Modification of a wideband spectral-acoustic method for controlling stress state of a face space

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Abstract. To control and manage a stress state of an underground working face space it is important to measure the components of actual stresses. Traditional method for relieving a core-sample with central drill is time and labour consuming and is characterized by a lack of accuracy. To improve these issues geophysical methods which do not interfere with mining are to be used for controlling stress state. Acoustic methods are less time and labour consuming. Justification of spectral-acoustic method modification for controlling stress state of a face space is introduced. It is done on the basis of the dependence of the acoustic signal of the operating equipment amplitude-frequency response median on average stresses. The acoustic signal is recorded in the entire sensitivity band of the geophone. The description of a flow chart and operating principle of intrinsically safe portable device for implementing the modification in mines on the seams dangerous on gas and dust and prone to sudden coal and gas outbursts and rock bursts are given. The device operates in three modes: determining amplitudes of background noise and setting signal amplification coefficient; controlling stress state while generating continuous acoustic signal produced by operating mining equipment (combined machine, drilling device, plough-type machine) into the massif; control of stress state during generation a discrete acoustic signal produced by artificial source (heavy hammer strokes) into a massif.

1. Introduction
Due to deepening coal deposit developments the stresses in face space of mine workings keep growing and the danger of dynamic phenomena manifestation appears [1-4]. This is the reason for initiating continuous monitoring of a stress state.

The necessity to control stress state in a face space also appears in a process of relieving measures such as directional hydraulic fracturing of hard roofs with the purpose of its effective fulfillment.

Applying a traditional method for relieving a core-sample with central drill for measuring is time and labour consuming. Besides, this method is characterized by wide scatter assessments of the measured values and defined directions of principal stresses [5].

Geophysical active ultrasonic methods of cross-well sounding and logging are less time and labour consuming nowadays. Recently, the application of acoustic emission method is closely studied. This method is based on applying Kaiser effect when installing composite materials with known and stable structural behavior into the drilled holes [5-7]. Both traditional and abovementioned ultrasonic methods of measuring are fulfilled with a certain discreteness in time and space and very often demand stopping mining operations. However, maximum of effective stresses are reached only in the...
process of mining \[8, 9\]. That is why, to monitor stress state of a face space in the process of mining, nondestructive (without applying controlling drills) continuous geophysical method is demanded. Very often, due to occasional necessity of the fulfilled works the device should be light, portable and blast-resistant that allows its application in mines dangerous on gas and dust and/or in seams prone to sudden coal and gas outbursts or rock bursts.

One of such methods is spectral acoustic one. It is implemented through analyzing frequency content of noises produced by operating mining equipment that passed the controlled zone of a face space. (In current regulatory documents this method is called “Method of coal seam outburst danger prediction according to artificial acoustic signal parameters \[10\]).

2. The idea of spectral acoustic method

This method is based on experimentally defined and later theoretically justified fact that high frequency harmonic amplitudes in noise spectrum of operating equipment increase higher than the low-frequency harmonics amplitude when the face working approaches to an increased stress zone \[11, 12\].

Rock massif is probed by wideband acoustic vibrations generated by operating mining equipment (cutting organ of a combined machine, drilling device, ploughing-type machine etc.) or by artificially produced source of a sound such as by stroking heavy hammer at the side of the working. At the distance of 5-30 m from the source of the sound, the acoustic vibrations are registered by a receiver and the relation of high-frequency and low-frequency parts of vibration spectrum that passed the controlled area of a massif from the source is calculated \[10\]. As the sound attenuation coefficient \(\alpha\) in a solid body in initial approximation is directly proportional to the signal frequency \(f\) and inversely proportional to the current values of average stresses in a massif, it can be written as \[12\]:

\[
\alpha = \alpha_0 \frac{f}{f_0} \beta \frac{\sigma_{l,av}}{\sigma_{c,av}},
\]

\(\alpha_0\) – attenuation at a certain frequency \(f_0\) without any stresses (in a relieved state); \(\sigma_{l,av}\) and \(\sigma_{c,av}\) are average limit (maximum possible without destruction in a form of a growing fracture for a controlled section of a seam) and current stress values in a massif correspondently; \(\beta\) - non-dimensional proportionality coefficient which is defined by acoustic properties of a massif.

It allows introducing the concept of relative stresses coefficient \(K_{r,t}\), as the relation of acoustic vibrations: high frequency \(A_h\) and low-frequency \(A_l\) portions of the spectrum \[12\]:

\[
K_{r,t} = \frac{A_h}{A_l} = \exp(-C \frac{\sigma_{l,av}}{\sigma_{c,av}} d).
\]

Here: \(A_h\) and \(A_l\) are effective acoustic noise amplitudes registered in the areas of high and low frequencies, respectively, V; \(d\) is a distance between a source and a receiver of the noise, m; \(C\) parameter equals:

\[
C = \alpha_0 \beta \frac{f_h - f_l}{f_0}, \text{ m}^{-1};
\]

where \(f_h\) and \(f_l\) – are characteristic frequencies from the high and low sub-bands of working frequencies of the acoustic signal source, respectively, Hz.

