Mathematical modelling of operation of the hydraulic support system of the powered support sections with impulse-free continuous regulation of its resistance to the roof rock lowering

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Abstract. The article describes the mathematical model of a hydraulic support system of the powered support sections with impulse-free continuous regulation of its resistance to the roof rock lowering. Safety valves of the hydraulic support perform only protective functions. Mathematical modeling was carried out using the Runge-Kutta method and the Wolfram Mathematica computer algebra system. The results of modeling the transient process of the hydraulic support system with a built-in block for regulating its resistance during impulse loading of the support section with a collapsed roof rock block at “Polosukhinskaya” mine are presented.

1. Introduction

The efficiency of coal mining in complex-mechanized working faces of mines depends on the operation of the powered support section during the long-term loading in a rock pressure control mode, that is, in a mode of adjustable resistance to the subsidence of roof rocks. This confirms the validity of regular research aimed to improve the operating modes of hydraulic props for powered support sections and devices for regulating their resistance [1-12].

Of interest are long-term operating modes of the hydraulic support system of powered support sections with continuous pulseless regulation of their resistance to the rock roof lowering by special devices - pulseless resistance control units [3, 4]. The choice of values of the parameters is associated with many factors, in particular, transient processes in the hydraulic system during cyclic switching of the operating modes of the objects under consideration, changes in external loads on the powered support and pressure of the working fluid in the pressure line of the powered support hydraulic system.

The most severe mode of operation of the hydraulic system corresponds roof rock block collapses, which last for a fraction of a second and occur rarely, although they can have severe consequences, especially when safety valves are blocked. Determination of the main regularities of transient processes in the hydraulic system with impulse-free continuous regulation of its resistance to the roof rock lowering under prolonged loading is a difficult task that depends on time, design and operating parameters of the hydraulic prop, control unit and hydraulic system of the powered support sections. In view of the nonlinearity of the system, it is advisable to solve the problem by the method of numerical mathematical modeling [12-18].
The aim of the study is to develop a mathematical model of force interaction of the elements of the "roof - hydraulic rack - control unit - pressure line" system with continuous regulation of the resistance of hydraulic props to lowering the rocks of the immediate roof and imposition of a pulse surcharge simulating the collapse of the roof rock block.

2. Materials and methods
Mathematical modeling is carried out by the Runge-Kutta method [19], which makes it possible to reduce mining conditions and design parameters to a universal computational scheme, easily implemented by the Wolfram Mathematica computer algebra system.

Due to the fact that the system has a high degree of nonlinearity and a large number of logical conditions, mathematical models are developed for each element. In addition, the mathematical model is flexible, therefore, control or disturbing actions can be implemented. The system contains variable coefficients of differential equations that are associated with external loads that vary in time in a random manner. The method of mathematical modeling takes into account the required number of parameters with a high level of accuracy. The stages of mathematical model development are: development of a calculation scheme; formation of a flowchart based on the calculation scheme and making assumptions; mathematical description based on accepted conditions.

To draw up the design scheme, a hydraulic diagram of the hydraulic support of a support section with adjustable resistance and energy recovery into the pressure line of the powered mining complex support has been analyzed (Figure 1).

![Figure 1. The hydraulic system of the hydraulic racks with a control unit](image1)

![Figure 2. The calculation scheme of hydraulic props with a control unit](image2)

Torque converter 1 of the control unit is built into cavity 17 of the rod of the second stage of hydraulic prop 7. The inlet cavity of the torque converter is connected by hole 13 with piston cavity 15 of the second stage of the hydraulic prop, and outlet cavity 14 is connected to delivery line 10 of the powered support by a channel with throttle 3 and back-up valve 4.

The principle of operation of the control unit is that when the pressure in piston cavity 15 of the second stage of the hydraulic prop reaches the control level, the piston block of torque converter 1 begins to move upward (Figure 1) displacing the working fluid from cavity 14 through throttle 3 and
pressure valve 4 into pressure head line 10 of the hydraulic support system. When moving the support section, the pressure in the piston cavities of its hydraulic props is less than the pressure in the pressure line, the liquid from which through check valve 2 enters cavity 14 of the torque converter, transferring it to a charged state.

