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Possibilities of the evaluation of acoustic signal from the rock disintegration in a frequency domain

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The contribution focuses on the experimental basis of acoustic signal evaluation in a frequency domain using experimental data acquired by a sound-level meter Mediator 2238 from scanning of the acoustic signal arisen during the rock disintegration process by means of rotary drilling. The paper also focuses on the model of mathematical processing of parallel-scanned acoustic signal. The research field is complex due to properties of the process and the subsequent proper physical application of measured values and the design of a proper mathematical model of the process. The research is based on a conception that a signal of mechanical vibrations, i.e. also an accessory acoustic signal, carries an information on a stage of disintegration process, which might be used for its identification, control and optimization of rock disintegration process. As the problem is very extensive, many patterns of several science areas have to be considered and coordinated, such as rock disintegration, acoustics, scanning and processing of monitored signals, not only during the experiments but also at their evaluation and finding new relations and models.

Key words: *drilling process, acoustic signal, sound-level meter Mediator 2238, frequency analysis, Fourier transforms.*

Introduction

A whole range of research projects at the Institute of Geotechnics SAS was focused on the process of rock disintegration by rotary drilling. The research was not only dealing with a model of mechanical disintegration but also with relations between the variables entering the system indentor-rock. One of the important experimental outcome within the energy-technological theories of rock disintegration was the introduction of a new variable φ, representing a working ability of a disintegration tool (Krúpa, 1998). As the φ is an experimentally measurable variable, it was chosen as a base for a further research on the experimental drilling stand, based on a concept that signal of mechanical vibrations, including an accessory acoustic signal, carry an information on a stage of the disintegration process, which might be used for its identification, control and optimization of rock disintegration process (Leššo, 2004), (Futó et al., 1997), (Kostúr et al., 1997). As this problem is very extensive and many patterns of several science areas have to be considered and coordinated, such as the rock disintegration, acoustics, scanning and processing of monitored signals, one of available possibilities is to evaluate the measured spectrum in various disintegration regimes and to search for relations with the variables outcoming from the rock disintegration process. This paper focuses on the comments and the comparison of a parallel-scanned signal from an electret microphone and of an acoustic pressure scanned and evaluated by a sound-level meter Mediator 2238. Accompanying acoustic signal scanned by the electret microphone was processed in frequency a spectrum using the spatial discrete Fourier transforms (Futó, 2004).

Theoretical basis for the acoustic signal evaluation

Noise as an acoustic waving of gaseous phase is usually defined as an undesirable, annoying sound of everyday activities detrimental to health. The current knowledge shows that effects of noise on the human being are influenced by how the noise is processed by an acceptor. In the physical consideration, the noise represents waving of liquid or solid phase, which propagates from its source and transfers an energy. The waving develops a periodical densification and dilution of the surroundings in a manner that it creates the wavefronts characterized by an instantaneous state of physical variables describing the acoustic field (Žiaran, 2006).

The sound power is a basic physical property of the signal source and thus is an important parameter for a comparison of various sound sources. It is defined as

$$P = \int_A I \, . dA \qquad \text{[W]} \qquad (1)$$

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where I is the sound intensity of noise [Wm^{-2}], A is the area around the source [m^2].

The integrating sound-level meter Mediator 2238 by Bruel & Kjaer was used for the measurement of the acoustic pressure. In such a case, the equivalent sound pressure level with the weight filter „A“ is calculated according to the formula

$$L_{Aeq,T} = 10\,log\left\{\left(\frac{1}{T}\int_{t_1}^{t_2} p_A^2 t / p_0^2\, dt\right)\right\} \quad [dB] \qquad (2)$$

where

$L_{Aeq,\,T}$ - equivalent continuous sound level A, determined in the total measurement time interval $T = t_2 - t_1$,
p_A - instant sound pressure of the acoustic signal frequency-weighted by a weight filter “A”,
p_0 - reference sound pressure 20 μPa.

$$f = \sqrt{f_d \cdot f_u} \quad [Hz] \qquad (3)$$

where

f - geometric center of measured band,
f_d - lower limit of band frequency,
f_u - upper limit of band frequency (Kostúr, 2007).

