CONTRIBUTIONS TO THE STUDY OF THE DYNAMIC OPERATING REGIME OF AN ELECTROMAGNETIC VIBRATOR

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Abstract*: This paper presents the results of the calculation of the maximum static force air gap dependence for a fixed magnetic circuit geometry, using the finite element method. This contributes to the writing of a dependency matrix of higher rank than that available in discrete simulation results, leading to the generation of analytic expressions of general nature and not subject to simplifying assumptions for the maximum static force of air gap variation*

1. INTRODUCTION

Although electromagnetic vibrators are much used in practice, they are not sufficiently studied from a theoretical perspective. While vibropercutant mechanical systems are much studied there are only a few studies in connection with electromagnetic systems and especially on the electromagnetic vibrator (VEM). To obtain results close to reality in the study of electromagnetic vibrators it is necessary to keep in mind that we are dealing with electromechanical systems and must start from the equations describing the behavior of the whole system.

2. CALCULATION OF THE FORCE OF ATTRACTION DEVELOPED BY AN ELECTROMAGNET

Knowing the flow, inductivity or permeation of an electromagnet one can determine the electromagnetic force of attraction developed by the formula:

$$F = -\frac{1}{2} \cdot \frac{\lambda}{sh^2(p\delta)} \cdot (N \cdot i)^2 = -\frac{1}{2} \cdot \frac{1}{\alpha\delta^2} \left(\frac{p\delta}{sh(p\delta)} \right)^2 \cdot (N \cdot i)^2 \tag{1}$$

and if we neglect dispersion ($\lambda \to 0$ and $p \to 0$), we obtain the force:

$$F = -\frac{1}{2\alpha} \left(\frac{Ni}{\delta} \right)^2 . \tag{2}$$

or

$$F = -\frac{1}{2} \cdot \frac{B^2 \cdot 2S}{\mu_0} \tag{3}$$

being found as the general expression of the force of attraction developed by an electromagnet.

3. RESULTS OF THE FEM ANALYSIS

The basic configuration of the electromagnet studied has as active materials the electrical steel sheet cold rolled CR 1010 column, yoke and armature and copper with electrical conductivity σ = 5.77 * 107 S / m for coils.

Analyses are performed, neglecting the hysteresis effect of magnetic materials, considering its behavior according to the magnetization curve and the winding current values ranging from 0.1 - 5 A.

Before the actual simulations the necessary degree of refining the mesh to avoid large time or system crashes was tested using the "step by step" method, but without significantly decreasing the analysis results, especially those concerning the calculation of forces. This led to the analysis of interpolation polynomials of the second order and a refinement of the mesh on the geometric configuration of the electromagnetic form shown in Figure 1. and 2. In fig. 1 is shown a mesh for column yoke and armature, and in Fig. Network of air gap 2 is played with a refining how best foot polar opposite.

