Increasing efficiency of linear stepper electromagnetic engine

V A Kargin, A V Volgin, A P Moiseev, A M Maradudin, A V Peretyatko

Saratov State Agricultural University n. a. N.I. Vavilov, 1, Teatralnaya Square, Saratov, 410012, Russia

E-mail: saratov-79@list.ru

Abstract. The rise and sustainable development of mining enterprises are inseparably linked with the search for and the introduction of progressive methods of intensification of operations and processes, among which pulsed or vibrational methods that allow to concentrate and efficiently expend energy occupy a significant place. In the development of characteristic technologies, an important role belongs to power discrete drives with linear electromagnetic engines that allow one to abandon motion transducers and especially successfully compete with traditional electric engines in machines and installations where reciprocating movements of the working element along a linear trajectory are necessary. In this paper, we propose a new functional arrangement of a linear electromagnetic engine with a through axial channel and an integrated clamping mechanism and a calculation of the clamping force of the ball clamps in a stepped linear electromagnetic engine. Taking into account the required driving force of the working element, it is possible to calculate the necessary tractive force created by the armature during its working stroke under the action of electromagnetic force, and to select the corresponding linear electromagnetic engine for this actuator drive.

1. Introduction

The rise and sustainable development of mining enterprises are inseparably linked with the search for and the introduction of progressive methods of intensification of operations and processes, among which pulsed or vibrational methods that allow to concentrate and efficiently expend energy occupy a significant place [1-3]. In the development of characteristic technologies, an important role belongs to power discrete drives with linear electromagnetic engines (LEME), which allow to abandon motion transducers and especially successfully compete with traditional electric engines in machines and installations where reciprocating movements of the working element along a linear trajectory are required [1-5].

Further expansion of the areas of rational use of LEME involves, among other things, research into the development of new efficient schemes of electromagnetic engines, in which the shortage of known machines is determined by the limited working stroke of the movable element [3].

The kinematic separation of the armature and the output shaft and the use of the axial channel in the LEME made it possible to create electromagnetic machines with new properties in which the mechanical power is removed by means of a barbell of any necessary length [6] or transferred to a replaceable tool, for example, a clogged rod through a lateral surface in an arbitrary transverse section by a special adjustable clamping mechanism [5]. However, these machines do not allow the use of flexible power cables of considerable length - cables, wires, etc. - to select the mechanical power of the armature.
A linear stepping electromagnetic engine with an axial channel and a draw device with washers [7], currently used in conveyors, comprising a guide body, a stator, a combined armature, a working element in the form of a rod, chain or cable with fixed washers at a fixed distance, has an increased cross section of the anchor channel, which reduces the energy performance of the LEME.

2. The object and method of research
In this paper, we propose a new functional configuration of LEME with a through axial channel and an integrated clamping mechanism and a calculation of the clamping force of ball clamps in a stepped linear electromagnetic engine.

Figure 1 shows the proposed design of a step-by-step linear electromagnetic engine with a ball clamping mechanism.

![Figure 1. The design of a stepper linear electromagnetic engine with a ball clamping mechanism.](image-url)

The device comprises a stator consisting of a side part 2 and a lower part 1. A winding 4 is arranged in the stator bore. The armature 5 is made of a combination of cylindrical and disk parts, spring loaded by a return spring 6 located between the lower part of the stator 1 and the cylindrical part of the armature 5 and a spring 7 located between the guide body 3 and the disk part of the armature 5. The operating member 9 can be made in the form of a smooth cylindrical rod passed into the axial channel of the armature through the holes in the guide body 3 and the lower part of the stator 1. The power joint of the working element with the armature in the working stroke is provided by spring-loaded locking elements 8 with the help of the spring 7 in the form of three metal balls which are placed in the conical grooves of the armature 5 on the side of the disk part and displaced relative to each other by an angle 120°. The non-magnetic elastic gasket 10 serves to mitigate the impact when the armature returns.

In the initial state, the combined armature 5 is clamped by a return spring 6 to the guide body 3, and the spring-loaded wedging clamping jaws 8 completely enter the tapered groove of the armature and are pressed firmly against the working element 9 along the side surface.

When a supplying electric impulse is supplied to the winding 4 from the source, the combined armature 5 is pulled into the winding 4 by the action of an electromagnetic force, compressing the return spring 6. The slight mutual axial movements of the ball clamps 8 contacting the tapered surface of the bores in the armature create significant radial forces that securely clamp the working element 9, which moves by the amount \( \delta \) of the stroke of the combined armature 5. Upon completion of the
feeding pulse, the combined armature 5 is returned by a return spring 6 to the starting position. On return spring-loaded spring 7 ball clamps 8 release the operating element. Then the cycle repeats.

To calculate the clamping force of the ball clamps, we will compose the power circuit for the case when the combined armature 1 (Figure 2) under the action of an electromagnetic force makes a working stroke. In this case, the ball clamps 3 transmit the translational movement from the combined armature 1 to the working element 2, being clamped in the conical channels between them.

