Mathematical model of simple spalling formation during coal cutting with extracting machine

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Abstract. A single-mass model of a rotor shearer is analyzed. It is shown that rotor mining machines have large inertia moments and load dynamics. An extraction module model with selective movement of the cutting tool is represented. The peculiar feature of such extracting machines is fluid power drive cutter mechanism. They can steadily operate at large shear thickness, and locking modes are not an emergency for them. Comparing with shearsers they have less inertional mass, but slower average cutting speed, and its momentary values depend on load. Basing on the equation of hydraulic fuel consumption balance the work of fluid power drive of extracting module cutter mechanism together with hydro pneumatic accumulator is analyzed. Spalling formation model during coal cutting with fluid power drive cutter mechanism and potential energy stores are suggested. Matching cutter speed with the speed of main crack expansion and amount of potential energy consumption, cutter load is determined only by ultimate stress at crack pole and friction. Tests of an extracting module cutter in real size model proved the stated theory.

1. Introduction.
Nowadays, high energy consumption during separation of mineral deposits from refuses, load increase on the actuating operating mechanisms (cutters), excessive grinding and dusting during extracting process, limited utilization of extracting machines due to rocks stiffness because of short durability of the working tools, costly cutters’ cooling and safety precautions for eliminating frictional spark-over, suppression, bunching and removing of combustible dust are the main factors restricting increase of mine-extracting and improving machines efficiency.

Nowadays, most extracting machines destroy coal deposits mechanically with cutters. So, the aim of the investigations [1-8], is to determine rational parameters of cutters and actuating mechanisms operation, lowering the load dynamics on actuating mechanisms [2]. New principles of destroying coals and minerals are developed [7], to provide higher efficiency of extraction, size increase of extracted bulks, lowering power consumption for destruction and decreasing dust formation.

Problems of efficiency increase in coal-mining are given in [1]. Acute research trends are influence of drive characteristics, lowering drive stiffness for one-two orders, lessening inertia masses, and load application time on cutting process smoothness.

During traditional coal-mining with shearer machines efficiency is achieved by drive power increase that increases inertia moment of rotors. Nesh-mining with constant mining speed results in high load dynamics and decrease of machines’ life period. Nowadays the shear–thickness of modern rotor mechanisms is variable, and the form of the cut is crescentic, and maximum layer thickness is
80-100 mm.

All drives of mining-machines can be divided into two types: with rotating details and rotor and those with linear motion of the actuating mechanism (without rotation).

2. Materials and methods.

Let’s study a single-mass model to analyze drive characteristics influence on rotor extracting machines loads, where the elastic strain is not taken into account, and total moment of resistance forces are led to electrodrive shaft \( M_{sl} \) and inertia total moment \( J \):

\[
M = M_{sl} + M_{dyn}, \tag{1}
\]

where \( M \) – rotation moment of electrodrive, N·m; \( M_{sl} \) – static load moment, at electrodrive shaft, N·m; \( M_{dyn} \) – dynamic moment, N·m, determined by formula:

\[
M_{dyn} = J \frac{d\omega}{dt}. \tag{2}
\]

Here, \( \omega \) is angle speed, \( s^{-1} \).

By increasing external load, and consequently, acceleration \( (d\omega/dt) \) dynamic moment may increase, that increases loads’ dynamics and decreases transmission life period. Hence, to decrease loads’ dynamics it is better to use drives with small inertia masses.

There are different ways and mechanisms to decrease dynamic loads of extracting machines. But, at the existing cutting speeds (2-4 m/s and higher) the use of spring-loaded cutters [8], and other similar devices [9] preserving traditional structure of shearers have no positive dynamics, as cutter displacement relative to cutter holder and load time are very small. For effective destruction it is necessary to change speed in large ranges, inertia moment should be small, shear thickness should be more than 80-100 mm, that is impossible for modern shearers.

