Some problems in control of the quality of the process of rotary drilling of rocks by using suitable visualization of concurrent vibrations

Patrik Flegner[1], ***Katarína Feriančiková***[2], ***Edita Lazarová***[3] *and* ***Igor Leššo***[4]

The process of separation of a rock massif by rotary drilling belongs to the most frequently used geotechnologies. Since their energy costs are significant, it makes sense to pay sufficient consideration to the subject of an efficient mode of drilling. Only an efficient drilling mode can guarantee the overall quality of this process. This contribution builds upon previous works of the authors in the area of utilization of abstract Hilbert spaces in control of specific processes. In this paper, some possibilities and aspects of visualization of concurrent vibrations with respect to efficient control of drilling are pointed out. The result of implementing the vibration signal as a vector in Hilbert space is the algorithm for recognition of the class into which the rock being separated belongs based on its geomechanical properties. The algorithm is based on geometrical interpretation of time or frequency characteristics of the concurrent vibrations. The method was applied to concurrent vibrations from drilling on an experimental stand and also from tunneling. The achieved results confirm the suitability of the proposed algorithm for its application in the system of automated setting of an efficient mode of drilling of rock massif.

Keywords: *quality of rotary drilling process, effectively control rotary drilling, control chart, visualization of concurrent vibrations, Hilbert space as signal space*

Introduction

Rotary drilling of rocks belongs to one of the most widely applied technologies of rock fragmentation in mining and geotechnical applications. Drilling is a very energy- and material-demanding process, and its efficiency might be expressed by specific drilling energy. The process of rock drilling has to be controlled in order to achieve the efficient operational regime considering the energy consumption. The drilling regime itself is usually controlled by the thrust force of the drilling bit, revolutions of the drilling bit and by the amount and quality of drilling mud. Conventional methods of process control (based on direct measurement of the process variables) are used only seldom, as direct measurement of specific energy is not feasible using common means. Heterogeneity of drilled rock types, a variety of drilling bits and different drilling conditions cause that it is almost impossible to determine a valid relationship between the drilling regime and its efficiency.

The paper outlines a feasible approach for control of such complex process as rock drilling, using the signal of vibration emissions accompanying the rock drilling process as the main source of information on the character of rock drilling process. Previous research of authors proved that the signal of measured vibration emissions corresponds to the geomechanical parameters of rock and also to the applied drilling regime. Acquisition of information from signals requires extracting a number N of specific features, which characterize the current state of the process in N-dimensional real state space.

The authors developed a complex and potentially more efficient methodology: Every realization of the vibration signal is considered as a time function in mathematical description, thus fulfilling the conditions of algebraic vectors of functional space of Hilbert-type. Consequently, using strong structures of such abstract spaces based on the definition if a scalar product, it is possible to compare the individual realizations of vibration signal in the geometrical description, e.g. related to the drilled rock type, to the drilling regime or the specific drilling energy, etc. The character of the vibration signal in both time and frequency domains delimits its position in space by a unique definition.

The paper presents modeled relations for expression of a metric distance between the pair of vibration signals, expressing the measure of their difference or similarity. It also covers a modeled relation of the angle between the geometrical representation of the pair of vibration signals expresses the measure of their spectral difference.

[1] *Ing. Patrik Flegner, PhD.*, Technical University of Košice, Faculty of Mining, Ecology, Process Control and Geotechnologies, Institute of Control and Informatization of Production Processes, Letná 9, 040 01, Košice, Slovakia, patrik.flegner@tuke.sk

[2] *Ing. Katarína Feriančiková, PhD.*, Institute of Geotechnics, Slovak academy of Sciences, Watsonova 45, 040 01, Košice, Slovakia, feriancikova@saske.sk

[3] *Ing. Edita Lazarová, PhD.*, Institute of Geotechnics, Slovak academy of Sciences, Watsonova 45, 040 01, Košice, Slovakia, lazarova@saske.sk

[4] *prof. Ing. Igor Leššo, CSc.*, Technical University of Košice, Faculty of Mining, Ecology, Process Control and Geotechnologies, Institute of Control and Informatization of Production Processes, , Letná 9, 040 01, Košice, Slovakia, igor.lesso@tuke.sk

