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**MODELING ELECTROMAGNETIC SYSTEMS**

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*The article is devoted to modeling electromagnetic systems which was carried out in a package of the applied ANSYS programs. ANSYS is universal program system of finite element analysis. Modeling and analysis in some areas of the industry allows to avoid expensive and long-lived cycles of development like "projection — manufacture — tests". The system works on the basis of geometric element. Each type of elements uses values of material properties.*

**Keywords:** electromagnet, constant magnet, simulation modeling, Lorentz force, magnetic induction, magnetic intensity.

**Introduction**

Nowadays along with creation of analytical models the great attention is paid to problems of assessment of characteristics of larger systems on the basis of the imitating models realized on the modern COMPUTERS with high quick action and large volume of random access memory. Besides, orientation to personal COMPUTERS for realization of experiments with imitating models of larger systems allows to carry out not only the analysis of their characteristics, but also to solve problems of structural, algorithmic and parametrical synthesis of such systems at the given criteria of effectiveness assessment and restrictions, unlike the method of direct analogy and method of electric modeling [1].

The simulation modeling of complex systems often is the only practically realized research method of functioning process of such systems at a stage of their projection. For the integrated analysis of functioning process characteristics of systems it is necessary to reproduce multiply the imitating experiment, varying input data of the task. That is it is possible to receive the complete solution of the objective of research [2].

**Technique of modeling and software**

One of the most widespread program complexes today is the package of the applied ANSYS programs using finite element method. The finite element method of ANSYS is widely known and enjoys popularity among the research engineers dealing with issues, not only loudspeakers and durability, but researches of electromagnetic field [3].

In the process of calculation by this method the network of finite elements is being constructed: the space occupied by the field, breaks by means of straight lines and curves in two-dimensional task, and also by means of even or curved surfaces in three- dimensional task, into the separate parts having rather small, but finite sizes. These parts are called finite elements. When solving two-dimensional task the finite elements more often have the form of triangles or rectangles, and in three-dimensional — the form of parallelepipeds of the tetrahedrons, all which lateral areas represent triangles [4].

In ANSYS system there are more than 100 various types of elements. As a rule, in various versions of the program not all types of elements are accessible. It depends on what types of calculation can be used in this version of the program [5].

In our work 2-D static magnetic analysis was carried out. In the static magnetic analysis it is possible to simulate saturable and unsaturable magnetic materials as well as constant magnets. For magnetic analysis we used elements with 2-D geometry. Though all objects and constructions are 3-D, in our analysis we replaced them with 2-D elements as 2-D is much simpler to generate and calculation takes less time. Such model operation is called flat or axisymmetric [6].

The static magnetic analysis was carried out in five stages:

1. Creation of the physical environment.
2. Creation of model and purpose of physical attributes for each area.
3. Application of boundary conditions and loading (excitation).
4. Obtaining solution.
5. Viewing of results.

For creation of the physical environment of the analysis types of the finite elements were chosen. Areas which can exist in 2-D models [7] are shown in table 1.

Table 1 – 2-D modeling areas

Air	Freedom degree: AZ. Material parameters: MUR (MURD2), rho (RSVD2)
Iron	Freedom degree: AZ. Material parameters: MUR (MURD2) or B-H curve (TB command)
Constant magnet	Freedom degree: AZ. Material parameters: MUR (MURD2) or B-H curve (curve TB); Hc (coercive force)

For modeling electromagnetic system we used PLANE233 element which is 2-D element for model flat or axisymmetric electromagnetic fields. The element consists of 8 or 6 clusters and has to 2 degrees of freedom for one cluster, also has opportunity to make the electromagnetic analysis with the electric potential (tension) integrated according to time as a degree of freedom [8]. The PLANE233 element has non-linear magnetic potential for modeling curves B-H or curves of degaussing of constant magnets for static and transitional time analyses. The clusters and system of coordinates are shown in figure 1. The element of triangular form can be created by K, L, O combination in one point.

