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NONIMPACT ROCK PRESSURE REGULATION WITH ENERGY RECOVERY INTO THE HYDRAULIC SYSTEM OF THE LONGWALL POWERED SUPPORT

The paper considers the advisability of continuous nonimpact regulation of powered support unit hydraulic props resistance to roof rock subsidence. It also examined the advisability of increasing the adaptability of the powered support within advanced high-powered mechanized longwall face complexes to mining-geological conditions that change as the blocks are extracted. A four-level characteristic with nonimpact regulation is proposed instead of a typical three-level operating characteristic of the support unit hydraulic prop with impact regulation of its resistance to roof rock subsidence. Such operation modes of hydraulic props with the power fluid displacement into the power support pressure pipe can be provided by a nonimpact resistance control unit. The paper presents the structure, connection diagram, and embodiment of the control unit. The production and in-mine testing of the MKYU 2SH13/27 powered support unit hydraulic prop equipped with a prototype control unit were carried out on OOO Zavod Krasny Oktyabr loading test bench and in the A. D. Ruban mine of AO SUEK-Kuzbass. The testing data is presented in the paper. The possibility of rock pressure energy recovery into the hydraulic system of the longwall power support has been proved.

Keywords: *coal, underground mining, working face, support unit, hydraulic prop, rock pressure, nonimpact regulation, pressure multiplier*
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Introduction

Underground coal mining development strategy in recent decades was aimed at an increased concentration of mining and increased per face output. It has been achieved by equipping working faces with advanced high-powered mechanized longwall face complexes (MLFC) [1–4]. An unprecedented per face output was set, a transition to longwall faces was carried out [5], the number of mines decreased, the structure of coal mining enterprises and organizations changed [6–8], and the requirements for mechanized stoping equipment changed [4, 9, 10].

The intensity of mining, the rate of advance [11, 12], the size of blocks cut [7, 13], and therefore mining-geological condition (MGC) ranges increased [14, 15] due to increased drive power, machine strength and specific amount of metal in machines that ensured a preset reliability and service life of MLFC machines and equipment.

An increased MGC range [16–18] results in a greater gap between the technically possible and actual production rates of MLFC and affects work safety [19–21] and economic efficiency of underground coal mining [22]. New requirements for MLFC have naturally occurred, in particular, it has become essential to provide them with adaptability to changing mining-geological conditions [23, 24]. In this context, the power support [25–27] as the main functional equipment of the fully-mechanized longwall (FML), which provides the necessary conditions for the intensive and safe operation of the working complex in the process of coal mining, plays an essential role in MLFC general adaptation to operating conditions.

In terms of the power system, in coal mine FML equipped with mechanized longwall face complexes, rock pressure control is currently energy-consuming and compensatory: the hydraulic energy created by the hydraulic system of the powered support of the complex is opposed to the rock wall convergence energy in the working face area. Rock pressure is regulated with impacts, i.e. by sequential responses of the hydraulic prop pressure safety valves with transfers and large power fluid pressure drop from the hydraulic prop head ends to the drain pipe of the complex or onto the ground [28, 29].

The main operation drawbacks of such "roof – hydraulic props – ground" system with elastic linkage are as follows:

- a compensatory energy-consuming method of regulating the powered support unit (PSU) hydraulic props resistance to roof rock subsidence. The method consists in electrical energy consumption, transformation into hydraulic and then mechanical energy, put into effect by PSU hydraulic props when interacting with the adjacent roof in FML [30];
- impact power character of PSU hydraulic props interaction with roof when controlling rock pressure (RP) [31], which makes conditions for a high probability of adjacent roof rock destruction and emptying into the space between the units [32];
- a large pressure drop that accompanies the response of the pressure safety valves with a large power fluid transfer into the drain pipe during RP regulation, resulting in dynamic impacts exerted on the elements of the hydraulic system and leading to their life loss [30, 33, 34];
- insufficient kinematic and contact adaptability of PSU to MGC that change as blocks are mined [25, 26], results in uncontrolled support unit loads and stresses of roof rock in contact with the unit laps.

