Fiber-optic sensors for monitoring the stress-strain state of construction objects

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Abstract. For the timely detection of significant changes in the stress-strain state in the bearing elements of various building structures, which may lead to a deterioration of the technical condition of the object or transfer it to the emergency state, the use of fiber-optic sensors is proposed. The main advantageous characteristics of fiber-optic sensors, describing the promise of their application for practical applications, are disclosed. As a parameter recorded by the measuring transducer, the fiber-optic sensors use the intensity of the light wave. The mechanism of changing the optical intensity can be due to reflection, absorption, refraction of light rays passing through the measurement zone. The authors have developed a fiber optic attenuator type deformation sensor capable of controlling mechanical deformations of structural elements caused by disturbed internal geometric characteristics, destruction of structural integrity and negative influence of external weather conditions, seismic factors, temperature drops during operation. When developing the design of a fiber-optic sensor, the fundamentals of circuit design of measuring devices, methods of geometrical and fiber optics are used. As a basic measuring transducer, a fiber-optic microdisplacement transducer with a limiting attenuator is used, in which the intensity of the optical signal is modulated by changing the position of the attenuator placed in its path or increasing the optical power. A design-structural diagram of a fiber-optic micro-displacement measuring transducer and a block diagram and the design of a new sensor are presented. The principle of operation of an attenuator-type fiber-optic strain gauge is described.

1. Introduction

Nowadays, ensuring the safety of the population, especially in large cities, at hazardous facilities both in Russia and abroad, in view of the occurrence of sudden destruction of structural elements of buildings and structures, requires improved control technology and monitoring of the stress-strain state of construction objects. Rapid assessment of the actual stress-strain state in the load-bearing elements of various building structures arising under the influence of internal and external loads, possible errors in the design, is an important scientific and technical problem, ensuring their safe operation [1, 2]. The solution to this problem is possible in the case of the introduction of fundamentally new information-measuring systems. One of these systems is based on the utilization of fiber-optic sensors. Fiber-optic sensors of various physical quantities are intensively created in the advanced countries of the world, including for monitoring systems of construction objects. In Europe and the United States, projects to create fiber-optic systems for monitoring the state of automobile and railway bridges, power lines, to measure the distribution of mechanical loads in structural elements [3–8] have been successfully
international projects are also being carried out in Russia, the result of one of which is the technical solutions presented in this article [9].

2. Methods
As a parameter recorded by the measuring transducer in fiber-optic sensors, use the intensity of the light wave.

As a basic measuring transducer, a fiber-optic microdisplay transducer with a limiting attenuator is used, in which the intensity of the optical signal is modulated by changing the position of the attenuator placed on its path or increasing the optical power, using geometric and fiber optics methods. The optical signal is converted in a measuring transducer in the far zone of diffraction with a uniform distribution of the intensity of the optical signal, which allows to obtain a linear conversion function.

To reduce additional errors caused by optical fiber bends that affect the measurement result, the luminous flux in the conversion zone is divided into two independent streams, which are then converted independently from each other in the two measuring channels, and the ratio of the electrical signals of these channels is located in the electronic unit.

In developing the design of a fiber-optic sensor, the fundamentals of the circuit design of measuring devices, synthesis methods based on the synthesis of patent and scientific and technical information, as well as available a priori information about the device of similar sensors for measuring other physical quantities, are used

2.1. Fiber optic sensor features
Fiber-optic sensors can be used in conditions of increased explosion and fire hazards, with remote registration of stationary and dynamic processes, in cases where there are no alternative measurement methods. Fiber-optic sensors due to the combination of such properties as small dimensions and weight, a large range of measurement of physical quantities, the ability to operate in difficult climatic conditions, at high temperatures and over a long period of time are most appropriate for use in control systems and monitoring the stress-strain state building structures. Fiber-optic sensors are able to control the mechanical deformations of structural elements caused by the violation of internal geometric characteristics, the destruction of structures and the negative influence of external weather conditions, seismic factors, temperature changes, etc. in the operation of objects and at the stage of their construction. In addition, they are chemically inert, are made of dielectric materials, which ensures the absence of paths of electric current passing through them, have corrosion resistance and workability in aggressive environments, consume a small amount of energy [9].

As a parameter recorded by the measuring transducer in fiber-optic sensors, use the intensity of the light wave. The mechanism of changing the optical intensity can be caused by the processes of reflection, refraction, absorption of light rays passing through an optical fiber [9, 10]. The degree of change in the intensity of the light wave as a result of the external environment (for example, deformation) on the measuring transducer allows determining the value of this effect.