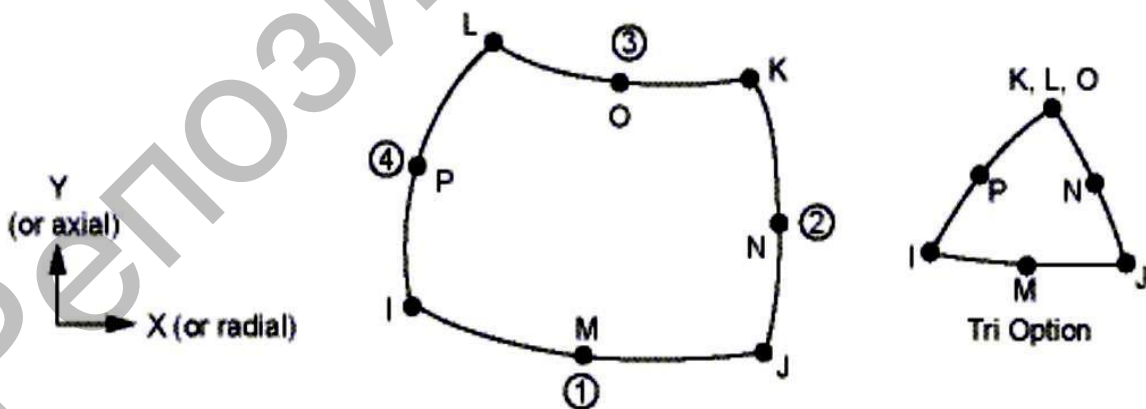


Fig.1. PLANE 233 element geometry

The purpose of work is to define interactions of electromagnet and constant magnet. For this purpose the parameters of electromagnet and constant magnet are changed.

For calculation of magnetic induction  $B$ , magnetic intensity of  $H$  and Lorenz force  $F$  we used the following input data:

Parameters of electromagnet of direct current:

$D1 = 3.048$ \*mm internal diameter of the coil  
 $R_1 = D1/2$  internal radius of the coil  
 $D2 = 3.9624$ \*mm external diameter of the coil  
 $R_2 = D2/2$  external radius of the coil  
 $L_1 = 1.524$ \*mm coil height  
 $SE = 0.127$ \*mm thickness of the end of the coil winding  
 $DEL = 0.234$ \*mm axial shift  
 $N = 280$  quantity of winds  
 $R = 57$  resistance of the coil, Ohm  
 $I = 0.050$  current, A  
 $AC = (R_2 - R_1) * L_1$  area of the coil,  $M^2$   
 $JS = N * I / AC$  current density  
 $SD = SE + DEL$  constant magnet  
 $D3 = 2.9972$ \*mm diameter of magnet  
 $R_3 = D3/2$  magnet radius  
 $L_3 = 1.6$ \*mm length  
 $BR = 1.02$  magnetic induction, T  
 $HC = 720000$  coercive force / A/m  
 $MU0 = 4 * \pi * 1E-7$  transmittivity of the free space / H/m

Calculations were carried out for various parameters of electromagnet and a permanent magnet. Changing one parameter, the others remained invariable. The following parameters changed:

Parameters of electromagnet of direct current:

$D1 = 3.048$ \*mm internal diameter of the coil  
 $D2 = 3.9624$ \*mm external diameter of the coil  
 $L_1 = 1.524$ \*mm coil height  
 $SE = 0.127$ \*mm thickness of the end of the coil winding  
 $DEL = 0.234$ \*mm axial shift  
 $I = 0.050$  current, A  
 constant magnet:  
 $D3 = 2.9972$ \*mm diameter of a magnet  
 $L_3 = 1.6$ \*mm length  
 $BR = 1.02$  magnetic induction, T  
 $HC = 720000$  coercive force / A/m  
 $MU0 = 4 * \pi * 1E-7$  transmittivity of the free space / H/m

System model electromagnet - the constant magnet and the received lines of electromagnetic field are shown in figure 2.

Depending on the modeled material Plane 253 can have in clusters a degree of freedom (DOF) which is called AZ. AZ - vector magnetic potential (in the twodimensional analysis it is supposed that vector magnetic potential has only one component - on the axis Z, that is in the direction, perpendicular to considered area). Vector potential of the electromagnetic field in electrodynamics is the vector potential, which rotor is equal to magnetic induction.

Influence of change of parameters of electromagnet and constant magnet on electromagnetic interaction is researched. Statistical data processing of the experiments received as the result of calculations for developed algorithms is carried out.

