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Numerical simulation of the magnetic field of a solenoid magnetic system with a shielding magnetic shell

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Abstract. The paper presents the investigation of the effect of a shielding magnetic shell in the solenoid magnetic system of an electromagnet. The influence of the magnetic shell is estimated by comparing the calculated power characteristics. The problem is solved by numerical simulation of the magnetic field in the solenoid electromagnet. The simulation takes into account the nonlinearity of characteristics of the magnetic conductor and magnetic shielding shell, leakage fluxes and the spatial distribution of the magnetic field. The results of numerical simulation make it possible to obtain a picture of the magnetic field in the form of magnetic flux lines and to determine the force characteristics. A qualitative assessment of the effect of the shielding properties of magnetic shells is carried out by comparing the calculated power characteristics of solenoid electromagnets with each other. An example of such a comparison is given.

1. Introduction

Solenoid magnetic systems are devices that have become widespread in many areas of human activity. These areas of activity include radio electronics, power engineering, mechanical engineering, etc. [1-3]. The main purpose of solenoid magnetic systems is to provide the necessary output power characteristics for their use in various technical devices. One of such devices is a linear electromagnetic actuator, which includes a powerful single-coil or double-coil solenoid electromagnet. [4, 5]. Solenoid electromagnets have nonlinear magnetic properties [6-11] and when obtaining the output characteristics it is necessary to solve problems that require the use of special computational approaches. One of these problems is the need to research the passage of magnetic fields through a thin-walled shielding magnetic shell, which is a guide in powerful solenoid electromagnets.

Figure 1 shows the design of the electromagnetic actuator based on a double-coil solenoid electromagnet. Electromagnetic actuator contains the core *1*, the working stroke coil *2* and the idle stroke coil *3*. The coils are inside the magnetic conductors *4* and *5*. The magnetic conductors and the coils are interconnected by the connecting flange 6. The core *1* moves inside the guide *7* co-axial with coils *2* and *3*. The guide 7 is the shielding magnetic shell.

Upon actuation of one of the coils, the generated electromagnetic force moves the core *1* to the up or down position. With the coils *2* and *3* actuated in turns, the core *1* carries out reciprocating motions.

Solenoid electromagnets are advantageous for the simpler structure and manufacturability. The increase of the core velocity is achieved owing to longer travels of the core and larger linear dimensions of the coils. The linear dimensions of the working stroke coil and the idle stroke coil may differ depending on the purpose and design of an electromagnetic actuator. In Figure 1, the working stroke coil is longer than the idle stroke coil although they have the same diameters.

