Geometry Interpretation of Differentiability of Rock Types in Hilbert's Space

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Abstract

Signal of vibrations accompanying the rotary drilling of three rock types (andesite, limestone and granite) by diamond core-drill bits was processed and evaluated in order to track the signal characteristics of tested rock types. Mathematical procedures of Hilbert's abstract space were applied to express the differences between the rock types based on vibration signal. Experiments were performed using the laboratory drilling rig designed and constructed at the Institute of Geotechnics SAS providing automated continuous monitoring of key process parameters (thrust force, rotation speed, torque, advance rate, etc.). Nominal regime of thrust force 5000 N and rotation speed 1000 rpm was used in the experiments along with monitoring with sampling frequency 17 kHz. The vibration signal was recorded by accelerometers in three orthogonal directions: axial in the drilling directions and two radial directions in horizontal and vertical planes. For the purposes of evaluation, only the vibrations in axial direction were assessed as their signal exhibits the highest entropy. A method providing the expression of mutual differences between the vibrations formed during the drilling of different rock types was developed, which enables to set the differences in abstract space to the planar visualization.

Keywords: rock cutting process, vibration signals, abstract spaces, Hilbert space, geometric relations

Introduction

The long-term research of mechanical rock at the Institute of Geotechnics SAS is focused on the study of interaction between the rock and cutting tool with a view to identify the significant characteristics and parameters of the rock-tool system, which provides possibilities for efficient control of rock cutting process even in complicated geological conditions (Krúpa et al., 2008, Lazarová et al., 2008).

Our previously developed monitoring and processing systems of rock cutting were based on a direct measurement of the input process regime variables (thrust force, rotation speed and torque of the drill bit, specific cutting/drilling energy), necessary for identification of rock conditions and for control and optimization of the cutting process in real in-situ conditions (Krúpa et al., 2011, Krúpa et al., 2011, Krepelka et al., 2010). In recent years the main focus of our research switched to vibrations accompanying the drilling process due to action of internal and external forces on mechanical parts of the drilling equipment and rock. Vibrations formed in mechanical drilling increase the cutting effect on rock, bear the information on the cutting mechanism, applied regime and condition of drilling tools (Kumar et al., 2011, Miklúšová et al., 2008, Vardhan, 2009, Miklúšová et al., 2009). Accompanying vibrations enable to detect the failure of drill bit and its components, drill bit wear and to identify the inefficient drilling process (Brett, 1991). Various evaluation techniques have been used for analysing of vibration signal, both in time and frequency domains (Wang et al., 2014, Kreuzer, 2012, Shi, 2004).

Research of vibration signal was performed in collaboration with the Institute of Control and Informatization of Production Processes of FMEPCG, Technical University in Košice (Leššo et al., 2012, Leššo et al., 2014). Previous theoretical knowledge verified by experiments implied the possibility to use the monitored vibro-acoustic signal for characterization of rock drilling process (Miklúšová et al., 2011, Krepelka et al., 2011, Lazarová et al., 2015, Feriančiková et al., 2015). Use of vibro-acoustic emissions for efficient drilling process control would potentially lead to decreasing the number of scanned signals needed for optimization and control from minimum 4 to 1 single signal.

The paper described the issues of representation of rock types in form of their accompanying vibration signals as elements of Hilbert's metric space, being an application of a functional analysis for rock classification based on accompanying vibration signal from rock drilling process. The vibration signals of analyzed rock types were measured in equivalent nominal drilling regimes in order to analyse the effect of geomechanical properties and their differences related to the drilling process itself. Spatial divergences between three distinct rock types were analysed using the metrics generated by a norm of the Hilbert's space.

Rotary drilling of rocks

Rotary rock drilling represents a dynamic process with a strong stochastic compound regarding its control. Measurability of status variables is quite problematic, as the mechanical processes are usually difficult to measure in industrial conditions and hence their mathematical models are rather based on theory, which brings drilling rigs with operational regimes pre-defined by producer or set according to average geomechanical properties of rock mass (Krúpa & Pinka, 1998).