### Discussion of results

As a result of calculations minimum and maximal values of magnetic induction of B and H magnetic intensity are received. For the purpose of the analysis of influence of change of parameters of electromagnet and constant magnet on electromagnetic interaction, a number of experiments were carried out at various parameters of electromagnet and constant magnet (fig. 3).

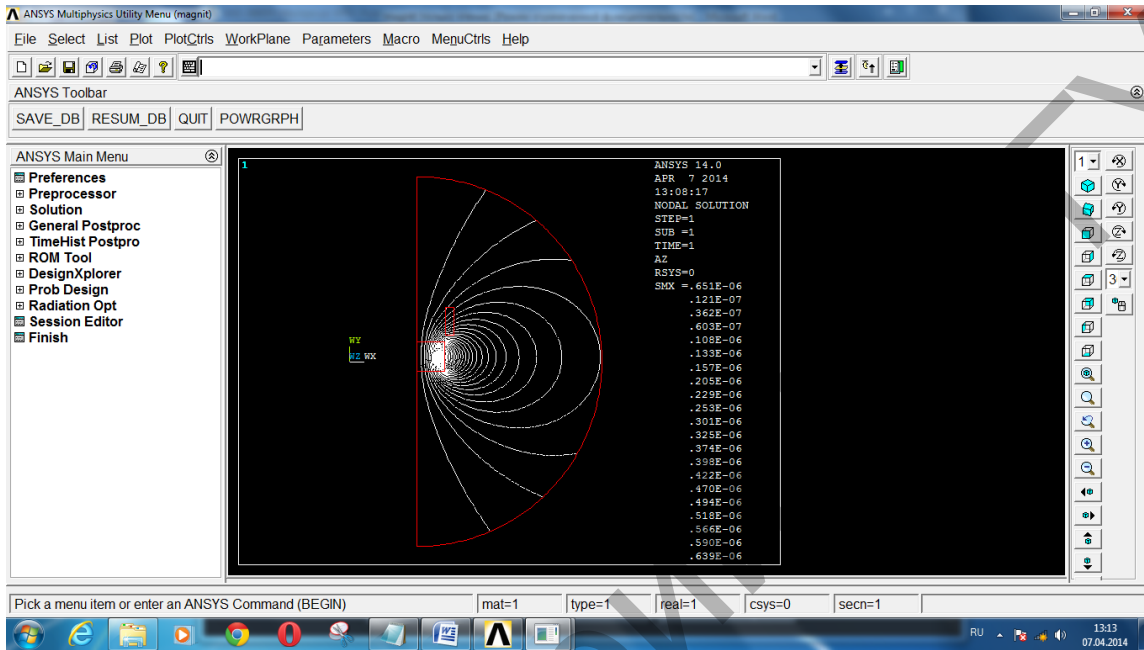


Fig.2. System model electromagnet-constant magnet

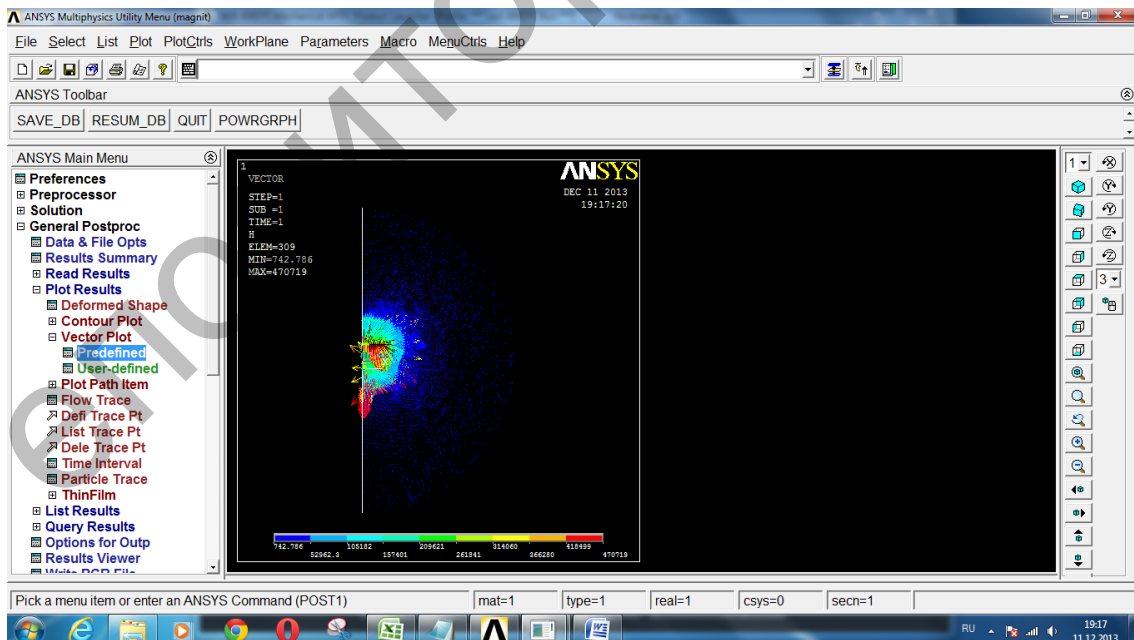


Fig.3. Results of calculations electromagnetic interaction of elements of the system

Dependences of a magnetic induction and magnetic intensity on the variable (changeable) parameter of electromagnet and constant magnet for the further analysis of properties of electromagnet and influence of its parameters on the magnetic field were constructed as results.

Approximating functions of dependences of parameters of electromagnetic field from change of parameters of electromagnet and constant magnet (figure 4) are received.

