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Impact on force decrease at the end of actuator plunger motion

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Abstract: It is shown that decrease and damping of the traction force at the end of the plunger move is possible not only due to application of a special keeper design, but also due to change of the plunger shank geometric form. The computer modeling with the use of finite element method is used to analyze the influence of system geometry on force distribution along plunger movement. The damping effect is confirmed when special shape plunger shanks are used.

Key words: actuator, geometry optimization, finite element method, magnetic force, damper

1. Introduction

Axial symmetry shell-type direct current electromagnets are characterized by relatively high traction forces at the beginning of the plunger move. These forces significantly increase as the plunger moves on and the operating gap decreases. If there is no need for such an increase of the traction force, special measures are taken in practice to reduce traction forces at the end of the plunger move and, correspondingly, to lower impact load on the electromagnet keeper. With such a goal, the electromagnetic actuator keeper is made with a magnetic collar of a special form (Fig. 1), which, in the case of small gaps, makes it possible to reduce the traction force acting on the plunger due to saturation of the collar and, consequently, increase of the effective gap [1]. In this case there occurs an increase of magnetic potential drop in steel sections of magnetic circuit, which decreases the winding magneto-motive force (MMF) portion that falls on the operating gap (traction force is known to be proportional to this MMF portion value squared). However, when such magnetic collars are used, the electromagnetic actuator traction characteristic has a sharp drop of traction force at the end of the plunger move. When the mechanically resistive force of certain characteristic is applied to the plunger, the undesirable vibration may occur [2].

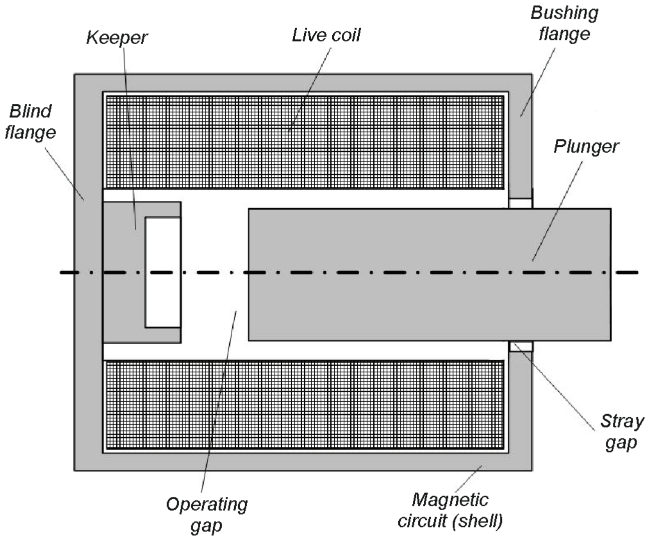

Fig. 1. Conventional design of an electromagnetic actuator with a magnetic collar on the keeper

As stated above and due to technological complexity of manufacture of the collars the authors were forced to search for some other ways to reduce the traction force at the end of the electromagnetic actuator plunger movement. One of such ways is considered in the present paper.

2. Problem statement

It is necessary to achieve damping of the traction force at the end of the electromagnetic actuator plunger move in a simpler way, as compared with the known methods, and also will not cause a sharp drop of the electromagnet traction characteristic.

Obviously, to reduce the traction force at the end of the plunger movement it is necessary to lower the flux in the operating gap. For this, it is offered to use the known influence of a stray gap on the traction force developed by the electromagnetic actuator. Namely, to enlarge this gap at the end of the plunger move by making the plunger shank in such a way as to have in small operating gaps increased reluctance to the flux passing through the stray gap. This can be achieved if the plunger shank is made in the form of a cone [3]. Then at the beginning of the plunger shift the traction force corresponds to the force of an electromagnetic actuator with a cylindrical plunger, and at the end of the movement the flux passing through the plunger (and thus through the operating gap) is reduced due to increase of the stray gap (Fig. 2).

