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Satbayev University

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ИЗВЕСТИЯ

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РЕСПУБЛИКИ КАЗАХСТАН
Satbayev University

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THE WORKING ROOF ROCK MASSIF DISPLACEMENT CONTROL SYSTEM

Abstract. This article discusses the issue of ensuring safety in coal mines using the fiber op-tic technology. The authors describe the developed fiber-optic sensors capable of monitoring and warning about mine working roof displacements. A detailed analysis of the use of such devices in the world has been presented, the ad-vantages and disadvantages of the existing control systems have been revealed. The design of a fiber-optic sensor is similar to a typical reference station, the de-sign of which is quite simple and proven, but the fundamental difference is the use of a single-mode fiber as a sensor. The authors have developed a laboratory bench that allows working out the design of a fiber-optic sensor and studying its parameters.

Based on the research results, a graph of the dependence of optical losses on the displacement value has been obtained, an automated data approximation has been performed, and single-factor mathematical models have been obtained. The sensor has shown fairly good linearity. Relatively high accuracy and linearity of characteristics are achieved through the use of specific software that allows com-bating the interference and exclude random values from the measurement results. The program uses the capabilities of artificial intelligence with elements of ma-chine learning. The developed fiber-optic sensor and information-measuring sys-tem have proven their efficiency and will be further implemented in one of the mines of the Karaganda coal basin.

Key words: Fiber optic sensor, monitoring system, opencast mining, safety, mining, optical fiber, deformation, displacement.

Introduction. The safety issues of mining operations have always been extremely acute. In recent years, due to the expansion of depth and scale, mining has deepened, and the task of preventing man-made accidents and exercising control has become more complicated. Deformation of the roof layers in the course of mining is the main cause of methane explosion, water injection and roof collapse during un-derground coal mining. At present, the methods of predicting changes in the geotechnical parameters of a mine working are reduced to the work of the mine surveyor service. In their arsenal there are a number of tools that allow visual determining the roof displacement.

One solution to this problem can be the use of fiber optic sensors (FOS) that have the ad-vantages of signal transmission over long distances and provide safety, which allows them working in explosive environments. Compared to the traditional monitoring methods, the use of fiber optic sen-sors has many advantages, such as a small size and a light weight; flexibility; a high throughput; relia-bility and a low cost; strength; immunity to electromagnetic interference and electrical noise. Given the high sensitivity and wide range of operating temperatures, the ability to remote and comprehensive monitoring, it can be concluded that using fiber-optic technologies in coal mines can solve several problems [1, 2].

An idea has been put forward to develop domestic fiber-optic rock pressure sensors and fiber-optic control systems to improve the safety level of mining operations, as well as to automate the pro-cess of rock pressure control and various rock displacements in underground workings. At the mo-ment, at the mining enterprises, reference stations are used that were developed in the times of the former USSR. The design of the reference station does not allow for automated and remote control over the change in the measured parameters. To control them, specialists from the mine surveyor ser-vice are involved, who periodically walk through all reference stations and enter all changes in the log, after which the data is analyzed. There is a human factor in the measurement system, which gives rise to certain difficulties in circumvention and inaccuracies in the data obtained. It should also be noted that the design of the reference station does not provide for a return to the initially set value of zero, which also introduces certain errors in measurements. The analysis of works [3-5] shows that this problem is quite acute and partially solved. Reliable in design and not expensive fiber-optic control systems have not yet been developed abroad. However, there is a significant amount of information of foreign research aimed at developing such systems [6-9], separate prototypes have been developed that are not accepted for production. A large share of research in these areas belongs to scientists from China and India [10-14]. Scientists from Russia [15-17] also carry out similar studies but there are no commercially available systems. An important point is their high added value, so, the search for solu-tions aimed at simplifying and reducing the cost is relevant. Developing our own software for the hardware and software complex will also reduce the cost of the system as a whole.

