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Fiber Optic Long Baseline Deformometer for Pit Wall Rock Monitoring System

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A fiber-optic long-base deformometer has been developed, which can be used in rock monitoring systems for open pit walls. The proposed deformometer is based on the method of controlling the additional losses of a light wave propagating in an optical fiber. The fiber optic sensor has a fairly high linearity and stability of the output signal, and is also not subject to the negative occurrence of fading inherent in fiber optic sensors based on the Mach−Zehnder interferometer, with fluctuations in ambient temperature and the appearance of false signals about the displacement of rocks.

Keywords: deformometer, interferometer, monitoring system, optical fiber.

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Optical fibers can be used to build distributed and quasi-distributed measuring systems for monitoring geotechnical parameters and ensuring the safety of mining operations in quarries [1]. Serious scientific work and analysis of the literature on the study topic of this paper are reflected in [2,3]. Detailed information about the development of fiber optic sensors can be found in these sources. The theoretical basis for the development of long-base strainmeters was the paper [4], which presents the results of studies of long-base strainmeters designed to monitor the mechanical states of large-scale objects. The authors managed to partially solve the important problem of reducing the fading of the strainmeter output signal with the external temperature change. In [4] it is noted that there is no information about the testing of a prototype fiber optic sensor (FOS) and its implementation. For FOS based on the Mach−Zehnder interferometer there is a problem of the output signal fading of the strainmeter when the external temperature changes, and false signals about the rocks displacement appear. Also note the rather complex design of FOS [5]. Taking into account the above and the world experience in the FOS design to monitor the rocks deformation, it was decided to create a fundamentally new simplified design of long-base strainmeters operating on a completely different principle, with their subsequent use for monitoring systems to prevent the collapse of quarry walls.

The proposed deformation monitoring method is based on the well-known principles of the additional losses appearance in the optical fiber (OF) under mechanical action on it. The developed amplitude FOS of the passing type has a rather simple design. Fig. 1 shows the measuring circuit of the FOS, which was used in the experiment. The proposed FOS design is similar to the FOS design described

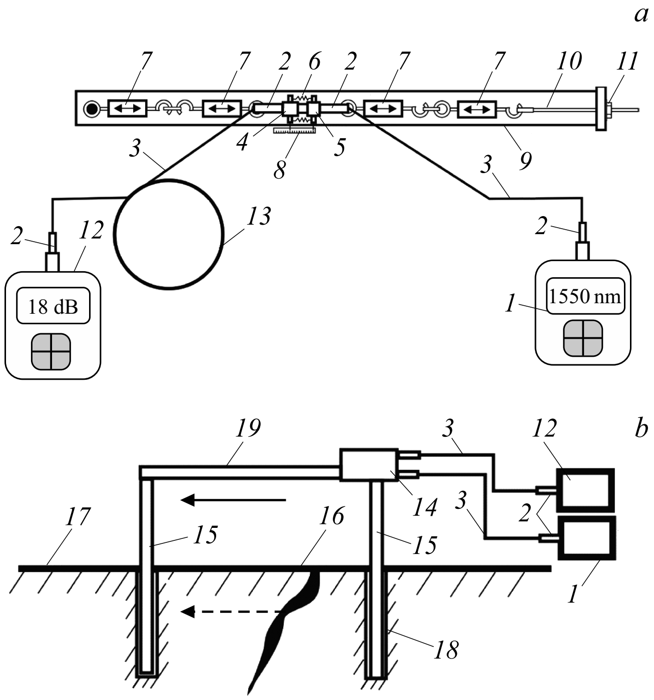

Figure 1. Scheme of the experiment. *1* — radiation source with wavelength from 1310 to 1625 nm (semiconductor laser), *2* — SC optical convector, *3* — optical single-mode patch cord, *4* — moving part of the FOS, *5* — fixed part of the FOS, *S6* — spring, *7* - – tightening sleeves, *8* — measuring scale, *9* — base for mounting circuit elements, *10* — adjusting pin M6, *11* — tightening nut M6, *12* — optical power meter, *13* — compensating coil, *14* — FOS, *15* - – benchmark, *16* — growing crack (indicating the direction), *17* — ground surface, *18* — borehole for benchmark, *19* — connecting beam. *a* — layout of the laboratory stand, *b* — layout of the FOS.