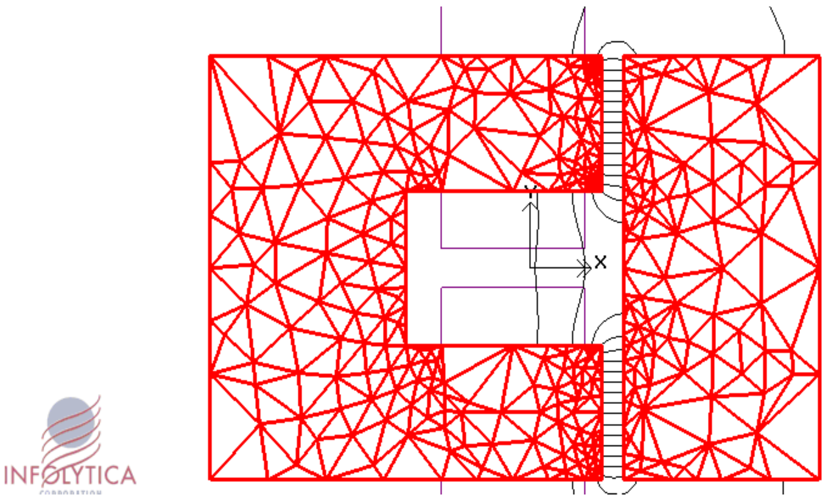

Fig. 1 Network and reinforcement mesh for column

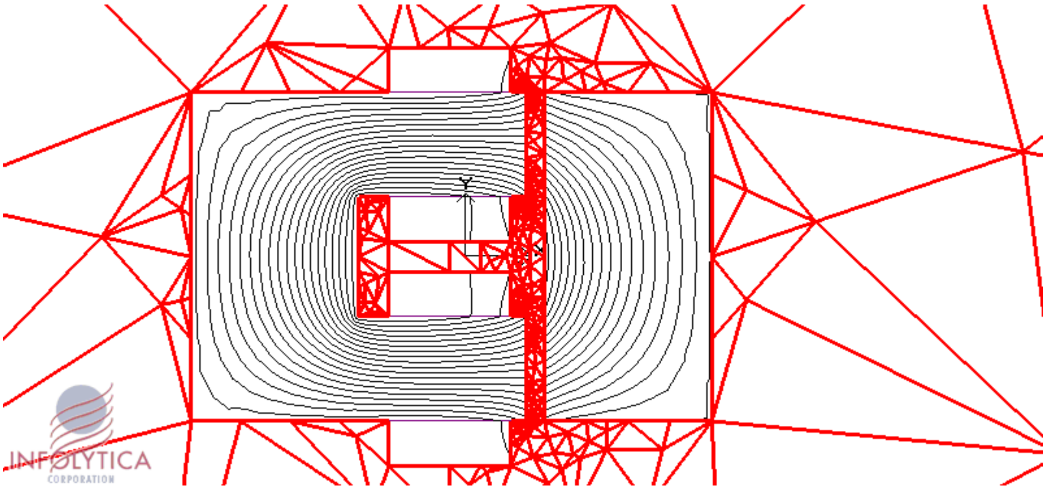

Fig. 2 The air gap mesh network

Below there are the results of the FEM analysis performed with the Infolytica MagNet software, version 6.11.

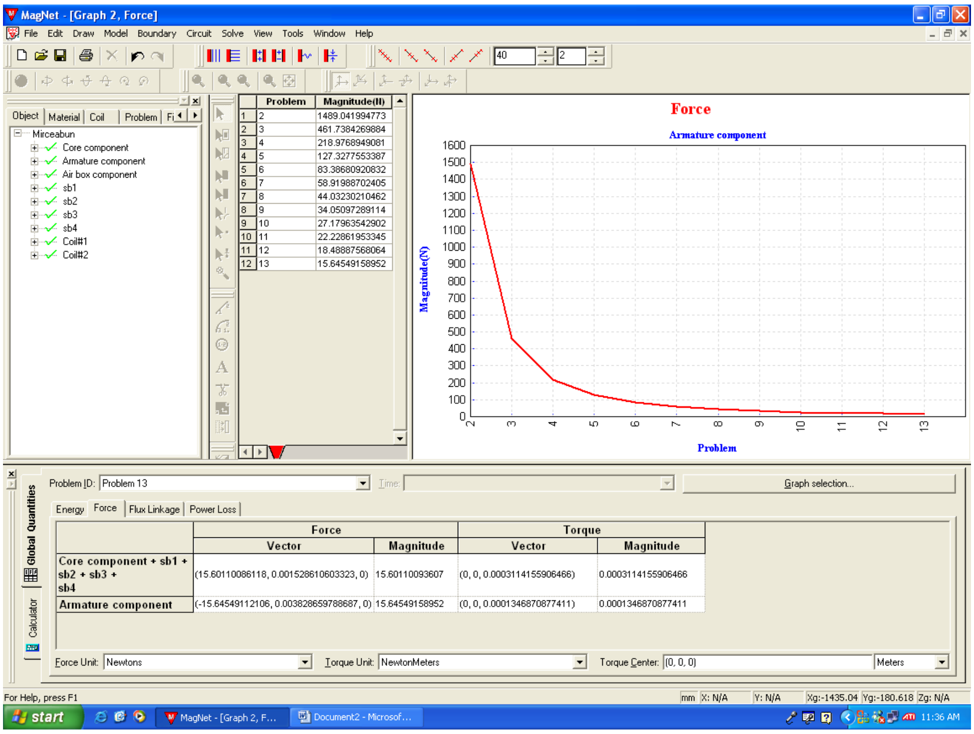

Fig. 3 Force characteristic for CR 10 and a current of 1 A

In the figure above the force chart is rendered, F = F (x) for varying air gap for the basic configuration of the electromagnet powered by a current of 1 A.

After analyzing all the models required and obtaining numerical results for each study model, we raised a family of characteristic curves of force for all configurations. Thus all air gap force characteristics could be analyzed comparatively according to size.