**Figure 2.** The design scheme of the forces of ball clamps: 1 - combined armature; 2 - working element; 3 - ball clamp.

The following forces will act on each of ball clamps [8]:

$G$ – gravity:

$$G = m_{bc} g$$  \hspace{1cm} (1)

where $m_{bc}$ – mass of ball clamp;

$F_{if}$ – inertia force:

$$F_{if} = m_{bc} a$$  \hspace{1cm} (2)

where $a$ – acceleration with which the combined armature and ball clamp move;

$F_{elas}$ – the reaction acting on the part of the spring, equal in modulus to the elasticity of the spring:

$$F_{elas} = c \Delta l$$  \hspace{1cm} (3)

where $\Delta l$ value of spring deformation, $c$ – coefficient of spring stiffness;

$F_{bc}$ – force of the combined armature pressure on the ball clamp;

$N_1$ and $N_2$ – the reactions acting on the part of the combined armature and working body, respectively;

$F_{fr1}$ and $F_{fr2}$ – the frictional forces of the rolling of the ball clamp on the combined armature and working member, respectively:

$$F_{fr1} = N_1 \frac{k}{r_{bc}}, \quad F_{fr2} = N_2 \frac{k}{r_{bc}}.$$  \hspace{1cm} (4)

where $k$ – the rolling friction coefficient (when rolling steel in steel $k = 0.5$ mm), $r_{bc}$ - the radius of the ball clamp.

We take the ball clamp for the material point. In accordance with the D'Alembert principle, the geometric sum of all active reactive forces and the conditionally applied inertia force acting on the ball clamp is zero, i.e.:

$$\vec{G} + \vec{F}_{if} + \vec{F}_{bc} + \vec{N}_1 + \vec{N}_2 + \vec{F}_{fr1} + \vec{F}_{fr2} = 0.$$  \hspace{1cm} (5)

Let us introduce the rectangular coordinate system $xOy$ and project the vector equation (5) on the $x$ and $y$ axes.
On the $x$ axis: $F_{bc} \cos \alpha + N_i \cos \alpha - F_{o1} \sin \alpha - N_2 = 0$, where $\alpha$ – the angle of the taper of the cone protrusions of the armature from the side of the disk part:

$$N_2 = F_{bc} \cos \alpha + N_i \cos \alpha - N_1 \frac{k}{r_{bc}} \sin \alpha = 0,$$

$$N_2 = F_{bc} \cos \alpha + N_i (\cos \alpha - \frac{k}{r_{bc}} \sin \alpha) = 0.$$  

On the $y$ axis: $F'' + F_{a1} - G + F_{a2} - F_{a1} \cos \alpha - F_{bc} \sin \alpha + N_i \sin \alpha = 0,$

$$m_{bc} (a - g) + c\Delta l - m_{bc} g + N_2 \frac{k}{r_{bc}} - N_i \frac{k}{r_{bc}} \cos \alpha - F_{bc} \sin \alpha + N_i \sin \alpha = 0.$$  

We substitute the formula (6) in the obtained expression and after simplification, we obtain:

$$N_i = \frac{m_{bc} (a - g) + c\Delta l + F_{bc} (\frac{k}{r_{bc}} \cos \alpha - \sin \alpha)}{\sin \alpha ((\frac{k}{r_{bc}})^2 + 1)}.$$  

Then expression (6) takes the form:

$$N_2 = F_{bc} \cos \alpha + \frac{m_{bc} (a - g) + c\Delta l + F_{bc} (\frac{k}{r_{bc}} \cos \alpha - \sin \alpha)}{\sin \alpha ((\frac{k}{r_{bc}})^2 + 1)} (\cos \alpha - \frac{k}{r_{bc}} \sin \alpha).$$  

The working element will be driven by frictional force against ball clamps. Then the driving force of the working element will be:

$$F_{df} = bF_{a2}$$  

where $b$ – number of ball clamps; according to the constructive scheme $b = 3$.

The force of the combined armature pressure on the ball clamp will be equal to the tractive force created by the armature during its working stroke under the action of an electromagnetic force:

$$F_{bc} = 0.5i^2 \frac{dL}{d\delta}$$  

where $i$ – current strength in the winding of the armature travel, $\delta$ - size of the working gap, $L$ - inductance of the winding.

The average value of the useful power of a linear stepping electromagnetic engine, developed in one operating cycle, can be determined by the formula:

$$N_{um} = F_{df} v_{av}$$  

where $v_{av}$ – average speed of movement of the working element during one working cycle.

$$v_{av} = \frac{\Delta S}{t_c}$$  

where $\Delta S$ – the distance to which the workpiece will move in one cycle; $t_c$ – the duration of one working cycle.

Since the duration of the working cycle and the distance to which the working member moves in one cycle have relatively small values ($t_c = 0.03\ldots0.04$ s; $\Delta S =0.035$ m), then the average speed $v_{av}$ with a small error can be equated to the instantaneous speed of movement working element $v_{ave}$, i.e. $v_{av} = v_{ave}$.

