Linear stepping electromagnetic engine for driving conveyors

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Abstract. The rise and sustainable development of mining enterprises are inextricably linked with the creation of competitive technology for advanced technologies in construction, mining, engineering and geological surveys. In the improvement of characteristic technologies, an important role is played by power discrete drives with linear electromagnetic engines, which make it possible to abandon motion converters and especially successfully compete with traditional electric engines in machines and installations where discrete translational motion of the working body is necessary. The kinematic separation of the armature and the output shaft and the use of an axial channel in a linear electromagnetic engine made it possible to create electromagnetic machines with new properties in which the mechanical power is derived using a toothed bar of any desired length. In the work, the force analysis of the interaction of the working body with the locking mechanism in a stepper linear electromagnetic drive engine of the conveyors is carried out. The degree of influence of the angle of inclination of the locking elements on the amount of effort required to drive the working body is revealed.

1. Introduction
The rise and sustainable development of mining enterprises are inextricably linked with the creation of competitive technology for advanced technologies in construction, mining, engineering and geological surveys [1, 2, 4, 11]. In the improvement of characteristic technologies, an important role is played by power discrete drives with linear electromagnetic engines (LEME), which make it possible to abandon motion converters and especially successfully compete with traditional electric engines in machines and installations where discrete translational motion of the working body is necessary [3, 5, 6, 7].

The kinematic separation of the armature and the output shaft and the use of an axial channel in a linear electromagnetic engine made it possible to create electromagnetic machines with new properties in which the mechanical power is derived using a toothed bar of any desired length [1, 3].

An important stage in the development of linear electromagnetic engines for the drive of conveyors is the rationale for devices for transmitting the mechanical energy of an engine to a displaceable working body [8, 9, 10, 12].

In the work, a force analysis of the interaction of the working body with the locking mechanism in the stepping LEME drive of the conveyors is carried out.

2. The object and method of research
Fig. 1 shows the construction of a stepping LEME.
The stepping LEME contains a stator 9, in the bore of which winding 7 is placed, a combined armature 6 with a disk part 5, a return spring 8 and a guide case 2. The combined armature 6 with a disk part 5 has a through axial channel into which the toothed bar 1 is placed. The discrete unidirectional movement of the rod serves as a feed 3 and holding 10 locking elements mounted, respectively, on the armature 6 and the motor stator 9 and made in the form of flat, radially moving sectors, which are in working condition preloaded by springs 4, 11 to the toothed rod 1. Mechanisms for opening the locking members 3, 10 to ensure the free (non-working) movement of the rod 1 relative to the armature 5, 6 and the motor in either direction, are not shown [3].

![Figure 1. The design of the linear stepper electromagnetic engine](image)

Stepping LEME for the drive of conveyors works as follows.

In the initial state, the combined armature 6 with the disk part 5 under the action of the force of the return spring 8 is in the extreme upper position. The feed 3 and holding 10 locking elements are in engagement with the toothed rod 1, because the springs 4 and 11 are pressed against it.

When the winding 7 is connected to the power source, the combined armature 6 with the disk part 5 is pulled into the winding by the action of electromagnetic force, compressing the return spring 8 and moving the toothed rod 1 in the axial direction with the help of the feed locking elements 3. At the same time tangential, radially directed forces arising between the contacting conical surfaces of the toothed rod 1 and the locking elements 10 overcome the action of the springs 11 and move the pawl 10 apart, which, therefore, do not prevent the movement of the toothed rod 1. After the armature 6 is fully drawn into the winding 7 by the value \( \delta \) and axial movement of the toothed rod 1 by one step \( l=\delta \) the locking elements 10 under the action of the springs 11 re-engage with the next tooth of the toothed rod 1.

When disconnecting the winding 7, the toothed rod 1 held by the elements 10 remains stationary, and the armature 5, 6 under the action of the return spring 8 moves to its original position. Now radial forces arise between the tapered surfaces of the tooth of the rod 1 and the locking elements 3, which
move apart, compressing the springs 4, and do not prevent the return of the armature 5, 6. As soon as the armature, having moved by the value \( l = \delta \), takes the initial position, the springs 4 will ensure the engagement of the locking elements 3 with the next tooth of the rod 1. Then the cycles are repeated and, thus, there is a discrete, translational movement of the working body limited only by the length of the toothed rod 1.

The process of interaction of the working body with locking elements during the working stroke is shown in Fig. 2. The force analysis is carried out.

![Diagram](image)

**Figure 2.** The power circuit of the working body: 1 - working body; 2 - locking element; 3 - clamping spring; 4 - LEME housing.