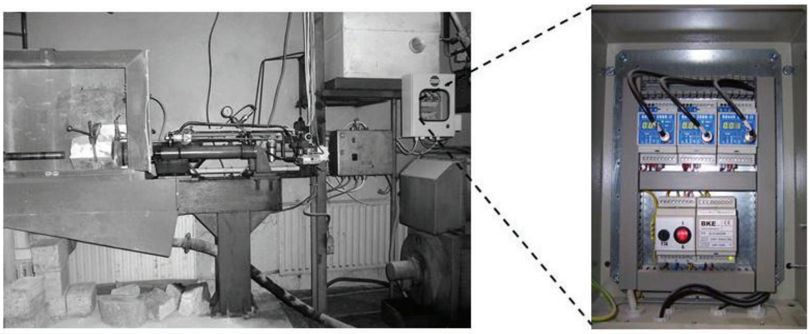

Fig. 1. Experimental drilling rig with detail of ADASH 3900-II vibration monitoring system
Rys. 1. Instalacja laboratoryjna oraz system monitoringu ADASH 3900-II

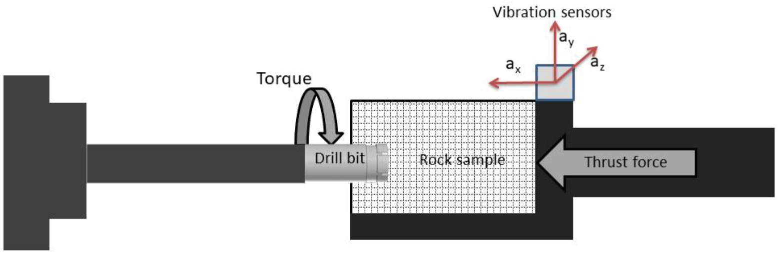

Fig. 2. Scheme of accelerometer installation
Rys. 2. Schemat instalacji akcelerometru

As any process in simplification, rock drilling is considered as system characterized by a set of input and output variables. On the input side, thrust force and rotation speed of drill bit are the most important parameters, whereas drilling speed and specific drilling energy stand on the output side.

Search for relation between two sets of values of various process variables is a complicated and long procedure delivering also inaccuracies; there have been attempts to find the algorithms for processing of vibro-acoustic signal as integral container for process information (Leššo, 2004).

Advanced methods of multidimensional data evaluation and artificial intelligence means have been introduced to search for such algorithms and in such, the output analog signal of process variable monitored by transducer is considered for information container (Feriančiková, 2012, Feriančiková et al., 2014).

Experimental part of this research was performed at the Institute of Geotechnics, Slovak Academy of Sciences in Košice, using the unique laboratory drilling rig equipped with facilities for monitoring the drilling process (Fig.1).

Relevant process or regime characteristics measured during the experiments involve:

a. rotation speed of the drill bit are set by a continuous regulation of electric drive unit ranging from 0–2220 revolutions per minute (rpm),

b. thrust force acting on rock specimen is regulated continuously from 0–20 000 N, measured by a pressure cell at the hydraulic cylinder,

c. drilled length measured by a magnetostrictive linear position sensor Baluff BTL7 Micropulse Transducer with accuracy 10 μm installed at hydraulic cylinder,

d. vibration sensors of oscillation motion of the drilling rig installed on the fixing frame of rock specimen, providing data on vibration acceleration in three orthogonal directions (Fig.2): accelerometers Wilcoxon 784A-3 and CTC AC102-1A, accompanied with the on-line vibration monitoring system Adash 3900-II,

e. torque and cutting forces in rock drilling measured by a 4-component dynamometer Kistler 9272 providing three orthogonal force components and torque, along with multichannel charge amplifier for multicomponent force measurement Kistler 5070.

Automatic mode provides the operator with possibility to take over control of the whole drilling process from a single computer by setting the required rotation speed and thrust force using the own designed software.

Methodology for assessment of rock drilling process data

One of the most sophisticated methods of signal processing is the vector quantization of abstract mathematic space with elements that represent the realizations of analyzed signals. The functional analysis stands as the theoretical baseline, with main idea to consider the function as a point representing an element in abstract mathematical space. The function in this case is represented by the information signal (Taylor, 1973, Naylor & Sell, 1981).

Functional analysis (involving also theory of abstract Hilbert's space) delivers the possibility to solve various technical and natural science problems as geometric tasks. Functional analysis considers any mathematical function (i.e. physical signal of any process) as an algebraic vector, and hence uses the algebraic, topologic and geometrical structure of these spaces (Zlatoš, 2011). Due to that it is possible to examine the mutual angles, dimensions and distances between the vectors, i.e. signals. Based on such geometric relations it is possible to define the algorithm of classifier for process conditions.