2.2. The principle of operation of the attenuator measuring transducer of a fiber-optic sensor for systems for monitoring the stress-strain state of construction objects
For measurement and control systems of the stress-strain state of various objects, the authors have developed an attenuator-type fiber-optic deformation sensor. An attenuator is a device for a fixed or stepwise change in the power of a light flux [11]. As a basic converter in a fiber-optic strain gauge, a fiber-optic microdisplay transducer with a limiting attenuator is used, in which the modulation of the optical signal intensity is carried out by changing the position of the attenuator / optical attenuator placed on its path [12].

The fiber-optic micro-displacement transducer (FOMDT), which is part of the sensor, is a constructive set of inlet and outlet optical fibers fixed opposite each other in the carrier part and coaxially with a circular hole in the attenuator moving relative to the ends of the optical fibers (Figure 1) [11].
FOMDT contains attenuator 1 tat thickness with a circular hole located at a distance $X_1$ relative to the radiating end of the feed optical fiber SOP 2, and the output optical fibers OOB 3 and 4 of the first and second measuring channels located at a distance $X_2$ from the OOV.

FOMDT works as follows.

From the radiation source (IR LED) on OFF2, the luminous flux $\Phi_0$ is directed toward the attenuator 1 with a round hole. Under the action of the measured deformation $\varepsilon$, the attenuator 1 moves by an amount $Z = \varepsilon$ relative to the ends of the ODF, which leads to a change in the intensity of the light fluxes $F_1(Z)$ and $F_2(Z)$ coming in the ODF to the photosensitive areas of the radiation receivers (photodiodes) of the first and second measurement channels respectively. The modulation of the optical signal is carried out by blocking a part of the luminous flux by the opaque part of the attenuator.

The FOMDT design scheme with an attenuator with a circular hole moving along the $Z$ axis is represented in the most general case in Figure 2. Its conversion function has the form:

$$\Phi(Z) = K_0K_{AT}(Z)\Phi_0$$

(1)

where $\Phi_0$ – the initial luminous flux at the output of the OFF; $K_0$ – coefficient characterizing the distribution of light in the measurement area; $K_{AT}$ – transmission coefficient of the path “supplying optical fiber OFF - attenuator - outgoing optical fiber ODF”;

$$K_{AT}(Z) = K_{AT1}(Z)K_{AT2}$$
Figure 2. FOMDT design scheme with attenuator with round hole attenuator converter.

For purposeful control of the behavior of the conversion function, it is necessary that the coefficient \( K_0 \) be equal to 1. For this, the attenuator is located in the zone with uniform distribution of the light flux over the cross-sectional surface [12].

With coaxial arrangement OFF and ODF

\[
K_{AT1}(Z) = \sum_{i=1}^{n/2} \frac{S_{zi}}{S_C} = \frac{1}{nS_C} \sum_{i=1}^{n/2} S_{zi}, \quad K_{AT2} = \frac{nS_C}{2S_{A-A}}
\]

(2)

where \( n \) is the number of OFF; \( S_{zi} \) - the illuminated part of the cross section of the core ODF; \( S_C \) is the cross-sectional area of the core of the core of radius \( r_C \); \( S_{A-A} = \pi r_C (2d_{OB} + r_C) \), where \( r_C \) and \( d_{OB} \) are the core radius and diameter of the optical fiber, respectively.

Taking into account expressions (2), we get

\[
K_{AT}(Z) = \frac{\sum_{i=1}^{n/2} S_{zi}}{2\pi r_C (2d_{OB} + r_C)}
\]

(3)

In accordance with Figure 2
\[ S_{\rho} = \frac{r_c^2}{2} \left[ \frac{\pi}{90} - \arcsin \frac{a_i}{2r_c} - \sin \left( 2 \arcsin \frac{a_i}{2r_c} \right) \right] + \]
\[ + \frac{R_{CP}^2}{2} \left[ \frac{\pi}{90} - \arcsin \frac{a_i}{2R_{CP}} - \sin \left( 2 \arcsin \frac{a_i}{2R_{CP}} \right) \right], \tag{4} \]

where \( i = 1, \ldots, n; \) \( n \) is the number of SOW;

\[ a_i = 2 \sqrt{r_c^2 - \left( \frac{D_i}{2} + \frac{r_c^2 - R_{CP}^2}{2D_i} \right)^2}, \tag{5} \]

where

\[ D_i(I) = \sqrt{\left( R_{CP} + Z_i \right)^2 + R_{CP}^2 - 2R_{CP}(R_{CP} + Z_i) \cos \frac{360^\circ}{n}} \tag{6} \]

\[ D_i(II) = 2\sqrt{\left( R_{CP} - Z_i \right)^2 + R_{CP}^2 - 2R_{CP}(R_{CP} - Z_i) \cos \frac{360^\circ}{n}}. \tag{7} \]

where \( Z_i \) is the attenuator offset along the Z axis.

