Dynamics control of powered hydraulic roof supports in the underground longwall mining complex

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Abstract. The study presents the dynamic analysis of the hydraulic cylinders operated in the powered roof support sections as an important part of the longwall underground mining complexes. This type of hydraulic unit is subjected to frequent shock impacts from the significant rock masses released on the top of mined caverns. Hydraulic props are equipped with safety valves with steel helical springs, which intend to reduce peak loads by the relief of internal pressure. These valves respond to shock with a time delay due to the limited velocity of the pressure wave inside the cylinder and an additional pipe of a small section, which restricts fluid flow in outer space. The new approach represented in this paper is based on mathematical modelling of the interaction of the hydraulic and mechanical parts and using additional signals to control safety valves. Detection of shock in advance (0.02-0.05 s) allows reducing pressure peaks by 30% and avoid failures. The challenges are the development of a "smart valve" with optimised control functions by the signals from additional sensors (vibration, deformation, piston position) and providing fast reaction time with a high flow rate under pressures up to 100 MPa.

1. Introduction
The powered sections of hydraulic props are among the main mechanisms in the underground longwall mining complexes providing safe work of personnel and Longwall Top Coal Caving (LTCC) process efficiency (see Figure 1a). The design of hydraulic props supposes two telescopic pistons for a wide range of serviced heights. The carrying capacity of everyone may reach 1000 t and working pressure 32-45 MPa (Figure 1b). Modern automation systems provide overall supervision and vertical or horizontal positions control over the section consisting of hundreds of double cylinder props. Numerical studies are known in this domain directed on mechanical design optimisation to restrain severe loading [1-11] and hydraulic system simulation [12-16] to reduce undesired dynamics.

Along with standard functions of pressure supply and redistribution for carrying capacity control in the whole section, every hydraulic cylinder is equipped with a safety valve, which intends to prevent overloading by releasing pressure above the pre-installed level. Nevertheless, the props are frequently failed due to dynamic loading from the released rock blocks with unrecoverable damages like sealing leakages, cylinder and piston deformations (Figure 1c). Therefore, safety valves are subjected to intensive testing on special facilities to optimise hydraulics control [17-22].
The maintenance and full replacement in the underground mines require significant costs and cause long downtimes. The hidden damages of sealing in cylinders are difficult to detect but they lead to dangerous consequences due to load redistribution among neighbouring props and their overloading.

2. Problem formulation

Summarising the aforementioned conditions, the following problems are encountered in safety valves:

- Not equivalence (by 15-20%) of applied load and internal pressure due to friction losses.
- Time delay of pressure to applied dynamic load due to the limited speed of a fluid wave.
- Harsh working conditions (dust, humidity, temperature) and explosive limitations for sensors.
- Deterioration of valve spring material due to fatigue and creep over the operation period.

Testing of safety valves is conducted on the special rigs where huge mass (about 20 t) falling from a certain height (up to 1.0 m) imitates dynamic impact from the rock (Figure 2a,b,c). The typical design of safety valves is represented in Figure 2d and its installation on the cylinder is shown in Figure 2e. Some approaches exist to reduce the dynamics of hydraulic systems: multi-plate valves [23], hydro-pneumatic accumulator [24], two-stage valves [25]. For example, the flow rate of two-stage valves of OSTROJ Company (Czech Republic) may reach 7000 l/min [26]. Fast inertial valves are proposed in [27] with a general strategy of roof supports adaptation to the stochastic loading [28].

The general scope of this research is to study the transient dynamics of hydraulic roof support (one of the cylinders) to determine a possible way for its high dynamics control by the regulation of the safety valve. The following tasks are set in this paper: to find the natural frequency of free oscillations under shock impact; to estimate piston displacement and pressure signal time delay at the safety valve input; to find relations of peak pressure in the cylinder with the advanced in time opening of electrically regulated safety valve.
3. Model of the hydraulic prop with safety valve control

The simulation model of a hydraulic prop is composed in the MATLAB Simulink and it includes the following blocks (see Figure 3): hydraulic cylinder, pump for pressure supply, safety valve with regulated opening time, impact load from falling mass, pipes for fluid delivery to a cylinder and exhaust pipe where the valve is installed. Parameters of the safety valve and hydraulic cylinder are adjusted by data of the hydraulic equipment supplier from works [17-21].

Control signals in the feedback loop can be supplied from any type of additional sensors (vibration, displacement or force) installed on a canopy of hydraulic prop or cylinders. The selection of sensors and their characteristics should be based on results of experimental research with taking into account the harsh operating conditions and the need for energy supply limited by explosive risk regulations. For this purpose, different autonomous energy harvesters can be used based on thermoelectric and piezoelectric elements or other sources.

