Original Research

Evaluating Noise Sources in a Working Environment when Disintegrating Rocks by Rotary Drilling

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Abstract

The mechanical disintegration of rocks plays an irreplaceable role in the exploration, preparation, and mining of minerals resources in geological and engineering surveys. When disintegrating by rotary drilling, the disintegration tool interacts with the rock and converts the mechanical energy to thermal energy caused by the friction of the disintegration tool on the rock. Consequently, undesirable accompanying sounds occur in the process of disintegration of the rock by drilling. These include vibrations that show up in the working environment as noise. The noise generated during rotary drilling can be scanned as an acoustic signal. From above, it is possible to say that noise and vibration have a direct negative impact on the machinery personnel, on the working environment and on the environment. At present, research in the field of the disintegration of rocks by rotary drilling is directed at analyzing the factors affecting the disintegration of rocks and the working environment. This article analyzes experimental measurements carried out on a horizontal drilling tool. Measured vibroacoustic signals in different operating modes will be processed in the time, frequency, and time-frequency domains.

Keywords: disintegration of rocks, horizontal drilling stand, noise, vibrations, vibroacoustic signal, spectrum, spectrogram

Introduction

The disintegration of rocks by rotary drilling is one of the most important technological operations in the mining and processing of raw material. In order for the disconnection process to be effective, it must be monitored, controlled and optimized. This requires the measurement of input technological variables such as the pressure on the drilling tool F (N) and the speed of revolutions n (rpm) of the drilling tool, as well as the output quantities noise, vibration, and bore length [1-3]. A relevant factor in this rotary drilling technology is the interaction of a disintegrated rock with the disintegrative tool. Interaction of the drilling tool with the rock is a source of noise and vibration, the negative effects of which are largely reflected in the machinery and the working environment. Due to these

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facts, the drilling process is a random process, mainly because of the inhomogeneity of the drilling material. It is then apparent that the measured oscillating motion of the drilling equipment is also a random movement. Therefore, analysis must be based on the statistical and frequency processing of the measured vibroacoustic signal of the drilling equipment. The vibroacoustic response of the drilling equipment is in this case acceleration of vibrational movement, in various operating modes [4-6].

Time and frequency analysis can provide useful information in vibrodiagnostics and the identification of the drilling equipment, followed by the current technological state of the plant as well as the behavior of the technological process and the working environment [7, 8].

Experiment Methodology

The object of time and frequency analysis of the vibroacoustic response was laboratory horizontal drilling equipment. The drill stand was developed and constructed by the Institute of Geotechnics of the Slovak Academy of Science (IGT SAS) in Košice [9-11]. The horizontal drill stand is designed for rotary drilling of rocks with small diameter diamond drilling bits up to 80 mm in diameter [12, 13]. The equipment allows for the drilling of rock specimens of the shape of the block of dimensions $a \times b \times c$ approximately to size $300 \times 200 \times 200$ mm. Relevant parts of the drilling equipment are three main aggregates, namely a DC motor, a hydrogenerator and a water pump. Their activity is the dominant exciting effect, resulting in the vibration-acoustic response of the entire drilling equipment.

In the experimental conditions of the drill stand we can basically distinguish two basic states for noise:
– Noise during no-load.
– Noise during rotation disintegration of rocks.
  Noise during no-load has the following components:
– Noise from main aggregates.
– Noise from water flush.

To obtain the vibroacoustic response of the drilling equipment, we focused on measuring the acceleration in the dominant horizontal direction. Measurements were performed at the set operating modes of the drilling equipment in no-load (without rock specimen) and in rotating rock disintegration (andesite) [14, 15]. Operating modes:
I. mode – only one engine was in operation as one of the three aggregates of equipment.
II. mode – a pair of aggregates, engine and water pump were in operation.
III. mode – all three units were in operation (i.e., engine, water pump and hydrogenerator), and spindle of the tool without crown, revolutions n = 1000 rpm.
IV. mode – rotary drilling of andesite rock with set drilling parameters F = 8000 N a n = 1000 rpm.

The horizontal drilling equipment consists of a support stand on which a spindle head with a drill spindle is mounted. The drill bit as a working tool is screwed into the spindle drill. The drill spindle is driven by a DC motor (12.5 kW, 220 V) with external excitation (180 V) via V-belts. A thyristor rectifier is the source of direct current for driving the electric motor. The flushing fluid is fed from the pump through a rubber pressure hose into the drill spindle. The rock sample is clamped into mechanical equipment that is mechanically coupled to the strain gauge sensing head of the axial pressure force and torque. The parts of the equipment from the spindle through the core barrel to the clamping equipment are located in the protective sheet metal housing. The tensometric head is hingedly connected to the piston of the hydraulic cylinders. The handle of the slide ram is firmly attached to the stand. The flushing water is drained through a high-pressure hose (see Fig. 1) [16-18].