In the chart below force characteristics for current levels of between 0.1 - 0.5 A are given.

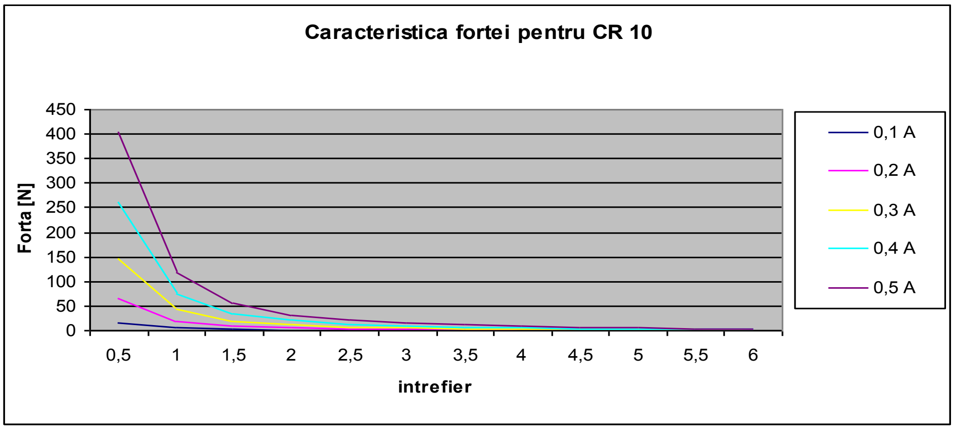

Fig. 4 Force characteristic for CR 10 and a current of 0.1 - 0.5 A

Accepting homogeneity and isotropy, at least in parts and assuming construction of finite elements so that they include inside an environment isotropic and homogeneous functional problems associated with such a perfectly valid both for linear and materials for nonlinear materials, noting that value is relative magnetic permeability is constant in the first case, be dependent on the value of magnetic induction, in the second.

The solution of a FEM analysis, of linear configurations is done simply by calculating the scalar magnetic potential values, similarly as the linear case, the values obtained representing the basis for the new values of the magnetic permeability of the magnetization curves. The cycle is repeated until the required convergence.

The study is conducted having as physical support of the electromagnetic phenomena nonlinear magnetic materials, linearity being considered only for the correlation of the presentation with intuitive aspects, analytically emphasizable, providing an overview of the phenomenology.

In general in usual design calculations, at least in the design phase of the basic model that optimization is later achieved on, linearity of magnetic materials is the key to solving them. This hypothesis is considered insignificant enough to attract errors, especially for small values of air gap, where the effect of magnetic saturation is smaller.

4. MAXIMUM FORCE STATIC DEPENDENCE AIR GAP

Based on the results of the FEM static simulation one can draw the maximum static force variation in the size of the air gap, with the parameter being the size the electric current i. Considering that the electromagnetic vibrator for which measurements were done, has the range of variation of current ranging from 0 to 3 A, we traced the curves F = F (x) for the following parameter values i = (0,3; 0,6; 1; 2; 3) A.

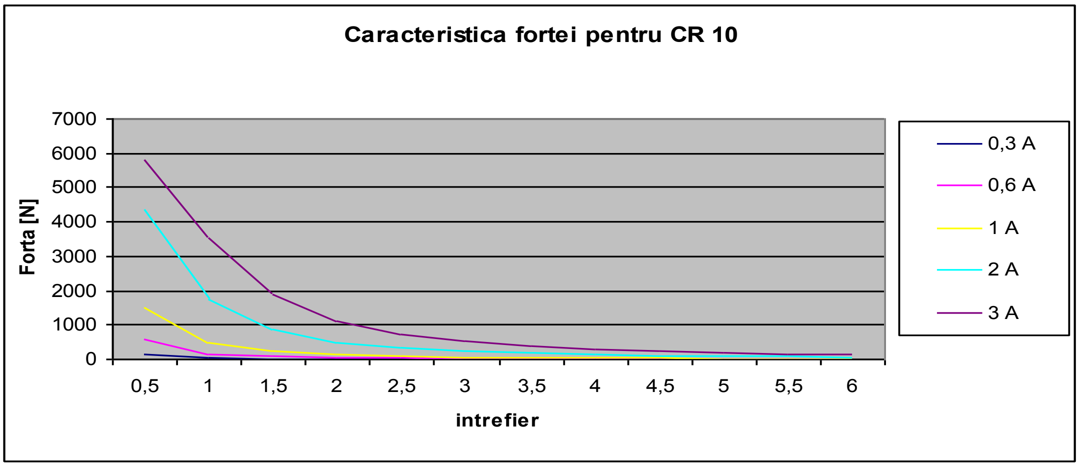

Fig. 5 Force characteristic for CR 10 and a current of 0.3 - 3 A

The shape is similar to a family of parabolas, for each value of *i* can easily determine the interpolation polynomial of the second order, which ensures a small deviation as:

