The influence of the geometric profile of the air gap on the power and energy characteristics of an electromagnetic engine

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Abstract. The influence of the geometric profile of the air gap of the magnetic circuit on the power and energy characteristics of an electromagnetic engine is considered. The research is relevant because of the need to improve the methods for the optimal construction of electromagnetic engines to solve the complex problem of increasing the efficiency of vibration systems with linear displacements of executive parts. The object of research is the construction of an electromagnetic motor created on the basis of an electromagnet with a flat attracting armature. The research was performed using finite element magnetic field simulation using the program Finite Element Method Magnetics (FEMM). Options for building models are considered. The differences in the efficiency of using the compared structures of electromagnetic motors of the same size and weight from the conditions of their economy are shown. The magnitude of the electromagnetic force and mechanical work are used as evaluation criteria. The research results are interesting for specialists in the field of electromechanical engineering devices with linear displacements of executive parts.

1. Introduction

Due to the relative simplicity of design, controllability and reliability, linear electromagnetic motors are widely used in various industries [1–5]. These are, for example, vibration and vibration-shock machines and installations, compressors, construction power tools, electric pumps [6–9]. The main requirements for modern electric drives based on electromagnetic engines are high reliability and performance, low power consumption, low manufacturing cost, the high value of force on the interval of armature movement, restrictions on overall dimensions and weight [10–13].

Analysis of existing types of electromagnetic engines shows that these requirements for a certain category of devices can be partially satisfied, for example, due to the special construction of the magnetic system. In that case, if the rational type and, accordingly, the shape of the magnetic system of the electromagnetic motor are known, the task of multivariate analysis with the choice of the best of several options does not cause difficulties.

An analysis of the existing types of electromagnetic engines leads to the main conclusion that during certain construction conditions must exist that correspond to some optimal function in the formation of the traction characteristic due to the spatial geometry of the interacting elements of the internal structure of the magnetic circuit [14, 15].

One of these provisions is the change in the geometric profile of the air gap, which allows getting different forces on the interval of movement of the armature, increase the magnetic induction in the working air gap due to the highest concentration of the magnetic field, decrease in magnetic resistances [16–19].

The main goal of the research is to solve the problem of improving the methodology for the optimal construction of an electromagnetic engine created on the basis of an electromagnet with a flat
attracting armature obtained on the basis of finite element modelling of the magnetic field in the FEMM program [20–22].

2. Methods and Tools

In this work, we performed a comparative analysis of electromagnetic engines of the same size and weight of active materials and showed the influence of the geometric profile of the air gap of the magnetic circuit through output indicators widely used in practice, obtained using finite element modelling of the magnetic field.

When obtaining static traction characteristics, only the shape of the air gap profile of the magnetic circuit was changed. The remaining parameters of electromagnetic engines, including the number of turns of coils, external dimensions and volumes occupied by active materials, were maintained unchanged throughout the experiment.

To obtain comparable data, all the studied profiles of electromagnets had the same steel grade and the cross-sections of the magnetic circuit in the main flow path. The number of turns of the coil $w = 1200$, current $I = 4$ A. The value of the working air gap varied within the same range of $0...10$ mm. Traction characteristics were taken at the same values of magnetizing forces. The measures taken ensure that the cooling and heating conditions are identical when comparing different options.

The design of the electromagnetic motor is shown in Figure 1. An example of calculating the magnetic field in the FEMM program is presented in Figure 2.

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{figure1.png}
    \caption{Basic geometric profile of the magnetic system of an electromagnetic engine with a flat pulling armature: 1 – armature; 2 – magnetic circuit; 3 – coil.}
    \end{figure}

\begin{figure}[h]
    \centering
    \includegraphics[width=\textwidth]{figure2.png}
    \caption{An example of calculating the magnetic field in the FEMM program.}
    \end{figure}

Despite the diverse design of the air gap profiles, all electromagnetic engines have magnetic systems with a flat attracting armature. Similar designs of electromagnetic motors with a relatively small magnitude of the working stroke of the flat armature have significant traction force.

In the final position of the armature, all electromagnetic engines have the same magnetic circuit profile.