In this case, the noise source is located in a closed space, confined between perpendicular and parallel planes. A sound wave that propagates in this closed space in any direction collides with walls, where reflections of the original wave arise, and further reflections of reflected waves are formed. The sound field, which arises with such multiple reflections in the closed space is very complex and hard-to-describe by simple relations defining its propagation. Therefore, we have to reckon the empirical or experimentally derived relations and dependencies. Multiple reflections in closed space in a relatively small distance from the sound source induce an acoustic field with a random direction of propagation and distribution of the sound, called the diffuse sound field. The fundamental law of acoustics, i.e. that the proportion of pressure decreases with a distance, is not valid in the diffuse sound field (Futó, 1997).

A detailed analysis of the sound field in the closed space results from the formula for the calculation of self-resonant frequency, which is derived from the basic wave equation. When measuring the acoustic pressure in one-octave of 1/3-octave bands, the acoustic field may be regarded as a diffuse one, and the frequency value is calculated from

$$f = \frac{400}{\sqrt[3]{V}} \cong 34\ Hz, \quad \text{or} \quad f = \frac{600}{\sqrt[3]{V}} \cong 51\ Hz, \qquad (4)$$

where V is the volume of closed space [m^3], (Žiaran, 2006).

Commonly used sound-metering devices usually perform a one-octave or 1/3-octave noise analysis. The analysis results present a frequency distribution of the acoustic energy, which provides the determination of the noise source.

The state of the rock disintegration device (drilling stand) may be observed using the acoustic energy emitted during the drilling stand operation. A selection of acoustic effects as an information source on technical state of the machinery is determined by several causes:

- acoustic signal is a response of fundamental physical processes running in inner parts of the machine (oscillations, deformation, stress, friction, etc.);
- acoustic signal bears a large information capacity;
- acoustic signal may be relatively easily registered in natural conditions during the disintegration device operation (Žiaran, 2006).

An acquisition of information about the operational state of the mechanical system from emitted vibro-acoustic signals requires a knowledge about the concept of their generation (Kumičáková, 1994). The analysis of dynamic processes (oscillations, noise, deformation, etc.) arising in machines with the stationary periodic motion showed that these processes are fairly periodical:

- mutual displacement of individual parts of the machinery;
- running technological process;
- wear and damage or failure of construction elements.

Following the directions in the experimental data acquisition and keeping the full-use of a whole technological range of operational values of the thrust force and revolutions of drilling device (ranging from 0 to 10000 N and from 0 to 23,33 s^{-1}, respectively), the parameters of all the measuring instruments and devices were used in order to provide a complex utilization in individual experiments. The acoustic pressure was measured using the sound level meter Mediator 2238 and by the electret microphone which registered the sound using the parallel acoustic channel and archived the scanned signal via PC into individual files.

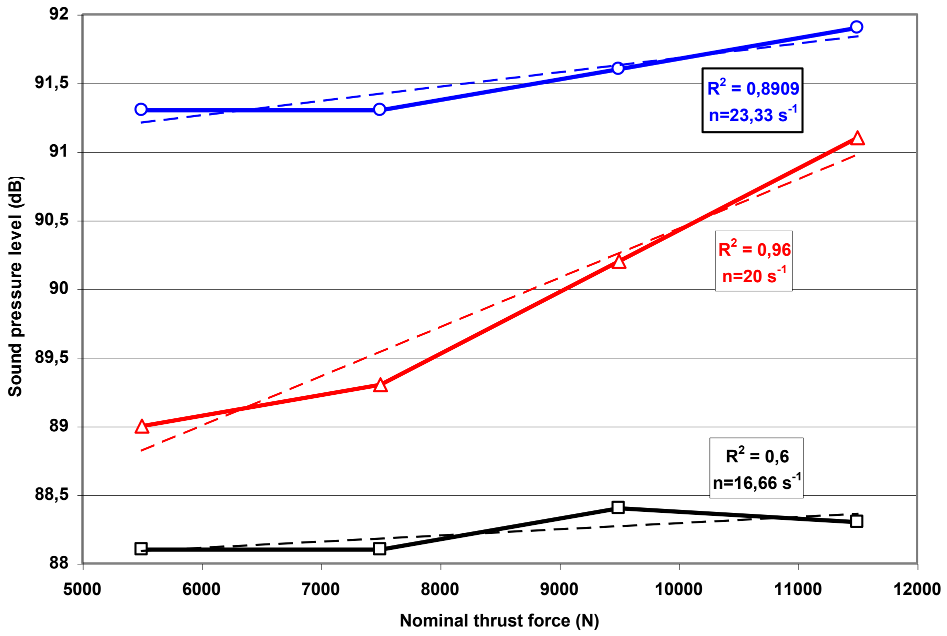

Fig. 1. Behaviour of sound pressure levels at various operational regimes during granite disintegration.

