Process of quantitative evaluation of validity of rock cutting model

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Most of complex technical systems, including the rock cutting process, are very difficult to describe mathematically due to limited human recognition abilities depending on achieved state in natural sciences and technology. A confrontation between the conception (model) and the real system often arises in the investigation of rock cutting process. Identification represents determination of the system based on its input and output in specified system class in a manner to obtain the determined system equivalent to the explored system. In case of rock cutting, the qualities of the model derived from a conventional energy theory of rock cutting are compared to the qualities of non-standard models obtained by scanning of the acoustic signal as an accompanying effect of the surroundings in the rock cutting process by calculated characteristics of the acoustic signal. The paper focuses on optimization using the specific cutting energy and possibility of optimization using the accompanying acoustic signal, namely by one of its characteristics, i.e. volume of total signal M representing the result of the system identification.

Keywords: *rock, cutting, drilling, acoustic signal*

Introduction

Current computer techniques provide new modern utilization of unexplored concepts and approaches in processes that have not been used yet. One of such possibilities is a design of models for control and optimization of rock cutting process.

A model stands for a depiction of substantial features of real system or process. An input $u(t)$ acts on the system in every instant of time t from a set of considered time instants T $(t \in T)$, which evoked the system to respond by an output $y(t)$. Suppose that the input variables $u(t)$ and output variables $y(t)$ will attain the values from the set of values of the inputs $U\,(u(t) \in U)$ and the outputs $Y\,(y(t) \in Y)$.

Regarding the identification this represents a design of such a functional that assigns the observed inputs $u(t)$ with the values of observed outputs $y(t)$, i.e.

$$y(t) = F(u(t)) \qquad\qquad y = F(u) \tag{1}$$

In fact there are also unobserved inputs $d(t)$, which have to be taken into the assessment. Such system is considered as a relatively closed one. In most cases, the dynamic systems including the rock cutting exhibit that the instantaneous value of the output does not only depend on instantaneous value of the inputs, but also on the values of previous inputs.

The main task of the identification is to design of such a model functional F based on observations of inputs u and outputs y. The object of identification should be generally considered as a multi-parameter system having m observed inputs, k unobserved inputs and n observed outputs.

The design of model operator in the identification process reckons the apriori and aposteriori information. Apriori information is available before the beginning of observation and aposteriori information is delivered by properly selected and evaluated experiments. Equivalence of consistence between the real process and the model is usually defined in a manner that the criterion of quality is a measure of consistence of operator model F_M and process F defined using a loss function

$$S(y, y_M) = (y - y_M)^T \cdot (y - y_M) = e^T \cdot e \tag{2}$$

Formula (2) represents a scalar function, which is a functional of the process output y and the model output y_M. Two models M1 and M_2 are equivalent if the value of loss function S is equal for both models

$$S(y, y_{M1}) = S(y, y_{M2}) \tag{3}$$

Optimal identification results in a determination of such model operator F from a whole set Ω, for which it is valid that the loss function S gains its minimum

$$S(y, y_M)_{\min} \quad for \quad F \in \Omega \tag{4}$$

The final result of identification is formed by such model operator F that provides information on structure of explored system and on the values of parameter of mathematical model [6]. In this case,

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a model acquired by specific cutting energy is compared to a non-standard model of optimization of the indentor-rock system using the acoustic signal, which arises due to mutual interaction. The main presumption of the investigation: accompanying acoustic effects of the environment are characteristic for each rock type individually and for the drilling regime as well, and the system parameters producing the most convenient cutting regarding the energy aspects should be determined.

Mathematical model used for system identification and optimization

Mathematical theories refuse the non-accurate input data in identification of such complex problems, which brings another issue to the investigation. Accuracy of operational measurements reaches at best 0.5 % of the measuring channel range and this fact restrains the range of available mathematical methods for experiments at the experimental drilling stand. Not respecting the data accuracy leads to the discords on theories relevancy and to misunderstandings in theories application.

The system is generally described by m inputs and n outputs which are defined by the equations in the area close to the working point

$$\mathbf{x}^{(1)}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t), \tag{5}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t), \tag{6}$$

where $\mathbf{x}(t), \mathbf{u}(t), \mathbf{y}(t)$ represent the state variables, input and output and **A, B, C** are the matrixes with relevant dimensions. System identification outcomes from measured variables, i.e. from the inputs and outputs, which after well-defined conditions of 'ideal' experiments, provided testing of the presumptions and comparison of various methods.

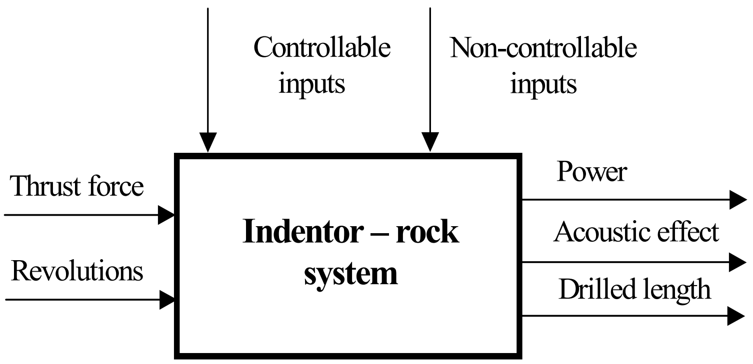

Fig. 1. Scheme of the indentor-rock system.