Moreover, a modeled relation for the norm of the signal is presented, expressing the measure of the effective value of the signal, i.e. its energy. Analyzes of the three signal parameters in functional space provide a possibility to acquire the knowledge to the relations between the rock types and regimes of their drilling processes. The paper also describes a methodology for visualization of the presented relations. The proposed methodology shows a precise resolution of tested rock types and enables to capture and interpret the dynamics of the rock drilling process, thus delivering a possibility of a real-time rock classification during the drilling process.

Hilbert space as signal space and its geometry

The highest degree of generalization and abstraction of the physical space E_3 represents the classes of functional spaces called Hilbert spaces. The definition of Hilbert space is the following: Hilbert space is a complete space with an inner product. It can be infinite-dimensional and complex. This definition contains notions whose detailed explanation at this point is not possible [1], [2], [3], [4], [5].

For a significant class of functional spaces (so-called L_2 spaces) it is a necessary condition for the functions as elements of the space to be integrable. That is because the definition of the inner product in these spaces has the form of an integral. The classical Riemann integral cannot be used for many important functions. Therefore, the Lebesgue integral is considered, which is more generally applicable while it is based on the notion of „measure“, and so-called measurability of the function is assumed. So the space of Lebesgue-integrable functions has a defined inner product. The explicitly stated condition of the existence of the inner product in the definition of Hilbert space shows its significance for these spaces since the inner product generates the norm of space and the norm in turn generates its metric. Consequently, Hilbert space is a normed linear vector space with metric.

The completeness of space means that every Cauchy sequence of functions $\{f_i\}_{i=1}^{\infty}$ in this space converges to a function that is an element of this space and thus is also Lebesgue-measurable. The Hilbert space character of being complex means that a function as an element – vector can, in general, be a complex function of a real variable, so that $f \in \mathbf{C}^{\infty}$ for $t \in [a,b] \subseteq \mathbf{R}$. This property of space is important for a practical point of view in the analysis of frequency Fourier spectra that are complex functions of real frequencies. The infinite dimensionality of this space follows from two mutually related facts. The function f takes on infinitely many function values – coordinates in its domain – closed real interval $[a,b]$. The base of this space also consists of infinitely many mutually orthogonal functions.

The properties of functional spaces, especially Hilbert spaces, yield many application possibilities. A condition for using the theory of Hilbert functional spaces in signal processing is that the signal could be interpreted as a function that satisfies the conditions for being an element of Hilbert space of the corresponding class. Therefore, it is useful to study general properties of each physical signal.

Each electrical signal of the sensor has the following properties:

- Signal is a physical manifestation of physical quantity of the process,
- Signal can take on non-zero values only in a finite time interval (physical signal is finite),
- Signal values – amplitudes are bounded (finite),
- No physical signal has complex character,
- Signal can be described with a unique continuous real function of time.

Only signals with these properties can be technically realized. Moreover, in a digital processing of the physical signal, the boundedness of the difference of its amplitude is important.

The physical signal can have a different form in technical systems. From our point of view, the two classes of electrical information signals are important, namely analog and sampled signals that are related to digitization. For both classes of signals, it is necessary to find the corresponding function as their mathematical model. In the following, we consider the most general class of signals, i.e. analog signals.

As follows from the above, the mathematical model (approximation) of the analog signal, defined in time interval $[0,T] \subset \mathbf{R}_0^+, T < \infty$, can be a uniquely bounded absolutely integrable continuous real function $x \equiv (x(t); t : 0 \mapsto T)$ of real variable t. A finite number of so-called discontinuities of the first kind is also permitted. In this case, at isolated points of discontinuity, the function as a model of the signal has zero energy. Then for this point, the value is the right-hand or the left-hand limit or their arithmetic average. There can be no discontinuity points in the original signal, however.