As analysis of extracting mining machines showed, drives of divided mechanisms have such characteristics, in particular, a front extracting module with linear motion of the actuating element [10]. Drive characteristics are important for these machines. Extracting modules of front complex can operate steadily at shear thickness more than 100 mm, and locking modes are not an emergency for them, but acceptable ones. They have less inertia moment comparing with shear loaders, average cutting speed is an order lower, while momentum cutting speed depends on load.

Similar to rotor machines the load of machines with linear motion of an actuating element may be presented by the equation:

\[
Z = \overline{Z} + m \frac{dV}{dt}, \tag{3}
\]

And deviation from average load:

\[
Z - \overline{Z} = m \frac{dV}{dt} = m\cdot a, \tag{4}
\]

where \( Z \) is load, \( H; m \) is cutting mechanism mass, \( kg; dV, dt \) – speed increase, \( m/s \) and time increase, \( s; a \) is acceleration, \( m/s^2 \).

Determining acceleration from (4), we have:

\[
a = \frac{Z - \overline{Z}}{m}. \tag{5}
\]

Using hydrostatic drive with restricting maximum value \( Z \) force change \( Z_f \) at small mass \( m \) results in significant change of acceleration \( a \).

Experimental investigations on the extracting module sample [11] showed that the range of average values of cutting forces, during coal-concrete bulk layers cutting with cuttability \( A_i = 180...300 \) kH/m is below corresponding calculated values. Figure 1 shows the dependence cutting forces average values on shear thickness, calculated (solid line —— ) and experimentally received (local values
determined – \( \times, \circ \) in the area of calculated lines).

![Graph showing average cutting strength dependence on shear thickness](image)

**Figure 1.** Average cutting strength dependence on shear thickness:

- \(-\) calculated; \(\times, \circ\) experimentally tested

Lower level of average cutter loads in comparison with calculated ones at one and the same shear thickness is a very important factor; it estimates the rock bulk cutting process with soft fluid power drive on the whole.

The peculiarity of the extracting module fluid power drive cutter mechanism is pneumohydroaccumulator with potential energy greater than consumed energy for a single cut, as well as smaller inertia mass of the actuating mechanism (cylinder group) comparing with rotor machines.

Figure 2 shows a simplified scheme of a fluid power drive cutter mechanism of an extracting module with a single cutter: 1 – electrodrive; 2 – pump; 3 – cylinder group; 4 – pneumohydroaccumulator; 5 – sample cutter; 6 – coal block.
Figure 2. Fluid power drive of an extracting module cutter mechanism

Considering the work of fluid power drive cutter mechanism of an extracting module together with pneumohydroaccumulator the consumption balance equation can be represented as:

$$Q_{lp} = Q_{th} + Q_{pha} + \Delta Q_t + \Delta Q_{le},$$  \hspace{1cm} (6)

where $Q_{lp}$ is theoretical pump feed, m$^3$/s; $Q_{th}$ – theoretical hydraulic cylinder spending, $Q_{th} = V \cdot S$, m$^3$/s; $Q_{pha}$ is consumption of liquid from pneumohydroaccumulator, $Q_{pha} = -\frac{W_{ra} \, dP}{Pk \, dt}$, m$^3$/s; $\Delta Q_t$ – leakage in hydro system, $\Delta Q_t = a_t P_u$, m$^3$/s; $\Delta Q_{le}$ – loss for liquid compression compensation, $\Delta Q_{le} = \frac{W_{ra} \, dP}{E_{liq} \, dt}$, m$^3$/s. Here $V$ is cutter movement speed, m/s; $S$ – cutter area, m$^2$; $W_{ra}$ – full volume of pneumohydroaccumulator, m$^3$; $P$ – gas pressure in pneumohydroaccumulator, Pa; $k$ – adiabatic curve; $a_t$ – total leakage coefficient; $P_u$ - pumping line pressure, Pa; $W_{ra}$ – volume of liquid in hydro system, m$^3$; $E_{liq}$ – module cubic elasticity of hydraulic liquid, Pa.