The following forces act on working body 1:
- \( G_{w.b.} \) – the force of gravity; \( G_{w.b.} = m_{w.b.} \cdot g \), where \( m_{w.b.} \) – the mass of the working body;
- \( F^{in} \) – the inertia force, \( F^{in} = m_{w.b.} \cdot a \), where \( a \) – the acceleration with which the working body moves;
- \( F_{dr} \) – the driving force required to move the working body 1;
- \( F_{res} \) – the force of resistance to the movement of the working body 1 due to its interaction with the guide walls 4 of the LEME housing and other objects of the environment;
- \( R \) – the reaction acting on the working body 1 from the side of the locking element 2. We expand the reaction of \( R \) into horizontal and vertical components: \( R_x = R \cdot \sin \alpha \), \( R_y = R \cdot \cos \alpha \), where \( \alpha \) is the angle of inclination of the locking elements;
- \( F_{fr} \) – the friction force of the working body over the surface of the locking element, \( F_{fr} = R \cdot f \), where \( f \) is the coefficient of sliding friction (when steel is rubbed on steel, \( f = 0.15 \) [13]).

Using the principle of d’Alembert, we project all the forces acting on the working body on the selected axis \( y \) (Fig. 2):

\[
-F_{dr} + R_y + F^{in} + F_{fr} \cdot \sin \alpha + F_{res} - G_{w.b.} = 0. \tag{1}
\]

The system of forces acting on the locking element is considered (Fig. 3):
- \( G_{loc} \) – the force of gravity; \( G_{loc} = m_{loc} \cdot g \), where \( m_{loc} \) – the mass of the locking element;
- \( F^{in} \) – the force of inertia, \( F^{in} = m_{loc} \cdot a_{loc} \), where \( a_{loc} \) – the acceleration with which the locking element moves;
\( F_{el} \) – the reaction acting from the side of the spring, equal in magnitude to the force of elasticity of the spring, i.e. \( F_{el} = c \cdot S \), where \( S \) – the deformation value of the spring, \( c \) – the stiffness coefficient of the spring; \( c = \frac{G \cdot d_{wp}^2}{8 \cdot d_{win} \cdot n} \) [13], where \( d_{wp} \) – the diameter of the spring wire; \( d_{win} \) – the diameter of the winding (measured from the axis of the wire); \( n \) – the number of turns; \( G \) – the shear modulus (for the spring steel \( G \approx 78.5 \) GPa);

\( R' \) – the reaction acting on the locking element from the working body, equal in modulus \( R \) and directed in the opposite direction;

\( R'_n \) – the friction force of the locking element on the surface of the working body, \( F'_n = R' \cdot f \);

\( N \) – the normal response of the guide surface;

\( F_{f.s.} \) – the friction force of the side surface of the locking element on the guide surface; \( F_{f.s.} = N \cdot f' \)

\[ \text{Figure 3. The power circuit of the locking element} \]

The locking elements have a relatively small mass, so with a small error in the calculations we can ignore the efforts \( F_{f.s.}, F^{in} \) and \( N \).

In accordance with the d’Alembert principle, we make the sum of the projections of the system of forces acting on the locking element on the axis \( x \):

\[ R'_s - F'_n \cdot \cos \alpha - F_{el} = 0, \]

\[ R'_v - R' \cdot f \cdot \cos \alpha - c \cdot S = 0, \]

\[ R'_r - \frac{R'_v}{\sin \alpha} \cdot f \cdot \cos \alpha - c \cdot S = 0, \]

\[ R'_r = \frac{c \cdot S}{1 - \cot \alpha f}. \] (2)

Taking into account expression (2), equation (1) takes the form:

\[ -F_{f.s} + \frac{c \cdot S}{\tan \alpha \cdot (1 - \cot \alpha f)} + m_{w.b} \cdot \alpha + \frac{c \cdot S \cdot f}{(1 - \cot \alpha f)} + F_{f.s} - G_{w.b} = 0. \]

Then

\[ F_{el} = c \cdot S \left( \frac{1}{\tan \alpha \cdot f} + \frac{1}{1/f - \cot \alpha} \right) + m_{f.s} \cdot \alpha + F_{f.s} - G_{w.b}. \] (3)
3. Conclusion

From the expression (3) it follows that the driving force is influenced by the design features of the locking elements, the kinematic mode of operation of the combined LEM armature and the components of the resistance to movement of the working body.

To identify the degree of influence of the angle of inclination of the locking elements $\alpha$ on $F_{dr}$, we will construct a graph of the dependence of the form $y = \frac{1}{\tan \alpha - f} + \frac{1}{f - \cot \alpha}$ on the interval $0^\circ < \alpha < 90^\circ$ (Fig. 4).

![Figure 4. Function graph](image)

The graph shows that the magnitude of the force that drives the working body decreases with increasing angle $\alpha$. When $\alpha > 35^\circ$, the value of the driving force does not change.

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