In the mathematical processing of the signal, various abstract procedures employing complex numbers are used. Transformations (Fourier, Laplace or Hilbert) are frequently used to transform the real function as a vector $x \in \mathbf{C}^{\infty}$ to a complex function as a vector $X \in \mathbf{C}^{\infty}$. Because of this, it is preferable to consider, for a mathematical model of the analog signal, generally a complex function $x \equiv (x(t); t : 0 \mapsto T) \in \mathbf{C}^\infty$ of a real variable with all above-mentioned properties as it was with the real function. A suitable type of Hilbert space given the above-mentioned function *x* as a model of the analog signal is the space $L_2[0,T]$. This Hilbert space is the set of all measurable real or complex functions *f* defined for all real $t \in [0,T]$ such that:

$$\int_0^T |f(t)|^2 \mathrm{d}t < \infty \tag{1}$$

(Lebesgue-integrable in square root). This functional space has all four structures of a linear normed metric space with inner product, i.e. set, algebraic (linear), topological and geometric structure. Then, from these structures, the following arithmetic relations with important geometric interpretation according to Fig. 1 follow for a given space:

- inner (scalar) product: $$\langle x_i, x_j \rangle = \int_0^T x_i(t)\overline{x_j(t)}\mathrm{d}t \in \mathbf{C}, \tag{2}$$

  key algebraic operation between two points of space.
- norm: $$\|x\|_2 = \sqrt{\int_0^T |x(t)|^2 \mathrm{d}t} \in \mathbf{R}_0^+, \tag{3}$$

  gives the distance of the point from the point zero as the origin of the coordinate system.
- metric: $$\rho_2(x_i, x_j) = \|x_i - x_j\| = \sqrt{\int_0^T |x_i(t) - x_j(t)|^2 \mathrm{d}t} \in \mathbf{R}_0^+ , \tag{4}$$

  gives the distance between two points of space.
- the cosine of the angle subtended by a couple of location vectors:

$$\cos\varphi_{i,j} = \frac{|\langle x_i, x_j \rangle|}{\|x_i\|_2 \|x_j\|_2} \in \left[0, \frac{\pi}{2}\right], \tag{5}$$

gives the size of the angle subtended by two points of space as vectors; the relation uses the Cauchy-Bunyakovsky-Schwarz inequality (so-called CBS inequality).

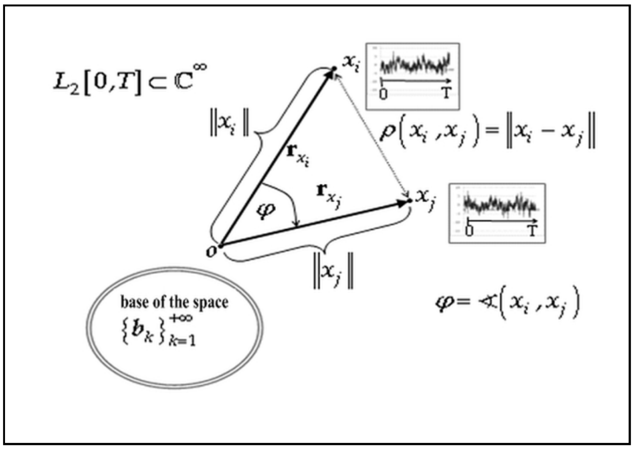

Fig. 1. Geometric interpretation of structures in Hilbert space as signal space.

The above geometric structure of Hilbert space as signal space is a high abstraction of functional analysis. However, it enables to make some „special distribution" of signals based on the measure of their mutual similarity or difference in the set of physical signals, represented by corresponding model functions as points in space. The mutual locations of signals, conceived this way, are quantifiable by using functions (2) to (5). The problem is, however, that these quantitative expressions do not provide a visual picture of such distribution of particular signals in an infinite-dimensional space $L_2[0,T]$. A possible solution to this problem appears to be the definition of a suitable mapping of Hilbert space $L_2[0,T]$ into classical Euclidean physical space E_3 that we can visually perceive. In some cases, we can even do with the mapping into space E_2 or E_1.