At present, the drilling stand allows us to operate within the following parameters:

pressure force, F	0 – 15 690 N
revolutions, n	0 – 2000 rpm
torque, Mk	0 – 196 Nm
drilled length, l	0 – 0.3 m
water flush, Q	0 – 1×10⁻³ m³s⁻¹
speed of drilling, v	0 – 16.8×10⁻³ ms⁻¹

Vibroacoustic acceleration signal for modes I-IV was measured by sampling frequency f_s = 18 kHz and sampling period T_s = 0.55 μs, whereby we gained a frequency range of (0-9) kHz.
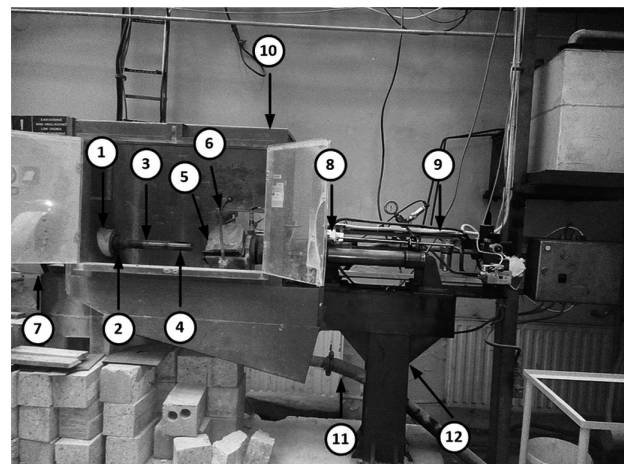

Fig. 1. Experimental drilling stand (Legend: 1 - headstock, 2 - spindle drill, 3 - core barrel, 4 - drilling bit, 5 - rock specimen, 6 - clamping mechanism, 7 - belting, 8 - piston of the hydraulic cylinder, 9 - double-acting hydraulic cylinder, 10 - sheet covering, 11 - hose for supply drilling fluid, 12 - stand).

Theoretical Background

Processing the Vibroacoustic Signal in the Time Domain

Values of vibroacoustic signal parameters generally change over time. For evaluation purposes, they are typically used by the peak amplitude, peak-to-peak amplitude and total energy content of the signal, which is given by the mean and the effective value. The following are the basic time characteristics for the vibroacoustic signal [19-21]:

– Amplitude $x(t)$ – the instantaneous value of the monitored signal parameter over time t.
– The amplitude of oscillation or so-called peak $x_p(t)$ is the maximum distance of the wave top from the reference value, usually on the x-axis.
– Peak-to-peak $x_{pp}(t)$ is the maximum distance of opposite wave peaks
– The average value $x_{avg}(t)$ is the mean value of amplitude during wave according to equation

$$x_{avg}(t) = \frac{1}{N} \sum_{i=1}^{N} \left| x_i(t) \right| \tag{1}$$

– The effective value of root mean square (rms) is the objective value used in diagnostic rules, determined by the equation [22, 23]

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2(t)} \tag{2}$$

An important statistical characteristic in time analysis is the autocorrelation of the signal or autocorrelation function $R_{xx}(\tau)$ of the measured vibration signal $x(t)$. Autocorrelation function $R_{xx}(\tau)$ represents the generalization of the mean quadratic value. It is defined by the equation:

$$R_{xx}(\tau) = \frac{1}{N} \sum x(t) x(t + \tau) \tag{3}$$

Periodic parts of the vibroacoustic signal $x(t)$ $x(t)$ remain in autocorrelation function, and non-periodicals quickly disappear. From the autocorrelation function, we can read the periodic period of the measured signal. It also provides information on dependencies of function values $x(t)$ at a time t from the values in time $t + \tau$ [24-26].

Processing the Vibroacoustic Signal in the Frequency Domain

Frequency analysis, when properly used, removes the shortcomings of analysis in time-domain. The method makes it possible to locate the occurring defects of the individual parts of the machine being watched. Frequency analysis gives the amplitude and phase spectrum of the measured vibroacoustic signal $x(t)$. The basis of the frequency analysis is in particular discrete Fourier transform (DFT) and fast Fourier transform (FFT) as calculation algorithms. By using this method, the measured vibroacoustic signal is variable in time numerically processed. Since the vibroacoustic signal $x(t)$ is sampled in the time domain in an analog-to-digital converter (ADC), its values are distant at time points by a regular sampling period T_s at sampling frequency f_s. Since in practice there is only the final number N of measured sample signals available, it is necessary to use a discrete Fourier transform. For signal processing by DFT or FFT it is necessary to be aware of the basic parameters that we encounter in the calculations [27-31]:

– Frequency range represents the basic band $(0\text{-}f_s/2)$ Hz.
– Factor "zoom," when using a frequency magnifier, indicates how many times the frequency range is smaller.
– The number of spectral lines is $N/2$.
– Spectral line serial number.
– Frequency analysis resolution, indicating a dehiscence between spectral lines.