It is seen from equations (1) - (3) the coefficient of relative stresses bears a qualitative information about a stress state of a rock massif section situated between the source and the receiver of acoustic frequencies. To get a quantitative estimates of actual stresses with the help of spectral acoustic method it is important to solve the range of theoretical and methodical problems. They are as follows: taking into account the dependence \(K_{r,t}\) on acoustic properties of a researched rock massif, the distance
between the source and the receiver of acoustic vibrations, selection of working frequencies etc. and the development of the procedure on defining critical values of a hazard indicator for losing stability due to dynamic phenomena manifestation [13].

3. Spectral acoustic method modification

Modifications, which are known at present time, can be subdivided according to two criteria: on the usage of working frequencies and on designing the equipment for applying the method (in permanently installed or portable forms) [14, 15].

There are three modifications according to the selection of working frequencies. In the first modification in case of analog signal processing the whole frequency band that geophone receives (about 20-1500 Hz) is subdivided into sub-bands by high and low frequency filters. Thus, in a reference document, while using AK-1 or AK-1M devices, it is recommended to fulfill evaluating and exploring observation for selecting cutoff frequencies of high-pass filters for one of three values 600, 800 or 1000 Hz, and cutoff frequencies of low-frequency filter for one of three values 160, 200 or 300 Hz [16]. In case of digital signal processing, values $A_h$ and $A_l$ included into equation (2) equal to harmonics sums, taken from high and low frequency sub-band respectively.

In the second modification, it is supposed that amplitude-frequency response of a received signal has a maximum value. Signal processing goes in digital form. The device software defines the frequency where the amplitude has a maximum value $A_{\text{max}}$. To the left of this frequency the software determines two frequencies that have amplitudes equaling to 0.5$A_{\text{max}}$ and 0.75$A_{\text{max}}$ respectively. These frequencies are the borders of low-frequency area of a spectrum. Similarly, to the right of the frequency corresponding to $A_{\text{max}}$, the software determines the frequencies at which the signals have amplitudes equaling to 0.5$A_{\text{max}}$ and 0.75$A_{\text{max}}$ respectively. These frequencies are the borders of high-frequency area of a spectrum [14].

One of general drawbacks of the abovementioned modifications is in non-usage of the whole amplitude-frequency response spectrum. An error in controlling stress state can arise if the change of amplitude-frequency characteristic take place during the change in a stress state in the part of the spectrum which is not taken for analysis. To avoid this drawback the third modification is being worked out. The whole spectrum of an acoustic signal in a geophone sensitivity area. The equipment software detects the median of amplitude-frequency characteristic, in other words, the frequency that breaks the whole frequency band into two parts so as the sum of amplitudes of all harmonics situated to the left of the median equals to the sum of all the amplitudes of all harmonics situated to the right of the median [15]. In this case, the coefficient of relative stresses $K_c$ is defined according to the shift of the median towards a certain limit value:

$$K_c = \frac{M_c}{M_l},$$

where $M_c$ and $M_l$ are current and limit median, respectively.

At present, the works on the development of the procedures for defining median limit value for a certain section of a coal seam for the given modification of spectral-acoustic method are being done.

Historically, for implementing spectral-acoustic method for controlling stress state, a set of stationary analog signal processing device of AK-1 type and later AK-1M was designed first. Here, the first modification of selecting working frequencies was used [16].

After that, a set of a stationary device of SACSM type with digital signal processing was worked out. Here the second modification for selecting working frequencies was used [17]. At present, this given set is installed in all AO “SUEK-Kuzbass” mines and it is used for controlling a stress state and predicting rock bursts. There is still no stationary devices for selecting working frequencies of the third modification. However, digital signal processing device of the second modification can be applied for the third modification if to install an appropriate software in it.

For occasional monitoring of a rock massif stress state in active mine workings intrinsically safe, portable acoustic signal register RIPAS and a program for processing the results of sounding
“Geoscan-RIVAS” were worked out. To use this hardware and software complex it is necessary to follow specially worked out guidance “Procedures for rock massif acoustic sounding with application of hard-software complex” [18]. The source of the acoustic signal for this hardware and software complex is a stroke of a heavy hammer on the walls of the working.

Several researches carried out at some Kuzbass mines with the use of RIPAS register revealed several main drawbacks. Firstly, the source of the acoustic signal must be situated at the distance of 1-3 meters from geophone. This is the reason why the controlling depth of a massif from the wall of the working does not exceed a half of the distance, it is 0.5-1.5 meters. It is often not enough. Secondly, “The Procedures…” supposes that geophone is to be pressed to a massif but not to be set into a well or a borehole. This is why an electric cable is inserted into the geophone perpendicular to longitudinal axis of the geophone. It does not allow entering geophone into a borehole drilled in the wall of the working and the massif rock jointing at the wall of the working influences on attenuation of a signal. Thirdly, control of registered acoustic signal amplitudes is not applicable in the device. So there is no certainty that the received acoustic signal does not fall outside the dynamic range of a signal amplifier and as a result non-linear distortion of its spectrum take place. Fourthly, “The Procedures…” does not offer physical justification and does not describe the algorithm of signal processing. Thus, it is impossible to judge about the accuracy of the results.