So the goal is to find a suitable mapping that would associate individual signals of the Hilbert signal space with corresponding positions in the visual Euclidean space in such a way that the mutual positions of these points as images of signals will express the measure of mutual similarity of the corresponding signals as the originals of mapping. In the design of such mapping, methods of analytical geometry, applied in Hilbert signal space, will be used. In the following part, an example of such mappings is shown.

Visualization of signal distribution on signal space based on the measure of their mutual similarity

Map $F_3 : L_2[0,T] \to E_3$ **-**this map has the best capability to distinguish individual signals. In this case, three measures of differentiation of signal location are used at the same time, namely their L_2 norm and a couple of angles subtended with two reference signals. The map F_3 determines a location in a bounded part of space $E_3 \equiv \mathbf{R}^3$ to each signal. The procedure is as follows (Fig. 2). In the signal space $L_2[0,T]$, we define a suitable reference signal x_{ref} and we construct an orthogonal vector $x_{\text{ref}}^{\perp}$ to the signal. Then, we have the following for their mutual inner product:

$$\left\langle x_{\text{ref},} x_{\text{ref}}^{\perp} \right\rangle = 0 \, . \tag{6}$$

Further, let us choose a Cartesian system of coordinates $(0; \mathbf{e}_X, \mathbf{e}_Y, \mathbf{e}_Z)$ with a triple of coordinate axes (X, Y, Z) in space E_3. This way, the Euclidean space is divided into eight octants.

Assume that for the location vectors of images of both reference signals in the mapping F_3 we have:

$$\mathbf{r}_{x_{\text{ref}}} = \left(\left\| x_{\text{ref}} \right\|_2 \mathbf{e}_X, 0\mathbf{e}_Y, 0\mathbf{e}_Z \right). \tag{7}$$

$$\mathbf{r}^{\perp}_{x_{\text{ref}}} = \left(0\mathbf{e}_X, 0\mathbf{e}_Y, \left\| x_{\text{ref}}^{\perp} \right\|_2 \mathbf{e}_Z \right). \tag{8}$$

In this way, we located a couple of images of mutually orthogonal reference vectors onto the axes X and Z. Let us further introduce a spherical system of coordinates $(0; r, \varphi, \vartheta)$, associated with the defined Cartesian coordinate system according to Fig. 2, in space E_3. Subsequently, there exist well-known transformation relations between Cartesian coordinates and spherical coordinates of the same point in space E_3.

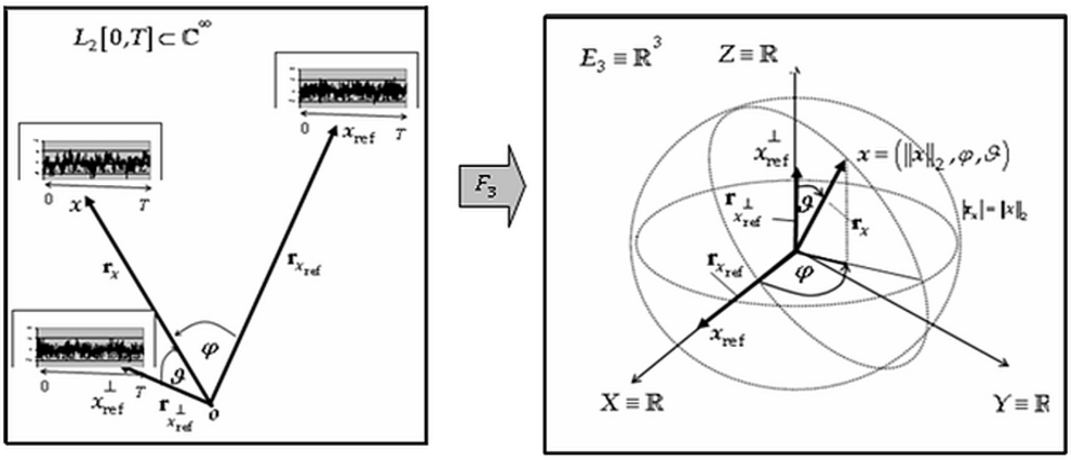

Fig. 2. Map of Hilbert signal space into space.