Using Fourier transform $X(j\omega)$ to obtain a spectrum of the vibroacoustic signal $x(t)$ from the individual operating modes of the monitored drilling equipment is defined by an integral relation:

$$X(j\omega) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt \tag{4}$$

However, if we process a directly measured signal generated by a part of the equipment then we use a numerical method known as discrete Fourier transform (DFT).

For the calculation (DFT), it is useful to use an efficient fast Fourier transform (FFT) algorithm that is used to process vibroacoustic signals in the frequency domain to obtain the resulting spectrum. DFT is defined by the formula:

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j2\pi k \frac{n}{N}} \quad \begin{array}{l} n = 0,...,N-1 \\ k = 0,...,N-1. \end{array} \tag{5}$$

The discreet value $X(k)$ represents amplitude. Values $x(n)$ and $X(k)$ have the same physical dimensions.

The amplitude spectra of the vibroacoustic signals from the individual parts of the monitored drilling equipment were analyzed. The FFT algorithm was used in measured signal with a sampling frequency $f_s = 18$ kHz, sampling period $T_s = 0.55$ μs, and segment length $N = 2048$ samples. We worked with the measured and sampled signal, so we are referring to equations in a discrete form [32-34].

Table 1. Statistical characteristics of operating modes.

Operating mode	Peak	Peak to peak	Average value	RMS
I. engine only	12.753	25.836	-0.277	3.831
II. engine and water pump	13.232	26.015	-0.233	3.697
III. drilling equipment without a bit	13.247	27.752	-0.276	3.552
IV. drilling of andesite rock	76.21	160.71	-0.17	21.97

Experimental Results and Analysis

When the drilling equipment operates in no-load mode but also in the process of rock drilling, a vibroacoustic signal is generated. Therefore, it is reasonable to assume that the vibroacoustic signal generated by the technological equipment will carry current information characterizing the state of the equipment and the drilling process [35].

The following presented experimental results obtained by the measurement, processing and subsequent analysis of vibroacoustic signals of acceleration of individual aggregates of drilling equipment in the different modes of operation identify significant sources of noise in the working environment.

Non-drilling mode (no load mode) with aggregates without rock drilling can be a reference mode of operation in relation to various other rock-drilling modes.

A first step in the time analysis of vibroacoustic signals of acceleration from individual aggregates was to create time behaviors and calculations of basic statistical characteristics. Amplitudes $x(t)$, peak $x_p(t)$, peak to peak $x_{pp}(t)$, average $x_{avg}(t)$, and RMS of the signal were observed in the time domain.

In the time domain, a segment of the measured signal with the number of samples was processed as $N = 2048$.

In Fig. 2(a-d) the resulting time courses of vibroacoustic acceleration signals for the individual operating modes of the drilling operation are shown. Time behavior of vibroacoustic signals of acceleration with the number of samples $N = 2048$ is more readable. A more detailed display of vibroacoustic signals is selected for a simpler view of the behavior of the measured signal. In some cases it is possible to directly read the basic statistical characteristics.
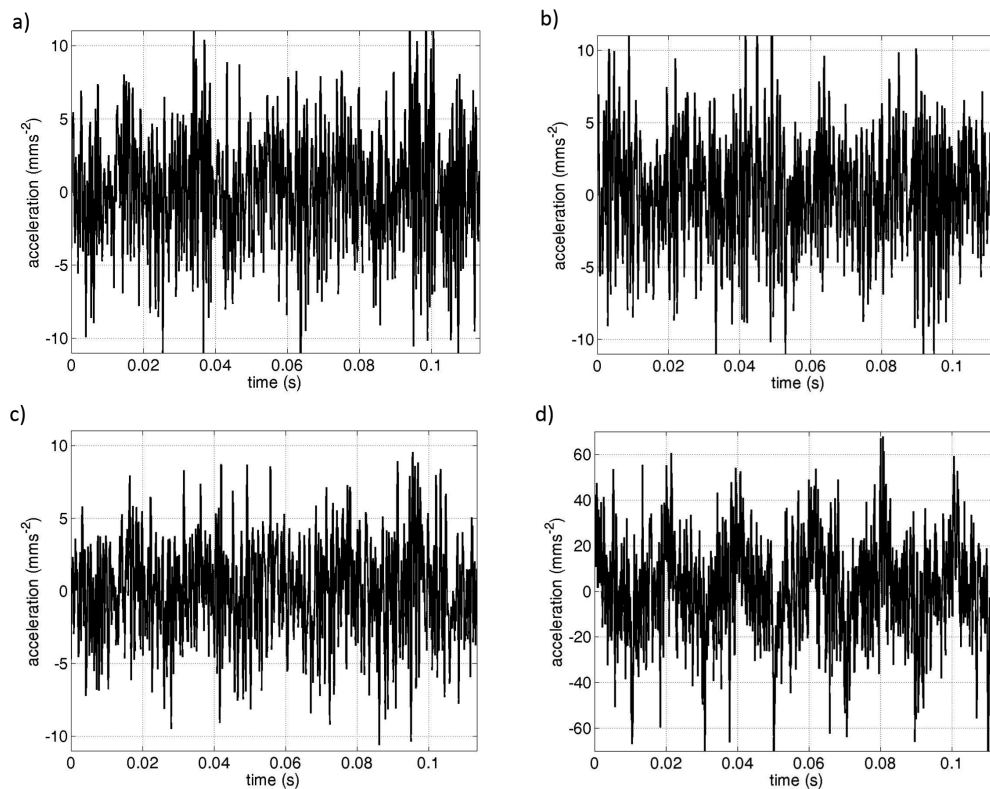