2 General issues of developing fiber-optic sensors of the roof rock massif displacement.

This article discusses the issues of developing fiber-optic sensors of the roof rock massif displacement (FODS). A FODS should have a simple in design and the cost lower than present day reference stations, which is very important for its implementation. The design of the reference station, which has been used for decades, and the proposed FODS have a number of common elements, as well as a number of fundamentally new differences that make it possible to bring the process of controlling the roof rock massif displacement to a new level. A FODS does not have complex technological details in its design and can be manufactured on the territory of Kazakhstan by the forces of factories serving the mining industry. A single-mode optical fiber is used as a sensing element. Figure 1 shows the FODS design. The use of single-mode optical fiber makes it possible to solve a number of fundamentally important problems. Firstly, a FODS is energetically passive and does not require electric power supply, which makes it possible to use it in any underground workings including those in supercategorized mines of the Karaganda coal basin, which are dangerous due to a sudden methane and coal dust outburst. Secondly, a single-mode optical fiber allows transmitting the measurement data over distances of more than 100 km with minimal attenuation parameters, which cannot be afforded by any of the existing electronic information and measurement systems using a wired or wireless directing data transmission system. Thirdly, a single-mode optical fiber is used as a guiding system for transmitting the measurement data and as a sensing element at the same time. Given the rapid growth and development of fiber optic technologies, an optical fiber is getting cheaper in the market every year and its cost is lower than $ 10 per kilometer. The cost of the other components, for example, lasers, photodetectors, optical splitters and circulators, from which a fiber-optic system for identifying the geotechnical state is subsequently assembled is also reduces annually. The concept of building a fiber-optic system for identifying the geotechnical state implies complete rejection of the power supply to sensors located in the underground mine workings, all the information is brought to the surface to the operator's pulp using a fiber-optic cable. The most science-intensive part of the fiber-optic system for identifying the geotechnical state is the optoelectronic unit for processing the measurement data, which has a hardware and software complex using the principle of artificial intelligence in data processing, which allows avoiding a number of technical problems with the measurement accuracy, as well as reducing the effect of temperature noise arising in measuring channels. Earlier these problems were considered in some detail and their nature was described in works [18-19]. Previously, a similar FODS based on the method of determining additional losses was considered; in essence, this sensor is simple in design and reliable in operation but it requires two fiber-optic conductors, a forward and a reverse branch, to supply and to return a light wave that passes through the sensor from the laser to the photodetector [20]. Using this method, it is possible to develop a point control system with the use of separate channels for each FODS, but there is a certain problem: if a mining enterprise has several hundred FODS, then a significant number of cores and length of fiber-optic cable will be required, since one sensor requires two conductors, which will increase the cost of the system as a whole. Foreign developers propose to use the optical interferometer method, but this does not reduce the number of optical conductors suitable for FODS and even increase them; there are also problems of the optical interferometer associated with the effect of temperature interference formed with a significant length of the optical channel. Accordingly, changing the temperature even by 0.5 degrees C will lead to changing the refractive index, a shift in the phase of propagation of a light wave and a drift of "zero". This problem is described quite well in work [20]. Foreign authors give a description of laboratory experiments related to the development of fiber-optic pressure and displacement sensors based on the effect of reflection of a light wave from Bragg gratings, but there is no need to talk about the immediate future of implementation, since the optical spectrum of the analyzer is used in the work, the cost of which is sufficient high. It is still possible to use the method of optical reflectometer, but the cost of an optical reflectometer remains quite high. Accordingly, on the scale of a mining enterprise and multichanneling, significant material investments will be required. Considering the above, a hypothesis was put forward for the development of a FODS based on the control of the parameters of the reflected light wave. To connect one FODS, only one optical conductor is used, through which a pulse is supplied from the radiation source and returns back to the data processing unit, where the photodetector is located, which is used as a television matrix. Then, the resulting image is processed by the hardware-software complex and the measured parameters of the displacement are formed.

