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Simulation of Movable Ferromagnetic Solid Object in Induced Magnetic Field by Diakoptic Methods

Abstract. *In the paper transient processes of the system what consists of three parts: mechanical (ferromagnetic material in magnetic field), magnetic field of solenoid, and electrical (power supply circuits of solenoid) are researched by diakoptic method. A mathematical model of the magnetic system formed in the form of individual subcircuit as a result of the additional modeling of the magnetic field.*

Streszczenie. *W artykule przedstawiono metody rozwiązywania stanów nieustalonych obwodów przez podzielenie ich na mniejsze problemy mechaniczne, magnetyczne i elektryczne zgodnie z metodyką diak optyczną. Model matematyczny podsystemu magnetycznego powstaje w formie indywidualnych podobwodów w wyniku dodatkowego modelowania pola magnetycznego. (**Symulacja obiektu przemieszczającego się w polu magnetycznym przy użyciu metod diakopytcznych**).*

Keywords: large complex system, diakoptic methods, subcircuit.
Słowa kluczowe: duże złożone systemy, metoda diskoptyczna, podobwody

Introduction

In [1] posed the problem of simulation of spatial coordinate of movable ferromagnetic solid object in induced magnetic field by diakoptic methods. In furtherance of this task, then the point solid substituted for space magnetic body. These changes will significantly complicate the task, because in general it is impossible to express through the known physical functional formula to describe an object with distributed parameters, which has a time-varying geometrical configuration.

Contrariwise known diakoptic methods of time domain simulation of complex system, which can be partitioned into heterogeneous parts [2]. In our case, the position of a ferromagnetic body in a magnetic field significantly affects its shape, resulting in a need to simulate the magnetic field at each time point, independently of previous computations. Then it's generally not possible to construct a difference scheme. In this case come to the aid the simulation software for electromagnetics, heat transfer and stress analysis in particular QuickField (English version) or ELCUT (Russian version), the student version of which are publicly available [3].

Formulation of the problem and forming a mathematical model of the magnetic system

This raises the problem of the implementation of simulation results by software that is closed product, which lock down of a call from another software package. The problem solving can be in two steps:

1) independent modeling of an object with distributed parameters of complex geometric configurations as a multipole (two-port network in our problem) in order to obtain the necessary input and output characteristics, which then can be used: a) in tabular or analytical form, if you can get it, and as well b) for construction of discrete macromodel;

2) using the resulting mathematical models of objects with distributed parameters as mathematical models of subcircuits in more complex heterogeneous objects (Fig. 1).

Analysis of large complex systems with lumped and distributed components usually is carried out by simulation of the some system by essential simplification of alternative model of subcircuit.

Magnetic part consists of solenoid of specific structure, its magnetic flux associated with current of loop of electrical part; magnetic field of solenoid affects on moving body in mechanical part, which can change the structure of the magnetic field (Fig.2).

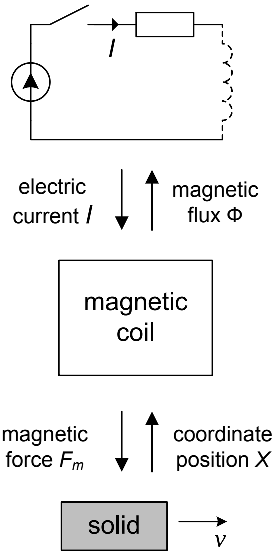

Fig.1. Complex system separated on three subsystems: electrical, magnetic, and mechanical parts

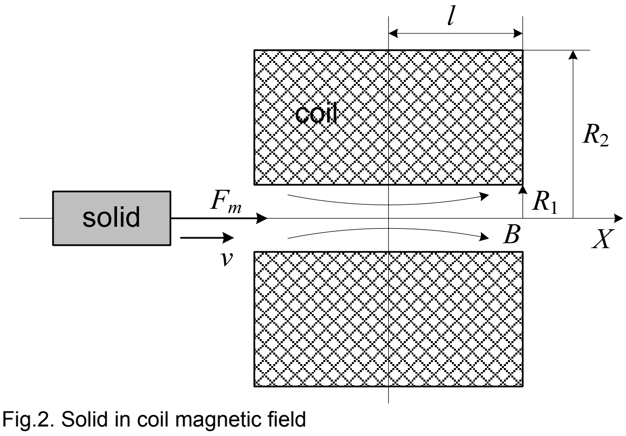

Fig.2. Solid in coil magnetic field

Forming the input and output characteristics of the magnetic system

Input and output characteristics of the magnetic system, represented as a two-pole, can be given experimentally, if there is an opportunity to explore the real physical device, or by modeling the system with distributed parameters known geometrical configuration and physical parameters of the components by relevant software. We don't consider the possibility of the link of such software in the main control software as subprogram for the once-only computation during the simulation of the transient process.