Fig. 2. Time behaviors of measured vibroacoustic signals: a) engine, b) engine and water pump, c) drilling stand with no load without drilling bit, and d) drilling of andesite rock

Operating mode IV has the highest values compared to other modes (Table 1.). The reason is that IV has a direct interaction with the rock in order to disintegrate it.

Practical knowledge indicates that an essential characteristic in time analysis is the autocorrelation function. It points to the property of periodicity and statistical dependence of samples in the measured vibroacoustic signal.

Autocorrelation functions $R_{xx}(\tau)$ of vibroacoustic signals of accelerations of aggregates are constructed from $N = 2048$ samples. The autocorrelation functions of the operating modes are shown in Fig. 3(a-d). We can see from these behaviors of autocorrelation functions $R_{xx}(\tau)$ that measured vibroacoustic signals of accelerations of individual aggregates and signal from the disintegration of rock have a quasi-periodic character with a strong stochastic component. Individual samples are statistically dependent on each other.

The processing of measured vibroacoustic signals by time analysis gives the assumption that accompanying vibroacoustic emissions are a potential reference source of information about the current state of the monitored aggregates and the drilling process. Respectively, the accompanying vibroacoustic signal is an indicator of fault-free operation of the aggregate, noise and vibration sources in the working environment and efficient drilling mode.

It will be appreciated that said time characteristics of the signal are only partially sufficient for analyzing the properties of the vibroacoustic signal in the steady and stationary mode. In the case of dynamic changes such as changing the drilling mode, the disintegrating tool, or changing the type of disintegrating rock, it is optimal to monitor ongoing change in the frequency domain.

Frequency analysis of vibroacoustic signals of acceleration from individual aggregates requires the construction of amplitude spectra. Spectra were constructed by FFT algorithm. The FFT algorithm was used for a vibroacoustic signal with the sampling frequency $f_s = 18$ kHz and sample segment length $N = 2048$ samples. In the frequency analysis and construction of the spectrum, it is necessary to consider the frequency spacing. The frequency spacing between the spectral lines of the output spectrum gives the density of the spectral lines. Denser spectral lines increase the resolution in the spectra. Frequency spacing in the spectra was determined by the equation:

