Application of adaptive filters in rock separation by rotary drilling process identification

***Patrik Flegner*[1], *Ján Kačur*[1], *Milan Durdán*[1] *and Marek Laciak*[1]**

Adaptive filters can be used for signal processing. Their utilization dwells in identifying an unknown system or process. The result of the adaptation process is finding an adaptive filter coefficient. The found coefficients represent a model of the identified system or process. This article deals with the possibility of adaptive filters utilization for identifying the process of rock separation by rotary drilling.

Key words: *disintegration of rock, adaptive filters, rotary drilling, identification, adaptive filter*

Introduction

Rock disintegration is the basic process in the raw materials mining but also in geo-technologies. There are several principles disintegration of rocks, the dominant position in the country and the world has disintegration based on the mechanical principle. Its energy and technological difficulty are in comparison with the other principles of disintegration lower. Disintegration of rocks on the mechanical principle may take the form of rotary drilling, rotary-percussive drilling, it may be a system with a disc roller chisels or cutting edges [1], [2], [3], [4]. The effectiveness of rock disintegration methods by mechanical means is a function of three sets of parameters:

- modal parameters: drilling speed ($m.h^{-1}$), respectively device performance ($m^3.h^{-1}$), further disintegration consumed specific energy ($J.m^{-3}$) and wear rate of drilling tool,
- design parameters of principled importance, for example, design parameters of disintegrative full-profile machine head,
- design parameters of principled importance, e.g. design parameters of isolating full-profile machine head.

In the past, but also in currently the attention was focused on the research and development of effectiveness aspects of a disintegration process based on mechanical principles. On the basis of published works but also on the basis of development practice it can be stated that in this area is in the world but also at home addressed observation in three basic ways:

- disintegrative indenter interaction with the rock and its impact on the efficiency of the process of disintegration,
- new material and design solutions of themselves disintegrative indenters,
- designs of drilling tool.

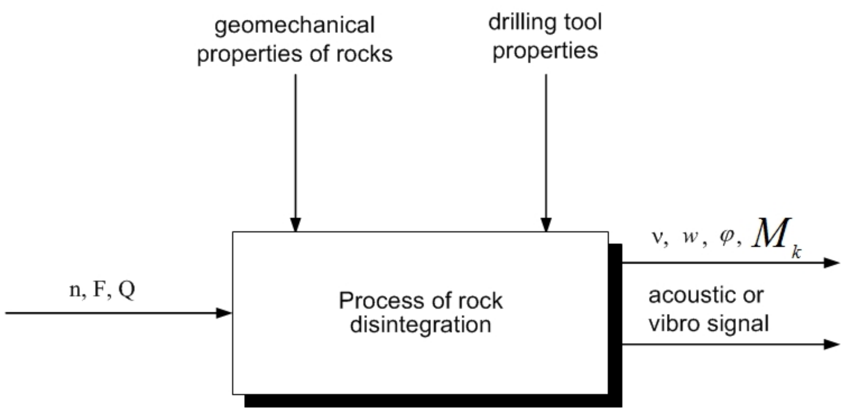

Fig. 1. Principle scheme of the rocks disintegration process.

[1] *Ing. Patrik Flegner, PhD., Ing. Ján Kačur, PhD., Ing. Milan Durdán, PhD., doc. Ing. Marek Laciak, PhD.,* Technical University of Kosice, Faculty of Mining, Ecology, Process Control and Geotechnologies, Institute of Control and Informatization of Production Processes, patrik.flegner@tuke.sk

From a systemic perspective, the process of disintegration of rocks can be understood as a complex system, which is characterized by measurable or non-measurable variables. Measurable are n – revolutions of the drilling tool (rpm), F – pressure force F (N), Q – volume of lavage of the drill with water (m3.s-1), v – speed of drilling (mm.s-1), Mk - torque (N.m), w – specific work of separation (J.m-3).State variables w and φ ($\varphi = v/w$ - work capability of the tool ($m.s^{-1}J^{-1}.m^3$)) belong to variables which in real life cannot be measured directly, therefore they are calculated during the drilling process. Important state variables are properties of indenter (drilling equipment) and geomechanical properties of disintegrated rocks (Fig. 1).

Fig. 2. Experimental drilling stand.

Faculty of Mining, Ecology, Process Control and Geotechnology on Technical University of Košice is already a few years ago involved in cooperation with the Institute of Geotechnics (Slovak Academy of Sciences) on solution of effective control of the rock disintegration process by rotary drilling (Fig. 2).

