Designing mining machinery screw modules

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Abstract. Screw modules are widely used in technological and transporting machines. Their main disadvantage is low productivity due to the fact that the material moves partly in the direction of the feed and partly rotationally as a result of the torque transmitted by the screw blade to the material. The rotational component of the material movement significantly reduces the performance of the screw. The work considers the possibility of mining machines with screw modules efficiency improving by determining the rational screw shaft configuration, depending on the properties of the feed material and the operating conditions of the module, realized at the designing stage. The aim is achieved by means of a mathematical description of the screw feed process that takes into account processes occurring both on the surfaces of the material contacts with the working bodies of the machine and inside the material mass, including the occurrence of a sliding surface in the material. Furthermore, some part of the material sticks to the screw and moves in concentric circles, with no axial movement in the feed direction, which reduces the performance of the screw. The screw shaft configuration is determined by means of design procedures based on the mathematical description of the screw feeding process, given in the work. The description takes into account the processes occurring in the mass of the feed material. The resulting mathematical model of the screw feeding process allows designing screw shafts with shape identical to the sliding surface in the material, which will increase the performance of the screw module by 20-23%, by reducing the rotational component of the material movement and increasing the translational component in the feed direction.

1. Introduction

Mining production and transporting machines perform their main functions via physical impact of their working bodies on the materials being processed or moved. The performance of mining equipment depends largely on the qualitative and quantitative indicators of the processes occurring in the materials [1]. Therefore, the properties of the original material and the final product specify the machine structure and the parameters of its working bodies. The complexity of the selection is due to the wide range of materials and the variety of their physical and mechanical properties. Moreover, the properties of the same material may change significantly if temperature, humidity, pressure, etc., change.

At present, there is theoretical interpretation and mathematical description of the machinery working bodies’ interaction processes with loose, moist, plastic, dust-like and fine-grained materials. But the phenomena occurring on the working bodies contact surfaces and in the material are not
always adequately described, which makes it very difficult to create high-performance machines [2, 3]. The lack of an accurate mathematical description of the processes occurring in the materials when interacting with the mining machinery working bodies often results in the working bodies parameters selection on the basis of experimental data or on the basis of experience gained in other industries processing materials with similar properties [4]. This approach to design and construction often leads to building low-performance mining and transporting machines, whose working bodies have structures and operating parameters which significantly differ from the rational ones [5].

It can be totally applied to processes in different materials interacting with the screw working bodies, which are quite common in mining machines [6].

The majority of cutter-loaders for mechanized coal extraction in the mining face have working bodies in the form of two screws equipped with cutters. Cutter-loaders do not have any special loading devices. The broken-down coal is loaded onto the conveyor by means of screws together with the loading shields.

For laying prepared concrete mixture behind the formwork to make an excavation support with monolithic concrete, concreting machines with screw feeders are used. For a lateral monolithic concrete lining erection, a mobile machine with a screw mixing and transporting working body is widely used [7]. Augers are used to excavate very thin and thin coal seams with soft walls.

Drill-rods with a screw blade are widely used to remove drill-cutting waste from wells. For dry backfill materials transportation and the mechanized preparation of solutions for plugging operations, a movable cement mixing unit is widely used, in which the supply of dry components to the mixing chamber is provided by a screw module. In drill and blast tunneling method, the drilling machine, which has a screw feeder, is widely used.

2. Materials and methods
Performance improvement of mountain machinery screw modules through the structural and parametric synthesis of their working bodies can be realized only on the basis of modern computer technologies for the selection of technical solutions and design features [8]. This enables to take into account the processes occurring both on the surfaces of the contacts of the material with the module working bodies and in the material massive under different module service conditions and different properties of the materials supplied [9].

Let us consider the balance of the material volume element cut from the channel formed by the internal cylindrical surface of the module tube, the shaft and the screw blade (figure 1).

The forces exerted upon the material volume element as follows.