Digital processing of physical signal, regardless of Hilbert's space, the limiting of its amplitude difference is important. Such physical signal is either an analog signal as a

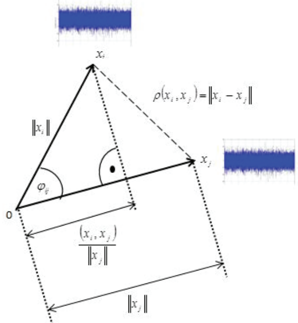

Fig. 3. Geometric relations between the pair of signals as vectors – points in Hilbert space (Leššo et al., 2012)
Rys. 3. Zależności geometryczne pomiędzy wektorami par sygnałów

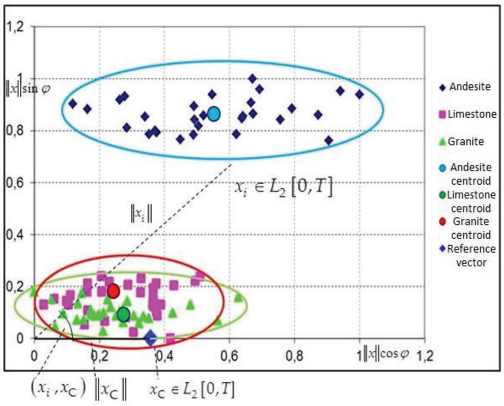

Fig. 4. Positions of images of 30 realizations towards the vector xC in time domain
Rys. 4. Pozycje obrazów 30 realizacji w kierunku wektora xC w dziedzinie czasu

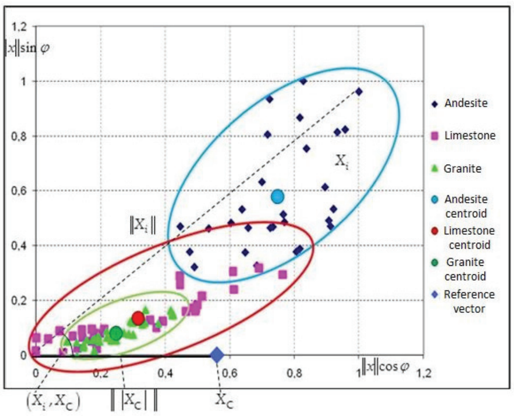

Fig. 5. Positions of images of 30 realizations towards the vector X_C in frequency domain
Ryc. 5. Pozycje obrazów 30 realizacji w kierunku wektora X_C w dziedzinie częstotliwości

continuous time function or a signal as a discrete function with discrete time. The first signal class is made by analog technique, the second class by digital technique. Both classes require to find the corresponding function expressed as a mathematical model. In case of analog signal, such mathematical model may be represented by a limited, absolutely integrable continuous real function of a real variable. No physical signal has a complex character. In processing of such signals, the constructions are made, which represent the complex functions of a real variable, such as a complex frequency spectrum.

The Figure 3 shows vectors x_i, i=1,2,... , i.e. realizations of accompanying vibration signal from rock drilling. The metrics ρ expresses the distance between two signal realizations. Let's assume that in such space, all realizations of accompanying vibration signals from drilling of all considered rock types covering their geomechanical properties are present (Ďurove & Maras, 2000), and that every vibration signal realization as a vector of such space represents a specific rock in nominal drilling regime.

For every rock class it is possible to calculate a centroid of the class x_{Ci} as a mean vector of all vectors classified in the i-th class. Then the actual measured vibration signal from drilling is assigned with the closest centroid, i.e. $\min_j \rho(x_i, x_{Cj}), j = 1,2,\dots,N$ Such algorithm of drilled rock classification is denoted in literature as algorithm of vector quantization (Taylor, 1973).

Figure 3 shows three basic geometric parameters between the pairs of vectors, i.e. their lengths, mutual distance and angle between them. The base of such geometric structure is the scalar product. Its application provides for definition of length, distance and angles of vectors in finite dimensional, but also infinite dimensional vector spaces, and hence its use for assessment of effective regime of rock drilling (Leššo et al., 2012).

Signals of vibrations accompanying the drilling process of three distinct rock types, andesite, limestone and granite were measured and analyzed. Experiments were performed using the laboratory drilling rig at Institute of Geotechnics SAS under nominal regime of thrust force 5000 N, rotation speed 1000 rpm. Vibration signals were monitored by accelerometers in three directions (drilling direction and two directions orthogonal to drilling axis) with sampling frequency 17 kHz as shown in the Fig. 2. As the axial direction exhibits the highest entropy, which was confirmed from previous experiments, only the signal from drilling direction was evaluated.

Signals were sampled with a constant sampling period T_{vz} (s). Sampled signal was digitally processed by individual realizations of signal, where each realization is considered as a sequence of successive n-samples of vibration signal, where n represents the number of samples in realization and it is called the length of realization. Realizations of length n=1024 signal samples were used in processing. As sampling used the constant sampling period, the length of realization is expressed as $T=n.T_{vz}$.