As an example, Figure 2 shows the final results of constructing the field of model variants in the form of magnetic flux lines. The results are obtained by numerically calculating the active volume of the created models using finite element modelling in the FEMM program [23–26].

As follows from Figure 4, in the range of the armature stroke $0.05 \ldots 2$ mm, the electromagnetic motor with the geometric profile of the magnetic circuit prevails with the classical (flat) configuration of the air gap in terms of maximum traction forces (Figure 3, e).
Figure 3. Geometric profiles of versions of magnetic systems of electromagnetic engines

Figure 4. The dependence of electromagnetic force on the size of the air gap: 1 – with 1 tooth (Figure 3, f); 2 – with a flat profile (Figure 3, e); 3 – semicircle shape (Figure 3, d); 4 – reverse semicircle shape (Figure 3, d); 5 – with an inclination of 30 degrees to the other side (Figure 3, b); 6 – with an inclination of 30 degrees (Figure 3, b); 7 – with an inclination of 45 degrees to the other side (Figure 3, b); 8 – with cone profile (Figure 3, a); 9 – with an inclination of 45 degrees (Figure 3, b); 10 – with 3 teeth (Figure 3, c); 11 – with an inclination of 60 degrees to the other side (Figure 3, b); 12 – with an inclination of 60 degrees (Figure 3, b)

With an increase in the size of the working air gap in the range of 6 ... 12 mm, the maximum values of traction forces are dominated by electromagnets with the constructive shape of the magnetic circuit, made according to Figure 3, b, with a plane inclination of 60°. The traction values in the interval of
2..12 mm for this configuration of the geometric profile of the air gap of the magnetic system differ from the basic configuration by more than 3 times.

The full mechanical work was defined as the area bounded by the corresponding traction curve and the abscissa axis within the armature displacement $x = 0 \ldots 12$ mm. The maximum conditional useful work was understood as the maximum value of the product of electromagnetic force and the value of the armature stroke corresponding to a given force. The maximum conditional useful work determined the optimal value of the working air gap. The same value of the working air gap corresponds to the optimum force for maximum work.

![Graph showing the dependence of work on the size of the air gap.](image)

**Figure 5.** The dependence of the work on the size of the air gap: 1 – with 3 teeth (Figure 3, c); 2 – with 1 tooth (Figure 3, f); 3 – with cone profile (Figure 3, a); 4 – with an inclination of 60 degrees to the other side (Figure 3, b); 5 – with an inclination of 60 degrees (Figure 3, b); 6 – with an inclination of 30 degrees (Figure 3, b); 7 – with an inclination of 45 degrees (Figure 3, b); 8 – with an inclination of 30 degrees to the other side (Figure 3, b); 9 – reverse semicircle shape (Figure 3, d); 10 – semicircle shape (Figure 3, d); 11 – with a flat profile (Figure 3, e); 12 – with an inclination of 45 degrees to the other side (Figure 3, b).

From Figure 5 it follows that with the standard (flat) configuration of the air gap profile of the magnetic system, the magnitude of the work at the optimum armature 4..10 mm does not exceed 0.35 N·m. For the configuration of the air gap profile made according to Figure 3, b, with a plane inclination of 60°, the value of the work performed in this section exceeds 1.0 N·m.

3. Conclusion

The research results prove the feasibility of determining the optimal use of different geometric profiles of air gaps from the analysis of the estimated traction characteristics obtained using finite element modelling of the magnetic field, which simplifies the solution of the optimal search problem.

For the same operating conditions for given dimensions and parameters of the magnetic system, the magnitude of the electromagnetic force and mechanical work substantially depend on the geometric profile of the air gap of the magnetic circuit.

For different geometric profiles of the air gap, the conditional useful work of the investigated variants of magnetic systems can differ significantly.