Fig. 1 illustrates a simple scheme of a dynamic system indentor-rock, which is affected by two decisive input variables, thrust force and revolutions. Measurable outputs of the system are represented by the power, drilled length, which both can be recorded as a time order, and an accompanying acoustic signal as an acoustic effect of environment in the rock drilling process. Controllable disturbances, such as indentor or rock type enter the system, as well as the uncontrollable inputs (rock properties, drilling tool condition, properties of environment, etc.)

Use of specific cutting energy belongs to conventional methods for determination of the optimum for indentor-rock system. Non-standard methods, such as acoustic effects, vibrations and their characteristics should be available for optimum determination of the system in the drilling process [1, 4].

As stated above, the investigation is based on a presumption that acoustic effect of environment in rock drilling process is characteristic for any individual rock type and drilling regime, and that it is possible to determine the system parameters, for which the drilling process reaches its minimal energy consumption [2, 4, 5, 7]. Presented issues are very complex as it is necessary to apply a whole range of factors acting in the system. At first, it has to be decided on which parameters to use in evaluation of the process, whether the working ability of drilling tool φ or specific cutting energy w [3]. Depending on this decision, the conditions of acoustic signal measurement have to be kept regarding the complex acoustic field, which is usually a closed – diffused field.

Search for optimal regime of rock cutting using the energy theory begins with instantaneous drilling rate and specific cutting energy, both depending on thrust force and revolutions. General behaviour of the variables and their relations are presented in the Fig. 2.

The optimal regime is determined for maximal instantaneous drilling rate v and minimal specific cutting energy w [3].

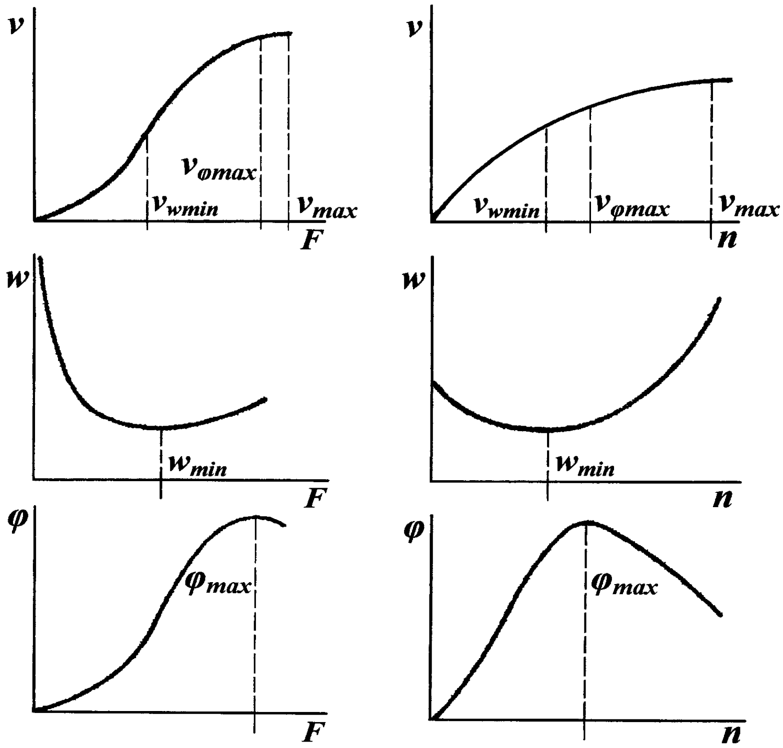

Fig. 2. Single-parametric relations of instantaneous drilling rate v, specific cutting energy w and the share of both variables, i.e. working ability of drilling tool φ, depending on thrust force F and revolutions n.

Identification of the indentor-rock system using the global characteristics in time domain

In the investigation of the system, the source of signal and contained information is either the system itself, or the signal is fed into the system or the information is incorporated into the signal by its interaction with the system. Another option is to affect the system with a signal of certain character, and the response of the system is then observed in the signal of a different nature.

Global characteristics describe the digital signal in more details and provide additional information. It is necessary to work with all the samples for the calculation of the characteristics, some of them show an integral character, i.e. they determine the signal properties as a whole in a certain time interval or in interval of an independent variable. Following characteristics describe the presented model: volume, mean value, standard deviation, median, instantaneous power, effective power, effective value, signal energy. The Eq.8 was applied in the process of rock cutting due to its mathematical simplicity. The graphs represent the experiments in 10s time span. The short time span is however long enough for proving the validity and sensitivity of the acoustic model as a proper model for the identification of the system tool-rock, based on the mechanical to acoustical energy transformation.