$$F_{\max} = a_2 \cdot x^2 + a_1 \cdot x + a_0 \tag{4}$$

Identifying a polynomial interpolation requiring null values for the coefficients a_1 and a_0, transforms equation (4) in the expression of maximum static force air gap dependence for a fixed geometry and linear magnetic circuit, into the relationship:

$$F_{\max} = a_2 \cdot x^2 \tag{5}$$

By comparing the maximum static force on the one hand determined by FEM simulation and on the other hand by identifying the coefficient a_2 in equation (5) one can express some useful considerations early in the design calculations, especially regarding the influence of the assumption of magnetic materials linearity over the final outcome.

Based on the results of the FEM simulation, we can write the maximum static force air gap dependence for fixed magnetic circuit geometry in an analytic form. This form is useful; it helps one write a dependency matrix of higher rank than that available in discrete simulation results, leading to the generation of analytic expressions of a general nature and not subject to simplifying assumptions, for the maximum static force of air gap variation.

Obtaining the maximum static force value for any parameter value that expresses the geometry and electrical charge is essential for making a cover design method, and for the statistic deduction of dependency analytical formulas.

Thus, based on the existing data, also based on the polynomial interpolation, we determined, by using Matlab 6.5 tool, polynomial expressions which achieve, on the one hand the smallest residual norm, and on the other hand an overlap graph of the polynomial function over representation Fmax Fmax = (x) determined by FEM. For all the values of parameter *i*, second and fourth degree polynomials are obtained; these are shown in Fig. 6-8 respectively in Tables I - IV.