On the basis of the hydraulic scheme, the calculation was made (Figure 2). \( V_1, P_1 \) and \( S_1 \) are volume, pressure and sectional area of the chamber of the large piston of the torque converter; \( V_2, P_2 \) and \( S_2 \) are volume, pressure and sectional area of the small piston chamber of the torque converter; \( V_3, P_3 \) and \( S_3 \) are volume of the piston cavity of the second stage of the hydraulic prop, pressure in the cavity and area of the working surface of its piston; \( V_4, P_4 \) and \( S_4 \) are volume of the piston cavity of the first stage of the hydraulic prop, pressure and area of the working surface of its piston.

On the basis of the calculation scheme, a block diagram of the system has been built (Figure 3). It is a set of blocks and their connections corresponding to the elements and connections of the real system.

![Block Diagram](image)

**Figure 3.** The block diagram of propagation of the shock wave during the transition period

Each structural element of the hydraulic props system contributes to the formation of the general process. This contribution can be represented by a differential equation describing the continuous process of pulseless regulation of resistance of hydraulic props to the subsidence of roof rocks in a complex mechanized working face with recovered rock pressure energy in the complex hydraulic system. The process of operation of the hydraulic system and its hydraulic props is a sequence of transient processes, caused by regular switching of the operating modes of the support sections, changes in the working face associated with the flank and frontal movement of the face, changes in rock pressure during primary and secondary roof sediments or block-type roof rocks collapse, etc. The most unfavorable case for hydraulic props of support sections is their impulse loading as a result of block collapses of main roof rocks.

When studying the transient process in the event of impulse surcharge of hydraulic props of a powered support section with collapsed rock blocks of the main roof in a complex mechanized working face, it is difficult to take into account all the determinants. Therefore, to simplify the problem being solved, factors whose influence is insignificant are not taken into account. The following assumptions are taken into consideration:
- there is no dry friction between the moving parts;
- the sliding friction force is proportional to the speed of movement, while the coefficient of proportionality remains constant;
- the values of coefficients of the flow rate of the working fluid through the valves are constant;
- the compressibility of liquid in the drain pipeline is neglected;
- the elasticity of system elements is constant.

3. Mathematical model
To establish the basic regularities of the transient process, the process of force interaction of the hydraulic props of the section with roof rocks in a complex-mechanized working face was modeled by the Runge-Kutta method.
The movement of the hydraulic rack rod under the action of the collapsed rocks is described by the differential equation of forces acting on it:

\[ m_s \cdot \ddot{y}_l = -\mu \cdot \dot{y}_l + P_3 \cdot S_3 - F_l - m g, \]  

(1)

where \( F_l \) is the disturbing force of the impulse impact of the collapsed roof rock block on the hydraulic support, kN; \( m \) is the mass of immediate roof rocks, kg; \( g \) is the acceleration of gravity, \( g = 9.81 \, \text{m/s}^2 \); \( m_s \) is the reduced mass of moving parts of the support section and hydraulic props, taking into account the mass of fluid in the hydraulic props, kg; \( \dot{y}_l \) - movement of the hydraulic rack piston, mm; \( \mu \) is the coefficient of fluid friction.

The results of mine research confirm that the change in the force acting on the support under the dynamic action of the roof occurs in a very short period (0.05-0.3 s). Considering the most severe operation of the support, we assume that the load on the support changes in the form of a rectangular force impulse.

According to Skochinsky [2, 20] and a number of foreign authors, the maximum load on the support should be calculated assuming that the stratification and possible destruction of the roof occur at a height equal to five thicknesses of the removed layer. Other researchers suggest taking into account the resistance of friction and thrust forces between the blocks. In this case, the adhesion coefficient can be taken equal to \( K_f = 0.7 \).

We assume that when the roof collapses, the block acting on the support rests on the collapsed rocks. To determine the maximum possible load on the support section at maximum values of the parameters of the main roof collapse, let us set the conditions of the Polosukhinskaya Mine JSC and use support M-138/2 of face 26-325 for the calculation.

Based on the passport data, we take the layer thickness \( m = 1.8 \, \text{m} \), the main roof thickness \( H = 12 \, \text{m} \), the secondary step of the collapse of the main roof \( L = 120 \, \text{m} \), the specific gravity of sandstone \( \gamma = 2.65 \, \text{t/m}^3 \), the width of the upper support section is taken to be equal to the pitch of the sections along the lava \( b = 1.5 \, \text{m} \).