Signal volume

Volume of an impulse of analogue signal is given by area confined by its graphic interpretation in time period. Mathematical calculation of the area of a continuous function is provided by a definite integral. The integral is substituted by a sum in case of digital signals. The volume is then given by a sum of all values of a finite signal. Volume unit is represented by unit of the signal, which is a unit of voltage (V) in this case.

$$M = \sum_{k=-\infty}^{k=\infty} s(k) \qquad (7)$$

Instantaneous power of signal

Instantaneous power is given by square of function modelling the signal; this is analogical in case of digital signals, where instantaneous power is calculated by square of digital value of the signal

$$p(k) = s^2(k) \qquad (8)$$

Active power

The term active power originated, similarly to instantaneous power, in the analogue signals. In evaluation of analogue signals, the active power represents the mean value of instantaneous power. The term ‘active’ points out to the measure of energy transformation from original electric energy to acoustic energy. Active power stands for mean value of instantaneous power

$$P = \frac{1}{N}\sum_{k=0}^{N-1} p(k) = \frac{1}{N}\sum_{k=0}^{N-1} s^2(k) \tag{9}$$

Effective value

Effective value was introduced in analogue signals for assessment of periodical effects in order to compare the impact of periodical and constant (unidirectional) signals. Effective value is calculated according to the formula (10), which reveals that the effective value equals the square root of mean power.

$$s_{ef} = \sqrt{\frac{1}{N}\sum_{k=0}^{N-1} s^2(k)} = \sqrt{\frac{1}{N}\sum_{k=0}^{N-1} p(k)} = \sqrt{p} \tag{10}$$

Energy of signal

Energy of signal is calculated as a power multiplied by a time period. In case of digital data, following formula is used

$$E = P.N = \sum_{k=0}^{N-1} p(k) = \sum_{k=0}^{N-1} s^2(k) \tag{11}$$

where E – energy of signal, P – mean power, p_k - instantaneous power of signal, s – original value of digital signal [2, 8].

Results and discussion

The Figures 3 – 5 illustrate the behaviour of the specific cutting energy in the conventional (w) and acoustic (M) model, which was performed in the experiments of rock drilling of three different rock types (andesite, limestone, granite). The 10s time intervals were evaluated for the further analyses. The graphs showed that despite of the low difference of the specific cutting energy in the conventional model, the acoustic model evaluated almost all defined drilling regimes analogous to the conventional model. The differences in the assessment occurred due to the accuracy of the measurements of the input and output variables. The accuracy has to be higher than 5% based on the previous experience.

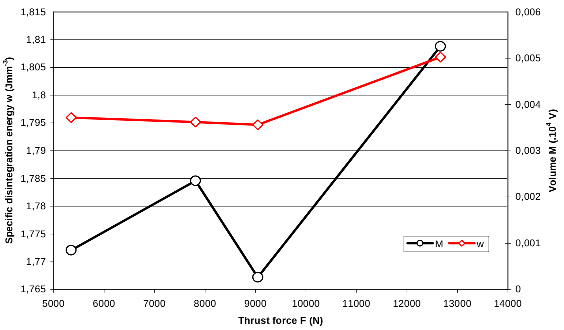

Fig. 3. Comparison of conventional and non-standard model in andesite drilling.

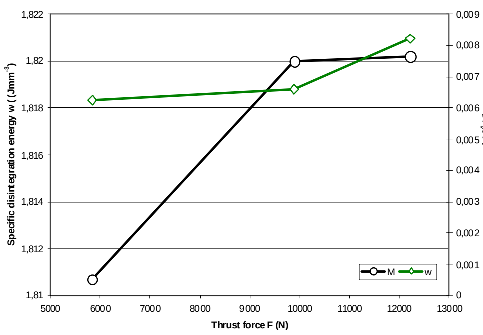

Fig. 4. Comparison of conventional and non-standard model in limestone drilling.

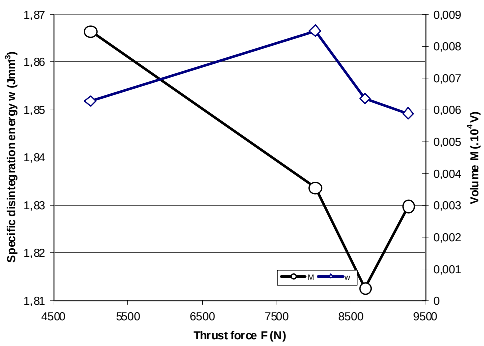

Fig. 5. Comparison of conventional and non-standard model in granite drilling.

Conclusions

Two types of models were used for assessment of accordance of observed system: conventional approach derived form specific cutting energy and model of accompanying acoustic signal. Evaluation of both models resulted from measured data of relevant working point, however issued from various measured variables. Specific cutting energy has been verified by a long-term research at the Institute of Geotechnics SAS for rotary drilling and full-face tunnel excavation.

Analyses proved that specific cutting energy is similar in its character to the volume of acoustic signal in all the working points of the system for different drilling regimes in experiments with various rock types. Optimization of the indentor-rock system should be available using the acoustic signal arising in the process of rock cutting by rotary drilling.

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