There were performed experiments on drilling stand when suitable algorithms for evaluating of the acoustic signal were looked. These algorithms could lead to information about the actual nature of indentor - rock interaction. Obtained information should allow setting the drilling mode (revolutions, depth, irrigation, indenter type) so that the process was efficient. In this paper is presented one of possible approaches to the process identification, when measurement of own state variables is not practically possible. The aim is to solve the parametric model of the rock disintegration process by measuring of the accessory sound, respectively vibro-acoustic signal [8], [9], [10], [11].

Measurements and characteristics of works on experimental drilling stand

The initial target of stand drilling works is to obtain information about the scope and dynamics of potential changes of pressure force and revolutions on a particular type of rock and type of disintegration tool.

After setting some basic speed value that must have in our case the minimum value of 700 (rpm), can be applied to various continuous changes of pressure force and speed.

Selection the character of the changes during the drilling of one rock samples is controlled so that the allowable subspace of adjustable levels was a "covered" by experimental points. These points are obtained from files so that the individual sensed values are divided in equal time intervals. Experimental works use the following changes modes:

- increase the pressure force at quasi-constant levels of revolutions,
- increasing the revolutions at different quasi-constant pressure force levels,
- increase the pressure force and revolutions,
- reducing the pressure force and revolutions.

Rocks samples of andesite, granite and limestone were experimentally disintegrated. For each of them was measured and recorded an acoustic signal at different revolutions n and different values of pressure force $F(\mathrm{N})$. Revolutions on the drilling tool can be set to values: n=500, n=1000, n=2000 rpm. Pressure force is possible to set for operating mode: F=500, 800, 10000, 12000, 14000 N. In experiments all possible modes of disintegration of rocks were tested.

Based on the waveforms shown in Fig. 3-4 we can state that these are the behaviours where revolutions is on a quasi-constant levels, but differ in the behaviour of pressure force. In Fig. 3 is a quasi-constant pressure force with slow fluctuations, while in Fig. 4 the pressure force slightly increases. These two pictures represent two possibilities of control mode change. Besides knowledge of drilling modes, it is important to know the actual process of disintegration of rock by rotary drilling. Based on knowledge of the disintegration modes and itself process is then possible to model the process of disintegration of rocks. In modelling of the process should be all acquired knowledge and aspects used. From Fig. 3-4 it can be seen that behaviour of the revolutions and especially the pressure force is relatively unstable. Therefore, to ensure constant conditions of disintegration is desirable to solve the issue of automatic stabilization of drilling mode [12, 13, 14, 15].

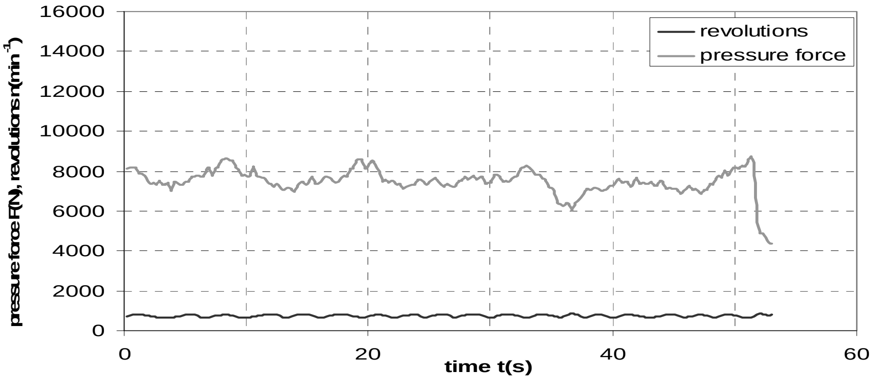

Fig. 3. Working mode of disintegration n = 500 rpm and F = 8000 N.

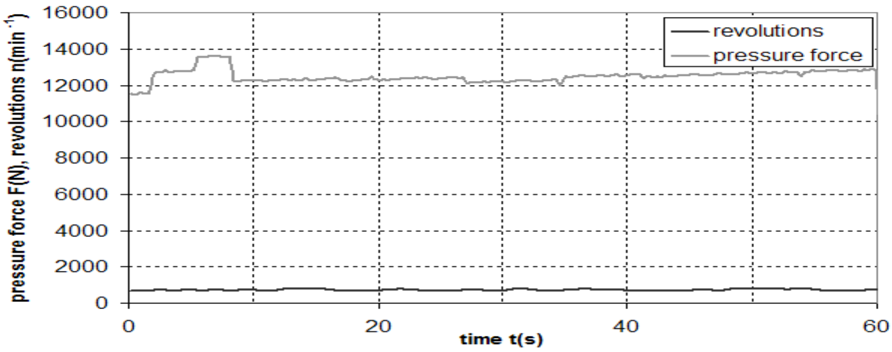

Fig. 4. Working mode of disintegration n = 500 rpm and F = 12000 N.