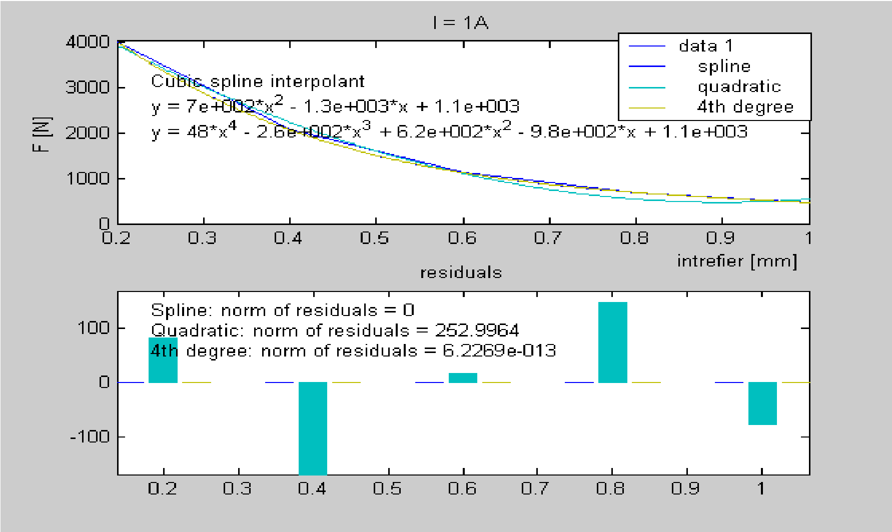

Fig. 6

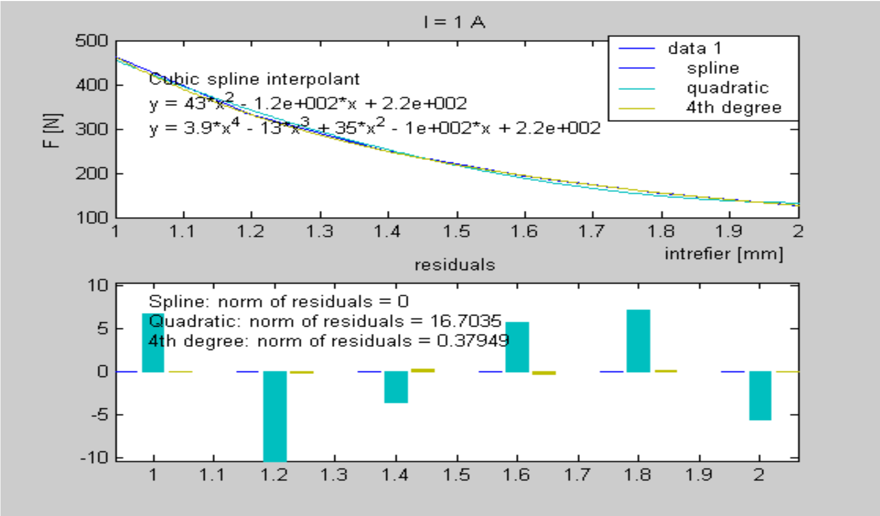

Fig. 7

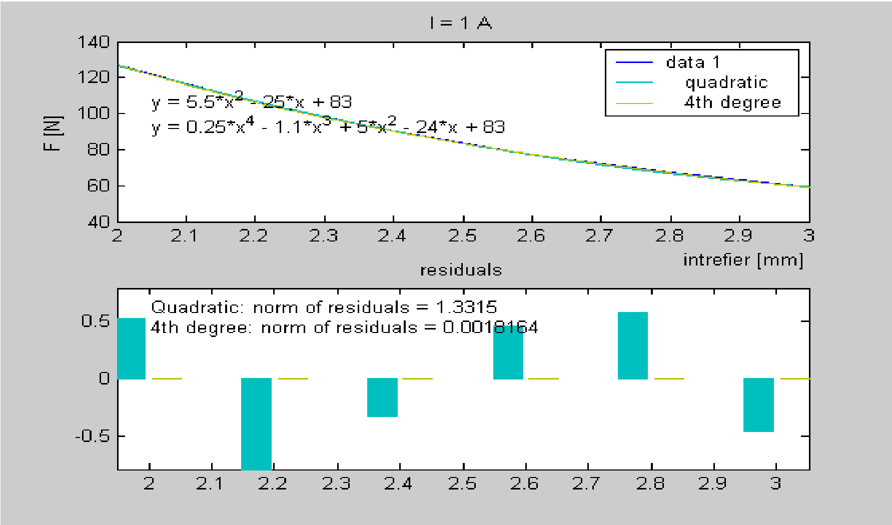

Fig. 8

Table I

i **[A]**	**Air gap 0 – 1 mm / Polynomials of degree two four**	**Norm of residuals**
0,3	1,5e+002*x^2-2,1e+002*x+90	91,316
	50*x^4-92*x^3+62*x^2-83*x+1,1e+002	7,32e-014
0,6	4,5e+002*x^2-6,9e+002*x+3,8e+002	243,736
	1,2e+002*x^4-2,5e+002*x^3+2,4e+002*x^2-3,5e+002*x+4,2e+002	5,28e-013
1	7e+002*x^2-1,3e+003*x+1,1e+003	252,997
	48*x^4-2,6e+002*x^3+6,2e+002*x^2-9,8e+002*x+1,1e+003	6,23e-013
2	1,4e+002*x^2-1,8e+003*x+3,7e+003	211,598
	47*x^4+2,2e+002*x^3+2,2e+002*x^2-2,1e+003*x+3,7e+003	2,53e-012
3	1,2e+002*x^2-1,3e+003*x+5,4e+003	23,569
	36*x^4+17*x^3-55*x^2-1,3e+003*x+5,3e+003	1,88e-012

Table 2

i **[A]**	**Air gap 1 – 2 mm / Polynomials of degree two four**	**Norm of residuals**
0,3	4*x^2-11*x+20	1,595
	0,38*x^4-1,3*x^3+3,3*x^2-9,2*x+20	3,9e-002
0,6	16*x^2-44*x+78	6,325
	1,5*x^4-5,1*x^3+13*x^2-37*x+79	0,152
1	43*x^2-1,2e+002*x+2,2e+002	16,704
	3,9*x^4-13*x^3+35*x^2-1e+002*x+2,2e+002	0,38
2	1,5e+002*x^2-4,5e+002*x+8,5e+002	54,685
	11*x^4-44*x^3+1,3e+002*x^2-3,9e+002*x+8,6e+002	1,044
3	2,5e+002*x^2-8,9e+002*x+1,9e+003	58,898
	0,38*x^4-48*x^3+2,6e+002*x^2-8,2e+002*x+1,9e+003	1,476