We accept the load on the support section and its hydraulic supports without taking into account the friction forces:

\[ F = \frac{1}{2} L b \gamma H = 5400 \, \text{kN} \]  

(2)

The effort per one hydraulic prop of the M-138/2 support section is:

\[ F' = \frac{F}{2} = 2700 \, \text{kN} \]  

(3)

The effort per one hydraulic prop, taking into account friction forces is:

\[ F_{p}' = F' (1 - K_f) = 810 \, \text{kN} \]  

(4)

The working resistance of one hydraulic support M-138/2 is equal to 1500 kN when the safety valve is adjusted to the response pressure \( P = 32.5 \, \text{MPa} \).

Thus, the force acting on the hydraulic props of the M-138/2 support section during the dynamic movement of the roof varies from 1500 to 2700 kN.

When developing equations describing the transient process in the piston cavity of the hydraulic rack under the dynamic load, we consider the hydraulic rack with a control unit and a torque converter.

The fluid flow in the hydraulic prop is

\[ G_l = S \dot{y}_l \]  

(5)

The flow rate in the rack, taking into account the liquid compression and the cylinder wall deformation is

\[ G = \beta V \frac{dp}{dt}, \]  

(6)
where $V$ is the volume of fluid in the hydraulic rack, mm$^3$; $\beta = \frac{d_1}{E_l} + \frac{1}{E_f}$ is the coefficient of volumetric compression; $d_1$ is the inner diameter of the hydraulic rack cylinder, mm; $\delta$ is wall thickness of the the hydraulic cylinder, mm; $E_l$ is modulus of elasticity of the cylinder material; $E_f$ is modulus of elasticity of the fluid.

The torque converter piston block movement is

$$m_b \cdot \dot{y}_b = -\mu \frac{dy_b}{dt} - P_1 \cdot S_1 + P_2 \cdot S_2$$

(7)

where $m_b$ is mass of the torque converter piston block, taking into account the liquid mass, kg; $y_b$ - displacement of the torque converter piston block, mm; $\mu$ is the coefficient of fluid friction.

The fluid flow in the chamber above the large converter piston is

$$\frac{V_1}{E_f} \cdot \frac{dp_1}{dt} = \dot{y}_b \cdot S_1 - G_1$$

(8)

where $V_1 = S_1(y_b^{max} - y_b) + V_{o1}$ is the volume of the large piston chamber, mm$^3$; $G_1 = \varphi S_1 \sqrt{\frac{2}{\rho}} (P_1 - P_p)$ is the flow rate of the working fluid through the hydraulic line, mm$^3$/min; $y_b^{max}$ is maximum displacement of the converter piston block, mm; $P_p$ is pressure in the pressure line, MPa; $V_{o1}$ is the volume of the harmful space (or dead volume) of the torque converter, mm$^3$.

The liquid flow rate in the chamber under the small converter piston is

$$\frac{V_2}{E_f} \cdot \frac{dp_2}{dt} = -G_1^1 - \dot{y}_b \cdot S_2$$

(9)

where $V_2 = S_2(y_b^{max} - y_b) + V_{o2}$ is the volume of the small piston chamber of the torque converter, mm$^3$; $G_1^1 = \varphi \cdot S_1^1 \cdot \sqrt{\frac{2}{\rho}} (P_1 - P_2)$ is the flow rate of the working fluid through the throttle, mm$^3$/min; $V_{o2}$ is the volume of the inner cavity of the second stage rod, mm$^3$.

The liquid flow rate in the piston cavity of the second stage of the hydraulic rack is

$$\frac{V_3}{E_f} \cdot \frac{dp_3}{dt} = G_1^1 + G_2^1$$

(10)

where $V_3 = S_3(y_l^{max} - y_l) + V_{o3}$ is the volume in the second stage piston cavity, mm$^3$; $G_1^1 = \varphi \cdot S_3^2 \cdot \sqrt{\frac{2}{\rho}} (P_3 - P_2)$ is the flow rate of the working fluid through the throttle, mm$^3$/min; $V_{o3}$ is the volume of the harmful space (or dead volume) of the second stage piston cavity, mm$^3$.

The liquid flow rate in the piston cavity of the first stage of the hydraulic rack is

$$\frac{V_4}{E_f} \cdot \frac{dp_4}{dt} = G_2^1 - G_3^3$$

(11)

where $V_4 = S_4 \cdot (y_l^{max} - y_l) + V_{o4}$ is the volume in the first stage piston cavity, mm$^3$; $G_3^3 = \varphi \cdot S_3^2 \cdot \sqrt{\frac{2}{\rho}} (P_4 - P_3)$ is the flow rate of the working fluid through the throttle, mm$^3$/min; $G_2^1 = \varphi \cdot S_2 \cdot \sqrt{\frac{2}{\rho}} (P_2 - P_4)$ is the flow rate of the working fluid in the pressure line, mm$^3$/min; $V_{o4}$ is the volume of the harmful space (or dead volume) of the first stage piston cavity, mm$^3$.

