Comparative analysis of options for applying spectral-acoustic method of gas-dynamic phenomena forecasting

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Abstract. The options of applying spectral-acoustic method of controlling stress state of a rock massif for preventing dynamic phenomena are analyzed in the paper. Two options are based on the dependence of relationship of high and low frequencies amplitudes of acoustic signal spectrum of operating equipment on a stress state of a massif in the area between the generator and the receiver of the sound. The difference between these two options is in choosing between high-frequency and low-frequency areas of a source sound spectrum. The drawback of both is in failure to use the whole spectrum of a sound that may cause the error in controlling stress state. To correct this drawback a modified option for applying the method based on the dependence of the median of amplitude and frequency characteristics of a sound on actual stresses is justified. The results of testing the method for controlling stress state of a working face space of a stope in the process of a hard roof directional hydraulic fracturing by hardware-software complex based on RIPAS apparatus are introduced.

1. Introduction
Initially spectral acoustic method for controlling stress state of a rock massif was applied as a geophysical method of current outburst danger forecasting [1-3]. That time it was named as a method of forecasting based on amplitude-frequency characteristic of a seam [2]. The given name did not take hold probably because of its length. Another name was taken as an acoustic method [3-4]. The name also didn’t take hold as there were many acoustic methods for controlling rock massif and its subject-matter was not expressed in the name. In regulating documents which are in effect at present time this method of forecasting outburst danger is named as a method of forecasting based on artificial acoustic signal parameters [5]. As we see it, the name is not entirely correct as the method is realized through spectral analysis of noises produced by operating mining equipment that went through the controlled rock massif. The sources of the noise are such mining machines as a heading-and-winning machine, a boring bit etc. and their acoustic signals are rather natural. Thus, as the bases of the method is in spectral analysis of acoustic signals the name “spectral-acoustic” is short and expresses its basic idea better.

Physical bases of the spectral-acoustic method is in the idea that the attenuation rate of an acoustic vibration in its first approximation is linearly proportional to the vibration frequency and inversely proportional to average stress that acts in propagation path of the vibrations [6-8]. This implies that with the growth of stresses the attenuation rate of high-frequency harmonics decreases more intensively than the low-frequency ones. That is why the relationship of amplitudes of high-frequency...
harmonics to low-frequency ones increases with the growth of stresses. This parameter is used in forecasting the outburst danger.

However, the outburst danger depends not only on the forces of rock pressure but also on in-situ pressure of free gas the volume of which does not practically influence on the attenuation rate of a sound signal [9]. Thus, spectral acoustic method controls only rock pressure. To forecast outburst danger the spectral acoustic control is to be enhanced by controlling methods of other basic factors of outburst danger, in particular, methods of controlling in-situ pressure and coal strength of the mostly crushed coal bench. Therewith spectral acoustic method is the basic one and the outburst danger criterion for it is corrected depending on gas pressure and coal strength [7-8, 10-11].

As the necessity to control stress state of a face working space appears not only during the mining of outburst danger seams the spectral-acoustic method is applied or justified for application for forecasting other dynamic phenomena and for monitoring acting stresses while performing specific technologies of mining [12-14].

2. The options for applying spectral-acoustic method

At present time there are two options of applying spectral-acoustic methods. They differ by the choice of frequencies used for determining the coefficient of relative stresses.

The first is characterized by splitting of operating frequency range of a noise source (for example, 20-150 Hz (cps)) into subranges of low and high frequencies [15]. The splitting is done with the help of analogue filters of low and high frequencies. The signals from the filters are detected by amplitude detectors and the relation of high-frequency $A_h$ and low-frequency $A_l$ detected signals is called the coefficient of relative stresses $K$ and equals to [6, 7]:

$$K = \frac{A_h}{A_l} = \exp \left( -C \frac{\sigma_{lm}}{\sigma_c} r \right),$$

where $\sigma_{lm}$ and $\sigma_c$ are limit and current values of average stresses, MPa, variable; $r$ is the distance from the source to the receiver of the signal, m, variable; h – notation “high”; l – notation “low”; lm – notation “limit”; c – notation “current”.