The location of the signal point x in this Euclidean space E_3 is then defined in the spherical coordinates by its location vector $\mathbf{r}_x = (\|x\|_2, \varphi, \vartheta)$ with the starting point at point 0. The length of this location vector is equal to the norm $\|x\|_2$ of the vector x in space $L_2[0,T]$ and represents the distance of point x from pole 0 of the spherical system of space E_3. The coordinate φ represents the magnitude of the oriented angle subtended by axis X with the vertical projection of the location vector $\mathbf{r}_x$ into the plane (X, Y). It is determined by the magnitude of the oriented angle $\varphi = \varphi(x_{\text{ref}}, x)$ in the signal space $L_2[0,T]$. The coordinate ϑ represents the magnitude of the oriented angle subtended by axis Z with the location vector $\mathbf{r}_x$. It is determined by the magnitude of the oriented angle $\vartheta = \vartheta(x_{\text{ref}}^{\perp}, x)$ in the signal space $L_2[0,T]$.

By using well-known transformation relations between spherical and Cartesian coordinates, we can define the following for the Cartesian coordinates of the signal point x in space E_3 :

$$\mathbf{x} = \left(\|x\|_2 \sin(\vartheta)\cos(\varphi), \|x\|_2 \sin(\vartheta)\sin(\varphi), \|x\|_2 \cos(\vartheta)\right). \qquad (9)$$

And for the location vector of this signal point we have:

$$\mathbf{r}_x = \left(\|x\|_2 \sin(\vartheta)\cos(\varphi)\mathbf{e}_X, \|x\|_2 \sin(\vartheta)\sin(\varphi)\mathbf{e}_Y, \|x\|_2 \cos(\vartheta)\mathbf{e}_Z\right). \qquad (10)$$

Application of map F_3

Some properties of the above map F_3 were analyzed so as to avoid erroneous interpretation of results while working practically with the map, to avoid unexpected distortions of mutual positions of the vectors being visualized and to avoid resulting disappointments. An experiment was realized with the signal of concurrent vibrations of the process of separation of rock massif by rotary drilling on a special drilling stand. The map F_3 was applied to this concurrent vibration signal.

The process of rotary drilling of rock massif generates concurrent vibroacoustic emissions that correspond to the character of the rock separation [6], [7]. The sensor of these vibrations (accelerometer) generates a random analog signal at its output with the shape of continuous random fluctuations (Fig. 3) [8], [9]. By fluctuations of the stochastic signal, we understand the random variation of its amplitude around the mean value. If the rock massif is homogeneous enough and the mode of drilling stabilized (constant rotations and pressure) then this process of drilling or separation is a stationary random signal. Moreover, this signal should be ergodic. The above concurrent signal can be considered to be a random function of time that represents a model of the inner process of separation of rock massif.

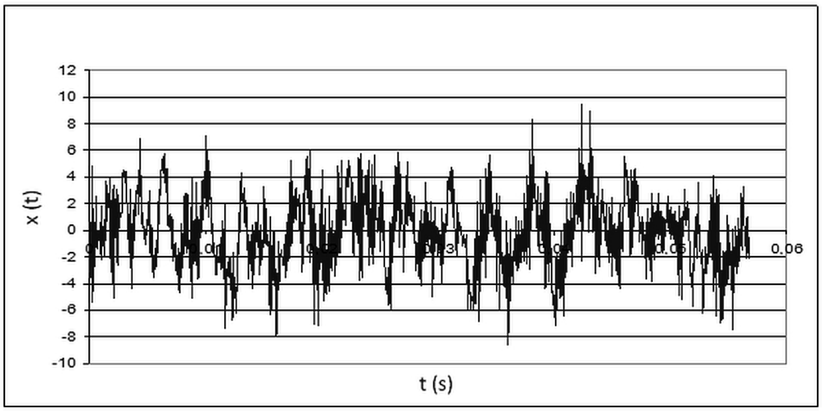

Fig. 3. The signal of concurrent vibrations from the process of rotary drilling of rock.