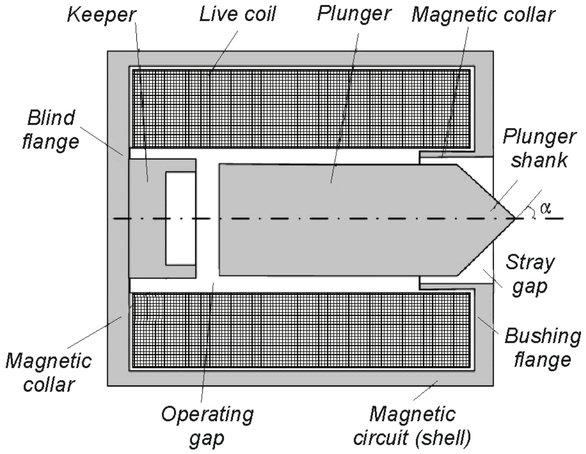

Fig. 2. The electromagnetic actuator with a plunger conic shank

In this case, as the plunger moves and before it stops, the stray gap effective value constantly grows (Fig. 3). This results in significant increase of the drop of magnetic potential in the stray gap, which reflects in decrease of winding MMF portion on the operating gap and also in traction force whose value is proportional to its square.

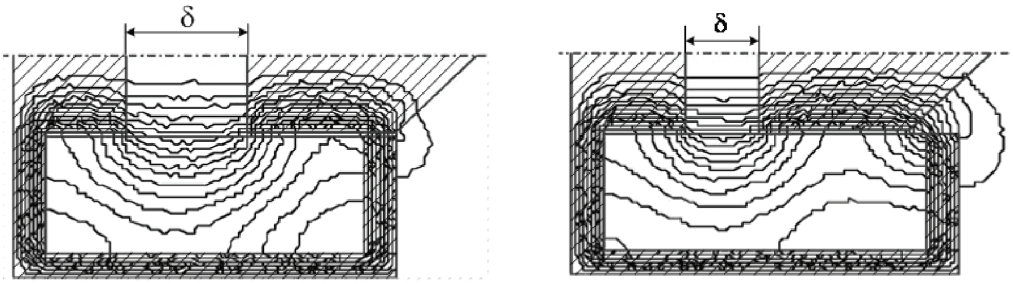

Fig. 3. Flux lines in electromagnet for different operating gaps

The electromagnetic problem consists in the verification of the traction force decrease at the end of the movement of a plunger equipped with a conic shank.

3. Performance analysis

The method of electromagnetic actuator plunger damping was checked by means of a computation experiment based on computer modeling of magnetic field. In the considered axially symmetrical direct current electromagnetic system analysis is based on finite element modeling [4].

It should be noted, that in finite element analysis the magneto-static field force action on an allocated part of electromagnet structure (plunger in our case) is determined by surface integral (by the allocated structure element outer surface S_e) of the kind:

$$\overline{F} = 0.5 \int_{S_e} \left[\overline{H}\,(\overline{n}\cdot\overline{B}) + \overline{B}\,(\overline{n}\cdot\overline{H}) - \overline{n}\,(\overline{H}\cdot\overline{B})\right] \mathrm{d}S, \tag{1}$$

where $\overline{H}$ and $\overline{B}$ are, correspondingly, magnetic field and magnetic flux density on the outer surface of the allocated structure; $\overline{n}$ is a unit vector normal to a differentially small area dS (directed outside of the volume limited by integration surface S_e).

If the plunger is separated from the electromagnet magnetic circuit by nonmagnetic medium, the surface S_e can be treated as a surface in nonmagnetic medium characterized by the following relation:

$$\overline{B} = \mu_0\,\overline{H}, \tag{2}$$

where μ_0 is the vacuum permeability. This allows rewriting the expression (1) into two forms, which are in our case identical:

$$\overline{F} = \mu_0^{-1} \int_{S_e} \left[\overline{B}\left(\overline{n}\cdot\overline{B}\right) - 0.5\,\overline{n}\,B^2\right] dS \tag{3}$$

and

$$\overline{F} = \int_{S_e} \left[\overline{H}\left(\overline{n}\cdot\overline{B}\right) - 0.5\,\overline{n}\left(\overline{H}\cdot\overline{B}\right)\right] dS. \tag{4}$$

Each of them is known to be adequate to use when total magneto-static field force acts on a selected body [5]. Thus FEMM [4] computation of magnetic-static field force acting on a shell-type electromagnet plunger according to (1) is identical to calculation according to (2) and (3). This provides the veracity of the obtained computation results.