Parametric model of the process

For control purposes of the rock disintegration process by rotary drilling would be a desirable, suitable process model that would basically allow for the direct or indirect measurement of some process variables also determining the operating parameters so that the drilling process was in accordance with defined criteria effective. The very process of the rock disintegration however takes place at the indentor - rock interface, where the measurement in real conditions is practically impossible. Also classical mathematical modelling of the process is rather complicated and has a theoretical range than practical application [16, 17, 18, 19, 20].

As a possible solution seems to be creating a parametric model of the process (Fig. 5).

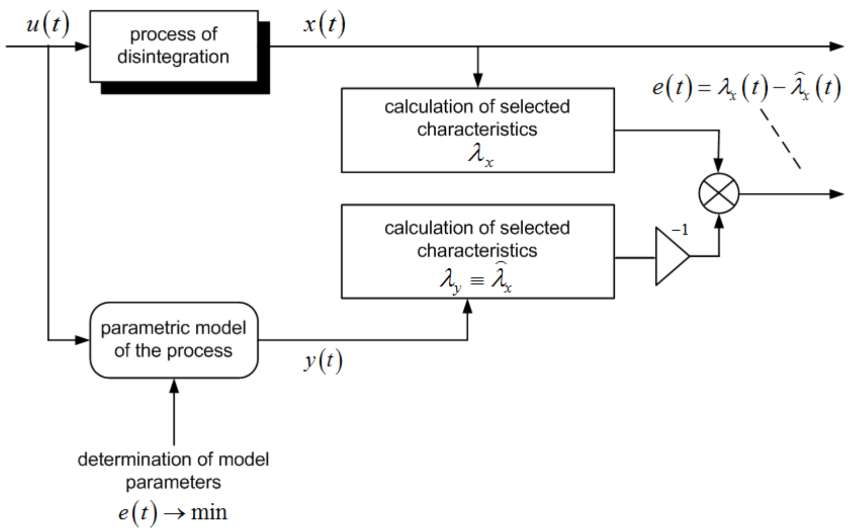

Fig. 5. Parametric model of the process.

Parametric model of the process has the form of a mathematical model of a suitable type and structure, but which is not based on the physical nature of the real process. The parameters must be set so that the vector of characteristics $\hat{\lambda}_x$ of the model response to the input $u(t)$ would be a maximum consistent with the vector characteristics λ_x of the response process, for the same input $u(t)$. In the case of the rock drilling process can be considered for feedback the process captured accompanying acoustic signal. Then the parametric model of the process in terms of Fig. 5 takes the form of the Wiener filter. Wiener filter (Fig. 6) as a parametric model of the process (signal) generally takes the form of rational fractional transfer function of a complex variable:

$$\mathrm{H_w}(\mathrm{i}\omega)=\frac{\sum_{i=0}^{M} b_i(\mathrm{i}\omega)^i}{\sum_{i=0}^{N} a_i(\mathrm{i}\omega)^i} \quad \text{pre } M \le N\,. \tag{1}$$

Whose parameters can be determined so that the output of this filter $y_w(t)$ beside specific suitable type of excitation signal $u_w(t)$ was approaching to the desired process (signal) $x(t)$. Then this adjusted transfer function $\mathrm{H_w}(f)$ of the filter is a wanted parametric model of the search process (signal) $x(t)$. The authors in work present three basic concepts of utilization of described above Wiener filter as a parametric model.

- adaptive estimator of system parameters (solves the problem of system parameters estimation, respectively its model),
- adaptive predictor of the signal (predicts the value of the signal based on sequence of previous samples, resulting in a parametric model of the signal - process),
- adaptive estimator of associated processes (the estimation of signal parameters such as integrating information source in the process - see the term "combined processes" , requires the separate excitation of the filter by suitable signal).

For the purpose of synthesis of a parametric process model of rock disintegration by drilling is offered using the third method of applying Wiener filter called adaptive estimator associated processes (Fig. 6).