One of the available software packages with the appropriate capabilities there are simulation software for field modelling, electromagnetics, heat transfer and stress analysis ELCUT (Russian student version) [3]. To research of the magnetic system was created task (Fig. 3), the characteristics of which have been defined in [4] and extended in [1].

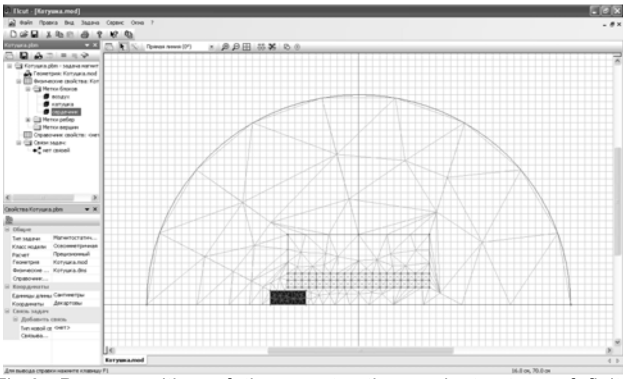

Fig.3. Decomposition of the construction and structure of finite element mesh

If necessary, you can show the distribution of the magnetic flux density or magnetic flux, or magnetic intensity in colour (Fig. 4).

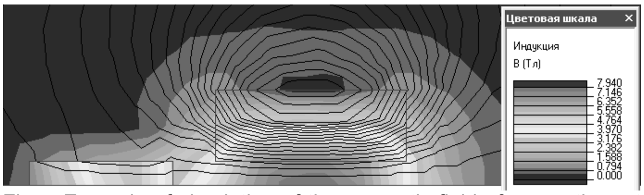

Fig.4. Example of simulation of the magnetic field of magnetic part with solid

Further action is the formation of a task to the mechanical movement of the solid in coil magnetic field and the calculation of dependence, for example, magnetic forces on the solid coordinate. These characteristics are necessary for the formation of the input and output equations of macro-model of magnetic system.

To reduce the error of approximation finite element mesh is recommended that the characteristics of the magnetic system are defined in two stages to left and to right, starting from the centre point at which the magnetic force is possessed on a minimum value.

Formation of a simplified analytical model of the magnetic system

The use from [1] of analytical dependences of the magnetic force on the distance for the solid in the form of a geometric point is making possible the calculation of the force for the body of any geometric shape:

(1) $$F_{m.X} = \mathbf{m} \cdot \mathrm{grad}\, B_X \,,$$

where F_m – magnetic force, **m** – magnetic dipole moment, B_X – magnetic flux density, X – distance from centre of solenoid to solid centre. For example [1], the force acting on 1g of iron is equal to

$$F_{m,X} \approx -k_0 \left| i \right| \frac{r^2}{l} \left(\frac{1}{\left((1-x)^2 + r^2 \right)^{3/2}} - \frac{1}{\left((1+x)^2 + r^2 \right)^{3/2}} \right),$$

where $k_0 = m\frac{\mu_0 w}{2}$, $r = R/l$ – average relative radius of solenoid, $x = X/l$ – relative distance of point from the centre of solenoid, $2l$ – length of solenoid, X and R – axial distance from centre of solenoid to point and radius of solenoid, respectively.

By volume integration of functions (1) obtain the expression

(2) $$F_m = \int_V F_{m.X} dV \,.$$

It should be noted that the argument here is not only the distance X and also the solenoid current I, which is an argument for the magnetic dipole moment **m**. In addition there are certain mathematical difficulties in calculating the magnetic flux Φ as a second output parameter, which is used to determine the state of the electrical part of the system (Fig. 1).