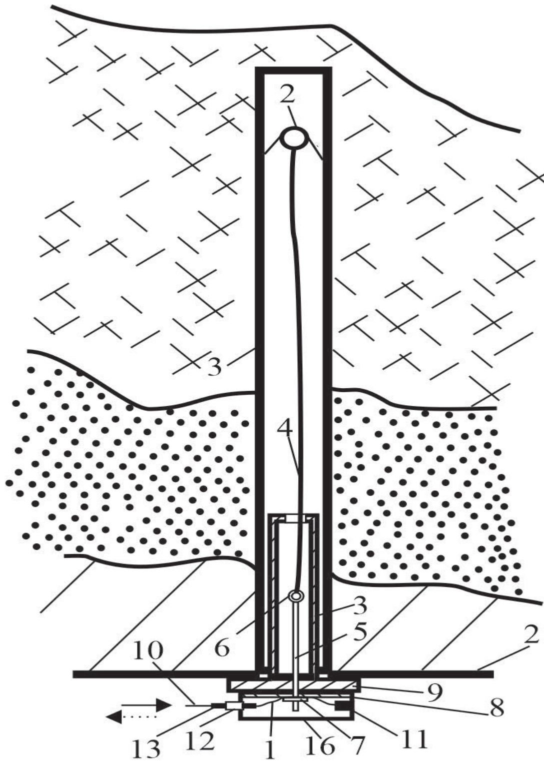

Figure 1 – The reference benchmark design with a FODS

The design of the FODS has much in common with a typical reference station, the design of which is quite simple and proven, but the fundamental difference is the use of a single-mode fiber as a sensor. With changing rock pressure and occurrence of displacements of layers in the working roof, a mechanical effect on fiber-optic sensor 1 occurs, this effect is carried out when spring retainer 2 is displaced, this retainer is placed in a certain area of the hole drilled in the working roof to fix the position of cable 4. The cable is attached to pin 5 by means of lug 6. Fiber-optic sensor 1 is located between steel washer 7 and elastic elements 8 on one side and on the other with steel washer 9. The light wave arriving along optical fiber 10 passes through sensitive element 1 and returns to the photodetector in the opposite direction reflected from mirror 11. To connect FODS there is used adapter 12 (UPP 2.5 mm) and optical connector 13 of the SC type. When acting on optical sensor 1, the intensity of the reflected light wave changes, which is fixed by the photodetector. The resulting changes are further processed using software. When the rocks of the working roof move, spring lock 2 is displaced and acts on sensitive element 1, which is located between washer 7, elastic elements 8 and steel washer 9, which leads to the mechanical effect on sensitive element 1.

The light wave pulse reflected from the mirror passes through sensitive element 1 and returns back to the photodetector of the data processing unit. This design of the FODS allows developing an already quasi - distributed control system. It is possible to use one optical fiber per FODS group, since it is possible to control not only the parameters of changing the intensity of the reflected light wave but also to determine the distance to the control point using the Doppler effect. Each FODS will output individual parameters of the change in the intensity of the pulse of the reflections of the light wave, the change in contrast and the pixel pattern, so that it can be identified for recognition. Four FODS will be installed on one optical channel. Achieving these indicators is possible when using a four-channel hardware and software complex that uses in its work the analysis of parameter changes with the use of artificial intelligence algorithms and, in particular, with establishment of the weight coefficients of each parameter and their analysis using a neural network. This will significantly reduce the cost of the control system, since there is no need to use expensive equipment to implement the Bragg grating effect and optical reflectometry methods for identifying FODS in a quasi-distributed scheme. The leaders in this field are scientists from China, who in 2020 tested their distributed fiber-optic displacement monitoring system in field [21]. After analyzing their results, we can say that, of course, a fiber-optic quasi-distributed system has a larger number of optical conductors compared to a distributed system based on Bragg gratings, but it will be simpler in its design and less expensive in terms of the equipment used, which can be decisive in making decisions on its implementation in the coal mines of the Karaganda coal basin.