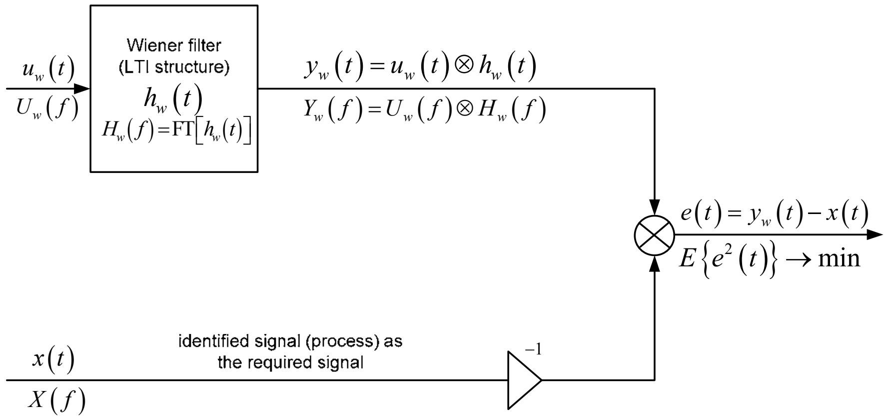

Fig. 6. Wiener filter as a parametric model.

Adaptive parametric model of the drilling process based on wiener filter

The task of the adaptive estimator of associated processes is to find adaptive filter coefficients so that the excitation process after overwinding through adaptive filter has been the best approximation of the identified signal – process $x(t)$. The resulting adaptive filter coefficients corresponding to the solution are found through a procedure based on minimizing the error signal $e(t)=y_w(t)-x(t)$. The output signal is then the best estimate of the process $x(t)$.

For the solution of the parametric model of the drilling in the form of so-called adaptive estimator of associated processes, says several facts:

- the process of rock disintegration generates accompanying acoustic signal, which based on past research works can be regarded as an integrating information resource, providing some information about the nature of "combined processes" taking place at the interface indentor - rock,
- processes occurring at the interface indentor - rock have in real-life non-stationary nature, therefore it is necessary to use a Wiener filter as an adaptive filter, responsive to changes in the nature of the accompanying sound signal,
- from theory of signal is valid signals each signal and thus also the complex accompanying acoustic signal $x(t)$ which can be considered as a response of a linear time-invariant system to white noise excitation (or unit impulse), whose power spectral density $S_{\mathrm{WN}}(\mathrm{i}\omega)$ is constant throughout the frequency range.

Specifically the solution of the parametric model of the rocks drilling process in the form of an adaptive estimator of associated processes is shown in Fig. 7. The essence of modelling the accompanying sound signal is synthesis of an identical signal from white noise by utilization of setup filters N-th order.

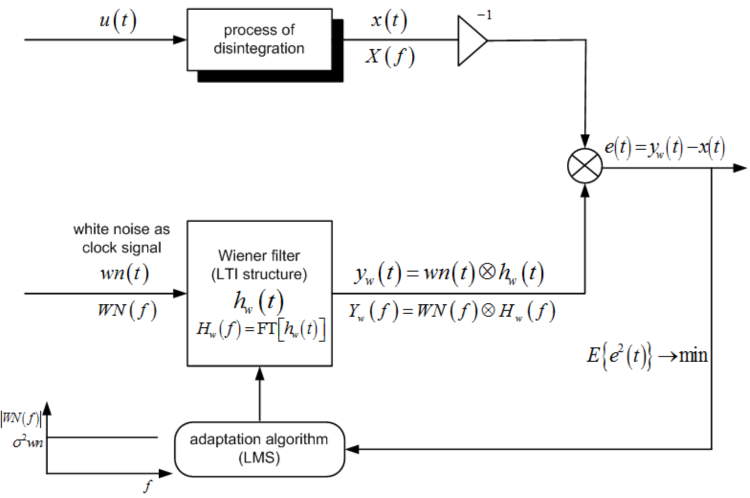

Fig. 7. Adaptive estimator of associated processes such as parametric model of the drilling process.

Parametric model of the rock disintegration process is here in the function of the Wiener filter. Its structure is chosen as a linear time-invariant FIR filter with transfer function in the frequency domain in the form of the complex variable function:

$$\mathrm{H_w}(\mathrm{i}\omega) = \sum_{i=0}^{M-1} b_i (\mathrm{i}\omega)^i \,. \tag{2}$$

In the time domain the discrete form of the transfer function has the form of linear differential equation with constant coefficients:

$$y_w(k) = \sum_{i=0}^{N-1} b_i wn(k-i) . \tag{3}$$

The adaptation algorithm used optimality criterion in the form:

$$\min J = \int_{t_0}^{t_1} e^2(t) dt \quad , \tag{4}$$

where J - is functional, which expresses the optimality criterion.