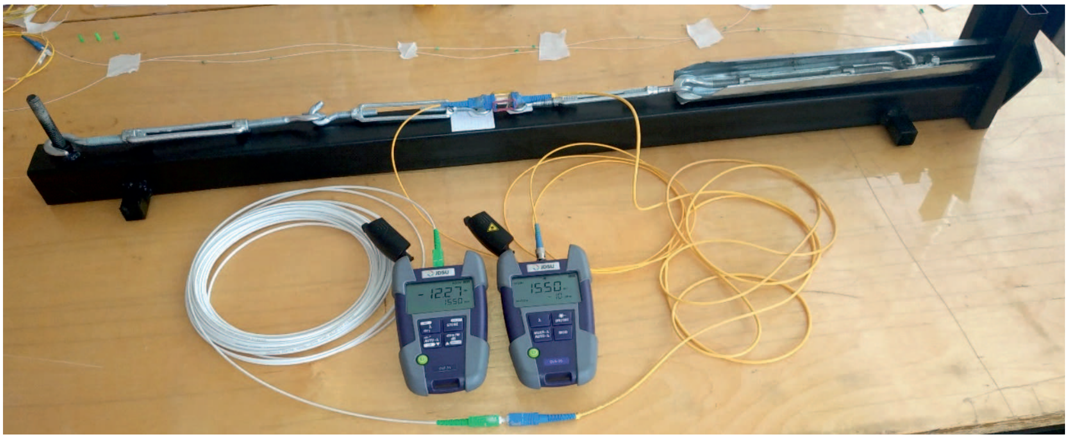

Figure 2. Photo of FOS prototype.

in [5], but differs from it in the principle of operation of the measuring part. Its basis is a single-mode optical fiber type G 652 (9/125 μm), which effectively operates in the light wavelength range from 1310 to 1625 nm with rather low losses (up to 0.2 dB /km). This makes it possible to have a rather extended measuring channel, as well as to locate FOS at a distance of 30 km from the data processing unit [1].

The advantages of FOSs use (their ability to work in explosive environments and low power consumption) are described in [1–3,5]. Instruments used in the experiment: optical radiation source SmartPocket OLS-34/35/36 (USA); optical power meter SmartPocket OLP-38 (USA) with measurement error $\pm 3\%$ and dynamic measurement range from -50 to $+26$ dB; measuring scale with division value 1 mm and measurement error 0.5 mm. The displacement of the moving part of the sensor is measured with a ruler. The temperature in the laboratory room ranged from 23 to 25°C. Boundary conditions for the moving part displacement relative to the fixed part: from 0 to 15 mm. As a compensation coil a single-mode fiber-optic patch cord 30 m long with SC type connectors was used. The FOS was connected to the radiation source and the optical power meter using two single-mode fiber-optic patch cords through a UPP 2.5 mm universal adapter and SC-type optical connectors. In the actual operating conditions of the system in a quarry, the temperature range varies over a wide range, which can form certain interference and disrupt the measurement process. In the future, during practical tests in actual conditions, the measuring instruments used in the experiments will be replaced by hardware-software monitoring system, which will correct the data received from the sensors, taking into account temperature changes. Unlike the interferometer, which can respond to temperature changes from 1°C, the laboratory sample of the proposed system did not respond to temperature changes within 3°C, which suggests less dependence on temperature changes.