The spectral analysis of the signals confirmed that a basic compound of the frequency is related to the rotation frequency of the disintegrating device and to a wide spectrum of linear-dependent higher frequency compounds regarding the frequency spectrum of dynamic processes.

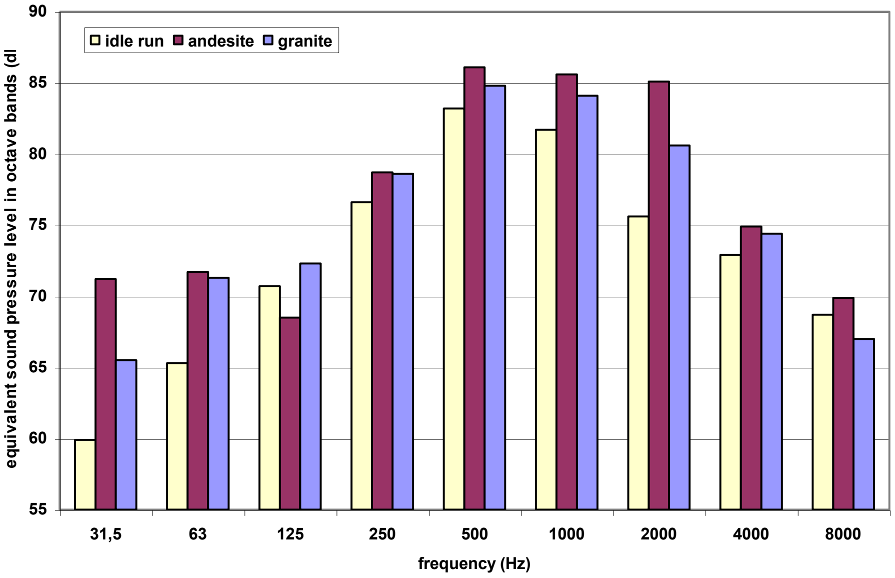

Fig. 2. Behaviour of equivalent sound pressure levels in octave bands measured with the sound-level meter Mediator 2238 in the idle run and during the drilling in andesite and granite at nominal revolutions n=16,67 s^{-1} and the thrust force F=10 000 N.

Fig. 1 illustrates the behaviour of the sound pressure levels in three different sound pressure levels at three different levels of revolutions depending on the thrust force applied during the granite drilling. The behaviour shows a linearity in the whole observed range of thrust force and the trends exhibit high values of regression reliability. The composition of the frequency spectrum bears more information on the state of the system regarding the dynamic effect of the acoustic environment (fig. 2 showing three different sound pressure levels in octave bands). The first bar represents the idle run of drilling device at nominal revolutions n=16,67 s^{-1}, the second bar represents the andesite drilling at nominal revolutions n=16,67 s^{-1} and the nominal thrust F=10000 N, the third one represents the granite drilling at nominal revolutions n=16,67 s^{-1} and the nominal thrust F=10000 N. The equal values of revolutions of all three cases showed a relation to the revolution frequency of the drilling device. Measured differences of the sound pressure values in the idle run and in the drilling process might be related to the disintegration process, oscillations of the rock and the tool during the drilling. The analysis of the measured values showed that the frequency spectra did not reveal major differences within the bands from 125 Hz to 8000 Hz, apart from the first two bands, i.e. 31,5 Hz and 63 Hz. The differences in both bands between the idle run and andesite drilling are 11,3 dB and 6,4 dB; between the idle run and granite drilling 5,6 dB and 6 dB. The difference might be caused by a self-resonance, which is close to the calculated value, approximately 34 Hz, and relates to the closed-space properties in the time of experiments. The measured and calculated values are shown in table 1.

Tab. 1. Measured values of sound pressure levels (SPL) in octave bands in the idle run, during the andesite and granite drilling and the differences in individual octave bands.