After substituting values of spending in (6) let’s find cutter motion speed:

$$V = \frac{Q_{th} + W_{ra} \, dP}{Pk \, dt} - a_t P_u \frac{W_{ra} \, dP}{E_{liq} \, dt}. \hspace{1cm} (7)$$

Hydro cylinder movement may be represented by the equation:

$$m \frac{dV(t)}{dt} = P_u(t)b - a - Z_c(t), \hspace{1cm} (8)$$

Where $m$ – moving parts mass, lead to hydraulic cylinder rod, kg; $P_u(t)$ – hydraulic cylinder pressure, Pa; $a$, $b$ – constant coefficients, depending on the hydraulic cylinder structure; $Z_c(t)$ – cutting resistance force, H.

From equations (7) and (8) it follows that, when load $Z_c$ is lessened potential energy of pneumohydroaccumulator ($Q_{pha}$) is consumed, that provides speed increase of cutter movement and leads to:

– chip “jamming” increases (the chip contacting with the cutter does not break apart);
– forces normal to the cutter surface increase, it results in moment increase at the top of the main crack; it spills over greater distances;
– the slope of the power characteristic curve decreases;
– building-up brunch spalling characteristic formation time decreases and initial force increases.
Kinetic theory statement, that when the load time decreases body resistance increases and deformation of the loaded body depends on characteristics, value, scheme and way of load application but mostly on the time of load application is experimentally proved [12].

3. Results and Discussion.
Let’s study two simple spallings (Figure 3). Taking into account time factor [13], maximum force can be decreased, the value translates from point “\( B \)” into point “\( B' \)”. Taking into account potential energy store, when the spalling happens the load decreases, the crack extends with greater speed that the cutter’s speed. Hence, drive kinematic energy can not be used. Here, potential energy increase results in cutter speed increase, tension in crack pole increases – the characteristic mounts (front “\( b'' \)”, figure 3). Back front becomes more sloping due to energy consumption increase for overcoming friction forces.

![Figure 3. Spalling formation during cutting with fluid drive cutter and with potential energy store](image)

At large potential energy store \( Q_{pha} (E_n \rightarrow \infty) \) and small inertia masses force impulse back front goes for more sloping view “\( b'' \)” (figure 3), that results in cutter force balancing.

If we match cutter movement speed with main crack expansion speed and amount of the consumed potential energy, then the cutter load is determined by maximum load in the crack pole. If the load in crack pole is critical, the crack will expand further without changing the main direction.

Tests of real-size extracting module cutter mechanism model prove these statements. Figure 4 shows an oscillogram, received during coal bulk cutting with fluid drive extracting module cutter.

![Figure 4. Cutting of a coal bulk during blocked (slotted) cutting with pneumohydroaccumulator (charge pressure 0.15 MPa), Shear thickness \( h=10 \text{ mm} \)](image)
Opposing to cutting with high load dynamics, cutting force is stabilized \((Z)\) and cutting speed is sharply changed \((V_p)\) (figure 4). After locking the cutter (cutter stop) spalling happens and cutter movement speed increases.

Increasing of the potential energy store in cutter drive and decresing of its kinetic energy due to moving parts mass decrease leads to eliminating inequality of cutting force \((Z)\) and increase of inequality of the cutting speed \((V_p)\), but physically coal separation from coal massif by single spillings remains the same, while the efficiency increases.

4. Conclusion.
1. Extracting machine drive characteristics influence the size of spillings which forms a shear.
2. Mining machines with small inertia forces of the moving parts and potential energy store can destroy coal massif with the variable cutting speed; lock operation modes are not emergency for them.
3. Potential power store increase in extracting module cutter drive can result in cutting mode with constant force load that allows:
   - increase shear thickness;
   - decrease load dynamics.

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