Forming the discrete macro-models of nonlinear dynamic subsystem

In [5, 6] affirm that is sufficient to build a macro-model to have the basic characteristics of typical modes of the system, for example, the linear regime and saturation, if a body is made of electrical steel.

From input and output characteristics in the table format (Table 1) macro-model of nonlinear dynamical subsystem formed as "black box" that allows to abstract from the internal structure of the simulated object and build the most simple macro-model in the matrix form [5].

Table 1. Dependence of the magnetic force on the distance

X, cm	F_m, N				
	$I \cdot w$ = 2 kA	$I \cdot w$ = 5 kA	$I \cdot w$ = 10 kA	$I \cdot w$ = 20 kA	$I \cdot w$ = 50 kA
0	2,4067	0,51279	-9,0616	-106	-869,22
2	-11,938	-55,17	-228,3	-896,95	-5509,5
4	-7,1048	33,736	-72,241	-274,01	-1602,4
6	-30,902	-163,88	-641,37	-2505,1	-15394
8	-113,25	-597,9	-2442,6	-9454,6	-57887
10	-133,62	-721,48	-2853,3	-11023	-67393
12	-171,52	-1010,2	-3775,4	-14540	-88802
14	-206	-1238,6	-4366,7	-16808	-102620
16	-299,37	-1812,2	-6718,3	-25626	-155600
18	-286,76	-1776,4	-6641,2	-24877	-150760
20	-222,04	-1385,4	-5172,9	-19603	-118300
22	-151,53	-951,81	-3625	-13609	-82628
24	-74,922	-468,37	-1885,6	-7050,2	-41691
26	-45,282	-284,56	-1137,3	-4435,8	-25963
28	-18,938	-118,36	-473,39	-1890,6	-11062
30	-9,2246	-57,659	-231,37	-925,09	-5515,5
32	-4,9395	-30,873	-123,5	-493,98	-3033,3
34	-2,7074	-16,922	-67,689	-270,77	-1690,4
36	-1,4982	-9,3641	-37,457	-149,84	-936,07
38	-0,7332	-4,5824	-18,33	-73,332	-458,39
40	-0,6968	-4,3548	-17,419	-69,677	-435,3
42	-0,3311	-2,0696	-8,2783	-33,113	-206,88
44	-0,2484	-1,5527	-6,2109	-24,844	-155,28
46	-0,117	-0,7309	-2,9237	-11,695	-73,084
48	-0,0765	-0,4784	-1,9136	-7,6545	-47,843
50	-0,0541	-0,3384	-1,3535	-5,4138	-33,837

Graphic representation of the set of obtained characteristics is shown in Fig. 5, where can be clearly seen the effect of the nonlinear magnetic permeability of the body on the output characteristic of the coil-body magnetic system.

Input characteristics of the magnetic system are presented in Table 2 and Fig. 6, respectively.

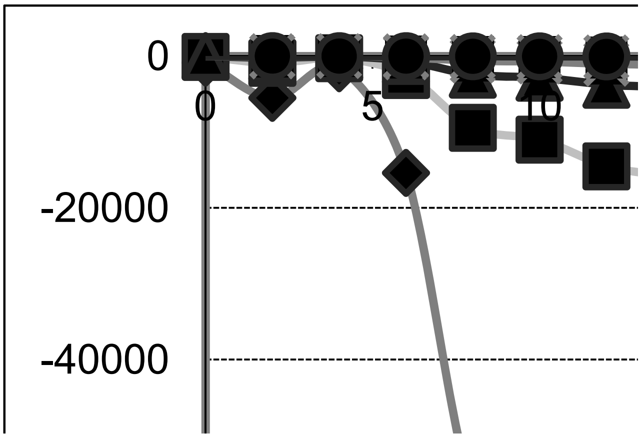

Fig.5. Dependence of the magnetic force on the distance to right of the absolute minimum in centre point for different coil currents