Experimental researches on defining the coefficient of relative stresses made by this complex revealed that due to the indicated drawbacks even under a little shift of the area for installing the geophon the registered result of defining $K_{r.t}$ can change drastically. Thus, the given hardware and software complex has a short range and a poor accuracy for defining $K_{r.t}$.

4. The description of a flow-chart and a principle of PKNS-1 device operating

To overcome the abovementioned drawbacks of RIPAS and “Geoscan-RIVAS” a portable device for controlling stress state of a rock massif face space with spectral-acoustic method PKNS-1 was worked out.

The device is intended to be used in a working zone of a mine dangerous on gas and dust in conformity with the requirements of “Safety rules in coal mines”.

The design of PKNS-1 device is given in figure 1. The device consists of the following basic components: 1 - geophone; 2 – basic processing device; 3 – mains charger.

The operational principle of the device is explained by flow-chart shown in figure 2.

To listen to acoustic oscillations generated by an operating mining equipment or by strokes of a heavy hammer a short (0.7-1.5 m) rising blast-hole is drilled in a wall of a working. Geophone is inserted into this rising borehole.

To listen to acoustic effects that take place in a massif (acoustic signal from the growing fractures, operating equipment) headphones are included into the scope of delivery. There is a debug connecting cable ST-Link V2 for downloading software.

A signal from geophone enters into preamplifier of the basic processing device and goes from its output into the programmable gain amplifier (PGA). The PGA have discretely regulated gains. The regulation takes place by pressing the buttons set on the front of the device. An enhanced signal enters into analog-to-digital converter (ADC) where it is digitized and transmitted into micro-controller with its further processing according to a specified software algorithm. The determined values $K_{r.t}$ appear on a display and are further transferred into Random Access Memory (RAM). Data from RAM are processed and periodically written into long-term memory store (Flash).

The operator’s headphone through the power amplifier receives a sound signal that corresponds to acoustic effects that a geophone receives. There is a microphone inserted into the device which allows the operator to record voice comments on measuring.

The charging of the device goes through intrinsic safety battery. To indicate a low charging level is provided with a battery discharge indicator (red light-emitting diode). To charge the battery a special charger is provided together with the device. The charger allows the device to be charger only outside of the explosion hazardous zone. The possibility to connect the device to a personal computer using
USB cord for transferring data and updating software is also provided. The device can operate in three modes.

![Design of the PKNS-1 device.](image1)

**Figure 1.** Design of the PKNS-1 device.

The first mode is meant for defining amplitude of a background “noise” produced by the operating equipment that works in the neighboring workings and for setting the coefficient of a useful input signal strengthening coefficient.

![Flow-chart of a stress state controlling device PKNS-1.](image2)

**Figure 2.** The flow-chart of a stress state controlling device PKNS-1.

The second mode is meant for controlling stress state of the working face space during the operation of mining equipment: combine machines, plough-type machine and a drilling rig which are the source of controlling space sounding signal. In this case a signal has a continuous form during a certain period of time. The device measures relative stresses coefficient out of the readouts registered...
in three-minute time period. In the end of each measuring interval the reading of relative stresses coefficient pops up and stays on the display until the end of the next measuring period.

The third mode is meant for controlling stress state during the operation of artificial acoustic signal source. This source can be a stroke of a heavy hammer on the wall of the mine working or a specially designed device. In this case defining the relative stresses coefficient is fulfilled on the signal of each stroke of a heavy hammer and is averaged out per 5-7 strokes.

The design of the processing device is introduced in figure 3a. There are: 1 - geophon connecting cable; 2 – liquid-crystal symbolically digital display; 3 – membrane keypad; 4 – a slot for external connections; 5 – signaling light emitted diode that indicates battery discharge.

The device technical specification:
1) the device dimensions: 120x45x120mm;
2) the mass of the processing device – not more than 0.3 kg.;
3) the dust and external actions protection level according to GOST 14254-2015 not less that IP;
4) explosion-proof marking РО ExiaIХ;
5) power supply – from rechargeable Li-ion power pack.

Figure 3. Basic processing device (a); a carrying case for PKNS-1 device and other accompanying devices (b).

Figure 3 b) shows a carrying case for transportation of PKNS-1 device with other accompanying devices. At present testing the device and adjusting its software are being done.

5. Conclusions
1. On the basis of the fulfilled analysis it is demonstrated that the modification of a spectral-acoustic method based on the dependence of the acoustic signal of the operating equipment amplitude-frequency response median on average stresses allows getting the most accurate data about a stress state of a massif situated between the source and a receiver.
2. The prototype of a portable PKNS – 1 device for controlling a stress state of rock massif face space by spectral-acoustic method was designed and produced.
3. PKNS – 1 device has three operating modes:
   • defining amplitude of a background “noise” and defining optimal signal amplifying coefficient;
• controlling stress state while generating a continuous acoustic signal produced by operating mining equipment (combine machines, plough-type machine and a drilling rig) into the massif;

• controlling stress state while generating discrete acoustic signal produced by artificial source (stroke of a heavy hammer hammer) into the massif.

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