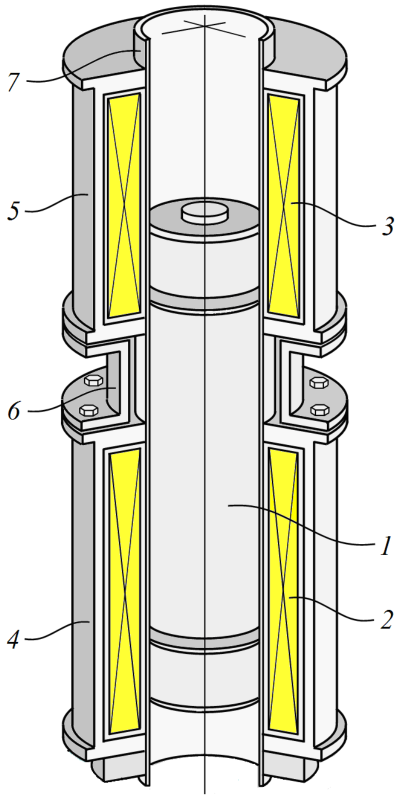

Figure 1. Electromagnetic actuator

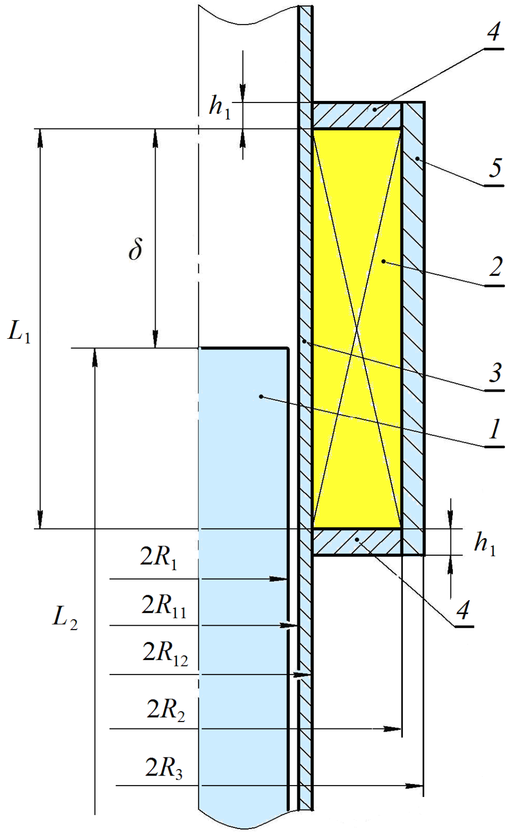

Figure 2. Design diagram of the solenoid electromagnet : *1*-core ; *2*- coil; *3*- guide; 4 - pole; *5* - magnetic conductor

The coil length to the core radius ratio ranges from 8 to 12, while the range of this ratio in the other devices using electromagnetic motors is not higher than 2-4. The research presented in this paper continues the previous research implemented by the authors in this area [12, 13].

The purpose of the research is the estimation of the influence of the shielding magnetic shell on the traction characteristics of solenoid electromagnets.

2. Materials and Methods

Usually the shielding magnetic shell is made of a nonmagnetic material. This allows nullifying the short-circulating effect of magnetic flux and maximizing the electromagnetic force when the core moves. One of the available materials is the nonmagnetic steel grade 1X18H9T, 1X18H10T. This is an expensive and very viscous material.

If the shielding magnetic shell is made of magnetic steel, then, with respect to the small cross-section of the material and its saturation under magnetic flow, the relative permeability of this steel can be similar to the relative magnetic permeability of air $\mu_r \approx 1$.

In order to check this supposition, it is necessary to calculate the electromagnetic force of the solenoid electromagnet. Such calculations are performed for two designs of the shielding magnetic shells made of different materials. The calculated amplitudes of the electromagnetic characteristics per intervals of the core movement are compared. Actually the calculation of the electromagnetic force in long-stroke systems requires precise register of stray fluxes, which is difficult in analytical approaches to the magnetic chain design. This means that there is no simple and accurate analytical method for the calculation of the long-stroke solenoid system.

The magnetic field numerical simulation gives the opportunity to calculate force characteristics of the solenoid electromagnet.

The equation describing the magnetic field in the solenoid has the form:

$$\nabla\times\left[\frac{1}{\mu(B)}\nabla\times\vec{A}_\varphi\right]=\vec{J}_\varphi, \qquad (1)$$

where $\vec{A}_\varphi$, $\vec{J}_\varphi$ are the components of the vector magnetic potential and the current density vector.

Magnetic permeability is the function of the induction B and determined through the magnetization curve of the material

$$\mu=\frac{B}{H(B)}.$$

When the equation (1) is solved, a finite element structure consisting of elements forming triangles is built.

When solving (1) in the meridian plane (r,z) one of the calculated boundaries is the central axis z. The remaining boundaries are considered outside the core, where the magnetic field is very small. The computational domain of the axially symmetrical model includes only half of the vertical section of the structure.

The resulting interaction force between the core and the stator is determined through the Maxwell tensor:

$$F_z=\frac{2\pi}{\mu_0}\int_l rB_rB_z dl, \qquad (2)$$

where B_r, B_z are the radial and axial components of magnetic induction, l is the contour of integration.

The results of magnetic field calculations are presented in the form of lines of equal level of magnetic flux in figures 3 and 4. The calculation of the field is performed at the same position of the core and the magnetizing force.

It is assumed that the solenoid electromagnet is geometrically and magnetically symmetrical relative to the axis (Figure 1).

The static electromagnetic forces at different positions of the core are determined in terms of the integral characteristics of the field. Geometry of the effective domain of the solenoid electromagnet model and all flux paths are plotted with respect to the magnetic field calculation results using the procedure described in [14-17].

Figure 2 shows the estimate structure of the solenoid electromagnet. The geometrical dimensions included in the modeling procedure are: R_1 is the radius of the core; $\Delta_1=R_{12}-R_{11}$ is the thickness of the shielding magnetic shell; $\Delta_2=R_2-R_3$ is the thickness of the magnetic conductor; h_1 is the height of the pole; δ is the air gap of the solenoid electromagnet; L_1 is the length of the coil. It is assumed that the coil contains W loops and is saturated by the constant current I. The core length L_2 is much more than the coil length L_1: $L_2>L_1$. The model parameters for the core radius $R_1=44.25$ mm are stated in table 1.