Frequency [Hz]	**SPL in idle run** [dB]	**SPL in andesite drilling** [dB]	**SPL in granite drilling** [dB]	**SPL difference idle run – andesite drilling** [dB]	**SPL difference idle run – granite drilling** [dB]	**SPL difference andesite – granite drilling** [dB]
31,5	59,9	71,2	65,5	11,3	5,6	5,7
63	65,3	71,7	71,3	6,4	6	0,4
125	70,7	68,5	72,3	-2,2	1,6	-3,8
250	76,6	78,7	78,6	2,1	2	0,1
500	83,2	86,1	84,8	2,9	1,6	1,3
1000	81,7	85,6	84,1	3,9	2,4	1,5
2000	75,6	85,1	80,6	9,5	5	4,5
4000	72,9	74,9	74,4	2	1,5	0,5
8000	68,7	69,9	67	1,2	-1,7	2,9

A comparison of measured values in individual octave bands implies that the largest differences, apart from the above-mentioned lower bands, reside in the octave bands of 1000 and 2000 Hz. The differences vary rather significantly. However, the integrating properties of the sound-level meter have to be taken into account, resulting from the formula (2). This means that during the measurement lasting for t=47 s, all the inhomogeneities of drilled rock, the changes in the thrust force and in the revolutions are included in the evaluation from the sound-level meter. Such changes are registered in the acoustic space, which is then reflected in the measured values of the acoustic pressure in the individual bands.

A significant reduction of the effect of integration compound may be delivered by the evaluation of the signal by discrete Fourier transforms. Such evaluation uses only a part of the signal (e.g. 1024 samples, corresponding to 0,0512 s) even if there is a large number of the registered values of the acoustic pressure (sampling frequency 20000 Hz). The advantage of the presented evaluation is that it does not show a large integration error as in the previous method of measurement (this method is also fast and proper for the on-line control system).

Concerning the further analysis of the rock disintegration process, the spatial Fourier transforms appear to be perspective method for the observation of the development of frequency characteristics depending on time. A display of the time interval of 1/10 s in presented evaluation method, the level of a single reply is obtained, which ensures the observation of the disintegration process of one revolution. Such a display represents a certain "blur" and a partial information loss, however there are formulas (5) and (6), whose display accuracy might be affected:

$$\Delta f \approx \frac{1}{T}, \qquad (5)$$

$$\Delta t \approx \frac{1}{f}\,. \tag{6}$$

Examples of such display of power spectral density are presented in fig. 3, 4 and 5 (Biering, 1983), (Futó, 2004). Parameters of the idle run and of the drilling process are the same as in fig. 2.

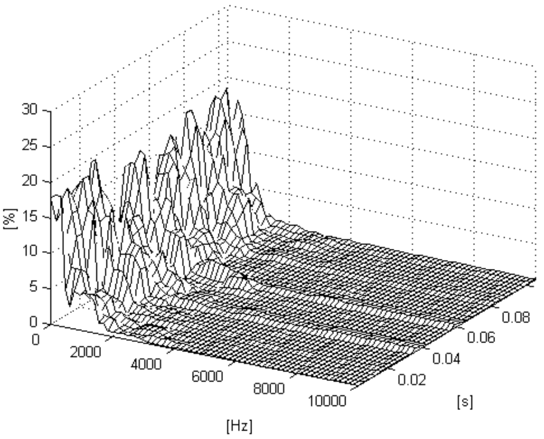

Fig. 3. Power spectral density of acoustic signal in the idle run of drilling device with revolutions n=16,67 s^{-1}.

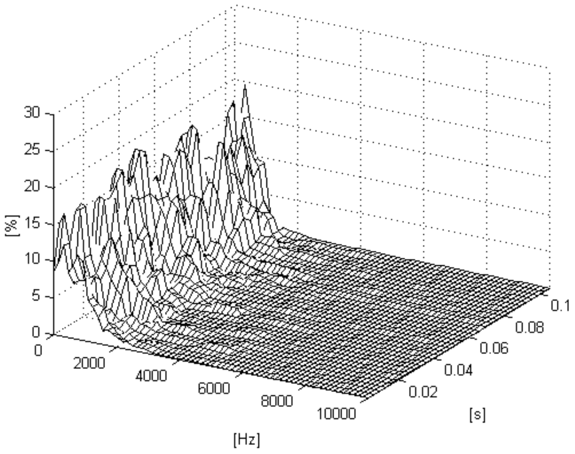

Fig. 4. Power spectral density of acoustic signal in the andesite drilling with revolutions n=16,67 s^{-1}and thrust force F=10000 N.