Then taking into account the expressions (8), (9), (10), the useful power of the linear step electromagnetic engine is determined by the formula:
The total power expended on driving the working element in motion is:

\[ N_{wp} = F_{bc} v_{we} \; ; \quad (14) \]

or taking into account formula (10):

\[ N_{wp} = 0.5i^2 \frac{dI}{d\delta} v_{we} \; . \quad (15) \]

The efficiency of the proposed structural and technological scheme of a linear step-by-step electromagnetic engine can be defined as the ratio of the useful power to the energy consumed, or taking into account formulas (11) and (14) as:

\[ \eta_{scheme} = \frac{F_{bc}}{F_{bc}} \; . \quad (16) \]

On the basis of the earlier expressions (8), (9) (10):

\[ b \left[ \frac{0.5i^2}{d\delta} \cos \alpha + \frac{m_{bc}(a - g) + c\Delta l + 0.5i^2}{d\delta} \frac{k}{r_{bc}} \left( \cos \alpha - \frac{k}{r_{bc}} \sin \alpha \right) \sin \alpha \left( \frac{k}{r_{bc}} \right)^2 + 1 \right] \frac{k}{r_{bc}} \]

\[ \eta_{scheme} = \frac{N_{wp} \cos \alpha - \frac{k}{r_{bc}} \sin \alpha}{0.5i^2 \frac{dI}{d\delta}} \; . \quad (17) \]

3. Conclusion

Thus, the value of the efficiency of the proposed LEME scheme will be affected by the number of ball clamps, their mass, geometric parameters and physical and mechanical properties, as well as the angle of slope of the tapered armature protrusions.

The dependence of the efficiency of the circuit on the slope angle of the tapered armature protrusions is presented in Figure 3.

\[ \eta_{scheme} \]

![Figure 3. The circuit efficiency from the α angle.](image)

From the analysis of the obtained graph, it is seen that the magnitude of the efficiency of the circuit is inversely proportional to the angle \( \alpha \). Therefore, in order to increase the efficiency of this constructive technological scheme, it is proposed to take the minimum possible angle \( \alpha \). The work of
this scheme is similar to the wedge non-self-locking mechanism with rollers; therefore, according to the recommendations of M.A. Anserova and B.N. Vardashkina, $\alpha > 10^\circ$.

Taking into account the above-mentioned, we take $\alpha = 11^\circ$. At the same time, the efficiency of the scheme will be 10.84%.

To graphically illustrate formula (9), let us consider the dependence of the driving force of the working element $F_{df}$ on the force of the combined armature pressure on the ball clamps $F_{bc}$ (Figure 4).

![Figure 4. Function of the driving force $F_{df}$ from the pressure force $F_{bc}$.](image)

From the presented graph, it is seen that the driving force $F_{df}$ is directly proportional to the force of the combined armature pressure on the ball clamps $F_{bc}$; this relationship can be expressed by the equation:

$$F_{df} = 0.1084 F_{bc}.$$  \hspace{1cm} (18)

On the basis of the plotted graph (Figure 4) and the dependence (18), taking into account the required driving force of the working element, it is possible to calculate the necessary tractive force created by the armature during its working stroke under the action of electromagnetic force and to select the corresponding linear electromagnetic engine for this actuator drive. It is possible to solve the inverse problem - the calculation of the value of the driving force of the actuator for the drive with a predetermined linear electromagnetic engine.

References

[1] Usanov K M, Volgin A V, Chetverikov E A, Kargin V A, Moiseev A P, Ivanova Z I 2017 Power electromagnetic strike machine for engineering geological surveys *IOP Conf. Series: Earth and Environmental Science* **87** (2017) 032049 doi :10.1088/1755-1315/87/3/032049

[2] Usanov K M, Volgin A V, Chetverikov E A, Kargin V A, Moiseev A P, Ivanova Z I 2017 Strike action electromagnetic machine for immersion of rod elements into ground *IOP Conf. Series: Earth and Environmental Science* **87** (2017) 032050 doi :10.1088/1755-1315/87/3/032050

[3] Usanov K M, Moshkin V I, Kargin V A, Volgin A V 2015 The linear electromagnetic engines and actuators pulse processes and technologies: monograph. (Kurgan: Publishing house of Kurgan state University press)

[4] Ugarov G G, Neiman V Y 2002 Trends in the development and use of handheld percussion machines with Electromechanical energy conversion *Russian Electromechanics* **2** 37-43

[5] Simonov B F, Neyman VYu, Shabanov A S 2017 Pulsed linear electromagnetic drive for downhole vibroseis source *Journal of Mining Science* **1** 118-126

[6] Usanov K M, Ugarov G G, Moshkin V I. 2006 Linear pulse electromagnetic drive of machines with autonomous power: monograph. (Kurgan: Publishing house of Kurgan state University press)

[7] Usanov K M, Moiseev A P, Kargin V A, Chetverikov E A 2015 Experimental evaluation of the power indicators of the electric drive of a crawler-type conveyor with a linear electromagnetic engine *Agrarian Scientific Journal* **6** 69-72
[8] Targ S M 1995 *A short course of theoretical mechanics* (Moscow: Higher school press)