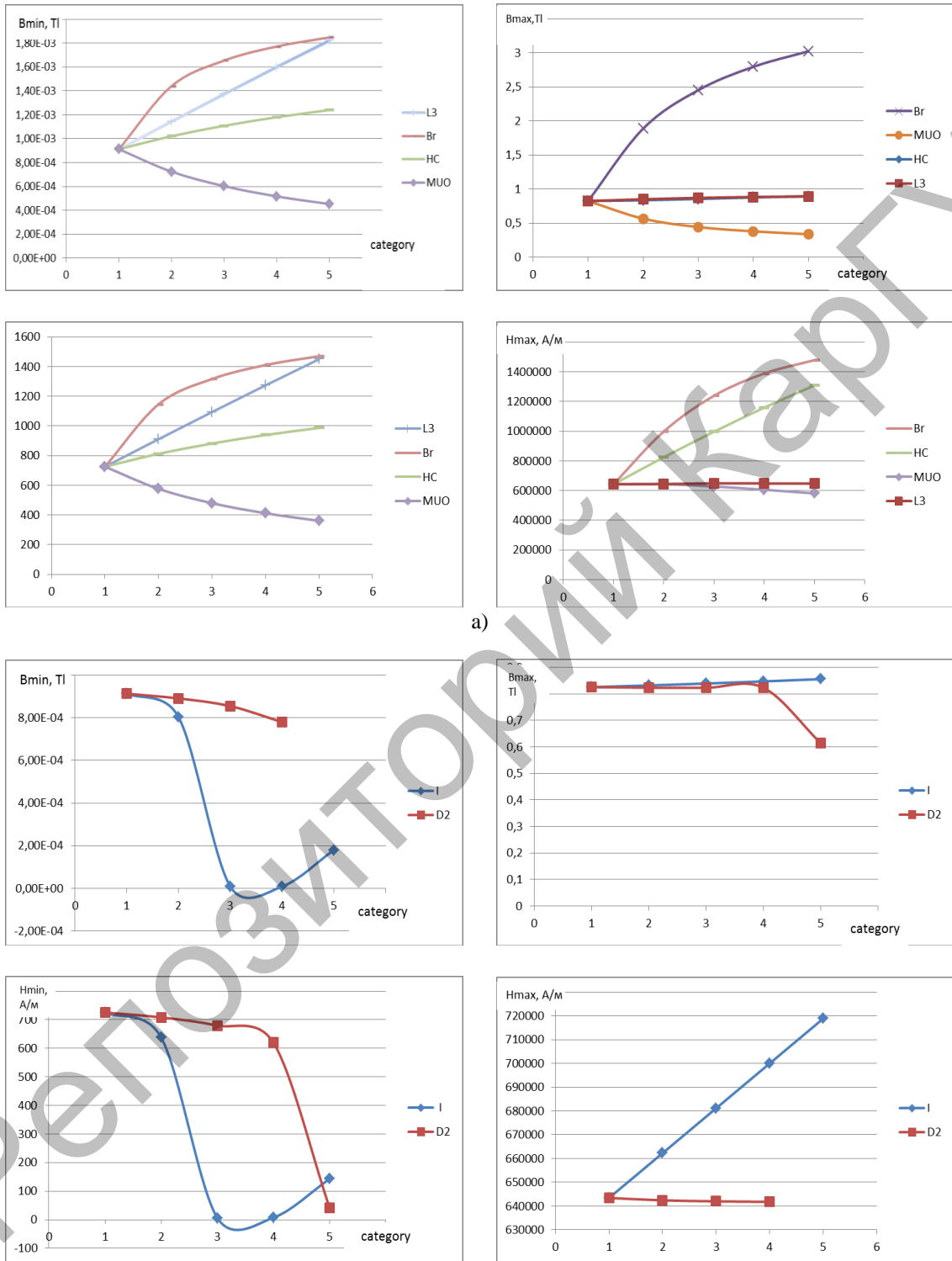


Fig.4. Dependencies of parameters of electromagnetic field on change of parameters:  
 a) constant magnet; b) electromagnet.

Experiments showed that parameters of magnetic field do not depend on thickness of the end of the coil winding and axial shift. At change of electric current, minimum value of a magnetic induction and a magnetic intensity in the initial points decrease, then increase, maximal value only

increase. While change of external diameter of the coil, the magnetic induction and a magnetic intensity decreases.

While change of magnetic induction of constant magnet, its length, coercive force parameters of magnetic field increase, and while change of magnetic conductivity of the free space they decrease.

When processing results the following target functions which can be applied at creation of electromagnetic installations were received.

When changing parameters of constant magnet:

$$\begin{aligned} B_{\min}(L3) &= -1E-05(L3)^2 + 0,0006(L3) - 6E-05 \\ B_{\max}(L3) &= 0,0116(L3)^4 - 0,1086(L3)^3 + 0,3558(L3)^2 - 0,4291(L3) + 0,9707 \\ H_{\min}(L3) &= -9,5759(L3)^2 + 498,83(L3) - 48,309 \\ H_{\max}(L3) &= 24159(L3)^4 - 236889(L3)^3 + 849391(L3)^2 - 1E+06(L3) + 1E+06 \end{aligned}$$