$$\Delta f = \frac{f_s}{N} = \frac{18000}{2048} = 8.79 \text{ Hz}$$

Dominant frequencies and frequency bands are visible from the amplitude spectra for individual operating modes. Dominant frequencies have pronounced amplitude. Fig. 4(a-d) shows the resulting amplitude spectra for operating modes I-IV when the drilling equipment is no-load and loaded. A more
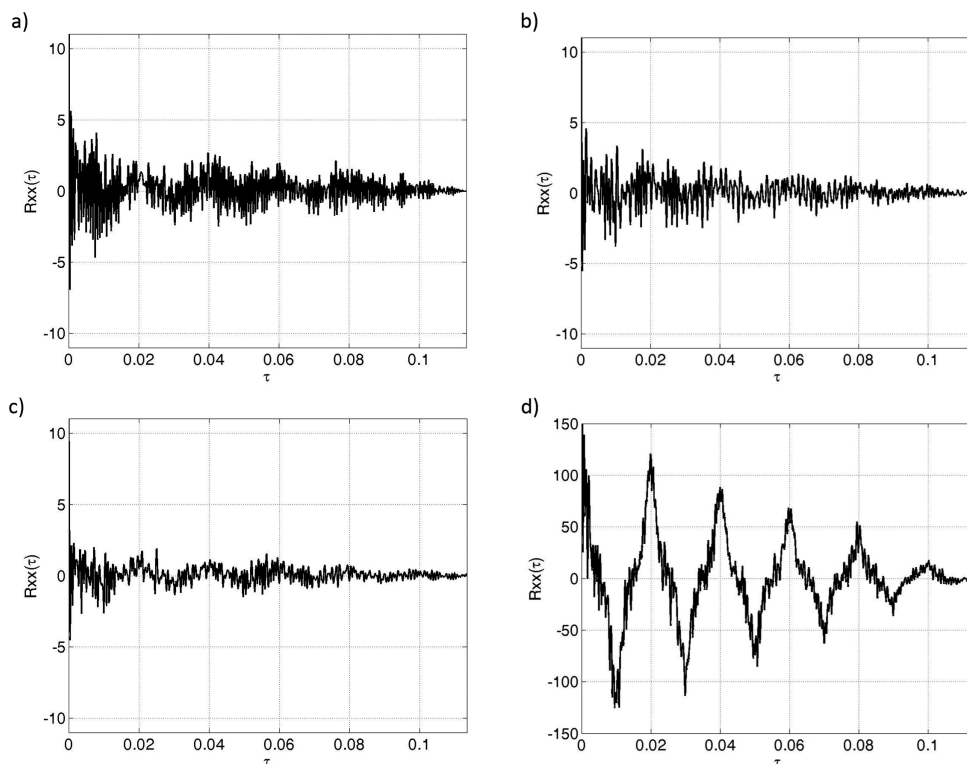

Fig. 3. Autocorrelation functions of measured vibroacoustic signals of operating modes: a) engine, b) engine and water pump, c) drilling stand with no load without drilling bit, and d) drilling of andesite rock.
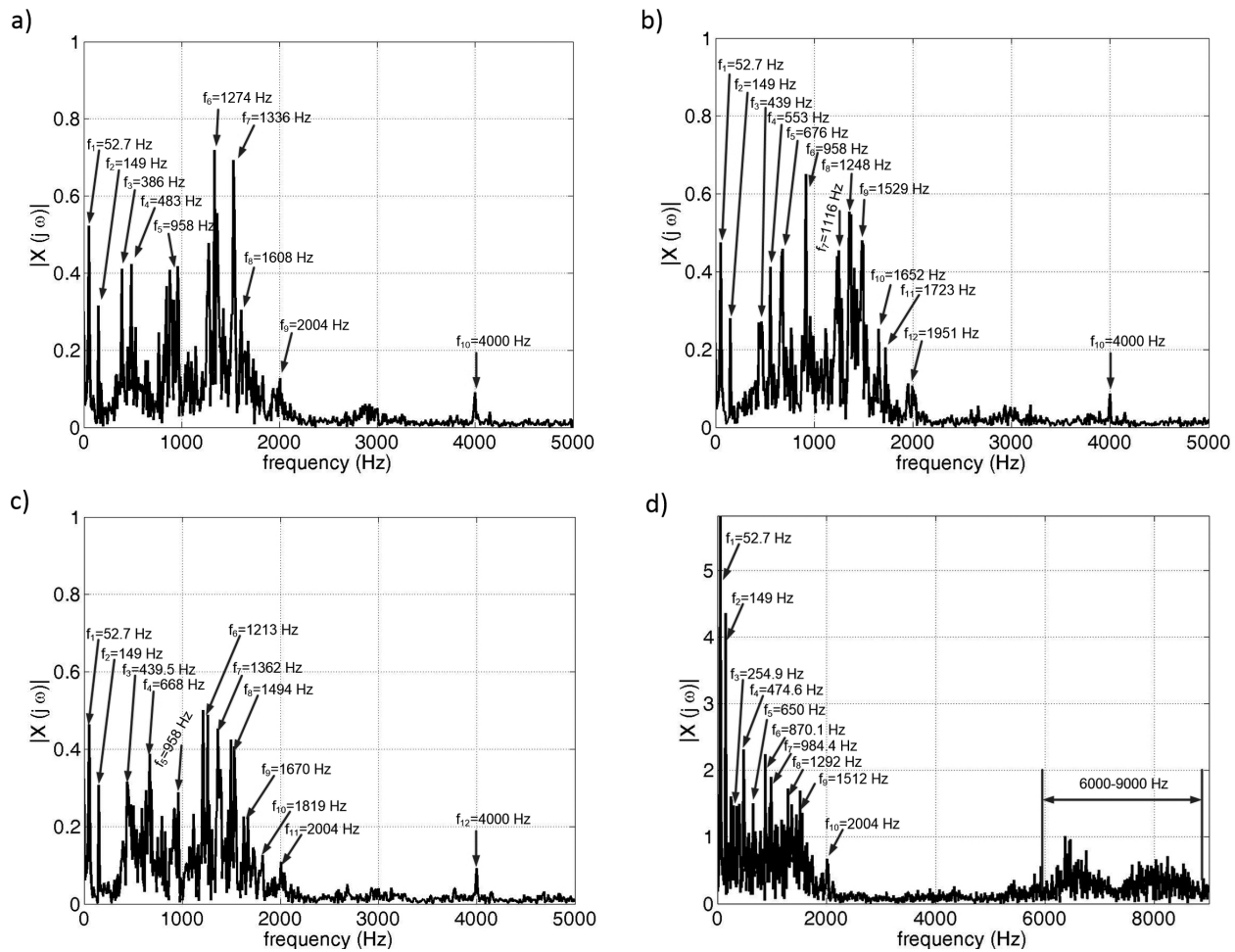
Fig. 4. Frequency amplitude spectrum of the vibroacoustic signal: a) engine, b) engine and water pump, c) drilling stand no-load and without drilling bit, and d) drilling of andesite rock.