Pressure force:

\[ F_4 = PS_{ch} \]  

where \( P \) - pressure of the material in the conveyor, Pa; \( S_{ch} = (R - r) t \) - screw channel section area, formed by the internal surface of the tube, the shaft and the screw blade, \( m^2 \); \( t \) - screw pitch, \( t = 2\pi R \tan \alpha \), \( m \); \( \alpha \) - pitch angle of the screw blade; \( R \) - radius of the screw blade, \( m \); \( r \) - radius of the shaft, \( m \).

Counterforce:

\[ F_5 = (P + \Delta P)S_{ch} \]  

where \( \Delta P \) - pressure difference on the front and back surfaces of the material to be considered, Pa.

Since the material being fed cannot be considered a Newtonian fluid [10], the values of the material pressure in the planes perpendicular to the plane of action of the pressure force and the counterforce can be determined using the formula:

\[ P_x = P_z = \mu P \]  

where \( \mu \) - side pressure coefficient.
Therefore, the force of the material friction on the internal surface of the module tube:

\[ F_3 = \mu P S_h f_h \]  

(4)

where \( S_h = \pi R d \phi = 2\pi R^2 d \phi g \alpha \) - contact area of the volume considered and the inner surface of the tube; \( f_h \) - coefficient of the material friction on the internal surface of the module tube; \( d \phi \) - angle of cut material sector.

Normal pressure on the screw blade dependence on force \( F_3 \):

\[ F_2 = F_3 \cos(\beta - \alpha) \]  

(5)

where \( \beta \) - angle between the material movement direction and the screw axis.

Friction force of the material friction on the screw:

\[ F_{fr, aug} = F_{fr1} + F_{fr2} \]  

(6)

where \( F_{fr1} = F_3 \cos(\beta - \alpha) f_{aug} \) - component of the material friction force on the blade of the screw due to the effect of force \( F_3 \); \( F_{fr2} = F_{fr,sh} + 2F_{fr,bl} \) - component of the material friction force on the screw due to the effect of pressure \( P \); \( F_{fr,sh} = \mu P S_{sh} f_{aug} \) - material friction force on the screw; \( S_{sh} = 2\pi R d \phi g \alpha \) - area of the considered material volume contact with the screw shaft surface; \( F_{fr,bl} = \mu P S_{bl} f_{aug} \) - component of the material friction force on the screw blade due to the effect of pressure \( P \); \( S_{bl} = (R^2 - r^2)d \phi /2\cos \alpha \) - area of the considered material volume element contact with the screw blade surface.

**Figure 1.** Diagram of the forces acting on the material volume element in the screw channel of the screw module.
Equilibrium of the considered material volume element follows the equation system:

\[
F_2 - F_3 \cos(\beta - \alpha) = 0 \\
F_{fr.sh.} + 2F_{fr.bl.} + F_{fr.1} + \Delta PS_{ch} - F_3 \sin(\beta - \alpha) = 0 \\
N_u - N_{sh} = 0.
\]  \hspace{1cm} (7)

The solution of the equations of statics (7) gives the condition for determining the angle \( \beta \) between the direction of the material movement and the screw axis. The result of substitutions and transformations is:

\[
f_h f_{Aug} \cos(\beta - \alpha) + \frac{r R}{f_{Aug}} f_{Aug} (R^2 - r^2) + \frac{(R - r) \Delta P}{R \mu P d \varphi} - f_h \sin(\beta - \alpha) = 0
\]  \hspace{1cm} (8)

Pressure in the screw is a function of \( \varphi \), it transforms linearly:

\[
P(\varphi) = P_0 + a \varphi
\]  \hspace{1cm} (9)

where \( P_0 \) - screw feed pressure; \( a \) - proportionality coefficient, depending on the properties of the feed material and the screw geometrics. \( P \) from (9) and \( dP = a d\varphi \) were substituted into (8) to integrate it with respect to \( d\varphi \) within the interval from \( 0 \) to \( 2\pi n \) (\( n \) - number of threads):

\[
\int_0^{2\pi n} f_h f_{Aug} \cos(\beta - \alpha) - \frac{f_{Aug} (R^2 - r^2)}{2\pi \sin \alpha} + \frac{(R - r) \Delta P}{R \mu P d \varphi} - f_h \sin(\beta - \alpha) \, d\varphi =
\]