A hypothesis was formulated that the stabilized process of separation of the homogeneous massif of rock on an experimental stand is a stationary random process and that the corresponding random signal $X(t)$ obtained is an ergodic stationary random signal (function). In general, these properties of the process signal have great significance for its digital processing. The validity of this hypothesis was verified with a standard method in accordance with the theory of random process.

The above method was experimentally used in the solution of the task of effective control of the process of rotary drilling of rock massif [10], [11], [12], [13]. The essence of the proposed control algorithm is a classification of the rock being separated on the basis of concurrent vibration signal [14]. Recognition of the class of the rock based on the concurrent vibroacoustic emissions, in which also its geomechanical properties are manifested, subsequently enables to choose the corresponding mode of drilling that is efficient for given class of rock from the table of experts [15], [16]. The mode will provide minimal specific energy of separation at a maximal speed of drilling [17]. From realizations of concurrent vibrations of the process of separation of four types of rock (A – andesite, V – limestone, Z – granite, B – concrete), the power spectra were calculated. They represent, in the sense of the above considerations, the functions – vectors of Hilbert space. Given random, but stationary character, these power spectra were averaged for each rock from 30 realizations of the signal. The mode of drilling (pressure, revolutions) was stabilized during the measurement. By the above procedure, the calculation of the triple of digital positional characteristics was performed for the centroid of each rock. Then, those characteristics determined a unique location in 3-D space (Fig. 4) for the centroid of each rock.

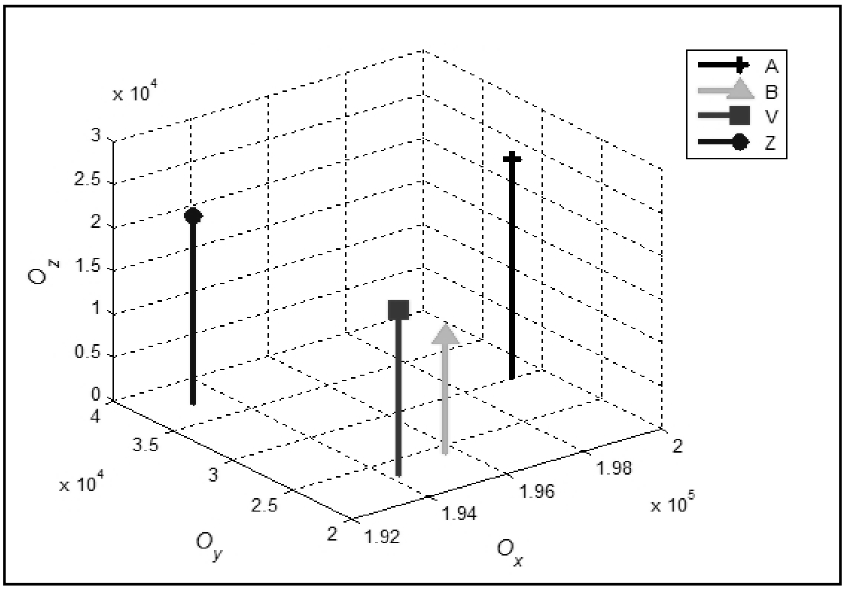

Fig. 4. 3D Visualization of differentiability of 4 separated rocks represented by concurrent vibrations as vectors in Hilbert space.

The above method of visualization was also used to demonstrate the fact that the concurrent vibrations contain information not only about the class of the rock being separated, from the viewpoint of its geomechanical properties, but also information about the current mode of drilling. The trajectory of the movement of the power spectrum of concurrent vibrations as a vector of Hilbert space, namely at a gradual increase of pressure, is shown in Fig. 5.