detailed view of the spectra (zoom factor) of the vibro-acoustic signals is selected for the easier and more distinctive identification of dominant frequencies and frequency bands.

It is clear that significant frequency components of the spectrum occur in the frequency range (0-4000) Hz from amplitude frequency spectrum for operating modes I-IV in the no-load of drilling equipment and with loading.

On spectra, we can observe 11 and more dominant frequencies that are characteristic for aggregates and rock drilling. From the presented results it is possible to clearly identify and recognize individual dominant frequencies. Table 2 shows common and different frequencies from frequency amplitude spectra. Frequencies in the range of (0-600) Hz are common and different in the range (900-1950) Hz. The frequency $f = 2004$ Hz appears in operating modes I and III, frequency $f = 4000$ Hz in modes I–III, and it does not appear in mode IV. From the scientific and professional point of view, we are most interested in those frequencies that are different. We assume that they characterize aggregates, operating modes and other random vibrations and noise.

Table 2. Dominant frequencies from amplitude spectra for aggregates and operating modes.

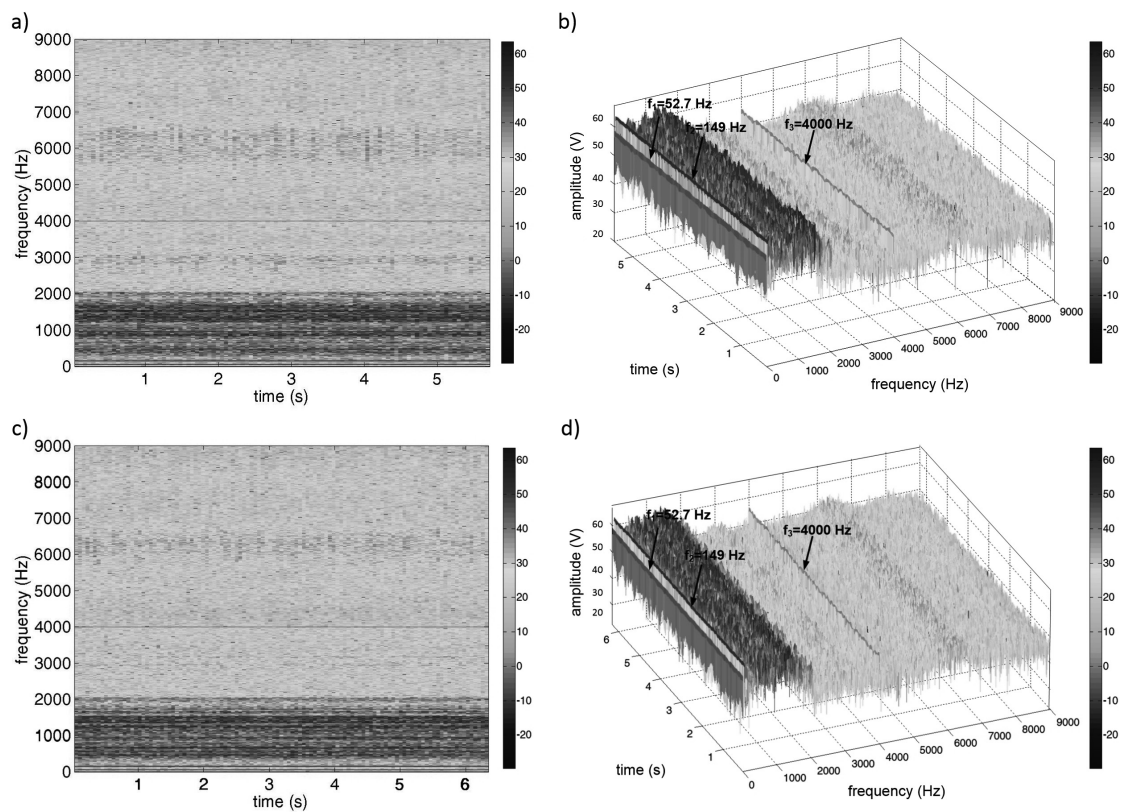| Operating mode	Dominant frequencies (Hz)										
I. engine only	52.73	149.4	386.7	483.4	958	1274	1336	1529	1608	2004	4000
II. engine and water pump	52.73	149.4	439.5	553.7	676.8	958	1230	1248	1723	1951	4000
III. drilling equipment without the bit	52.73	149.4	439.5	668	956	1213	1362	1494	1670	1819	4000
IV. andesite	52.73	149.4	246	474.6	650	870	984	1292	1512	2004	6000-9000