So, modern PSU designed to withstand maximum loads in the hardest specific service conditions, are characterized by excessive specific amount of metal, impact method of regulating their resistance to roof rock subsidence [30, 35], and a wide range of power fluid pressure changes in pressure pipes. They are neither adaptable to changing mining-geological conditions, nor energy-saving, and when powered support

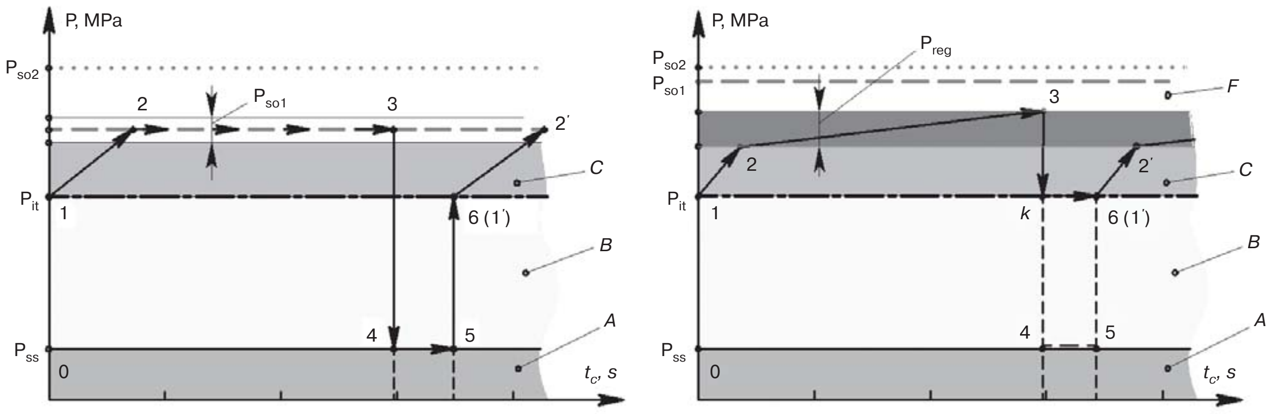

Fig. 1. Ideal operating characteristics of powered support unit hydraulic props:
a – typical operating characteristic of the hydraulic prop with three pressure levels; *b* – operating characteristic of the hydraulic prop with four pressure levels

units are shifted and pressure safety valves respond, they carry out static and dynamic trampling of the roof rocks.

Analysis and Method

The typical operating characteristics of the operating modes of PSU hydraulic prop hydraulic drive has the pressure levels that are set in the hydraulic prop head ends during the cycle operations and provide the necessary support to the units when they shift P_{ss}, the initial thrust of the unit P_{it} enough to avoid adjacent roof stratification, and the combined level of PSU regulation and protection from static (P_{so1}) overload. Dynamic overload P_{so2} protection is also provided. It is proposed to employ a four-level hydraulic prop operating characteristic (**Fig. 1b**) [26] in FML instead of the typical three-level one (Fig. 1a) to eliminate the drawbacks in PSU interaction with the bed top. The combined regulation level of PSU "equal resistance" and protection from overload (section 2–3 in Fig. 1a) of the typical characteristic is replaced by independent levels of hydraulic prop resistance regulation P_{reg} and hydraulic prop overload protection P_{so1} in the proposed operating characteristic (Fig. 1b). It ensures independence and increased hydraulic prop efficiency and adjustment accuracy.

Hydraulic props loads during the cycle operations (Fig. 1), namely, the initial thrust (section 0–1), increasing resistance (section 1–2), unload and shift of the support units (section 3–4–5–6), vary over a wide range. A significant power fluid pressure difference in hydraulic prop head ends (thrust force) during the cycle of operations and the shifting contact of the support expansion unit with the roof when shifting with support activates cracking in adjacent roof rock in contact with the lap. These mechanical behavior sections are responsible for the negative impacts within the "powered support-roof" system that are called "static trampling of adjacent roof rock" [28].

The upper and lower boundaries of the hydraulic prop resistance control zone P_{reg} (Fig. 1b) set the range of the powered support unit adaptation to adjacent roof rock subsidence.

All pressure levels are separated by intermediate zones *A, B, C* and *F* (Fig. 1) to avoid false response caused by their possible overlap. To reduce the effect of roof rock trampling caused by the difference in thrust forces per a cycle of operations, it is advisable to raise the support pressure P_{ss} during PSU shift up to the level of the initial thrust P_{it}, then unloading and shifting the support section is section 3-k-6 (Fig. 1b). However, in this case, PSU shifting operation will be non-executable due to the high resistance to shifting. To fulfill the above requirements, PSU structure should be improved, continuous nonimpact regulation of PSU resistance should be carried out with the extraction, transformation and use of the RP energy, and the mechanism of PSU cyclic shifts should be improved.

This method and modes of hydraulic prop operation with the power fluid displacement and a small pressure drop into the pressure pipe of the powered support were proposed in paper [26] and can be provided by a unit of nonimpact regulation of props resistance to roof rock subsidence (here in after referred to as the control unit). It should be noted that PSU hydraulic prop is an ideal converter of the mechanical rock wall convergence energy into the hydraulic energy and its transfer to the powered support hydraulic system pressure pipe.