For realization of optimization objective function J was used Gradient iterative method. For the calculation of the elements of the vector of the weights in the equation (3) was used relationship:

$$b_i(k+1) = b_i(k) - h \frac{\partial J(b_i(k))}{\partial b_i} \,. \tag{5}$$

Step h of gradient method is chosen in this case experimentally, because the most effective step h is different for different kinds of input signals and for different parameters. In general we can say that a very small step value h causing slow adaptation to the signal. Very large values of h adaptation disable, or at best only reduce the accuracy of adaptation although it can be very fast.

Experiment realization description and the results

In actual experiments, we processed selected segment of acoustic signal $x(t)$ from the process of rock disintegration. Due to accurately and efficiently adaptation was used a larger segment of acoustic signal $x(t)$ with the number of samples $n = 65536$ and with the original sample rate $f_{vz} = 44.1$ kHz . The same number $n = 65536$ at the same frequency of generation $f_{vz} = 44.1$ kHz was generated also a white noise from the generator. At this point it should be noted that the generated was white noise, which had the characteristic statistical properties. The basic criterion was the distribution of the probability density of the values. We chose two types of probability density distribution, namely the uniform and normal one. Histograms of the generated white noise $wn(k)$ are shown in the following figures (Fig. 8 and Fig. 9). In Fig. 10-12 the behaviours of all signals during the adaptation process in the time domain are shown. Fig. 10 shows the input signal $x(t)$ to the system, Fig. 11 is generated white noise $wn(t)$ and the output signal from the adaptation process is shown in Fig. 12. Signals $x(t)$ and $y_w(t)$ in Fig. 12 show the whole process of adaptation filter in the time domain.

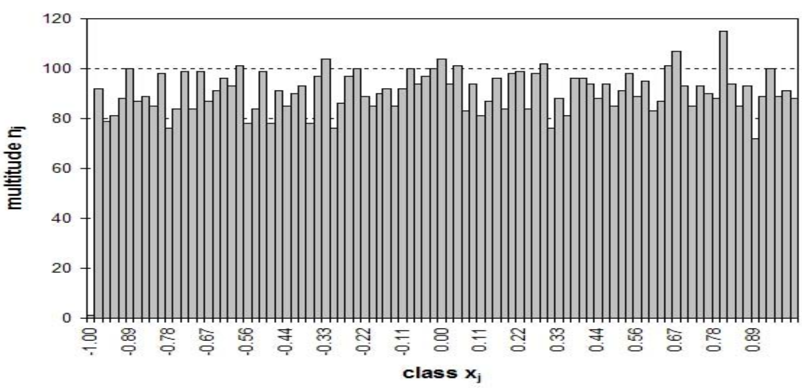

Fig. 8. White noise with uniform distribution.

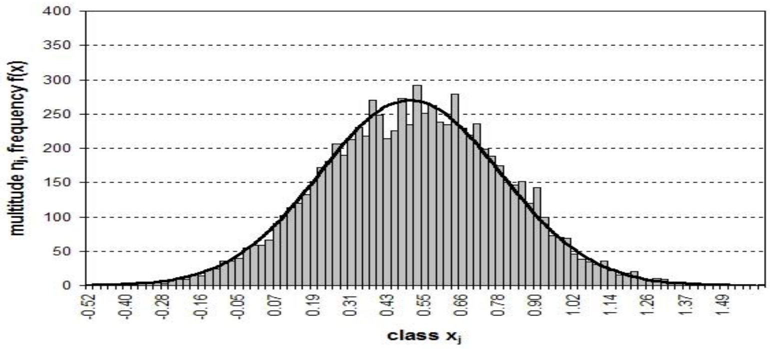

Fig. 9. White noise with a Gaussian distribution.

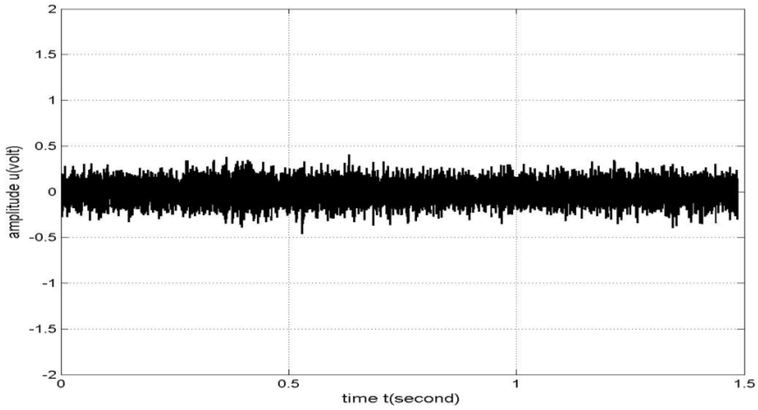

Fig. 10. The accompanying acoustic signal x(t).