Changes in the volume of the hose of the hydraulic line are

$$G_1 - G_2 = \beta \cdot V_p \frac{dp}{dt}$$

(12)

where $\beta$ is the expansion coefficient of the sleeve; $V_p$ is the volume of the pressure line, mm$^3$.

The logical conditions are
\[ G^t_3 = \begin{cases} \frac{G^t_3}{P_4 > P_3} \\ 0 & \text{if } P_4 - P_3 \leq 0 \end{cases} \]  

(13)

When combining equations 7-13, we have a system of equations describing the transient process in the hydraulic system of the rack with a torque converter as a result of the impulse action of disturbing force \( F_i \). In this system, an appropriate set of differential, auxiliary equations and logical conditions can be used.

The system of basic differential equations is as follows:

\[
\begin{align*}
    m_a \cdot \dot{y}_a &= -\mu \cdot \dot{y}_l + P_3 \cdot S_3 - F_i - mg; \\
    m_b \cdot \dot{y}_b &= -\mu \frac{dy_b}{dt} - P_1 \cdot S_1 + P_2 \cdot S_1; \\
    \frac{s_1(y_b^\text{max} - y_b)}{E_f} \frac{dp_1}{dt} &= \dot{y}_b \cdot S_1 - \varphi \cdot S_1 \cdot \sqrt{\frac{2}{\rho} (P_1 - P_p)}; \\
    \frac{s_2(y_b^\text{max} - y_b) + V_{a2}}{E_f} \frac{dp_2}{dt} &= -\varphi \cdot S_1^l \cdot \sqrt{\frac{2}{\rho} (P_1 - P_2)} - \dot{y}_b \cdot S_2; \\
    \frac{s_3(y_t^\text{max} - y_t) + V_{a3}}{E_f} \frac{dp_3}{dt} &= \varphi \cdot S_1^l \cdot \sqrt{\frac{2}{\rho} (P_1 - P_2)} + \varphi \cdot S_2 \cdot \sqrt{\frac{2}{\rho} (P_3 - P_2)}; \\
    \frac{s_4(y_t^\text{max} - y_t) + V_{a4}}{E_f} \frac{dp_4}{dt} &= \varphi \cdot S_2 \cdot \sqrt{\frac{2}{\rho} (P_3 - P_4)} - \varphi \cdot S_3 \cdot \sqrt{\frac{2}{\rho} (P_4 - P_3)}; \\
    \varphi \cdot S_1 \cdot \sqrt{\frac{2}{\rho} (P_1 - P_p)} - \varphi \cdot S_2 \cdot \sqrt{\frac{2}{\rho} (P_3 - P_4)} &= \beta \cdot V_p \cdot \frac{dp_0}{dt}.
\end{align*}
\]

Table 1. Initial data for modeling

| Parameter | Description | Quantity | Unit measure |
|-----------|-------------|----------|-------------|
| Liquid in the pressure line coal face system: | | | |
| pressure | \( P_{\text{nom}} \) | 16-32 | MPa |
| Disruption valve: | | | |
| - fluid flow | \( G_{\text{max}} \) | 8 | l/min |
| - pressure | \( P_{\text{pk}} \) | 30-32 | MPa |
| Check: | | | |
| - pressure | \( P_{\text{nom}} \) | 32 | MPa |
| - fluid flow | \( G_{\text{nom}} \) | 25 | l/min |
| - diameter | \( \varnothing_{\text{pr}} \) | 0.5-1.5 | mm |
| Check valve: | | | |
| - pressure | \( P_{\text{nom}} \) | 32 | MPa |
| - fluid flow | \( G_{\text{nom}} \) | 63 | l/min |
| - diameter | \( \varnothing_{\text{pr}} \) | 3 | mm |
| Torque converter: | | | |
| - small piston diameter | \( D_{\text{mp}} \) | 20 | mm |
| - large piston diameter | \( D_{\text{bp}} \) | 45 | mm |
| - length of stroke | \( L_{\text{x, n}} \) | 800 | mm |
| Hydraulic line: | | | |
| -diameter | \( \varnothing_{\text{r}} \) | 7 | mm |
| -length | \( L_{\text{r}} \) | 3000 | mm |
| Actuation fluid: | | | |
| - viscous friction coefficient | \( m_y \) | 0.1 | d/q |
| - flow coefficient in throttle | \( \gamma \) | 0.8 | d/q |
| - liquid density | \( \rho_o \) | 1000 | kg/m³ |
Due to the nonlinearity of the system of equations (Figure 2) and the need for cyclical triggering of the logical conditions describing the movement of sliding elements of the hydraulic rack, the classical four-stage Runge-Kutta method is used. The task was solved by the Wolfram Mathematica computer algebra system.