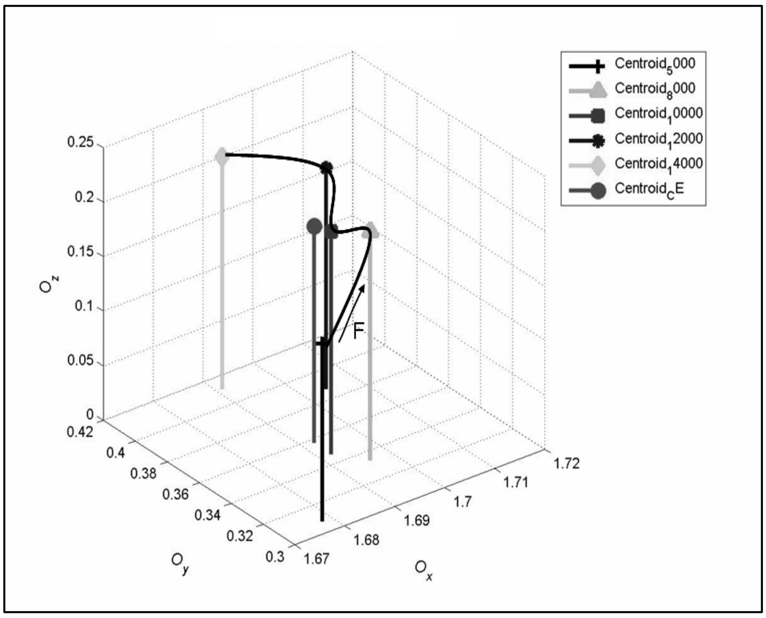

Fig. 5. The trajectory of concurrent vibrations of the process of drilling limestone at a gradual increase of pressure.

Geometry interpretation of non-stationary character of tunneling process of Branisko by functional analysis

Engineering-geological investigation classified the rocks in the course of excavated tunnel based on similar properties into the 42 geological sections (GS) and into lithology defined by 12 engineering-geological rock types. The paper presents the results of 22 geological sections covering 5 engineering-geological rock types:

- A - rock formation represented by dominant amphibolites as part of the biotitic-amphibolic and amphibolic gneisses (13 geological sections),
- Rbp - biotitic and plagioclase gneisses (2 sections),

- Rab – amphibolic to biotitic-amphibolic gneisses (3 sections),
- KMy – geological sections comprising mylonites resulting from tectonic faults, only local positions up to 20-30 m length (3 sections),
- G – granitoids in the form of dike systems and bodies (13 geological sections).

Every geological section is represented by a centroid calculated as the arithmetical mean of a certain number of realizations of the accessory signal. These position vectors are compared relatively to the properly selected reference position vector. The horizontal position $(\varphi_i \equiv 0)$ of the centroid vector of certain geological section means that the geological section shows rock cutting process very similar to the reference process. If the centroid vector of GS is inclined at a larger angle $(\varphi_i > 0)$, this shows the larger difference from the reference process. The length of the GS centroid vector compared to the length of the reference vector expresses the energy of the rock cutting process.

The Figures 6 and 7 present the position vectors of accessory process signal corresponding to the individual geological sections. The whole evaluated section was divided into two separate figures for better clarity. Such visualization method of the accessory signal in both time and frequency domains documents the non-stationary character of the rock cutting process caused by inhomogeneity of the rock mass in geological sections. The data analysis showed that there were some similar geological sections and several sections with the completely different character of the rock cutting process.

The presented method of visualization enables to analyze the rock cutting process also by assessing the energy demands during the tunnel excavation. The lengths of position vectors in the Fig.6a) b) corresponds to the amount of energy consumed for rock cutting in individual sections. Similar information is involved in the Fig.7a), b), whereas the length of the position vector expresses the mean cutting energy consumed per one revolution of the TBM cutter head.