Table 2. Dependence of the magnetic flux on the distance

X,	Φ/w, Wb				
cm	$I{\cdot}w$ = 2 kA	$I{\cdot}w$ = 5 kA	$I{\cdot}w$ = 10 kA	$I{\cdot}w$ = 20 kA	$I{\cdot}w$ = 50 kA
0	0,0062	0,0147	0,02843	0,05587	0,1382
2	0,00583	0,01385	0,0268	0,05271	0,13041
4	0,00577	0,01373	0,02656	0,05221	0,12918
6	0,00605	0,01436	0,02776	0,05455	0,13494
8	0,00537	0,01282	0,02482	0,04882	0,12081
10	0,00549	0,01312	0,02531	0,04971	0,12288
12	0,00553	0,01322	0,02549	0,05005	0,12371
14	0,00468	0,01131	0,02187	0,043	0,10637
16	0,00439	0,01067	0,02049	0,04007	0,09883
18	0,00398	0,0098	0,01885	0,03686	0,09089
20	0,00342	0,00855	0,01704	0,034	0,08488
22	0,00336	0,00839	0,01675	0,03344	0,0835
24	0,00325	0,00812	0,01623	0,03243	0,08101
26	0,00322	0,00805	0,0161	0,03219	0,08042
28	0,0032	0,00801	0,01602	0,03204	0,08007
30	0,00324	0,0081	0,0162	0,0324	0,08098
32	0,00325	0,00813	0,01625	0,0325	0,08125
34	0,00324	0,00811	0,01622	0,03244	0,0811
36	0,00323	0,00807	0,01614	0,03228	0,08071
38	0,00325	0,00812	0,01623	0,03246	0,08116
40	0,00325	0,00812	0,01624	0,03249	0,08121
42	0,00324	0,0081	0,0162	0,03239	0,08098
44	0,00325	0,00812	0,01624	0,03248	0,0812
46	0,00324	0,0081	0,0162	0,03239	0,08098
48	0,00324	0,00811	0,01622	0,03243	0,08108
50	0,00325	0,00812	0,01625	0,0325	0,08124

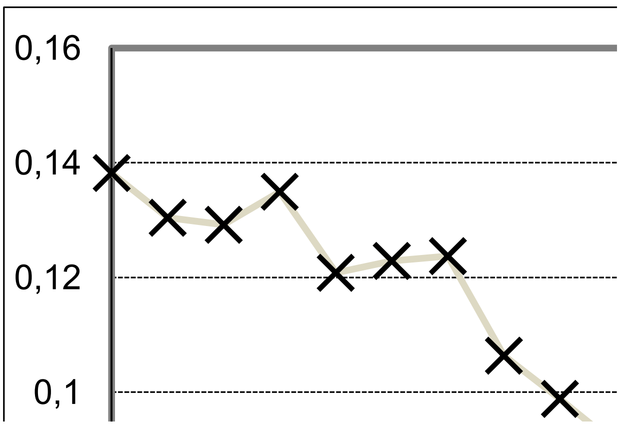

Fig.6. Dependence of the magnetic flux per one coil on the distance to right of the absolute maximum in centre point for different coil currents

The task of constructing macro-models reduced to finding a some mathematical operator, with which model reaction **y** can be calculate based on known input variables **v** and the initial value of the vector **x**. Here vector **y** consists of magnetic flux Φ and magnetic force F_m, vector **v** – electric current I and coordinate position X.

One form of representation of macro-model is discrete state equation:

$$\begin{cases} \mathbf{x}^{(k+1)} = \mathbf{F}\mathbf{x}^{(k)} + \mathbf{G}\mathbf{v}^{(k)} + \mathbf{f}\left(\mathbf{x}^{(k)}, \mathbf{v}^{(k)}\right) \\ \mathbf{y}^{(k+1)} = \mathbf{C}\mathbf{x}^{(k+1)} + \mathbf{D}\mathbf{v}^{(k+1)} \end{cases} \qquad (3)$$

where **F**, **G**, **C**, **D** – matrices of macro-model coefficients; f (*) – some nonlinear vector-function of several variables; k – number of discrete time.

Discrete form is convenient for the calculations on a PC computer, because you can avoid the approximation output, and this form is more practical in the application. Discrete form of state equations is also due to the convenience for later use of macro-model object as component of a complex dynamic system. However, this macro-model form has shortcoming, namely a fixed time step, which manifests itself when calculating the dynamic modes of complex system by diakoptic methods that limiting of matching step of heterogeneous subsystems.

Conclusions

Obtained mathematical macro-models of subsystem with distributed parameters is effectively used in the software package for time domain simulation of complex heterogeneous system by diakoptic methods, thus eliminating the need of using of special software on each integration step for the field simulation and calculation of integrated values to match the subsystems.

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