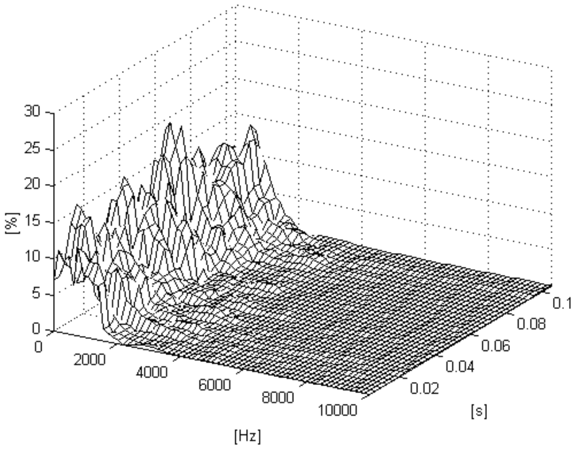

Fig. 5. Power spectral density of acoustic signal in the granite drilling with revolutions n=16,67 s^{-1}and the thrust force F=10000 N.

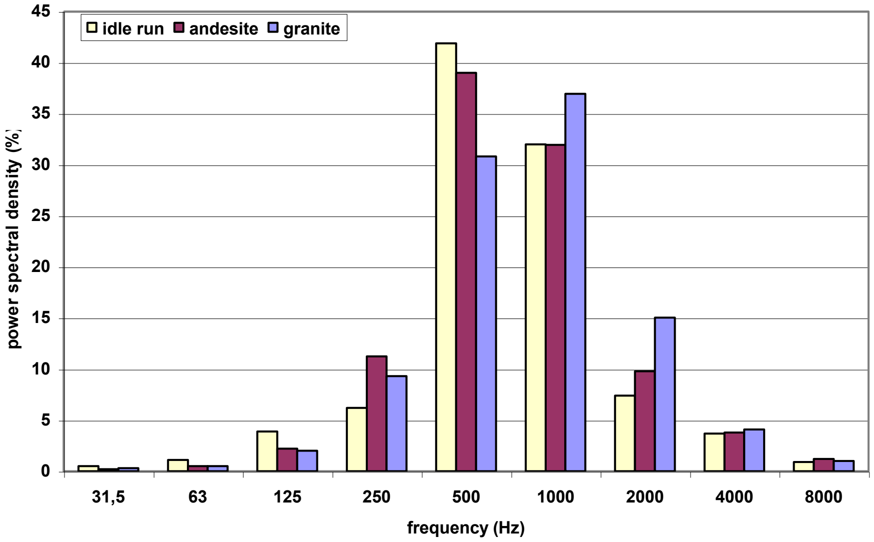

Fig. 6. Histogram of power spectral density of acoustic signal at the idle run and during the andesite and granite drilling with revolutions n=16,67 s^{-1} *and the thrust force F=10000 N.*

Figure 6 presents histograms of the power spectral density of acoustic signal taken in the cases shown in fig. 3, 4 and 5. The presented spectrum exhibits major differences between individual octave bands, due to:

1. the type of acoustic transducer (electret microphone) having different parameters than the Mediator 2238,
2. results obtained from a small number data (1024 samples),
3. the results expressed as a percentage of the measured signal.

Despite of such fundamental differences, the electret microphone appears to be a more convenient for the acoustic signal evaluation due to several reasons:

1. measured signal may be recorded and analyzed later,
2. recorded signal may be adjusted later or resampled according to requirements,
3. processing of the recorded acoustic signal using various digital filters and algorithms, e.g. RASTA,
4. the use of the recorded signal for the process control as the signal processing is very fast and enables the real-time control for a dynamic system.

The results acquired by the electret microphone allows us to test the fundamental concepts, which might be used in practice and industry for obtaining fast complementary information on the rock drilling process.

Conclusions

The paper comments two different concepts of evaluation of acoustic signal arising during a process of rock disintegration by rotary drilling. Both concepts bear the information from the disintegration process.

The measurements using the sound-level meter Bruel&Kjaer were used to evaluate the rock drilling process concerning the acoustic pressure. Based on such measurements, the measure of sound pressure level may be assessed in decibels. An orientative character of the presented measurements has ensued from a long time interval of measurements including inaccuracies in the experiments. The sound-level meter data did not provide the determination of the presence and share of spurious signal, i.e. the effect of the surrounding environment in rock drilling process. The data measured by a sound-level meter did not provide the reliable identification of the disintegration regime and the rock type.

Based on the results acquired from the measurements by the electret microphone, possibilities of the acoustic signal utilization are much larger and a proper mathematical processing and interpretation of the scanned signal might deliver better results.

A further research has to be conducted in order to confirm the current results, which indicated that the signal acquired by the electret microphone contains more information on possibilities of the process control.

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