The distance \( L \) between the emitting end of the OFF and the plane in which the receiving ends of the ODF are located is chosen so that the luminous flux in the A – A plane completely covers the ends of the ODF in the neutral position of the attenuator (with \( Z_i = 0 \)). From the triangle in Figure 1 is determined \( L = \frac{d_{OB}}{2\Theta_{OA}}, \) where \( \Theta_{OA} \) - is the aperture angle of the optical fiber. Then the inner radius of the OFF light spot in the plane of the arrangement of the output optical fibers in the expression (4) will be \( R_{CP} = d_{OB}. \)

Taking into account expressions (2) - (7), expression (1) for one measuring channel (for example, the first one) will be rewritten as follows:

\[ \Phi_1(Z) = \frac{\Phi_0}{2\pi r_c (2d_{OB} + r_c)} \times \sum_{i=1}^{n/2} \left[ \frac{r_c^2}{2} \left[ \frac{\pi}{90} - \arcsin \frac{a_i}{2r_c} \right] + \frac{R_{CP}^2}{2} \left[ \frac{\pi}{90} - \arcsin \frac{a_i}{2R_{CP}} - \sin \left( 2 \arcsin \frac{a_i}{2R_{CP}} \right) \right] \right] + \]

Analysis of expression (8) shows that the form of the conversion function of the microdisposition attenuator with the limit attenuator with a circular hole is determined by the following parameters: core radius \( r_c \), outer diameter \( d_{OB} \), aperture angle \( \Theta_{OA} \) of optical fiber (ie, the type of fiber used); the number of SOB \( n \); the distance \( L \) between the inlet and outlet fibers.

2.3. The design of a fiber-optic sensor for monitoring the stress-strain state of construction objects

Figure 3 shows the constructive scheme of the proposed fiber-optic deformation sensor of the attenuator type, and figure 4 shows a photo of the sensor, respectively.
Figure 3. The design of the fiber optic attenuator-type strain sensor.

Figure 4. Photo of fiber optic strain sensor (at the final assembly stage).

The design and technological features of the new fiber-optic sensor are as follows.

The sensing element of the sensor consists of two rods of circular cross section 1 and 2, respectively. To the object of measurement that is deformed outside the ends of the rods 1 and 2 are attached by welding. The working end of the rod 1 has two rectangular protrusions with holes for fastening the sleeves 7 and 8, in which the inlet and outlet optical fibers 12 are glued. The working end of the rod 2 has a rectangular protrusion with a hole that is closed by a plate 9 with a thickness of 0.2...0.25 mm, having a hole with a diameter equal to the diameter of the core of the optical fiber, and mounted on a rectangular protrusion by welding. The protrusion of the rod 2 is located between the protrusions of the rod 1 so that the optical axes of the inlet and outlet fibers and the holes in the rod 2 coincide. For precise positioning of the listed elements (at distances $X_1$ and $X_2$) and fixing the rods 1 and 2 using welding, a cylindrical sleeve 3 is used by the windows. The outer diameter of the sleeve 3 is equal to the outer diameter of the rods 1 and 2, and the internal diameter is equal to the diameter of
the hollows on the surface of the rods 1 and 2. For tightness of the design, the body 4 is used, the inner diameter of which is equal to the outer diameter of the rods 1 and 2, and its length the length of the sleeve 3. The casing 4 is attached to the rods by welding. For input/output of optical fibers, the sleeve 5 is used, which is also attached to the housing 4 by welding. To protect optical fibers 12 from breakage during critical bending and against squeezing, the tube 10 made of OFF, in which optical fibers are placed, is placed in metal hose 11. To fix metal hose 11, tapered nut 6 is inserted on sleeve 5. Cavity 5 of cavity A is filled with “Viksint K-68”, and the cavity B of the sensor is filled with inert gas of high purity argon with a dew point of minus 70 °C

3. Results

The developed fiber-optic attenuator-type strain sensor as part of information-measuring fiber-optic systems will allow the on-line monitoring of the deformation and deflection of the supporting structural elements of buildings and structures. Sensors can be installed on ceilings, load-bearing walls, roofing elements, cantilever elements and other elements to control their deformation. The use of fiber-optic sensors will allow to expand the scope of control of the stress-strain state in the system of technical monitoring of the state of buildings and structures for taking measures to eliminate the emergency condition.

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