$$\begin{aligned} B_{\min}(Br) &= -4E-07(Br)^4 + 1E-05(Br)^3 - 0,0001(Br)^2 + 0,0006(Br) + 0,0004 \\ B_{\max}(Br) &= -0,0004(Br)^4 + 0,0128(Br)^3 - 0,1529(Br)^2 + 0,9973(Br) - 0,0454 \\ H_{\min}(Br) &= -0,3414(Br)^4 + 9,1005(Br)^3 - 93,626(Br)^2 + 481,92(Br) + 322,02 \\ H_{\max}(Br) &= 565,66(Br)^3 - 19626(Br)^2 + 249807(Br) + 408319 \end{aligned}$$

$$\begin{aligned} B_{\min}(HC) &= 1E-22(HC)^3 - 6E-16(HC)^2 + 1E-09(HC) + 0,0003 \\ B_{\max}(HC) &= -1E-19(HC)^3 + 5E-13(HC)^2 - 5E-07(HC) + 0,9609 \\ H_{\min}(HC) &= 8E-17(HC)^3 - 4E-10(HC)^2 + 0,001(HC) + 210,26 \\ H_{\max}(HC) &= -1E-07(HC)^2 + 1,1269(HC) - 100480 \end{aligned}$$

$$\begin{aligned} B_{\min}(MUO) &= -4E-06(MUO)^3 + 5E-05(MUO)^2 - 0,0003(MUO) + 0,0012 \\ B_{\max}(MUO) &= 0,0015(MUO)^4 - 0,0272(MUO)^3 + 0,1942(MUO)^2 - 0,673(MUO) + 1,33 \\ H_{\min}(MUO) &= -2,9752(MUO)^3 + 42,858(MUO)^2 - 256,06(MUO) + 941,46 \\ H_{\max}(MUO) &= -197,38(MUO)^4 + 3473,1(MUO)^3 - 23728(MUO)^2 + 50064(MUO) + 613805 \end{aligned}$$