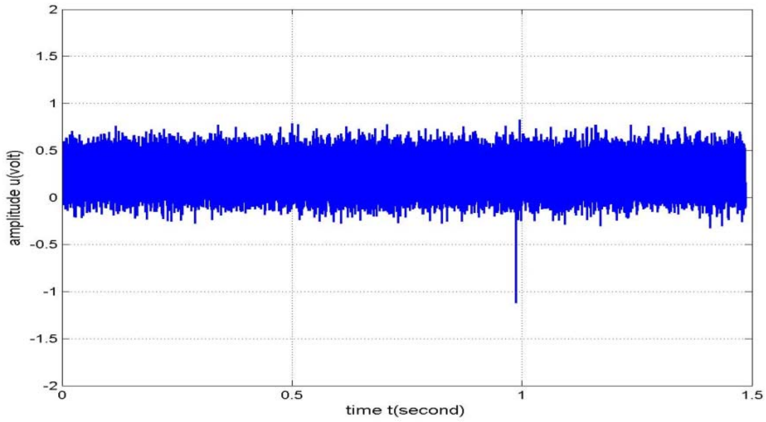

Fig. 11. White noise wn(t) as an excitation signal of adaptive filter.

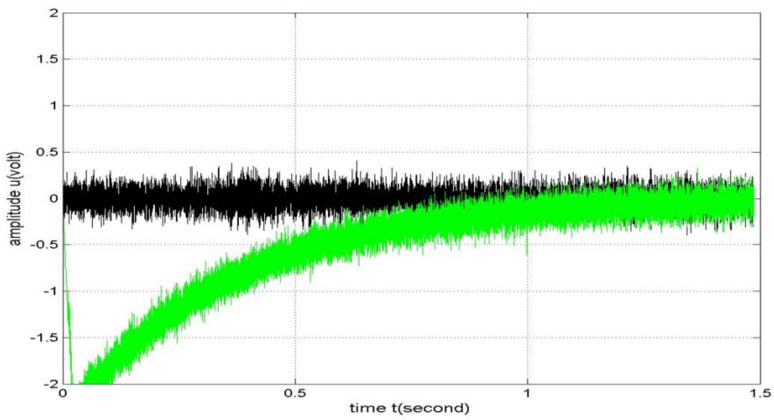

Fig. 12. Waveform x(t) and $y_w(t)$ in the process of filter adaptation.

Guidance evaluations of the experiment results were carried out at the end of adaptation. In evaluating of the experiments we considered only with certain selected segment of samples, in this case the number of samples $N = 8192$. Subsequently, the results of adaptation were processed and compared in time and frequency domains. In Fig. 13 - 15 are the time behaviours of the input and output signals from the end of adaptation. The following figure (Fig. 16) shows the time behaviour of adaptation errors of adaptive filter with LMS algorithms. From the time behaviour, it is possible to say that the adaptation error decreases. Figure 17 is a representation of the errors using an autocorrelation function. For successful adaptation is necessary to look to other criteria such as the filter order, filter coefficients, the adaptation gradient step and etc., as in the evaluation of the adaptation deterministic signal.

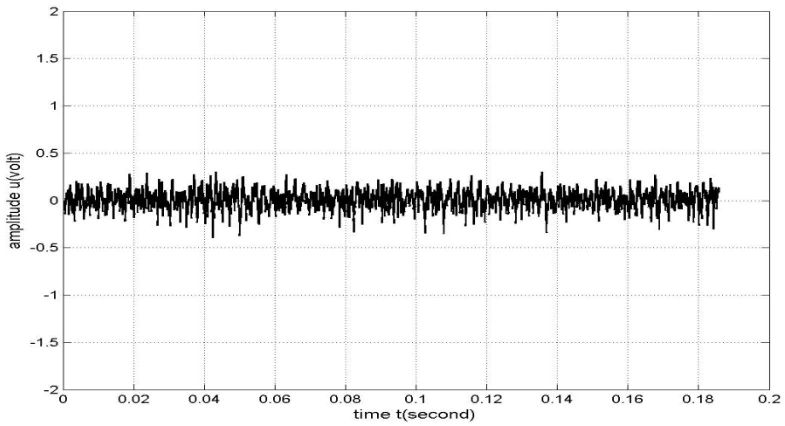

Fig 13. The accompanying acoustic signal x(t).