In the explained computational experiments the presented electromagnetic actuator typical geometry variations were analyzed: model No. 1 – a cylindrical plunger without a conic shank, a keeper without a magnetic collar; model No. 2 – a cylindrical plunger without a conic shank, a keeper with a magnetic collar (Fig. 1); model No. 3 – a cylindrical plunger with a conic shank, a keeper without a magnetic collar; model No. 4 – a cylindrical plunger with a conic shank, a keeper with a magnetic collar and model No. 5 – a cylindrical plunger with a conic shank, a keeper with a magnetic collar and a bushing flange has a collar too (Fig. 2).

The computations were done for an electromagnet of the following dimensions: outer (shell) diameter 56 mm; electromagnet (shell) length 48 mm, thicknesses of bushing and blind flanges 4 mm; shell thickness 3 mm; keeper height (without collar) 15 mm; collar height 5 mm; keeper diameter 20 mm; plunger diameter 15 mm; bushing flange collar height 10 mm; stray gap 0.5 mm. The following material and excitation were assumed for all the models: steel grade St3 for magnetic circuit; coil magneto-motive force 2000 A and plunger operating range was 10 mm. Plunger conic shank is assumed to be 10 mm high (plunger shift) with cone top angle 90°, that means $\alpha = 45°$.

The ferromagnetic material non-linearity is also applied by practical recommendation from [6, 7], reminding that magnetizing curve approximation is to serve the needs of the problem under consideration. According to this recommendation, to solve the problem with reduction of possible errors in numerical computation regarding electromagnets in magnetic saturation condition the extrapolation of permeability curve, which will meet the condition $\mu \to \mu_0$ at $H \to \infty$, beyond the range of magnetizing curve table setting was used.

So, taking into account the said qualitative character of the material magnetic permeability change in function of applied magnetic field, the following approximation, meeting the condition $\mu \to \mu_0$ at $H \to \infty$, can be pointed out for magnetic permeability at magnetic field $H > H_{\mathrm{n}}$:

$$\mu = \mu_0 \left(1 - \frac{B_{\mathrm{n}} - H_{\mathrm{n}}\,\mu_0}{\mu_0 H} \right), \tag{5}$$

where H_{n} and B_{n} are the two last and the largest values in table setting of applied magnetizing curve.

Using equation (5), it is not difficult to get the following dependence (extrapolation) for function $B(H)$ at $H > H_{\mathrm{n}}$

$$B = \mu_0 H - B_{\mathrm{n}} + \mu_0 H_{\mathrm{n}}, \tag{6}$$

which presents the linear dependence.

According to equation (6) the extrapolation being analyzed, as well as the extrapolation realized in finite element analysis, is linear. Application of equation (6) significantly decreases the error of computation of electromagnetic actuators in conditions of magnetic saturation [8].

The simulation results (traction force in function of plunger position) are shown in Fig. 4.

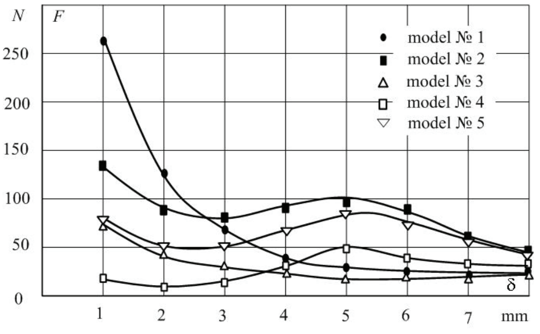

Fig. 4. Computed dependences of traction force F on operating gap δ for various design modifications of an electromagnetic actuator

4. The influence of plunger shank conic shape on the traction characteristic

To investigate the influence of the plunger shank conic shape on the electromagnetic actuator traction characteristic with damping effect, the analysis based on model No. 3 with a changing angle α (Fig. 2) were also done. The angel α variations were: 15^{o} for model No. 3*; 45^{o} for model No. 3 and 60° for model No. 3**. Traction force characteristics shown in Fig. 5 were obtained for these models as a result of the computational experiments.

Besides the computational experiments described above, the physical models of all modeled structures (Fig. 6) with the same geometric, magnetic and electrical parameters were produced. The measurements were carried out to confirm the effect of damping of the plunger at the end of its move. The measurements coincide very well with the computed data (less than 10%). The results are not explicitly discussed [3].

The considered computational experiments were carried out with implementation of magnetic nonlinearity of the magnetic circuit steel discussed in [7, 8].