Parameter $C$ equals to:

$$C = \frac{a_0 \beta(f_h-f_l)}{f_m},$$

where $a_0$ is the attenuation at a middle frequency of working range $f_m$ in stressless position (under stressless condition), m$^{-1}$; $m$ – notation “middle”; index 0 means stress absence; $\beta$ is nondimensional coefficient of proportionality, characterized by acoustic properties of the massif, variable; $f_0$ and $f_l$ – are average frequencies chosen for controlling the areas correspondingly of high and low operating subranges of spectrum that mining equipment radiates, Hz.

The second option of choosing the operating frequencies is done as follows: the received (by geophone) acoustic signal is digitalized and by applying fast Fourier transformation the amplitude-frequency characteristic (AFC) of a signal is determined. Harmonic $A_{max}$ with maximal amplitude is determined on it. To the left and to the right of this harmonic harmonics with amplitudes equal to 0.5$A_{max}$ and 0.75$A_{max}$ are determined. Subrange of frequencies between the harmonics with amplitudes 0.5$A_{max}$ and 0.75$A_{max}$ to the left of the frequency with $A_{max}$ is referred to low-frequency area and similar subrange of frequencies to the right of the harmonics with $A_{max}$ is referred to high-frequency area. The coefficient of relative stresses in this case is determined according to the formula:
\[ K = \frac{\sum_{j} A_j}{\sum_{i} A_i}, \]

where \( A_j \) and \( A_i \) are the harmonic amplitudes in high-frequency and low-frequency areas; \( i \) and \( j \) - numbers of low and high frequency harmonics respectively.

The peculiarities of both options are considered in details in [16]. One of their significant drawback is the non-use of the entire spectrum of a useful signal. Multiple experimental data show that due to the diversity of mining and geological conditions of coal seam excavation the rise of amplitude-frequency characteristic before a sudden outburst was registered in different frequencies (for example, see [15]). It can bring about the effect when the change of a stress state ahead of the working causes the significant changes of a signal spectrum in the area of the spectrum which is situated out of previously set low and high frequency subband.

To eliminate the drawback we justified the modification of spectral-acoustic method using the whole continuous spectrum of an acoustic signal of an operating equipment within the range between 20-1000 Hz. The usage of higher frequencies can decrease the sensitivity depth of the method ahead of a development working which is determined by minimal length of a wave in the spectrum of a sounding signal where the wave front is determined in accordance with Huygen’s principle [17, 18].

The justification is in the following: suppose that after the digitalization of an analogue sounding signal and fast Fourier transformation we get a spectrum of \( N \) harmonics. The amplitude of \( n \)-th harmonic in the distance of \( r \) from the source can be written as:

\[ A_n(r) = A_{n,s}F(r)e^{-\alpha_n r}, \]

where: \( A_{n,s} \) – is an amplitude of \( n \)-th harmonic at the signal source (noise of an operating equipment); index \( s \) – means that the distance between the sound source and the receiver is equal to zero; \( F(r) \) – is a function that considers the diagram of signal source directivity (for example, \( F(r) = 1 – \) for a plane wave; \( F(r) = 1/r – \) for spherical wave); \( \alpha_n \) – the attenuation rate of \( n \)-th harmonic signal; \( r \) – the distance between the source and the receiver of the signal.

Let’s assume that the interval between the neighboring harmonics \( \Delta f \) equals, for example, 20 Hz, and the maximum frequency of chosen by us working range is equal to 1000 Hz.

Then the frequency of \( n \)-th harmonic will be equal to

\[ f_n = 20n, \quad n \in [1; 50]. \]

In first approximation, the attenuation rate \( \alpha_n \) depends on its frequency \( f_n \) and current average stresses \( \sigma \) as follows [6]:

\[ \alpha_n = \alpha_0 \beta \frac{f_n \sigma_m}{f_0 \sigma_c} = \varepsilon f_n \frac{\sigma_m}{\sigma_c}, \]

where: \( \sigma_m \) – is an average limit stress (maximal possible for a controlled section of a seam that precedes the shattering of a massif caused by dynamic phenomenon) on the propagation path of an acoustic signal, Pa; \( \varepsilon = \frac{\alpha_0 \beta}{f_0} \), m\(^1\)Hz\(^{-1}\).