The proposed FOS operates as follows: a light wave passes from the radiation source *1* through the sensor *14* to the optical power meter *12*. Tension clutches *7* set the pretension of the springs *6* and ensure the movement of the moving part *4* relative to the fixed part *5*, when they diverge, additional losses increase linearly. In the initial position the level of additional losses is minimal and is formed by the circuit elements. FOS consists of two optical ferrules with a diameter of 2.5 mm, diverging at a certain distance from each other, while they are placed in a tubular light guide. For the studied FOS the maximum distance between the ferrules is 15 mm. To increase the monitoring zone it is necessary to increase the length of the ferrules and the optic fiber guide tube. Further, the proposed sensor will be upgraded to increase its measuring base from 15 to 200 mm, and, if necessary, even more due to the use of a gear mechanism that allows you to select the necessary parameters for benchmarks movement. Also, the length of the optical ferrules will be increased up to 100 mm, which, together with the gear mechanism, will increase the measuring base of the sensor. Measurement accuracy will be achieved by recalibration.

Fig. 2 shows a photograph of FOS prototype for rock deformation monitoring, and also shows the design of the tensioning mechanism.

Fig. 3 shows the dependence of additional optical power losses on the distance between ferrules in tubular optical fiber guide. The measurement error can be approximately up to 5%, i. e. ± 0.2 dB.

Within this model, in view of the experimental orientation of this paper, we limit ourselves by the methods of geometric and classical wave optics, without going at this stage of study into microscopic relaxation mechanisms associated with the interaction of the registered light wave (optical signal) with the substance of the fiber optic element (one of the main working elements of the sensor deformations) [4], and into the quantum nature of optical-mechanical phenomena in the material of the experimental sample under study [6]. In the general case, we write an expression for calculating the theoretical values of the measured in the experiment power volumetric density of the electromagnetic field of the wave (previously averaged

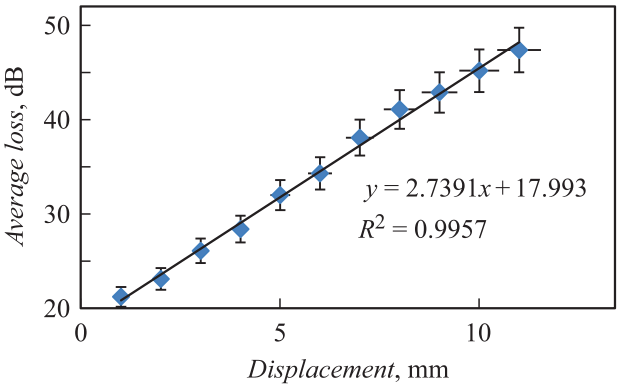

Figure 3. Growth of additional losses vs. displacement.

over the wave period)

$$P_{V_t}(d;\theta;\alpha_0) = 2\langle \mathrm{Re}[\mathbf{E}] \times \mathrm{Im}[i\omega\varepsilon_0\hat{\varepsilon}\mathbf{E}]\rangle_T = \omega\varepsilon_0 \mathrm{Re}[\hat{\varepsilon}] \times \mathbf{E}_0^2,$$

detected by the sensitive element of the experimental strain gauge, after refraction of the outgoing (primary optical signal) in the deformed sample:

$$\langle P_{V_t}(d;\theta;\alpha_0)\rangle_{\alpha_0} = \frac{2\omega}{c\pi}\int_0^{\pi} I(\alpha_0) n_\infty(d;\theta;\alpha_0)\, d\alpha_0.$$

Here, the calculated value of the high-frequency refraction index of the fiber $n_\infty(d;\theta;\alpha_0)$ is calculated as a function of the geometric parameters (d — sample thickness, θ and α_0 — angles of beam incidence on the surface of the OF and on the surface of the sensitive recording element, respectively) taking into account the relaxation time for electro-optical processes in the OF; $I(\alpha_0)$ — intensity of the optical signal (refracted in the OF) distributed over the angle α_0; ω — circular frequency of the light wave; c — speed of light in vacuum.

Thus, the designed FOS has a rather high linearity and stability of the output signal. The sensor is not subject to the negative occurrence of fading, inherent in FOS, created on the basis of the Mach–Zehnder interferometer, with fluctuations in external temperature and the appearance of false signals about the displacement of rocks.

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Conflict of interest

The authors declare that they have no conflict of interest.

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