References

[1] Usanov K M et al. 2018 Electric converters of electromagnetic strike machine with battery power *IOP Conference Series: Materials Science and Engineering* 87 052031

[2] Tatevosyan A S, Tatevosyan A A and Zharova N V 2018 Calculation of non-stationary magnetic field of the polarized electromagnet with the external attracted anchor *Journal of Physics: Conference Series* 1050(1) 012086
[3] Ugarov G G and Neiman V Yu 1996 Evaluation of operating conditions for electromagnetic impactors Journal of Mining Science 32(4) 305–312

[4] Sattarov R R and Almaev M A 2019 Electromagnetic worm-like locomotion system for in-pipe robots: novel design of magnetic subsystem IOP Conf. Ser.: Earth Environ. Sci. 315 062013

[5] Manzhosov V K et al. 1985 Dynamics and Synthesis of Electromagnetic Generators of Power Pulses (Frunze: Illim)

[6] Ryashentsev N P et al. 1981 Electric Drive with Linear Electromagnetic Motors (Novosibirsk: Science)

[7] Ryashentsev N P, Ugarov G G and Levitsin A V 1989 Electromagnetic Presses (Novosibirsk: Science)

[8] 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) 117–125

[9] Neyman L A and Neyman V Y 2016 Dynamic model of a vibratory electromechanical system with spring linkage 11 International forum on strategic technology (IFOST 2016) 2 23–27

[10] Kazakov L A 1978 Electromagnetic Units of Radio Electronic Equipment (Moscow: Soviet radio)

[11] Gordon A V and Slivinskaya A G 1960 DC Electromagnets (Moscow, Leningrad: Gosenergoizdat)

[12] Sattarov R R 2016 Electromechanical transients in passive suspension systems with eddy current dampers 9th International Conference on Power Drives Systems (ICPDS 2016) Conference Proceedings 9 7756676

[13] Neiman V Yu and Smirnova Yu B 2006 New principles and increase of energy efficiency of electromagnetic machines Proceedings of the 1st International Forum on Strategic Technology (Ulsan: University of Ulsan) pp 314–315

[14] Batischev D V and Pavlenko A V 2012 On designing electromagnetic drives operating under conditions of high vibrations Russian Electrical Engineering 83(8) 423

[15] Sattarov R R, Ismagilov F R and Pashali D Y 2016 Investigation of the amplification of an electromagnetic field at the end wall of a conducting thin-wall body during its interaction with an alternating magnetic field Russian Journal of Nondestructive Testing 52(5) 269–275

[16] Pevchev V P 2009 Principal dimensions of the short-stroke electromagnetic motor for a seismic wave generator Journal of Mining Science 45(4) 372–381

[17] Ugarov G G et al. 1997 Operating cycle of an electromagnetic percussion machine with storage of magnetic energy during the no-load period Journal of Mining Science 33(3) 253–257

[18] Usanov K M, Moshkin V I and Ugarov G G 2006 Linear Impulse Electromagnetic Drive of Machines with Self-Contained Power Supplies (Kurgan: KSU)

[19] Shoffa V N, Russova N V and Svintsov G P 2002 Optimal symmetric U-shaped two-coil dc electromagnets with prismatic cores in intermittent operation Russian Electrical Engineering 73(2) 63–68

[20] Malinin V I and Ryashentsev A N 1989 Optimal geometry of the electromagnetic module of a percussion machine News of higher educational institutions. Electromechanics 4 84–88.

[21] Neyman L A, Neyman V Y and Shabanov A S 2017 Vibration dynamics of an electromagnetic drive with a half-period rectifier The 18 international conference of young specialists on micro/nanotechnologies and electron devices (Novosibirsk : NSTU) pp 503–506.

[22] Pevchev V P 2009 Principal dimensions of the short-stroke electromagnetic motor for a seismic wave generator Journal of Mining Science 45(4) 372–381

[23] Sylvester P and Ferrari R 1986 Finite Element Method for Radio and Electrical Engineers (Moscow: Mir)

[24] Neyman V Yu, Neyman L A and Petrova A A 2008 Calculation of efficiency of DC electromagnet for mechatronic systems Proceedings of IFOST 2008: 3rd International Forum on Strategic Technology (Novosibirsk, Tomsk) pp 452–454

[25] Meeker D 2004 Finite Element Method Magnetics. Version 4.0 User’s Manual, January 26, 2004 http://femm.berlios.de

[26] Bull O B 2005 Calculation Methods for Magnetic Systems of Electrical Apparatus: Magnetic Circuits, Fields, and the FEMM Program (Moscow: Publishing Center "Academy")