Then for the selected frequency range the sum of discrete series of amplitudes of an acoustic signal spectral component \( A(f, r) \) considering Eqs. (3-5) will be equal to:

\[ A(f, r) = \sum_{n=1}^{50} A_{n,s}F(r)e^{-\varepsilon f_n \frac{\sigma_m}{\sigma_c} r}. \]
Assuming that amplitude-frequency characteristic of an acoustic signal at the source has a maximum value then its components near the signal transmitter tool can be described by two exponential functions (increasing and decreasing) as follows:

\[ A_{n,s} = \begin{cases} A_{0,s}e^{\xi 20n}, & n \in [1, 14] \\ A_{0,s}e^{-\eta 20n}, & n \in [15, 50] \end{cases} \]

(7)

where \( A_{0,s} \) is an amplitude of hypothetic “zero” harmonic with \( n = 0 \), V; the parameters \( \xi \) and \( \eta \) determine the exponents change rate.

Determine parameters \( \xi \) and \( \eta \) out of the condition that \( A_0 = 1,75 \text{ V} \) and amplitudes of the following harmonics satisfy the condition \( A_{14,0} = A_{15,0} \approx 1,0 \text{ V} \) with \( r = 10 \text{ m} \) and \( d = 1,0 \) (the condition of joining of two exponents). Then equation (7) is:

\[ A_{n,0} = \begin{cases} 0,333e^{+0,073n}, & n \in [1, 14] \\ 2,86e^{-0,07n}, & n \in [15, 50] \end{cases} \]

(8)

Substitute Eq.(8) into Eq.(6). The results of calculating the amplitudes of separate harmonics are shown in figure 1 with the following values of input parameters: \( \alpha_0 = 1,3 \text{ m}^{-1} \); \( \beta = 0,07 \); \( f_0 = 500 \text{ Hz} \); \( F(r) = 1 \); \( r = 10 \text{ m} \); \( d = \frac{\sigma_c}{\sigma_{im}} = 0,2 \) and 1,0.

Figure 1 demonstrates that together with the stresses growth the amplitudes of high-frequency harmonics increase more significantly than the low-frequency ones and the median of the amplitude-frequency characteristic moves to the right.

For introduced parameters of an acoustic signal we will determine the dependence of a current value of discrete series of spectral component amplitudes median on the relation \( \frac{\sigma_c}{\sigma_{im}} \). Thus according to the definition median will be understood as the root of equation \( A(f,r) = 0,5 \), in other words \( M_c \) – it is a value of harmonic frequency \( f_{md} \) (\( M_c = f_{md} = 20p \)), where the following condition is satisfied:

\[
\begin{align*}
\sum_{n=1}^{p} A_{0,s} e^{-\frac{\epsilon_{20n} \sigma_{im}}{\sigma_c}} & \leq 0.5 \sum_{n=p+1}^{50} A_{0,s} e^{-\frac{\epsilon_{20n} \sigma_{im}}{\sigma_c}}, \\
\sum_{n=1}^{p+1} A_{0,s} e^{-\frac{\epsilon_{20n} \sigma_{im}}{\sigma_c}} & > 0.5 \sum_{n=p+2}^{50} A_{0,s} e^{-\frac{\epsilon_{20n} \sigma_{im}}{\sigma_c}},
\end{align*}
\]

(9)

where \( p \) – the number of harmonic; \( md \) – notation “median”.

Figure 1 shows that with the growth of average current stresses from 0,2 \( \sigma_{im} \) to 1,0 \( \sigma_{im} \) the value of the median grows from 100 to 260 Hz.

Introduce the concept of relative stresses coefficient \( K_{md} \) for the given modification of spectral-acoustic method that equals to the ratio of the current value of the median \( M_c \) to the reference value \( M_{rf} \):

\[ K_{md} = M_c / M_{rf}, \]

(10)

where \( rf \) – notation “reference”.

To simplify this, assume that \( M_{rf} \) corresponds to the ratio of current and limit average stresses values \( d = 0,2 \). The table demonstrates the calculation of \( K_{md} \) value from the ratio \( d \).
Table 1. The value of the relative stresses coefficient $K_{md}$ for different values $d$ of average current and limit stresses ratio.

| $d=\sigma_c/\sigma_{lm}$ | $K_{md} = M_c/M_f$ |
|-------------------------|--------------------|
| 0.2                     | 1.0                |
| 0.4                     | 1.8                |
| 0.6                     | 2.2                |
| 0.8                     | 2.4                |
| 1.0                     | 2.6                |

Functional testing of this modified spectral-acoustic method took place in “Yubileinaya” Mine “TopProm” Ltd. with the help of software-hardware complex based on intrinsically safe portable recorder of an acoustic signal RIPAS, produced by “MNTL RIVAS” company [13]. The task of the researches was in registering the changes of a stress state ahead of the long face caused by directional hydraulic fracturing of the roof performed through the boreholes drilled into the airway. The estimation of the face working space stress state was performed before and after the directional hydraulic fracturing (DHF) process.