Control unit *5* involving (**Fig. 2a**) multiplier *6*, throttle *7*, and return valve *8* is connected to the hydraulic prop valve block *1* involving relief valve *2*, hydraulic lock *3*, and pressure sensor *4* [26]. Valve 10 is required to easily connect control unit to the existing pumping station hydraulic lines and to the hydraulic prop. When the pressure in the head end of the first level of the hydraulic prop rises to the regulation level, the piston block of multiplier *6* will start to shift displacing the power fluid through throttle *7*, back pressure valve *9* and valve *10* into pressure pipe *11* of the powered support (PS) hydraulic system. During PSU unloading and shifting, the power fluid will be fed to multiplier *6* under pressure in the pressure pipe and transfer its piston block into a charged condition ensuring the coordinated work of control unit and PSU when it performs secondary operations.

The capabilities of the proposed engineering solution provide not only continuous nonimpact regulation of PSU hydraulic prop resistance to adjacent roof rock subsidence, but also RP energy transformation and transfer into the pressure pipe of MLFC powered support hydraulic system.

With the support from SUEK-Kuzbass JSC, Zavod Krasny Oktyabr, Leninsk-Kuznetsk city, manufactured and tested a control unit prototype designed to experimentally prove

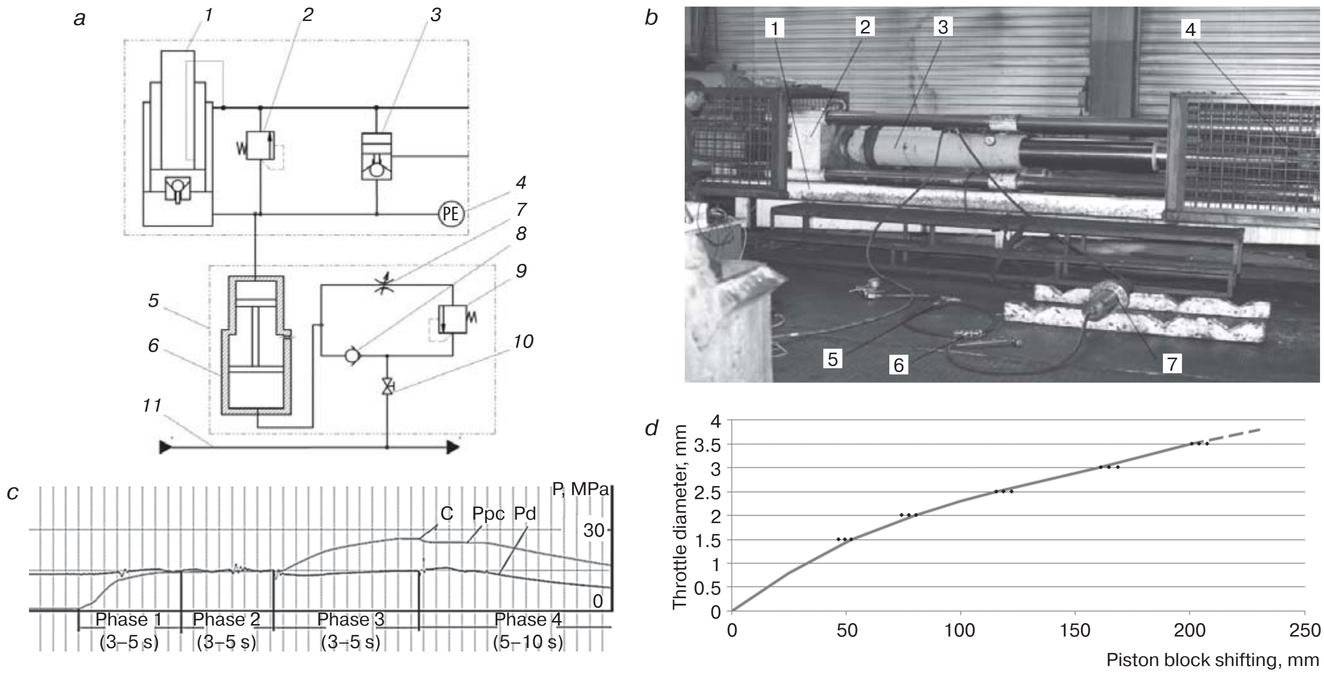

Fig. 2. Testing the nonimpact control unit:
a – the diagram of block connection to hydraulic prop MKYU 2SH 13/27; *b* – loading test bench; *c* – oscillogram of the process: throttle diameter is 3.5 mm, piston stroke is 200 mm; *d* – dependence between the multiplier piston block shifting and the throttle hole diameter

the very idea of nonimpact rock pressure regulation with the extraction, conversion and use of the rock wall convergence energy in the process coal mining in the coal mine FML.