Statement of the problem, methods of studying and results. The problem is carrying out experiments to refine the design of the FODS and to verify the previously advanced hypothesis about the use of the analysis of the reflected wave incident on the surface of the photodetector. A laboratory bench has been developed that allows working out the design of the FODS and studying its parameters. Figure 2 shows that the bench consists of laser source 2, the power of which can be varied from 10 to 50 mW with the wavelength of 650 nm. The bench consists of metal frame 1 with elements that simulate the tension of the cable when the rocks of the roof are displaced. When the cable is pulled, the pin moves, thereby exerting an effect on the sensitive element (see Figure 1), which is located between the washer and the elastic element. To record changing the intensity of the reflected light wave of the television matrix, webcam 3 with resolution of 1080P has been used. The results of the experiments are presented in the graph of dependence in Figure 3.

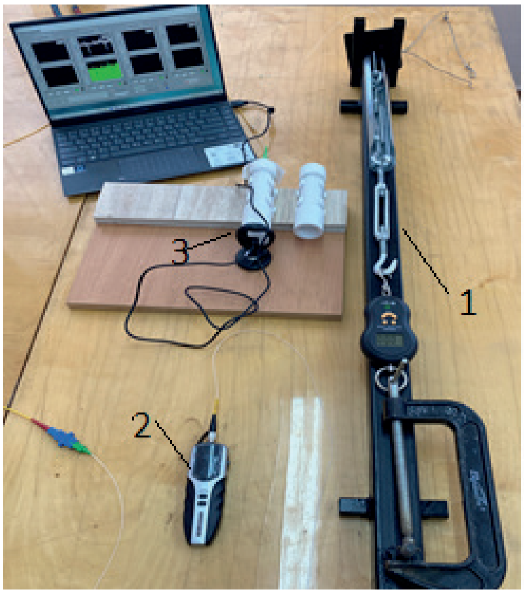

Figure 2 – The laboratory bench of the information-measuring system with the sensor of the roof displacement: 1 – metal frame with elements, 2 – laser radiation source, 3 – web camera

The results obtained are explained by the inverse relationship existing between the value of the elasticity coefficient: the greater the number of optic finer turns, the lower the elasticity coefficient. Experiments have been carried out to determine the additional power losses of the optical fiber passing through the fiber-optic sensor with various displacements. The displacement values have been measured many times with subsequent processing of the experimental data and averaging of the obtained values. The experimental results have been processed taking into account the smallest value of the Akaike information criterion; the best option has been selected by approximation of the second degree, at which the de-termination coefficient R^2 = 0.9705. As a result, the laboratory sample of a fiber-optic sensor have shown fairly high linearity, changing the parameters. In addition, the results suggest that it can definitely be a high-precision sensor. Subsequently, on the basis of the laboratory sensor, it is possible to work out a sensor for monitoring the displacement of the pit walls. According to the measurement results, there have been calculated the absolute error of 2.27, the relative error of 8.844 % and the Student's coefficient of 2.120 with the confidence interval of 0.94.