Table 3

i **[A]**	**Air gap 2 – 3 mm / Polynomials of degree two four**	**Norm of residuals**
0,3	0,5*x^2-2,3*x+7,5	0,12
	0,023*x^4-0,097*x^3+0,45*x^2-2,1*x+7,5	1,47e-004
0,6	2*x^2-9,1*x+30	0,482
	0,091*x^4-0,39*x^3+1,8*x^2-8,5*x+30	5,9e-004
1	5,5*x^2-25*x+83	1,332
	0,25*x^4-1,1*x^3+5*x^2-24*x+83	1,82e-003
2	21*x^2-99*x+3,3e+002	5,067
	0,94*x^4-4,1*x^3+19*x^2-94*x+3,3e+002	0,016
3	46*x^2-2,2e+002*x+7,4e+002	10,55
	1,9*x^4-8,5*x^3+42*x^2-2,1e+002*x+7,4e+002	0,014

Table 4

i **[A]**	**Air gap 1 – 3 mm / Polynomials of degree two four**	**Norm of residuals**
0,3	$5{,}4*x^2-11*x+11$	5,51
	$1*x^4-2{,}4*x^3+3*x^2-6{,}6*x+12$	0,523
0,6	$21*x^2-42*x+44$	21,918
	$4*x^4-9{,}6*x^3+12*x^2-27*x+46$	2,064
1	$58*x^2-1{,}2e+002*x+1{,}2e+002$	58,76
	$11*x^4-26*x^3+34*x^2-74*x+1{,}3e+002$	5,336
2	$2{,}1e+002*x^2-4{,}4e+002*x+4{,}9e-002$	204,02
	$35*x^4-90*x^3+1{,}3e+002*x^2-2{,}9e+002*x+5{,}1e+002$	15,895
3	$4e+002*x^2-9e+002*x+1{,}1e+003$	318,8
	$39*x^4-1{,}4e+002*x^3+3{,}1e+002*x^2-6{,}7e+002*x+1{,}1e+003$	6,423

From the analysis of the above figures and summarizing table, small deviations are observed for the entire range of variation of electric current.

In fact, despite the fact that the polynomial interpolation deviation from the results of the FEM analysis is small, the error of the linear behavior of the magnetic material can be considered unimportant up to a value of 1 mm air gap and an electrical load of 1 A. In this case, generating a geometric configuration VEM is acceptable, the model being easily optimized by FEM. Over a gap greater than 1 mm, the error resulting from the calculation of the maximum static force increases with the increase of the power application, as confirmed physically by the appearance of saturation.

The possibilities of "linearization of magnetic materials" subject to medium and large electrical applications, being relatively low due to saturation, the correction based on the model using coefficients having a relatively low degree of generality and less controllable precisions, the numerical analysis is required as a way of solving the nonlinear field problems.

The major disadvantage of numerical analyses dependent on many parameters is the occurrence of solutions as discrete representations, i.e. values to which the parameter values that led to these values must be linked. With the increasing number of parameters it is more difficult to express the solution in areas with continuous aspect (small ranges of variation of parameter values).

A particular case is the current study, which analyzes several models and where, in order to avoid obtaining a solution whose behavior in relation to the variation of the approached parameters is impossible to gauge, it was conducted in selected areas of their variation, i.e. chosen so as to cover optimal ranges of variation under the current technologies and materials.

5. CONCLUSIONS

Comparing the characteristics of the force obtained using the analytical calculation and data processing [4] and using the finite element method through the MagNet, we found out the following:

- both methods achieved a maximum strength for minimum air gap;
- the more the air gap increases, the more dramatically the force decreases;
- it was demonstrated by means of the two methods that the dynamic mode of operation of an electromagnet is the regime in which both the electric and magnetic quantities, and the mechanical ones vary simultaneously in time; it is the most general operation of an electromagnet, corresponding to a situation in which the moving fittings move, achieving the conversion of electric energy into mechanical energy;
- state quantities characterizing the dynamic regime of an electromagnet, while variable in time, independent or associated, are: the current, the flow, the force of attraction, the mobile fittings movement, (the air gap), speed and acceleration of the movement;
- the qualitative emphasis of these characteristic quantities is achieved most conveniently by computer graphics using methods based on the finite element theory.

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