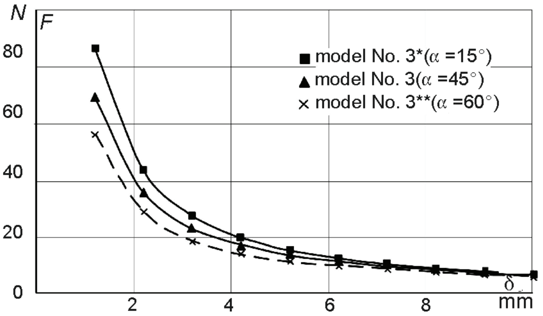

Fig. 5. Computed traction characteristics of an electromagnetic actuator with a conic plunger shank with different conic angle α

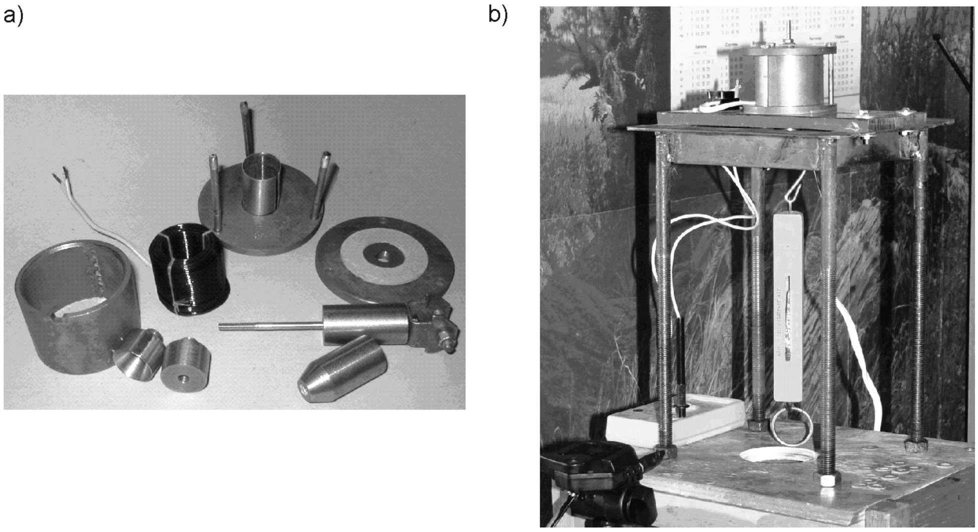

Fig. 6. Disassembled electromagnet (a) and the experimental set-up (b)

5. Discussion

As it can be understood from the curves shown in Figure 4, application of a conic shank considerably decreases the traction force at the end of the plunger move, and practically unchanging it at the initial moment of the move. It should be mentioned that, if the keeper and flange have no magnetic collars (model No. 3), traction force characteristic has no drops. This distinguishes it from the characteristic of model No. 4 having a sharp drop of the characteristic at the final portion of plunger move. This drop can be reduced using a magnetic collar on the bushing flange (model No. 5). However, in this case, there is still some irregularity of traction force characteristic, which is also typical of the conventional damping method (model No. 2).

It should be noted that used software makes it possible in each particular case to verify the assigned character of traction force change depending on the operating gap conditioned by the kind of characteristic of the counteracting force. In such case, by choosing corresponding parameters of the conic shank (cone height and its top angle), it is possible to manage traction force characteristic with counteracting force characteristic.

The analysis of the influence of the angle of the plunger shank cone top showed that increase of this angle results in reduction of traction force and the traction characteristic remains of the same kind. That is why the coordination of the characteristic with the counteracting force characteristic should take into consideration the parameters of the keeper and bushing flange magnetic collars.

6. Conclusions

1. Manufacture of the electromagnetic actuator plunger shank in the form of a cone makes it possible to reduce traction force at the end of the plunger move, while the force at the beginning of its shift remains unchanged. The same effect results when there are magnetic collars on the keeper and on the bushing flange.
2. Application of a conic plunger shank and magnetic collars on the keeper in the area of the stray gap allows one to obtain the required damping effect of the traction force before the plunger stops without the drop of traction force at the end of the plunger move. And it also provides sufficient forces at the initial stage of the shift.
3. Applied software gives the possibility to coordinate the counteracting and traction forces of the electromagnetic actuator whose plunger is equipped with a conic shank.

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