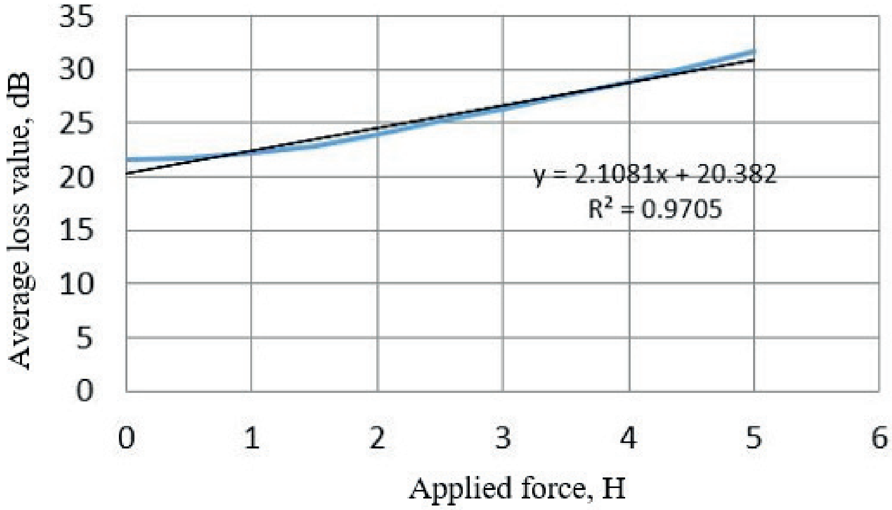

Figure 3 – Optic losses dependence on the displacement value

A personal computer with software was used to process the measurement data. A single-mode optical fiber of the G652 125/9 microns standard and the protective sheath diameter of 0.9 mm has been used as a sensitive element. For connection, UPP adapters 2.5 mm and SC type optical connectors have been used. The calibration of the laboratory sample has been performed using a VIAVI (JDSU) SmartPocket OLP-38 optical power meter and an optical radiation source using SmartPocket OLS-34/35/36. These devices are used to control the parameters of additional losses of fiber-optic transmission lines. An electronic dynamometer has been used to measure the magnitude of the mechanical load. The boundary conditions have been as follows: pressure on the fiber from 0 to 50 N. The displacement has been measured with a ruler. The temperature in the laboratory room has ranged from 23 to 25°C. As a result of automated data approximation, one-factor mathematical models have been obtained. Each measurement has been carried out 10 times. The numerical study has been carried out using the Wolframalpha program, which is an interactive system of processing experimental results and is focused on working with data arrays. The data processing methods used by Russian scientists have also been used [22-24].

The developed FODS has shown fairly good linearity of characteristics. Relatively high accuracy and linearity of characteristics are achieved through the use of specific software that allows combating the interference and exclude random values from the measurement results.

Figure 4 shows the interface of the developed four-channel hardware and software complex capable of simultaneous working with four FODS but the number of channels in the future will be increased to 120, which is quite sufficient to control the bottomhole roof. With the help of the hardware and software complex, it is possible to determine not only changing the additional losses but also the dynamics of their changing in real time. A number of alarm settings are available to expand the measurement capability. It uses the capabilities of artificial intelligence with elements of machine learning and setting the weighting coefficients of each parameter for analysis by the neural network. In the event of dangerous situations, the hardware and software complex gives a warning sound signal, and all alarm events are stored in the device memory.

Only one FODS has been used in the experiments and its parameters have been displayed in the program window. The hardware and software complex is capable of responding with a high speed to changes in the measured value and displaying the numerical value of all the parameters. The program independently performs the temperature correction and adapts the measuring channels to changes in the external temperature. The lower window marks the coverage area in which the FODS is located. The program also allows making various settings to improve the measurement accuracy. An important point is the ability to send an alarm signal to the operators in the event of a rapid change in the pattern of rock pressure and the emergence of the sudden collapse of the mine workings danger.

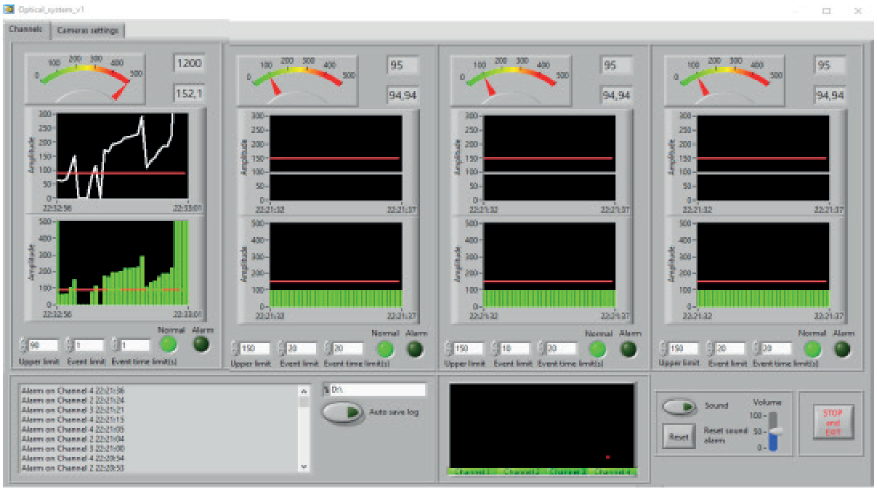

Figure 4 – The system software interface.