\[
= -\frac{R(R - r)}{\mu} \ln \left[ \frac{2\pi n a + P_0}{P_0} \right] + 2\pi n f_h R^2 \sin(\beta - \alpha) -
\]

\[
-2\pi n R^2 f_h f_{Aug} \cos(\beta - \alpha) - 2\pi n f_{Aug} R r \frac{nf_{Aug} (R^2 - r^2)}{\sin \alpha} = 0
\]  \hspace{1cm} (10)

where \( 2\pi n a + P_0 = P_{out} \) - screw discharge pressure.

Analysis of the material equilibrium condition (10) shows that its movement direction depends on the following parameters:
- coefficient of the material friction on the screw;
- coefficient of the material friction on the inner surface of the tube;
- screw feed pressure and screw discharge pressure ratio;
- pitch angle of the screw blade;
- number of threads of the screw blade;
- area of feed material contact with the screw blade surface and the shaft;
- area of feed material contact with the screw module inner surface.

The first two parameters depend on the feed material properties and the quality of the screw module working bodies’ surfaces. Together with other properties of the material, they determine rational values of the structural parameters of the screw module.

The third parameter considers the operating conditions of the module - a feeding pressure at the input of the screw (the height of the material in the loading bunker, the use of feed rolls, etc.) and a locking pressure at the output of the screw (the resistance of the forming, grinding or other working bodies of the machine).
Consider the material volume element cut from the screw channel, taking into account the coordinates of the forces and loads application points. The load application type of the material volume element, which is a tapered thickness plate, as well as the slight difference between the coefficients of external and internal friction of the material, suggests the possibility of a curved sliding surface connecting the edges of the screw blade (figure 2). The maximum lateral force is applied to the cylindrical surface of the contact between the material and the module tube. However, there are a number of hollow rotational surfaces connecting the edges of the screw blade, whose area is smaller than the area of the corresponding cylindrical surface. If the shear stresses in the material in the direction of the axis $Y_1$ (figure 2) exceed maximum permissible limits on any of these surfaces, the material layers will slide relatively to one another and the material will be split into two parts. Furthermore, the part of the material located closer to the screw will gyrate in concentric circles, which will adversely affect the screw module performance. The material shear will take place on a surface where the tangent stresses are maximal:

$$\tau = \frac{Q}{S_m} = \text{max}$$  \hspace{1cm} (11)

The value of shear stresses on any curvilinear lateral surface of a material element depends on the area of that surface $S_m$ and the lateral force $Q$ applied to that surface in the direction of the axis $Y_1$ (figure 2).

The value of the lateral force $Q$ at the material cross-section depends on the shape of the surface (figure 2) and can be determined from the equation:

$$Q = F_{p,sh} + 2F_{p,bl} + \Delta P S'_{ch},$$

where $S'_{ch}$ - area of the part of the screw channel limited by the intersection line of the material cross-section with the plane $X1Z1$ (curves 1, 2 and 3, figure 3) and line segments $Z1=r$, $X1=-t/2$ and $X1=t/2$; $\Delta P$ - pressure difference on the front and back surfaces of the material to be considered.

The screw channel section area $S_{ch}$ (figure 3) is:

$$S_{ch} = \int_{-r/2}^{r/2} (R-r)dx , \text{ so } S'_{ch} = \int_{-r/2}^{r/2} (f(x)-r)dx.$$ 

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**Figure 2.** Curved sliding surface in material being fed.

The value of shear stresses on any curvilinear lateral surface of a material element depends on the area of that surface $S_m$ and the lateral force $Q$ applied to that surface in the direction of the axis $Y_1$ (figure 2).
where \( f(x) \) - function whose graph is the intersection of the surface being considered with the plane \( X1Z1 \) (curves 1, 2 and 3, figure 2); \( t \) - screw pitch; \( R \) - radius of the screw blade; \( r \) - radius of the shaft.