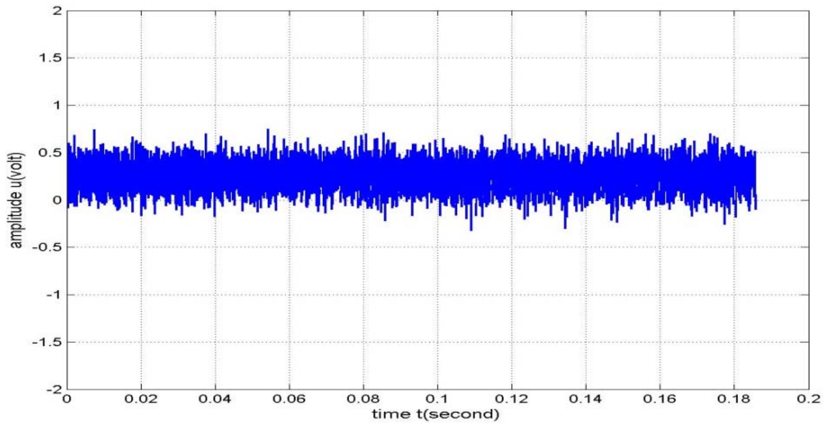

Fig 14. White noise wn(t) .

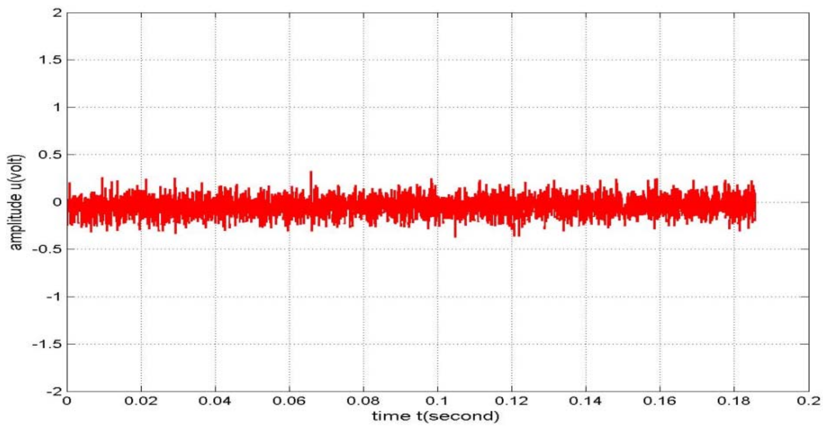

Fig 15. The resulting signal $y_w(\tau)$ at the output from filter after adaptation.

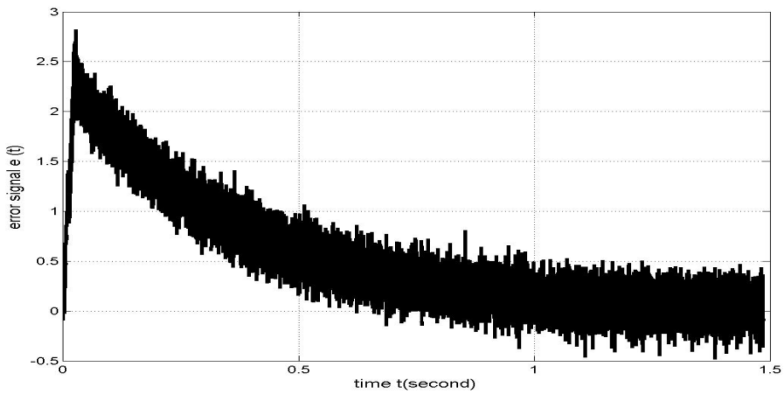

Fig 16. Error signal behaviour in the process of the filter adaption.

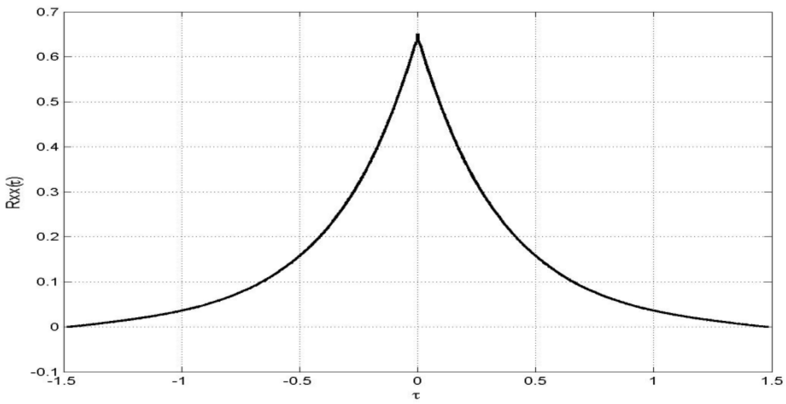

Fig. 17. Autocorrelation function of the error signal.