Table 1. Solenoid electromagnet model parameters

R_1, mm	R_{11}, mm	R_{12}, mm	R_2, mm	R_3, mm	Δ_1 mm	Δ_2, mm	$\frac{\Delta_1}{R_1}$	L_1, mm	h_1 mm	W	I, A
44.25	46	49	92.5	98	3.5	5.5	0.068	430	15	1110	30–70

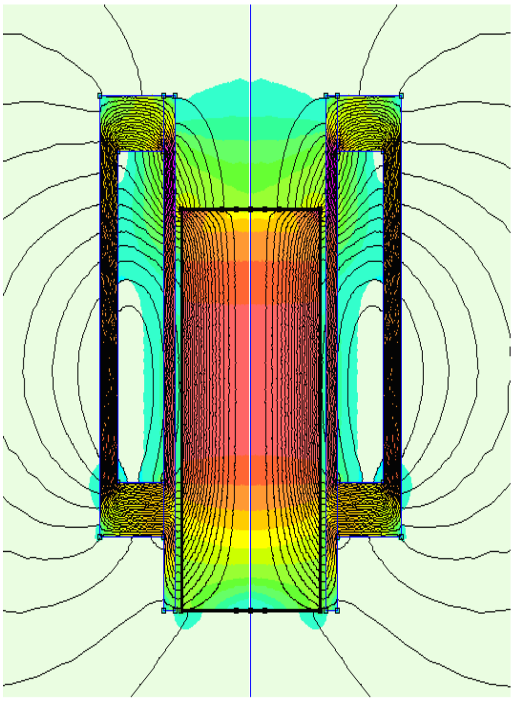

Figure 3. Magnetic flux lines in the solenoid with a shielding magnetic shell

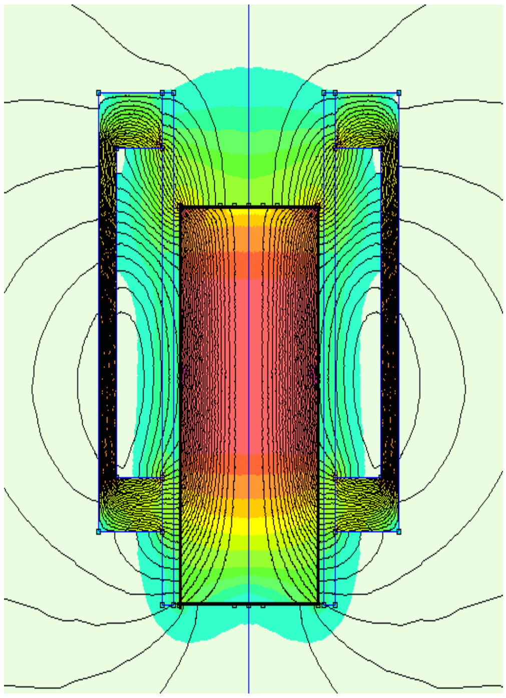

Figure 4. Magnetic flux lines in the solenoid with a shielding non-magnetic shell

3. Results and Discussion

The numerical simulation results are shown in figure 5 for the solenoid electromagnet whose nonmagnetic shielding magnetic shell is made of the stainless steel 1X18H9T and magnetic conductor is made of the structural Steel 20.