Conclusions. The laboratory studies of the fiber-optic roof displacement sensor and the four-channel hardware-software complex proved consistency of the proposed scientific idea of their use; the FODS also possesses sufficient workability and linearity of characteristics. The rock pressure monitoring system based on fiber-optic technologies will not only improve the safety level of mining operations but also reduce the costs of supporting mine workings in general.

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ҚАЗБАЛАР ЖАППАЛАРЫНЫҢ ТАУ-КЕН МАССИВІНІҢ ЫҒЫСУЫН БАҚЫЛАУ ЖҮЙЕСІ

Аннотация. Бұл мақалада талшықты-оптикалық технологияларды қолдана отырып, көмір шахталарында қауіпсіздікті қамтамасыз ету мәселесі қарастырылады. Мақалада адам қызметінің әртүрлі салаларында талшықты-оптикалық сенсорларды пайдалану тәжірибесі талданып, олардың артықшылықтары атап өтілді. Талшықты-оптикалық сенсорлар қолданыстағы аспаптық әдістерге қарағанда тау-кен шатырын тиімді басқара алады. Әлемде осындай құрылғыларды пайдаланудың егжей-тегжейлі талдауы ұсынылған, қолданыстағы басқару жүйелерінің артықшылықтары мен кемшіліктері анықталған. Талшықты-оптикалық сенсордың дизайны стандартты тірек станциясына ұқсас, оның дизайны өте қарапайым және тексерілген, бірақ негізгі айырмашылық сенсор ретінде бір режимді талшықты пайдалану болып табылады. Талшықты-оптикалық сенсордың дизайнын жасауға және оның параметрлерін зерттеуге мүмкіндік беретін зертханалық стенд жасалды. Зерттеу нәтижелері бойынша оптикалық шығындардың орын ауыстыру шамасына тәуелділік графигі алынды, деректердің автоматтандырылған жуықтауы жүргізілді және бір факторлы математикалық модельдер алынды. Сенсор жақсы сызықты көрсетті. Сипаттамалардың салыстырмалы түрде жоғары дәлдігі мен сызықтығына кедергілермен күресуге және өлшеу нәтижелерінен кездейсоқ мәндерді алып тастауға мүмкіндік беретін нақты бағдарламалық жасақтаманы қолдану арқылы қол жеткізілді. Бағдарламада Машиналық оқыту элементтері бар жасанды интеллект мүмкіндіктері қолданылады. Әзірленген талшықты-оптикалық датчик және ақпараттық-өлшеу жүйесі өзінің тиімділігін дәлелдеді және алдағы уақытта Қарағанды көмір бассейні шахталарының бірінде енгізілетін болады.

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СИСТЕМА КОНТРОЛЯ СМЕЩЕНИЯ ГОРНОГО МАССИВА КРОВЛИ ВЫРАБОТОК

Аннотация. В данной статье рассматривается вопрос обеспечения безопасности на угольных шахтах с использованием волоконно-оптических технологий. Авторами описывается разработанный волоконно-оптический датчик, способный отслеживать и предупреждать о смещении кровли горных выработок. Представлен подробный анализ использования подобных устройств в мире, выявлены достоинства и недостатки существующих систем управления. Конструкция волоконно-оптического датчика аналогична типовой опорной станции, конструкция которой достаточно проста и проверена, но принципиальное отличие заключается в использовании одномодового волокна в качестве датчика. Создан лабораторный стенд, позволяющий отработать конструкцию волоконно-оптического датчика и провести исследование его параметров. По результатам исследований получен график зависимости оптических потерь от величины смещения, проведена автоматизированная аппроксимация данных и получены однофакторные математические модели. Сенсор показал неплохую линейность. Относительно высокая точность и линейность характеристик достигнута путем использования специфического программного обеспечения, позволяющего бороться с помехами и исключать из результатов измерений случайные значения. В программе использованы возможности искусственного интеллекта с элементами машинного обучения. Разработанный волоконно-оптический датчик и информационно-измерительная система доказали свою эффективность и в дальнейшем будут внедрены на одной из шахт Карагандинского угольного бассейна.

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