The experimental prototype of the control unit and the MKYU 2SH13/27 support unit hydraulic prop were tested and examined in cooperation with the electromechanical services of SUEK-Kuzbass and Zavod Krasny Oktyabr on a loading test bench (Fig. 2b). The tested hydraulic prop *3* is installed in two pressure carriages *2* and *4* moving in opposite directions along guides *1*. The control unit contains the following elements: multiplier *7*, throttle with return valve *5*, valve *6* connected by high-pressure hoses to the test bench pumping station pipes and to the tested hydraulic prop MKYU 2SH 13/27.

During the tests, the stability of phases in the mode of increased hydraulic prop load was assessed: phase 1 – increasing pressure in the hydraulic prop head end to the pressure level in the pumping station network during $t = 3÷5$ s; phase 2 – maintaining the pressure value in a given range during not less than $t = 3÷5$ s; phase 3 – increasing pressure in the hydraulic prop head end during $t = 3÷5$ s up to the time when the pressure safety valve responds (point C); phase 4 – reducing the test prop load to a level determined by pressure in the test bench pumping station drain pipe during $t = 5÷10$ s. It can be seen from the oscillogram (Fig. 2c) that phase duration in the experiment was kept within the given limits, and the pressure safety valve response time as well as the device response to pressure in multiplier chamber were recorded exactly. Here P_{pc} is the pressure in the hydraulic prop head end and P_d is the pressure in the hydraulic system pressure pipe.

The tests determined the operating mode parameter values for the control unit with installed calibrated throttles with different hole diameters. A change in the throttle diameter proportionally changes the multiplier piston block shifting under a constant pressure difference (Fig. 2d). It therefore confirms that it is possible to efficiently form the operating characteristics of PSU hydraulic props.

Bench test results showed that the unit provides continuous nonimpact regulation of hydraulic prop resistance under the increasing load with energy recovery into bench hydraulic system. The pressure safety valve responses were not accompanied by sudden pressure changes and wave processes in the hydraulic prop or multiplier. The experimental studies have proved the unit workability and regulation method effectiveness.

Mine Experiment

Control unit field trial was carried out between November 6, 2018 and November 12, 2018 in the face of longwall 12-06 of Nadbaikaimsky bed at A. D. Ruban mine of AO SUEK-Kuzbass. The in-mine testing aim is to evaluate the workability of control units in production conditions considering the actual state of the MKYU 2SH13/27 powered support hydraulic systems and their parameter values.

Two prototypes of the nonimpact control unit were installed in longwall 12-06 in support units no. 97 and 105. The high-pressure chambers of the nonimpact control unit were connected to the head end of MKYU 2SH13/27 support unit hydraulic prop, and the low-pressure chamber was connected to the hydraulic system pressure pipe of the complex through the return valve, throttle and valve (Fig. 2a). When testing the control unit, the power fluid pressure in the hydraulic system pressure pipe and in the support unit hydraulic prop head end was controlled by pressure sensors PS1, PS2 (**Fig. 3a**) with visual monitoring in OHE block control unit (Fig. 3b): pressure in the hydraulic prop head end is to the left, and pressure in the pressure pipe is to the right.