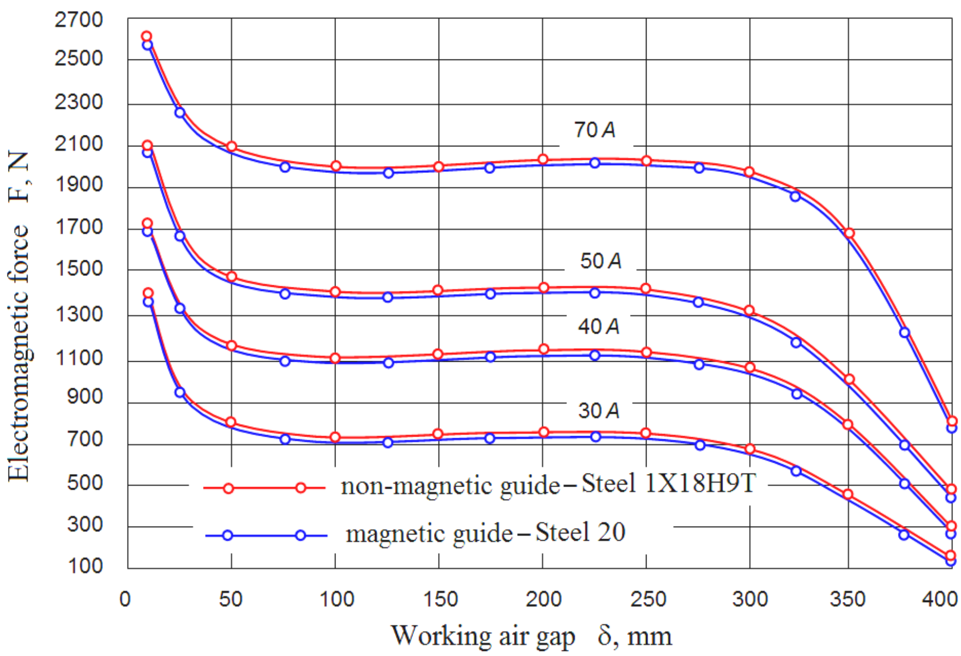

Figure 5. Static electromagnetic forces of the solenoid electromagnets with the shielding magnetic shell made of various materials

The calculations were performed at the same coil currents 30, 40, 50 and 70 A. The curves in figure 5 prove that the use of the shielding magnetic shell made of the inexpensive magnetic steel causes the reduction of the electromagnetic force no more than 3–4% that does not exceed the calculation error.

4. Conclusion

The numerical simulation of the magnetic field is a perspective method of estimation of the influence of the shielding magnetic shell on the force characteristics of the solenoid electromagnets. The simplified models limit capabilities of this estimation.

As it follows from the modeling data on magnetic field in the solenoid electromagnet, it is clear that replacement of a nonmagnetic shielding magnetic shell by a magnetic shielding magnetic shell made leads to insignificant decrease of the electromagnetic force.

The expected reduction of the resulting force of the solenoid electromagnet with the shielding magnetic shell instead of the nonmagnetic one is not higher than 2–3%.

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References

[1] Sosnin D A and Mitin M V 2007 Electromagnetic solenoid drive of gas distribution valves of a piston ice *Transport electronics and electrical equipment* **4** pp 32-35.
[2] Adygezalov B C 2005 Inductive solenoid displacement converter *Electrical engineering* **7** pp 37-40.
[3] Ivashin V V and Pevchev V P 2012 Electromagnetic drive for impulse and vibro-impulse procces *Proc. of Institutions of Higher Education. Electromechanics* (**1**) pp 72–75
[4] Gordon A V and Slivinskaya A G 1960 *DC Electromagnets* (Moscow, Leningrad: Gosenergoizdat)
[5] Ryashentsev N P and Ryashentsev V N 1985 *Electromagnetic Drive of Linear Machines* (Novosibirsk: Science)
[6] Rusinov A I 1994 High precision computation of solenoid magnetic fields by garrett's methods *IEEE Transactions on Magnetics* **30(4)** 2685-2688
[7] Dorfman Ya G 2010 *Magnetic properties and structure of matter* (Moscow: Publishing house LKI) p 376
[8] Gromyko G F 2015The effectiveness of the screening of constant magnetic fields by a cylindrical screen nom taking into account nonlinear effects *Physical foundations of instrument buildings* 4(4) pp 30–39
[9] Rezinkina M M 2007 The use of numerical calculations to select the means of screening from the action of a magnetic field *Journal of Technical Physics* 77(11) pp 17–24
[10] Erofeenko V T 2012 Model of screening of constant magnetic fields by a multilayer finite cylinderdry screen *Informatics* **3(35)** pp 80–93
[11] Gromyko G F and Erofeenko G M 2016 Numerical study of the structure of the magnetic field in a cylindrical film screen *Informatics* **2(50)** pp 5-18.
[12] Simonov B F, Neyman V Y and Shabanov A S 2017 Pulsed linear solenoid actuator for deep-well vibration *Source Journal of Mining Science* **53(1)** pp 117–125
[13] Simonov B F, Neyman V Y and Shabanov A S 2017 New conception of an electromagnetic drive for a vibration source in hole *International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices* pp 507–510
[14] Segerlind L. J. Applied Finite Element Analysis / 2nd edition, Wiley, New York, 1984.
[15] Cute V I 2018 System of automated formation of calculating models of electric machines for FEMM software environment *Technical electrodynamics* **4** pp 74–78.

[16] Meeker D 2004 *Finite Element Method Magnetics. Version 4.0* User's Manual, January 26, 2004 http: // femm.berlios.de
[17] Bull O B 2005 *Calculation Methods for Magnetic Systems of Electrical Apparatus: Magnetic Circuits, Fields, and the FEMM Program* (Moscow: Publishing Center "Academy")