4. Transient process analysis under impact loading

At the first stage of research with the MATLAB Simulink model, shock impact was applied without opening the safety valve to verify the model by the natural frequency of oscillations. Results of the simulation are represented in Figure 4 and Figure 5.

In this case, the stiffness of the hydraulic spring in a cylinder is as follows:

$$K(t) = \frac{E_0 A}{h(t)}$$

where $E_0$ – fluid bulk modulus under normal conditions (includes influence of the air content, temperature and fluid pressure); $A$ – effective inner area of piston chamber; $h(t)$ – a fluid height in the cylinder. For double-acting telescopic cylinders, this formula is applied to every section. The full stiffness of the cylinder includes deformations of the barrel wall and piston [29].

In the testing rig of safety valves, a hydraulic spring under a certain test weight (20 t) constitutes a dynamical system with the main natural mode of vibration about 200 Hz (Figure 4).
In real work conditions, the prop height is always changing in time depending on static load over the roof supports section. Hence, all hydraulic props (with pair of cylinders) are dynamical systems with variable parameters. The natural frequency of oscillation is also variable:

\[
\omega_n(t) = \left(\frac{K(t)}{m}\right)^{1/2}
\]

where \(m\) – is a joined mass, which changes for every impact in the conditions of an underground mine. With a bulk modulus of hydraulic fluid \(E_0 = 2.1 \text{ GPa}\), effective inner area of piston chamber \(A = 0.07065 \text{ m}^2\) \((D = 0.3 \text{ m})\), fluid height 1.0 m, rock mass 20 t, formulas (1), (2) give the value of stiffness for two parallel cylinders \(K_\Sigma = 296.9 \text{ MN/m}\) and natural frequency about \(\omega_n / 2\pi = 19.4 \text{ Hz}\). In this case, the half-period of piston oscillation is about \(T/2 = 0.026 \text{ s}\). The higher natural frequencies give shorter times for reaction and dynamics control by the safety valves.

The current natural frequency depends on the initial piston position \(x_0\) determined by its static load (see Figure 5). Then, in the case of safety valve opening under conditions of overloading, the hydraulic spring deforms up to \(x_1\) (negative down direction) and becomes non-linear (piecewise softening characteristic). Further deformation depends on the flow rate \(Q_i\) of the safety valve.

Some important features should be noted:
- Pressure peaks are reducing with advance time lags.
- Flow rate has a greater influence on dynamics than time lag.
• Dynamics is related to frequency and shock duration ratio.
• With every next oscillation, the natural frequency is changing.
• Higher props have less stiffness and more shocks damping.

The greater flow rates ($Q_1<Q_2<Q_3$) correspond to softer stiffness characteristics above the fracture point in the graphs and better dynamics damping. On the other hand, big flow rates increase the risk of piston full contact at the bottom of the cylinder when fluid height becomes close to zero especially after several subsequent oscillations above the pressure limit.

Signal of impact applied to the upper elements of canopy can be detected in advance of time and used for shocks damping. Results of model simulations are summarized in Figure 6 where pressure peaks are reducing with an increase of pipe diameter and advance time lags physically allowable for detection by additional sensors installed on the hydraulic prop housing.

![Figure 6. Dynamical pressure peaks reduction by the safety valve control with different time lags.](image)

5. Conclusions
A new approach is proposed of dynamic impacts reduction based on mathematical modelling of the hydraulic and mechanical parts and using additional signals to control safety valves after modification. This approach is not used in underground mining although is well known in other fields of technique as active damping. It is implemented in heavy industry to control vibrations in rolling mills [30-34].

The created model allows for certain impact parameters (duration, amplitude, rock mass), piston size and position to calculate the natural frequencies and use this information in the design of the dynamics control system to estimate the reaction, time delays and required flow rates of safety valves.

Model simulations showed that the time delay between force application on the top of the piston and pressure signal reaction at the safety valve position (near the bottom of the cylinder on the exhaust pipe with a small diameter) is about 0.02-0.05 s. It is enough long time if to measure shock impact and generate a feedback signal to control the safety valve. In this way, the pressure peak can be reduced by 30% and even more.

Further research is directed on the development of optimal control by the signals of additional sensors (vibration, displacement or force) and selection of fast electrically regulated valves with minimum reaction time providing a high flow rate under pressures up to 100 MPa. The existing automation and monitoring systems provide a basis for the smooth implementation of a new solution in the mining industry. The huge amount of hydraulic props ensures a great potential for application.

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