When solving the system of equations 7-13, force $F_i$ can be specified: with a smooth change in the load and with an instantaneous impulse loading of the system.

For the calculation, the operating characteristics of real serial equipment used as a prototype were taken as the initial data (Table 1).

4. Results and Discussion

Figures 4-6 show the results of computer modeling. Pressure changes in the piston cavity are insignificant. The duration of the first pulse was no more than 0.01 seconds and did not exceed 2.5 MPa, which reflects an increase in damping.

The bearing capacity of the hydraulic props of the powered support section with continuous impulseless control units under various dynamic loads (from $A(t) = 1600$ kN to $A(t) = 3200$ kN) can be estimated from the pressure change in the rod cavity of the second stage of the hydraulic prop (Figures 4-6) under loading.

Figure 4. The transient process during impulse loading of the hydraulic rack force $A(t) = 1600$ kN

Figure 5. The transient process during impulse loading of the hydraulic rack force $A(t) = 2500$ kN
Figure 6. The transient process during impulse loading of the hydraulic rack force $A(t) = 3200$ kN

The modelling results (Figures 4-6) confirm adequacy of the mathematical model of transient processes when moving the elements of the gyro-resistant section of the powered support when changing the acting forces. This provides significant damping of power impulses and pressures in the elements of the hydraulic rack and its hydraulic system. The comparison of theoretical results and experimental data on tests of the MKYu 2Sh-13/27 hydraulic support with a control unit at Krasny Oktyabr plant [20] confirmed adequacy of the mathematical model with an increase in the external load on the hydraulic support until the safety valve was triggered (point C on the pressure line, Figure 7). There was a steady displacement of pistons of the torque converter of the control unit with displacements of the working fluid into the discharge line of the pumping station.

Figure 7. The setting mode of the experiment at "Red October" plant: $P_{pc}$ - pressure in the piston cavity of the hydraulic prop; $P_d$ - pressure in the hydraulic system drain line.

At the same time, no pronounced increase in the pressure amplitude or oscillatory phenomena in the hydraulic system were observed. This confirms adequacy of the mathematical model of the transient processes of movement of elements of the hydraulic support section of the powered support to the real processes when the external forces change.

From the analysis of Figures 4-6, it can be concluded that the nature of the process coincides with the experimental one (Figure 7) [20], and errors of the calculated values do not exceed 10%.

5. Conclusion
The mathematical model of the transient process in the hydraulic system of the rack equipped with a control unit for its resistance to roof rock lowering under the prolonged and impulse loading makes it possible to assess the influence of changes in the structure and values of the parameters of the control unit on the efficiency of hydraulic systems and possibilities of choosing their rational values at the
stages of design development, which is confirmed by a number of established factors:

- displacement of the working fluid from the piston cavity of the second stage of the hydraulic prop into the pressure line takes place without oscillatory processes, i.e. the control unit is a damping element;
- with an impulse load surge on the hydraulic rack, the duration of the transient process is no more than 0.03 seconds, and the pressure drop is no more than 2.5 MPa, which corresponds to the permissible values.