Mathematical expression of this task issues from assumption that every realization of signal xi(t) of i^{th} rock is a continuous function in closed interval [0,T]. Then such function is considered as a vector of Hilbert space of class L_2 [0,T] and the space is a complete Banach space with scalar products, involved in Hilbert space.

Every drilled rock type was represented by 30 realizations of accompanying vibration signal. The main goal was to confirm or deny the differentiability of rock types in abstract space. Each realization of every drilled rock represents a vector. These values of signal define the unique position of vector in the space L_2 [0,T].

Then it is possible to examine the geometric relations between the individual realizations, their norms, angles and distances. There is assumption that the norm of vibration signal is a significant feature of drilling process, as it is a measure of energy of damped vibration of drilled rock block with polyharmonic excitation of the oscillating system from the drill bit. The calculations of geometry structure presented in algebraic structure were transformed to discrete form due to digital realization.

In order to use the two-dimensional illustration for visualization of geometry relations between the rocks, it was necessary to place a reference vector on horizontal axis. In the first attempt, the white noise was used as a reference vector. Later calculations showed that it was impossible to compare the realizations with white noise as the distance of rock realizations from white noise was too large. It showed that it was more proper to compare the rocks mutually. Therefore the reference vector was set as a centroid vector x_C where k-th component represents the arithmetic mean of k-th components of all realizations of three examined rock types.

Figure 4 shows positions of 30 realizations of all three rock types towards the reference vector x_C in polar coordinates based on calculated angles and norms in time domain. Moreover, every rock is represented by its centroid (arithmetic mean of realizations). This illustrates the location of rock vectors in space, which brings a certain method for expression of mutual differences of vibration signals in abstract space transferred to planar picture in 2D. The realizations of vibration signal of limestone and granite are close to each other and differ only slightly. On the other hand, andesite is distinguishable from other rock types.

Similarly, the accompanying vibration signals were analyzed in space towards the orthogonal base of harmonic functions. Ever signal realization was transformed to amplitude spectrum using the DFT algorithm. Considering that the calculations were made in discrete form on digitalized realizations, the discrete forms were used instead of continuous relations for $\omega \in \langle 0, 2\pi f_{vz} \rangle$. Calculated geometry parameters of vectors in space were transferred to plane similarly to time domain (Fig. 5).

Conclusions

Developed method showed good differentiability of rock types based on the vibration signal accompanying the rock drilling process, i.e. it was possible to differentiate the andesite from granite and limestone. Both time and frequency domains appear to be proper for evaluation. Individual realizations of rocks are less differentiable in frequency domain compared to time domain. In the developed method of visualization of geometry relations to 2D space, the measure of difference between the signals is represented by their mutual position in plane. The visualization method enables to observe the drilling rock process states represented by the monitored signals of vibrations accompanying the drilling process.

Acknowledgement

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Interpretacja geometryczna zróżnicowania typów skał w przestrzeni Hilberta

Sygnały drgań pochodzących z wierceniu obrotowego trzech rodzajów skał (andezyt, wapień i granit) za pomocą diamentowych wierteł rdzeniowych został przetworzony i oceniony w celu śledzenia charakterystyk sygnałowych badanych rodzajów skał. Zastosowano matematyczne procedury przestrzeni Hilberta, aby wyrazić różnice między rodzajami skał w oparciu o sygnał wibracyjny. Eksperymenty przeprowadzono na laboratoryjnej platformie wiertniczej zaprojektowanej i skonstruowanej w Instytucie Geotechniki SAS, zapewniającej zautomatyzowane ciągłe monitorowanie kluczowych parametrów procesu (siły ciągu, prędkości obrotowej, momentu obrotowego, prędkości posuwu itp.). W doświadczeniach zastosowano nominalną wartość siły nacisku 5000 N i prędkości obrotowej 1000 rpm wraz z monitorowaniem częstotliwości 17 kHz. Sygnał drgań został zarejestrowany przez akcelerometry w trzech kierunkach ortogonalnych: osiowym w kierunkach wiercenia i dwóch promieniowych w płaszczyznach poziomej i pionowej. Do celów oceny oceniono jedynie drgania w kierunku osiowym, ponieważ ich sygnał wykazuje najwyższą entropię. Opracowano metodę wyrażania wzajemnych różnic między drganiami powstającymi podczas wiercenia różnych rodzajów skał, która umożliwia przeniesienie różnic z przestrzeni Hilberta na wizualizację dwuwymiarową.

Słowa kluczowe: proces cięcia skały, sygnały wibracyjne, przestrzenie abstrakcyjne, przestrzeń Hilberta, relacje geometryczne