Fig. 5. Spectrograms of vibroacoustic signal: a) engine, b) engine (3D view), c) engine and water pump, and d) engine and water pump (3D view).
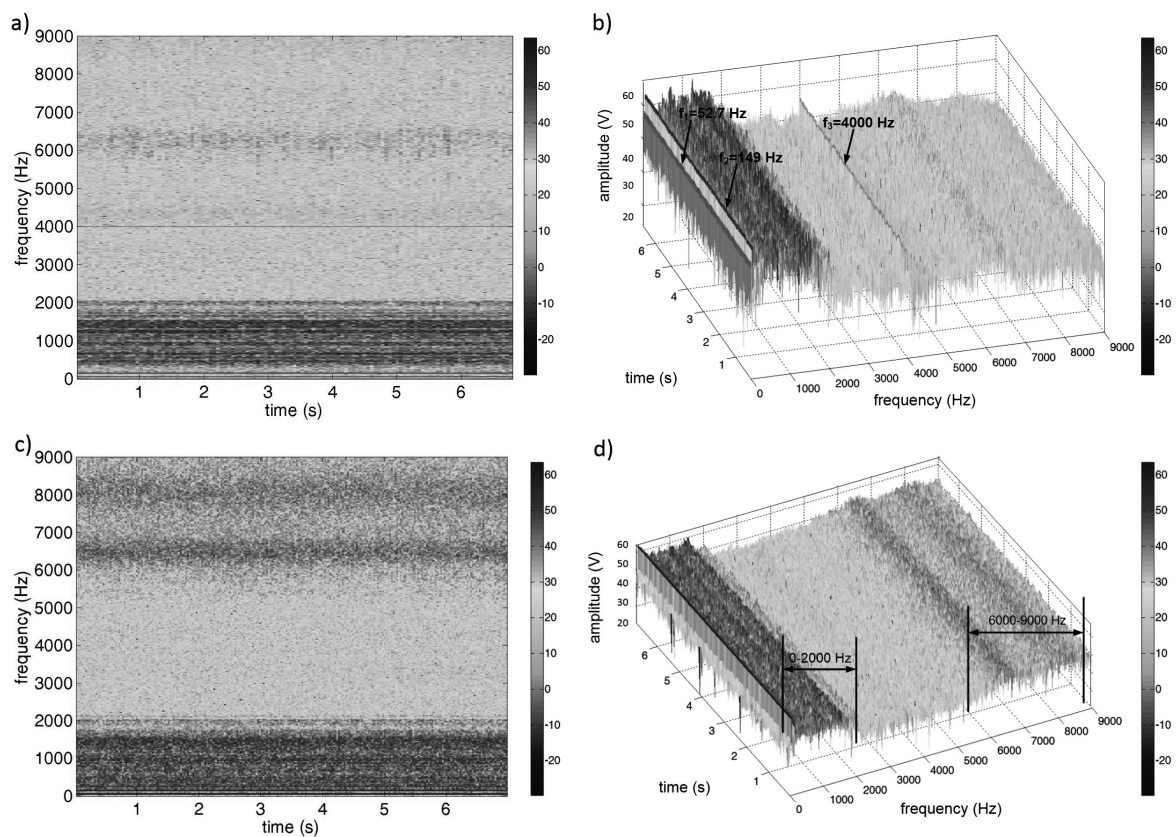

Fig. 6. Spectrograms of vibroacoustic signal: a) drilling stand no-load and without drill bit, b) drilling stand no-load and without drilling bit (3D view), c) drilling of andesite rock, and d) drilling of andesite rock (3D view).

Dynamics of operating modes and the drilling process can be observed, especially when designing spectrograms, which are the result of time-frequency analysis. We can state that they present the representation of frequencies or frequency bands over time. The presented spectrograms are constructed with the period of experimental measurement of the vibroacoustic signal $t = 20$ in sampling frequency $f_s = 18$ kHz. Spectrograms were obtained from operating modes I–IV. In Figs 5(a-d) and 6(a-d), spectrograms are shown in 2D and 3D. In 3D view, dominant frequencies are highlighted, and frequency bands in mode IV.