References

[1] Jin Z 2008 Mechanical model study on roof control for fully-mechanized coal face with large mining height *Chinese J. of Rock Mechanics and Engineering* 27 193-198

[2] Babyr N V, Korolev A I and Neupokoeva T V 2018 Enhancement of powered cleaning equipment with the view of mining and geological conditions *IOP Conf. Ser.: Earth Env. Sci.* 194 032004. doi:10.1088/1755-1315/194/3/032004

[3] Stebnev A V and Buevich V V 2017 Improvement of Performance Indicators of Hydraulic Drive of Props of Powered Support Units of Heading Complexes *Zapiski Gornogo instituta* 227 576-581. DOI: 10.25515/PMI.2017.5.576

[4] Gabov V V, Zadkov D A and Stebnev A V 2016 Evaluation of structure and variables within performance rating of hydraulically powered roof support legs with smooth roof control *Eurasian Mining* 2 37-40. DOI: 10.17580/em.2016.02.09

[5] Zeng X T, Meng G Y and Zhou J H 2018 Analysis on the pose and dynamic response of hydraulic support under dual impact loads *Int. J. of Simulation Modelling* 17(1) 69-80. DOI: 10.2507/IJSIMM17(1)412

[6] Byakov M A, Buyalich G D, Buyalich K G and Uvakin S V 2020 Radial strains in two-stage hydraulic extension legs *MIAB. Mining Inf. Anal. Bull.* 1 133-140. DOI: 10.25018/0236-1493-2020-1-0-133-140.

[7] Pavlenko M V, Khaidina M P, Kuziev D A, Pihtorinskiy D and Muratov A Z 2019 Impacts of the combine harvester in the production of coal to increase methane recovery array in the workspace lava *Ugol’* 4(1) 8-11. DOI: 10.18796/0041-5790-2019-4-8-11

[8] Zubov V P 2017 Status and directions of improvement of development systems of coal seams on perspective Kuzbass coal mines *Zapiski Gornogo instituta* 225 292-297. DOI: 10.18454/pmi.2017.3.292

[9] Buyalich G D, Buyalich K G and Umrikhina V Yu 2016 Study of Falling Roof Vibrations in a Production Face at Roof Support Resistance in the Form of Concentrated Force *IOP Conf. Ser.: Mater. Sci. Eng.* 142012120. DOI: 10.1088/1757-899X/142/1/012120

[10] Kazanin O I 2015 About the design of underground mining of series of flat gas-bearing coal seams *Zapiski Gornogo instituta* 215 38-45

[11] Kazanin O I and Sidorenko A A 2017 Interaction between gas dynamic and geomechanical processes in coal mines *ARPN J. of Engineering and Appl. Sci.* 12(5) 1458-1462

[12] Buyalich G D, Byakov M A, Buyalich K G and Uvakin S V 2018 Model to analyze hydraulic legs with two-stage extension in mines *Mining Informational and Analytical Bull.* 665 21-28. DOI: 10.25018/0236-1493-2018-12-65-21-28

[13] Zuev B Y, Zubov V P and Smychnik A D 2019 Determination of static and dynamic stresses in physical models of layered and block rock masses *Gorny Zhurnal* 7 61-66. DOI: 10.17580/gzh.2019.07.02

[14] Gospodarikov A P 2016 Nonlinear math model development and numerical model of strain deformed rock mass conditions prognosis *Zapiski Gornogo instituta* 219 382-386. DOI 10.18454/PMI.2016.3.382

[15] Gospodarikov A P, Vykhodtsev Y N and Zatsepin M A 2017 Mathematical Modeling of Seismic Explosion Waves Impact on Rock Mass with a Working *Zapiski Gornogo instituta* 226 405-411. DOI: 10.25515/PMI.2017.4.405
[16] Gabov V V and Zadkov D A 2018 Mathematical model of simple spalling formation during coal cutting with extracting machine *J. of Phys.: Conf. Ser.* **1015** 52007. DOI:10.1088/1742-6596/1015/5/052007

[17] Khazanovich G S, Voronova E Yu and Otrokov A V 2017 Simulation of the performance formation process of the loader with wedge-like working elements as a part of the blast and bulk tunneling complex *Procedia Engineering* **206** 457-464

[18] Ershov D Y, Zlotnikov E G and Timofeev D Y 2019 Analysis of proper fluctuations of technological systems *IOP Conf. Ser.: Mater. Sci. Eng.* **560** 012015. DOI:10.1088/1757-899X/560/1/012015

[19] Ascher U M and Petzold L R 1998 *Computer Methods for Ordinary Differential Equations and Differential-Algebraic Equations* (Philadelphia: SIAM Publications)

[20] Stebnev A V, Muhortikov S G, Gabov V V and Babyr N V 2018 Test of the unit of non-impact regulation of resistance of hydraulic stands of mechanical roof support to lowering of breeds of hanging wall *Mining Informational and Analytical Bull.* **S48** 416-425. DOI: 10.25018/0236-1493-2018-11-48-416-425