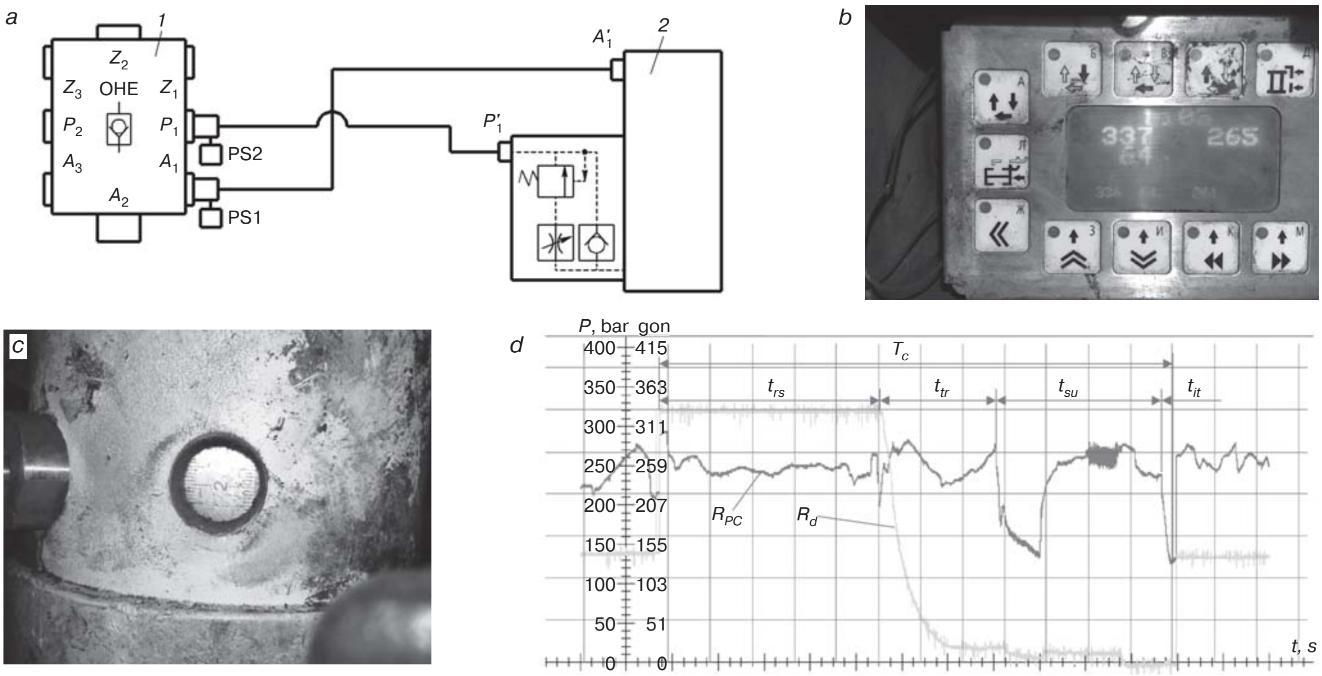

Fig. 3. In-mine testing of the control unit:
a – scheme of external connections of the hydraulic prop OHE valve block and the control unit: *1* – valve block OHE; *2* – control unit with a multiplier; *b* – block control unit; *c* – control unit viewing window with a measuring ruler; *d* – oscillogram of pressures in the hydraulic prop head end and MKYU 2SH13/27 support unit pressure pipe per cycle

The multiplier piston block shifting in the control unit during the cycle of operations was visually monitored by the position of the measuring ruler fixed on the piston rod relative to the viewing window mark (**Fig. 3c**).

Figure 3d shows an oscillogram of pressures for a cycle of operations: P_c is the piston cylinder pressure of hydraulic prop of MKYU 2SH13/27 support section; P_h is the head line pressure. The oscillogram temporally reflects the process features during all cycle operations in clear terms: roof support and ground control t_{rs}; removal of extension of props t_{tr}; advance of support section t_{su}; initial extension t_{it}.

Thus, it is possible to estimate the cyclic processes in the hydraulic drive of the powered support unit hydraulic prop: the thrust removal time is t_{tr} = 2,5÷2,7 s, PSU shifting time is t_{su} = 4÷5 s, the time of PSU hydraulic prop initial thrust is t_{it} < 1 s, and the resistance adjustment time t_{rs} is determined by the coal mining operation time.

During the shifting operations, the pressure in the prop head end, hydraulic advancing cylinder and pressure pipe of MKYU 2SH13/27 support change abruptly. Sufficient dynamics of pressure processes and the presence of transient processes in prop hydraulic drive and pressure pipe provided rationale for a back pressure valve installation at the outlet of the control unit where it is connected to the pressure pipe.

When the pressure in PSU prop head ends reached the regulation level, stable shifts of the control unit multiplier piston block were observed and recorded by the measuring ruler displacements (see Fig. 3c). The total displacement of the piston block is 20–30 mm confirming the fact of rock wall convergence energy transfer into the pressure pipe of the longwall face complex hydraulic system.

When the prop was unloaded and the support unit was shifted, control piston block unit returned to its original position. It confirms the unit's workability when performing operations recurring in cycles.

Conclusion

Based on the research results, it can be claimed that the control unit of the proposed structure ensures:

- continuous nonimpact regulation of hydraulic prop resistance to the increasing load in the rock pressure control mode. The dynamics of the adjacent roof rock load decreases, the cracking intensity in the adjacent roof rock supported by the unit overlaps decreases, and the probability of their destruction and emptying into space between the units decreases;
- stable cyclic shifting of the piston block in the control block multiplier in accordance with the operations performed by the support units in the longwall;
- rock wall convergence energy recovery into the pressure pipe of mechanized longwall face complex hydraulic system;
- reduced dynamics, mean and maximum operating load on the support unit hydraulic props improving their service life.

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