MODELING AND SIMULATION OF THE MAGNETIC SUSPENSION SYSTEMS

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ABSTRACT
The objective of these research efforts is to create the software product that could be useful for modeling, analysis and design of magnetic suspension systems. The model description, designed computer program details, and results of practical magnetic suspension system simulation are presented.

INTRODUCTION
Prediction of magnetic fields and forces is especially important problem in magnetic suspension system design. There are computer programs (Ansoft, Opera) for magnetic circuit modeling and simulation, but they are expensive and complicated. The objective of these research efforts is to define the simplified models appropriate for analysis and simulation of magnetic suspension systems, and to implement these models into software that can be used in design process.

MODEL DESCRIPTION
The magnetic reluctance equivalent model in the first approach can present the most of the practical magnetic suspension configurations.
Each part of magnetic circuit for such model is described by equation

$$R_{mj} = \frac{L_j}{\mu_0 \mu A_j} = \frac{1}{G_{mj}} \qquad (1)$$

R_{mj} is the magnetic reluctance of the corresponding section; G_{mj} is the magnetic conductance (inverse to reluctance value); L_j is length of section, μ_0 is permeability of vacuum; μ is permeability of material; A_j is the cross section area of corresponding section.
The reluctance model can include the cross coupling, flax leakage, eddy currents, nonlinear magnetization characteristics.

The magnetic flux equations for n circuit nodes can be presented by the following system

$$\left.\begin{array}{l} U_{10}G_{11} - U_{20}G_{12} - \ldots - U_{n0}G_{1n} = \Phi_{1\Sigma} \\ -U_{10}G_{21} + U_{20}G_{22} - \ldots - U_{n0}G_{2n} = \Phi_{2\Sigma} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ -U_{10}G_{n1} - U_{20}G_{n2} - \ldots + U_{n0}G_{nn} = \Phi_{n\Sigma} \end{array}\right\} \qquad (2)$$

U_{j0} is magneto motive force (MMF) between nodes j and 0. G_{jj} is total magnetic conductance of branches, connected with node j. G_{jk} is magnetic conductance between nodes j and k. $\Phi_{j\Sigma}$ is total magnetic flux of node j.
System (2) allows us to calculate the MMFs U_{j0} that in combination with corresponding turns-current products $n_j i_j$ define the magnetic fluxes Φ_j in branches of circuit. Magnetic fluxes define the magnetic flux densities

$$B_j = \frac{\Phi_j}{A_j}. \qquad (3)$$

From the magnetic flux densities we can estimate the magnetic forces. The relation between magnetic force and flux density for a pair of poles each of area A is:

$$F = \frac{AB^2}{\mu_0}. \qquad (4)$$

The mentioned above mathematical equations were implemented into computer program. The computer program was realized in C++ programming language and allows one to simulate the magnetic circuits in the interactive mode. The user menu options include the standard interface options (File, Edit, Help) and some special ones (Elements, Simulation parameters, Simulation results). Simulation results can be imported into another programs for further analysis.

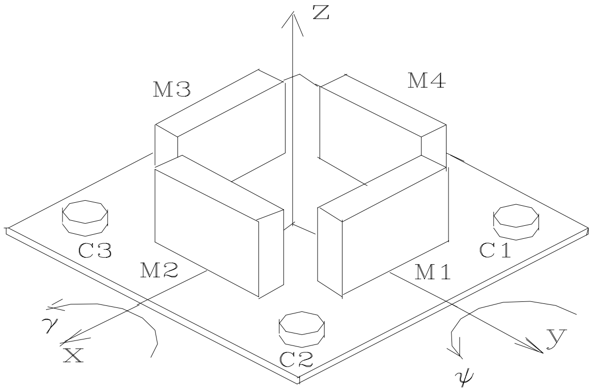

FIGURE 1: Schematical System Design

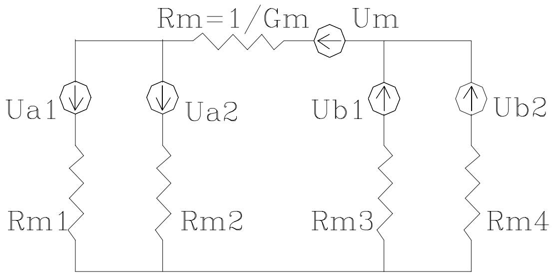

FIGURE 3: Equivalent Circuit of Actuator

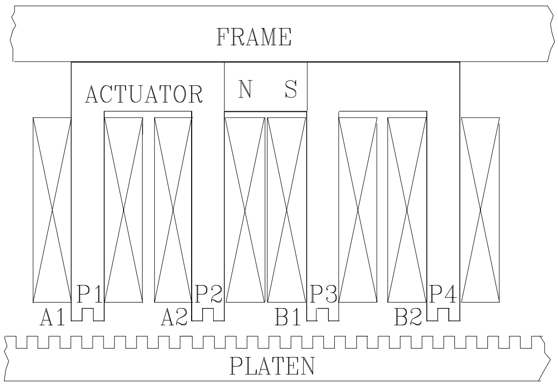

FIGURE 2: Structure of Actuator

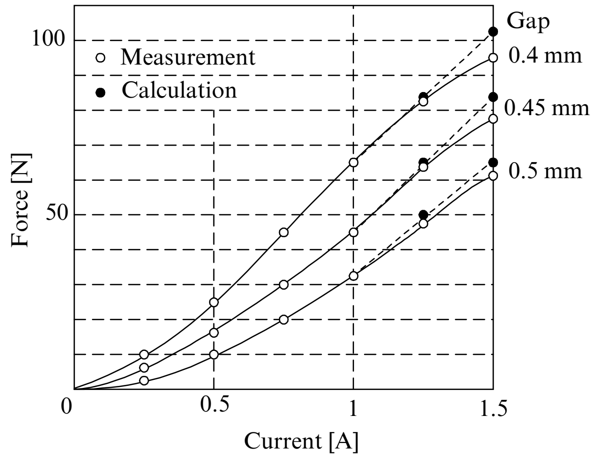

FIGURE 4: Measured and calculated actuator force curves

IMPLEMENTATION OF SOFTWARE

Some practical magnetic suspension system configurations were studied including actuator of a precision magnetically suspended motion control stage (Fig. 1). An actuator design combining permanent magnet and electromagnet has the advantages of compact size, high efficiency and low heat generation (Fig. 2).

Figure 3 shows the corresponding equivalent circuit of actuator, where U_m is the magneto motive force (MMF) of permanent magnet (PM), U_{aj}, U_{bj} are the MMFs of the coils, R_{mj} is the magnetic reluctance of the air gap under the corresponding pole; G_{mj} is the magnetic conductance (inverse to reluctance value); R_m is reluctance of the permanent magnet.

In our analysis we suppose that effect of iron saturation is negligible and there are no leakage fluxes.

Magnetic reluctance of the iron core is negligible in comparison with that one of PM and air gap.

The reluctance mathematical model of actuator allows us to derive the equations for attractive and propulsive forces. Figure 4 shows the measured and calculated actuator attractive force curves.

CONCLUSIONS

The computer software was developed that allows us to analyze, simulate and design electromagnetic circuits of different configurations. The model description, designed computer program details, and results of practical magnetic suspension system simulation are presented. The future efforts will be concentrated on further improvement of models and development of user opportunities.