Following the measuring technique of RIPAS apparatus geophone was installed on the gallery edge and both sides of it were hammered at a distance of about 2 meters. Then geophone was taken to...
another place far from the stope and the sounding procedure, similar to the previously described one, was performed.

Signal processing with the purpose of determining the coefficients of relative stresses $K$ according to the algorithm recommended by the Technique [13] and according to the algorithm based on the analysis of amplitude-frequency characteristic (AFC) median shifting $K_{md}$ was performed after the exiting the mine, under laboratory condition. The data are presented in figure 2.

![Figure 2](image)

**Figure 2.** The dependence of the relative stresses coefficient $K$ determined by RIPAS apparatus and $K_{md}$ coefficient calculated on the AFC median shift before and after DHF on a distance to a stoping face.

As it is seen from figure 2 firstly, coefficient $K$ changes drastically along the gallery. Secondly, the coefficient $K_{md}$ is characterized by lesser changeability than $K$ coefficient therewith the direction of changes do not always coincide with $K$ changes. Analyzing these experimental data we can indicated the following:

Noncoincidence of the coefficient $K$ and $K_{md}$ directions as you move away from the stoping face can be explained only by the difference of algorithms applied for their determinations. Additional experiments should be performed for defining the most trustworthy algorithm out of these two.

It is unlikely that such significant changes of $K$ coefficient along the gallery can be caused by changes of a massif stress state. Significant changes of $K$ coefficient can be caused by both different rock jointing in the places where the geophone is installed or by different quality of the geophone contacting with the massif in various points of installation. To avoid the influence of near the face rock jointing on determining the coefficient of relative stresses it is planned to use geophone the design of which allows us to install it into the borehole with the length of 1.0-1.5 m behind the zone of intensive rock jointing.

Changing of $K$ coefficient can be conditioned by the fact that geophone is placed into the closest zone of the transmitter tool where exponential dependence of a signal amplitude on the distance between the transmitter tool and the receiver is not fulfilled [19]. In the indicated literature source, the transmitter tool is point-like whereas the cutting unit of a combined machine cannot be referred to as a point-like due to its significant size. To organize the research on the dependence of acoustic signal amplitude generated by the mining combined machine into the massif in the closest zone while mining is extremely difficult. That is why the research on determining the peculiarities of the acoustic signal behavior in the closest zone was performed on the model.
Electron accelerator “Impulse” was used as an acoustic signal source with the transmitting surface in the form of a circle. Energetic beam of electrons (EBE) generated by the electron accelerator was directed on the metallic target with the piezoelectric element pressed to its backside and with the acoustic trap in form of cone for absorption of a transmitted signal attached to the opposite side. The duration of electron momentum was 5 nanoseconds, its diameter equaled to 10.2 mm and average EBE energy made 0.36 J. Under these EBE parameters and with its interaction with the target an acoustic impulse on thermoelastic mechanism was generated at the surface of the target. The form of the acoustic signal was registered by piezoelectric element and the signal was sent to a storage oscilloscope. Having found the length of the impulse and the velocity of signal propagation the length of the wave of a basic acoustic signal harmonic was determined in the target material. It depended on the target material and for the examined samples it reached from several decimals to one mm. Thus, the closest zone of the transmitter tool reached about 3-5 mm.

Figure 3 represents the results of the experiment. Here we can see that the signal amplitude in the closest zone of a transmitter tool is characterized by its changeability, the value of which depends on the target material.

![Figure 3. The dependence of acoustic impulse amplitude that went through the sample, on its thickness.](image)

3. Conclusion
The option of applying spectral-acoustic method on the bases of the dependence of AFC median on the stresses uses the whole signal spectrum, that is why it eliminates the forecasting error arisen due to the loss of data in uncontrolled part of a spectrum. However, the sensitivity of it is less than other applied options.

High changeability of the relative stress coefficient can be referred to joint influence of the following factors: various degrees of a massif rock fracturing along the gallery, unequal conditions of the geophone contacting with the massif, peculiarities of the signal propagation in the closest zone of a transmitter tool and measuring errors.

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