Spectrograms (Fig. 6c-d) show that the range of frequency domain of andesite disintegration is 6000-9000 Hz. The processing of the vibroacoustic signals in the frequency domain presented by the spectra and in the time-frequency domain by spectrogram are adequate and document the suitability of the methods used. We can say that analyses of the measured signals are correct.

Results and Discussion

Experimental measurements of the vibroacoustic signal were carried out at two basic equipment states, when the equipment was no-load and when the equipment was drilling the rock. Within the states of the equipment, four operating modes were measured. The noise sources in the rotary drilling environment are all aggregates and the noise generated at the interface between the rock and the drill bit. Interaction of the tool with the rock is a source of vibration and noise, which has negative effects on the machinery, the human working environment and the environment. The identification of noise and vibration sources is important in minimizing adverse effects [36]. Dominant frequencies can be recognized from spectra and spectrograms. We can say that individual operating modes have common frequencies 52.73, 149.4, 439.5 Hz and different in (1000-1900) Hz in lower frequency bands. A significant frequency is the value $f = 4000$ Hz that occurs in operating modes I–III. When drilling rock andesite, although IV is not recognized, there is a higher frequency band (6000-9000) Hz. We assume that the lower dominant frequencies in the spectrum correspond to the revolutions of the drilling tool and individual parts of the drilling stand that generate vibrations (i.e., engine, water pump, and floating parts of the stand). The band of higher frequencies in the spectrum can be attributed to the process of rotating drilling into the rock. Higher frequencies are visible when fully drilling into the rock with set operating mode (i.e., the speed of revolutions and pressure force). This pressure force in operating mode of drilling is due to higher frequencies in the spectrum.

A three-dimensional view that allows us to observe the dynamic behavior of the vibroacoustic signal in the time-frequency domain [37, 38] is important. Of primary impact on increased noise and vibration is the engine without a drill bit. This is when comparing operating modes without direct drilling of the rock. The greatest noise and vibration of the drilling equipment causes mode IV, because the measured vibroacoustic signal contains higher frequencies and rock drilling occurs there. The highest statistical characteristics in the time domain confirm the accuracy of the signal processing result and the conclusion regarding mode IV, which includes all drilling aggregates of the drilling equipment. This mode adversely affects the surrounding working environment and the environment.

Various geomechanical properties (i.e., abrasivity, grain size, hardness, strength, disintegrability of the disconnected rock) and the control quantities F (N) and rpm are also affected by drilling and noise and vibration. Higher strength and granularity as well as other geomechanical properties result in stronger vibrations and hence increased noise.

We can say that the noise and vibrations generated by the equipment have the following components:
– The noise of driving aggregate (engine, water pump).
– Noise caused by drilling into the rock.
– Noise due to abrasivity of drilling tools during drilling.

In essence, it can be said that the reduction in the dynamic load of the drilling stand considering the surrounding environment and humans makes itself felt by reducing noise and mechanical vibration, thus improving the working environment and the environment. Reducing dynamic utterances (i.e., vibrations, impacts, and noise) of all technological devices is necessary for design, development, installation and maintenance. Particularly in the assembly and maintenance, vibroacoustic diagnostics and monitoring of machinery are of great importance [39, 40]. Of considerable influence on oscillation and noise of primary sources are also precision of production, technological assembly, suitable arrangement and storage of individual parts of the machine, used material components, load, and technological process. It is clear that oscillation and noise can only be reduced to the extent to which current scientific and technical knowledge allows us and most machines produced at the level of contemporary knowledge.

Conclusions

The drilling tool, in rotary disintegrating of rock, builds up mechanical vibrations, vibrations, and noise that have adverse effects on the drilling machine. In addition, the vibrations and noise of drilling rocks carry the important information that can be studied in terms of the disintegration mechanism and also carry

information for monitoring, identifying and controlling the disintegration process. Based on the processing and acquisition of knowledge from the vibroacoustic signal, we can state that the measured signal from no-load and rock drilling states is dynamic, quasi-periodic with a strong stochastic component and broad-spectrum. In each spectrum, there is encoded information about the dominant frequencies of selected operating modes. The evaluation of the vibroacoustic signal generated by this process is very complex because over the course of the measurement there is a superposition of multiple sources of noise in the aggregate area and the interaction of the drilling tool with the rock. For this reason, it is important to measure mechanical vibrations – the vibrations that are the source of the acoustic signal of the rock-drilling process. Since the process of disintegrating rocks is a stochastic and nonlinear process, it is necessary to perform further experimental measurements in different operating modes.

Conflict of Interest

The authors of this paper declare that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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