Appropriate expression of the adaptive filter coefficients of the input signal model $x(t)$ is an expression of coefficients directly or in decibels (Fig. 16, 17). Adaptive filter coefficients represent the signal model $x(t)$ of the rocks disintegration process. In this case it was the drilling into the andesite (Fig. 18, 19).

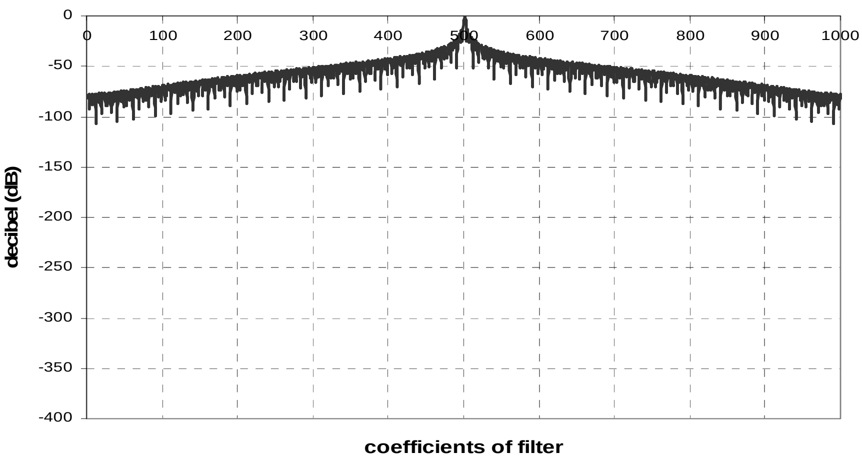

Fig. 18. Wiener filter coefficients as parameters of the drilling process of andesite - process model (dB).

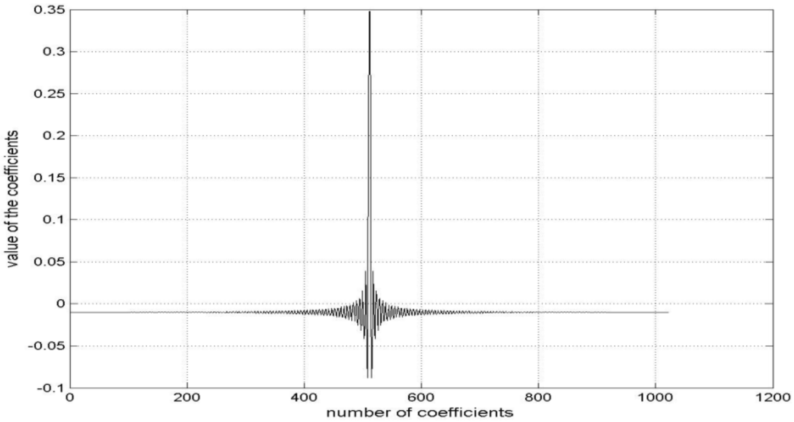

Fig. 19. Wiener filter coefficients as parameters of the drilling process of andesite – model.

Created model represented by coefficients can be statistically verified, thus confirm the hypothesis that it is sufficiently consistent with the original signal $x(n)$. Verification of conformity of individual signals can be done using statistical tests of compliance. Such a test is the Fisher's test of the parameters difference.

Conclusion

Modified adaptive methods are currently the modern means for the identification of nonlinear systems. In our case it was an audible expression of the rock disintegration process by rotary drilling. Acoustic expression of the drilling process is stochastic in nature. When adaptive filters were applied to the acoustic expressions in the drilling process, it is shown that adaptive methods are suitable for the identification of the system. Adapted signals had low value of the objective function J. It follows that the proposed adaptation algorithm on the principle of LMS is suitable for adaptation. Successful adaptation depends on the appropriate settings of input parameters such total number of signal values, a filter stage and step of gradient optimization method. Adaptive FIR filters with LMS algorithm are the appropriate type of algorithm for practically any kind of signals that do not change their properties too often and need to be adapted. It is a fast-flexible and is suitable for adapting the acoustic signal from the rock disintegration process of rotary drilling. Further scientific research is directed towards algorithms of the rock disintegration condition recognition, which is considered with the method of vector quantization. The ultimate goal is to contribute to the knowledge of the solution of control the process of disintegration by rotary drilling.

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