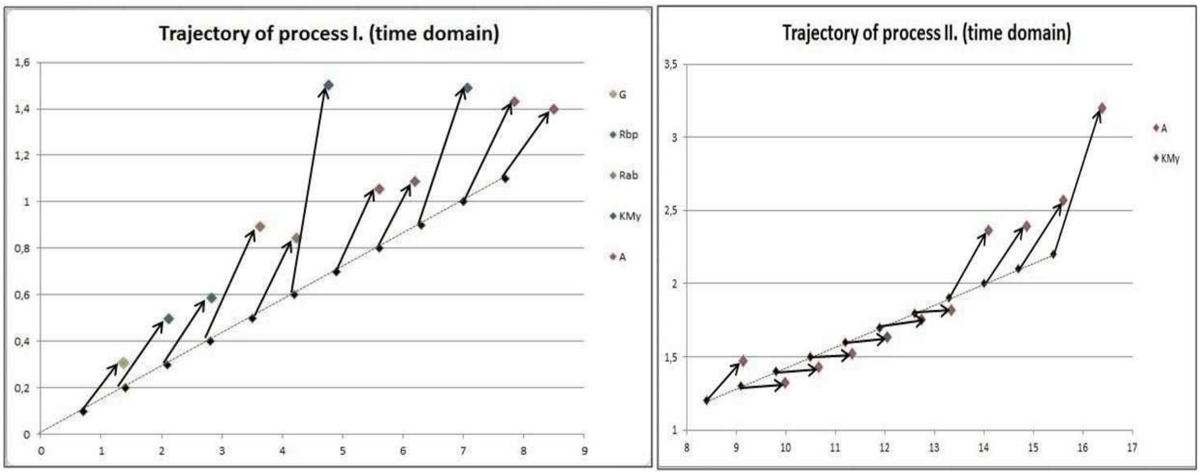

Fig. 6. a) b) Visualization of rock mass inhomogeneity based on the accessory process signal analyzed in the time domain.

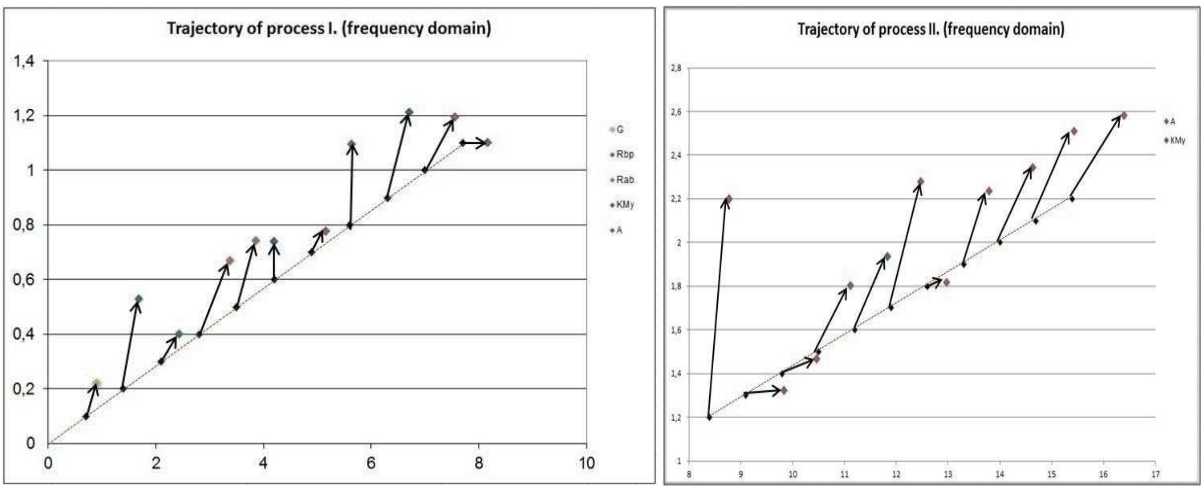

Fig. 7. a) b) Visualization of rock mass inhomogeneity based on the accessory process signal analyzed in the frequency domain.

Conclusion

The above methods of processing physical signals using the so-called new mathematics enable the solution of many complex problems. Functional analysis, namely Hilbert spaces, makes it possible to analyze signals as functions and generalize geometric relations among them. However, the fact that these geometric relations of signals as vectors in Hilbert space cannot be empirically perceived as in the case of vectors in 3D Euclidean space is problematic. This contribution tries to show one of the possible solutions to this problem.

The proposed method of a unique map of vectors of Hilbert space into the 3D space was applied to geophysical vibration signals from the process of rotary drilling of rock. The differentiability of four kinds of rock on the basis of vibrations and also the sensitivity of the location of vibration signal in Hilbert space on the mode of drilling were visualized.

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