When changing parameters of electromagnet:

$$\begin{aligned} B_{\min}(D2) &= -1E-07(D2)^4 + 4E-06(D2)^3 - 5E-05(D2)^2 + 0,0003(D2) + 0,0004 \\ B_{\max}(D2) &= -3E-05(D2)^4 + 0,0013(D2)^3 - 0,0186(D2)^2 + 0,1049(D2) + 0,6275 \\ H_{\min}(D2) &= -0,076(D2)^4 + 2,9797(D2)^3 - 41,398(D2)^2 + 231,44(D2) + 291,74 \\ H_{\max}(D2) &= -36,897(D2)^4 + 1469,2(D2)^3 - 20451(D2)^2 + 115858(D2) + 423134 \end{aligned}$$

$$\begin{aligned} B_{\min}(I) &= -0,0021(I)^4 + 0,0089(I)^3 - 0,0114(I)^2 + 0,0039(I) + 0,0007 \\ B_{\max}(I) &= 0,0019(I)^2 + 0,0132(I) + 0,8252 \\ H_{\min}(I) &= -1702,4(I)^4 + 7089,4(I)^3 - 9079,6(I)^2 + 3068,6(I) + 593,86 \\ H_{\max}(I) &= 41921(I) + 641317 \end{aligned}$$

At various parameters of constant magnet and electromagnet calculation of the Lorentz force (figure 5) was carried out. Lorentz force is force with which the electromagnetic field according to classical electrodynamics affects a pointwise charged particle. Sometimes Lorentz force call force operating on moving with speed from electric and magnetic water.

From figure 5 it follows that when changing magnetic induction of constant magnet, its length, coercive force Lorentz force increases smoothly exponentially. And at change of a transmittivity of the free space Lorentz force decreases exponentially (fig. 5, a). When changing

such parameters of electromagnet as the external diameter of the coil, axial shift and thickness of the end of the coil winding Lorentz force decreases exponentially (fig. 5, b)

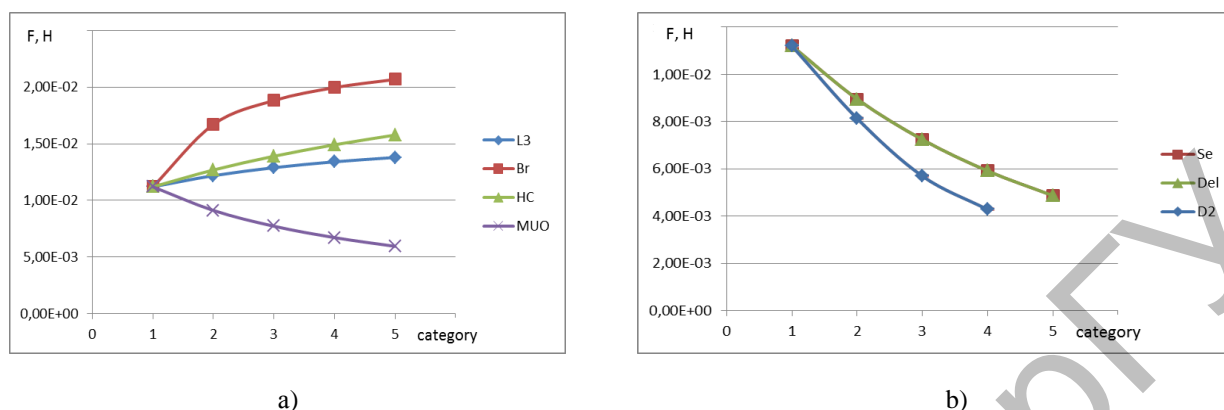


Fig. 5. Dependence of Lorentz force on parameters a) constant magnet, b) electromagnet

These results are necessary for further researches of electromagnetic installations. During research the finite element method for the solution of electromagnetic tasks is studied, algorithms of definition of the mechanism of an electromagnetic interaction of structural components of electromagnetic system in the environment of the ANSYS program are developed.

## Conclusion

On the basis of the conducted researches the following new scientific and reasonable theoretical results were received:

1. The functional dependences of parameters of electromagnetic field on change of parameters of electromagnet and constant magnet are received.
2. The assessment is given to Lorentz force at various parameters of electromagnet and constant magnet.

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