The surface being considered is formed by the movement of a certain curve \( z(x) \) in a spiral direction in such a way that, in one revolution around the axis \( X \) it is displaced one pitch distance \( t \) along the axis \( X \). The surface area can be determined by the formula:

\[
S_a = 2\pi \int_{-t/2}^{t/2} \sqrt{f^2(x) + T^2} \sqrt{1 + f'^2(x)} \, dx
\]

where \( f'^2(x) \) - square of the first derivative of function \( f(x) \); \( T = t/2\pi \).

**Figure 3.** Possible projections of the sliding surfaces in the material on the X1Z1 plane.

Taking into account symmetry of the considered material element about \( Z1 \) and equilibrium equations (7), condition (11) can be written as follows:

\[
\tau = \frac{2mf_{avg}R + nf_{avg}(R^2 - r^2)}{\sin \alpha} + 2mR^2f_{h,f_{avg}}\cos(\beta - \alpha) + 4\pi \int_0^{t/2} \sqrt{f^2(x) + T^2} \sqrt{1 + f'^2(x)} \, dx
\]

\[
= \frac{2}{\mu} \ln \left[ \frac{2m + P_e}{P_0} \right]^{1/2} \int_0^{t/2} (f(x) - r) \, dx
\]

\[
= \frac{2}{\mu} \ln \left[ \frac{2m + P_e}{P_0} \right]^{1/2} \int_0^{t/2} (f(x) - r) \, dx
\]

The resulting equation determines the shape of the sliding surface in the material - \( f(x) \). The analysis of the values in (13) shows that \( f(x) \) generally depends on the friction coefficients of the material on the screw and on the internal surface of the tube, the geometrical parameters of the screw, and the ratio of the screw feed pressure and the screw discharge pressure.

When solving the equations (13), function \( z = f(x) \) was predetermined as power function \( z = c + mx^n \) with different coefficients. The study of the dependence (13) enables to determine effects of the screw discharge pressure, the properties of the feed material and the geometrical parameters of
the module working bodies on the shape of the shear surface in the material in the screw module channel.

Figure 4 shows the profiles of the material shear surfaces in the screw channel at different pressure values at the outlet of the module and at the following values of the geometric parameters of the module working bodies: the radius of the screw blade $R = 0.2m$; the radius of the shaft $r = 0.05m$; the pitch angle of the screw blade $\alpha = 20^\circ$; the number of threads $n = 4$. Analysis of the obtained results shows that the shape of the material shear surface in the screw channel of the module depends on the ratio of the screw feed pressure and the screw discharge pressure.

When $P_0 = P_{out}$ (curve $a = 0$, figure 4), the shear surface in the material is the same as the surface with minimum area, whose line of intersection with plane $XZ$ connects the blade edges, and is copunctal for the line $Z = r$. In this case, the area of the part of the screw channel in which the material has a progressive movement is maximum. It is shown in figure 4 as the area of the figure bounded by lines $a = 0$ and $Z = R$.

With the increase in the locking pressure, the intersection lines of the material sliding surfaces with the plane $XZ$ are lower sloped, and the passive region in the screw channel filled with material having no axial movement in the feed direction increases. The higher the locking pressure at the screw discharge, the more the material moves in concentric circles without moving in the direction of the feed. At a certain pressure, the movement of the material in the screw channel of the module ceases.

Similar results can be obtained by studying the dependence of the sliding curve on the number of threads, the friction coefficients of the material (external and internal), and the screw pitch.

3. Conclusion
The determination of the material flow patterns in the screw module, taking into account that a sliding surface can occur therein, is of great practical importance. It allows for more rational selection of geometric parameters of working bodies, when designing screw modules, and makes it possible to use
various design and structural solutions that ensure maximum performance of the screw module, taking into account the properties of the feed materials and the technological regulation requirements [11]. The resulting mathematical model of the screw feeding process allows designing screw shafts with shape identical to the sliding surface in the material, which will increase the performance of the screw module by 20-23% by reducing the rotational component of the material movement and increasing the translational component in the feed direction.

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