation for the experimental sample of the sensor.

Nevertheless, the studies performed demonstrate the fundamental possibility of manufacturing a rudder position sensor based on micro-bending modulation of the light transmission of an optical fiber. The design of the sensor possesses simplicity of manufacture and change of characteristics, satisfactory repeatability. The transfer characteristic of such a sensor is close to linear and can be adjusted over a wide range by changing the parameters of the profiled plates, the pitch of the screw thread, using single-fiber cables with a protective sheath instead of the optic fiber, simultaneously compressing several optical fibers or cables, etc.

References
[1] Cox M F, Lwin R, Large M C J and Cordeiro C M B 2007 Optics Express 15 11843-8
[2] Singh S, Subramaniam K, Chittora N, Brolin A and Palani I A 2020 J.of Intelligent Material Systems and Structures 31 869-81
[3] Rofianingrum M Y, Widiyatmoko B, Kurniawan E, Bayuwati D and Afandi I 2019 J. of Physics: Conference Series 1191 012007
[4] Yang X, Chen Z, Elvin C S M, Janice L H Y, Ng S H, Teo J T and Wu R 2014 IEEE Sensors Journal 15 757-61
[5] Huang R, Yuan S, Jiang Y and Tao B 2001 Fiber Optic Components, Subsystems and Systems for Telecommunications 4604 148-53
[6] Li P, Zhao Z, Hong X and Yu H 2008 Smart Materials V 7267 726717
[7] Wu L, Wang Q, Guo M, Du C and Zhang Y N 2016 Instrumentation Science & Technology 44 471-82
[8] Denisov I V, Sedov V A and Rybalchenko N A 2005 Instruments and Experimental Techniques 48 683-5