MODELLING OF ELECTROMAGNETIC ACTUATOR WITH FERROFLUID

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Abstract: *In this work an electromagnetic actuator with ferrofluid is investigated. 3D finite element method model is developed and implemented to obtain the distribution of magnetic field in magnetic circuit. Static electromagnetic characteristics of the solenoid type actuator are determined. Electromagnetic force is calculated by Maxwell stress tensor method. Developed model employs the ANSYS 12.1 software package. Results for magnetic field distributions and static electromagnetic characteristics are presented and analysed.*

Keywords: *Electromagnetic systems, Nanomaterials, Modeling, Ferrofluid, Electromagnetic actuators, Finite element method.*

INTRODUCTION

In recent years, growing interest of many electrical engineers and researchers is elicited by electromagnetic systems with ferrofluid nanoscale materials. These systems are characterized with better work characteristics, reduced energy consumption, compact in size and etc. The presence of ferrofluid materials in electromagnetic system leads to important features in the operation of devices under consideration. Some of electromagnetic systems with ferrofluid are considered in [1, 2].

Ferrofluid is a colloidal stable suspension of ferrite nanoparticles in liquid and surfactant. The surfactant molecules covered the solid particles and the fluid behaves as a homogeneous system even in the presence of external forces such as magnetic and centrifugal. The nanoparticles are usually iron oxides or different compounds as manganese-ferrite, zinc-ferrite, manganese-zinc-ferrite, cobalt-ferrite, copper-ferrite, and nickel-ferrite. The liquids are deionized water or a mixture of organic solvents or synthetic oils. The sizes of nanoparticles can vary from 1 nm to 100 nm and determine the properties of ferrofluid. In addition there are two other key parameters used to specify ferrofluids, namely the saturation magnetization and viscosity. By varying the constituents, a wide variety of ferrofluids with varying properties can be created [3, 4].

Ferrofluid in electromagnetic actuators increases electromagnetic force and thus, with such construction could be obtained greater force in smaller volume. Ferrofluid perfectly adapts to any geometry and could moves through very small channels. Ferrofluid is characterized with high magnetization saturation with no remanence. Furthermore, a significant problem associated with solenoid type actuators is that they tend to generate noise. This noise is caused by the plunger striking the core and rubbing against the walls of the core. These movements also lead to wear of construction. The ferrofluid provides eliminating or substantially reducing the noise. Such actuators are operational over long periods of time because of minimizing or preventing mechanical wears of the construction [5].

Devices working with ferrofluid are various types of MEMS pumps, different transducers and sensors [6, 7]. Ferrofluid is applied to seal technology for miniature pneumatic and hydraulic actuators [8].

In this article an electromagnetic solenoid type actuator with ferrofluid is modelled. 3D finite element method is implemented to obtain the distribution of magnetic field in the actuator. Electromagnetic force characteristics of the solenoid actuator are determined and analysed for different magnetic properties of ferrofluid material.

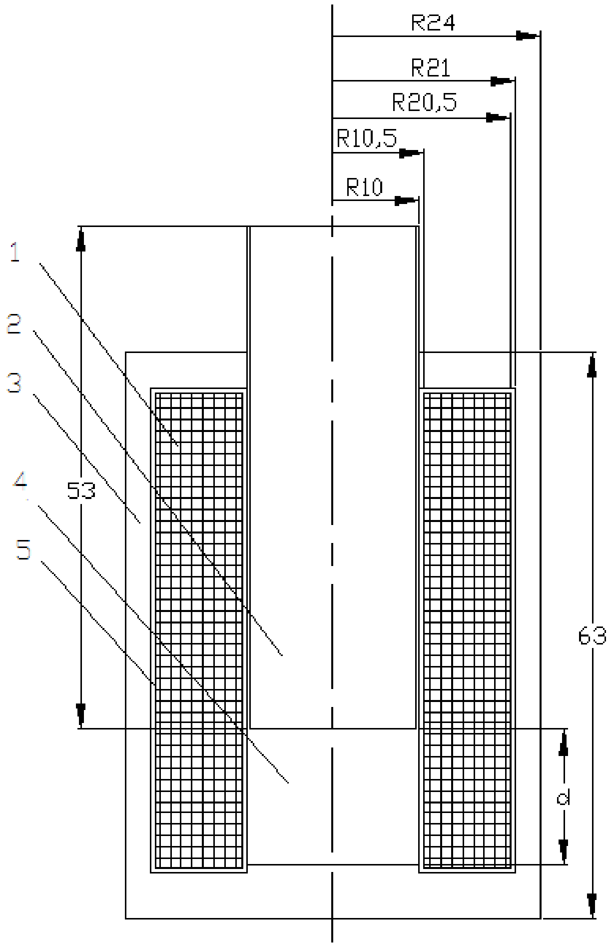

Fig. 1 *Electromagnetic actuator cross-section*
1 - coil, 2 - ferromagnetic plunger, 3 - ferromagnetic core,
4 – magnetic gap with ferrofluid, 5 - insulation of coil

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ELECTROMAGNETIC ACTUATOR

The electromagnetic actuator is solenoid type construction and consists of a stationary ferromagnetic core, a movable cylindrical ferromagnetic part (plunger) and magnetic gap with ferrofluid. In Fig. 1 are given the dimensions in millimetres of electromagnetic actuator.

The material of core and plunger is carbon steel 12 040. The air gap is filled with ferrofluid. The coil is with 500 turns, copper wire with diameter 1mm is used. Current density at coil region is $J=1.6\times10^6$ A/m^2. The coil serves as a source of power to energize the magnetic circuit. Magnetomotive force (mmf), determined by the current I and number of turns w, creates magnetic flux. Magnetic flux creates electromagnetic force attracting the plunger. Ferrofluid is used to reduce the dissipation of magnetic flux in the gap of the electromagnet.

MAGNETIC FIELD PROBLEM

Magnetic field distribution is described by Poison's equation

$$rot(\frac{1}{\mu}rot\mathbf{A}) = \mathbf{J} \quad , \qquad (1)$$

where **A, J** and μ are the magnetic vector potential, the source current density and the magnetic permeability**,** respectively.

Homogeneous Dirichlet's boundary conditions are imposed over the boundary of buffer zone surrounded the actuator.

Electromagnetic force acting on plunger is calculated by Maxwell stress tensor method

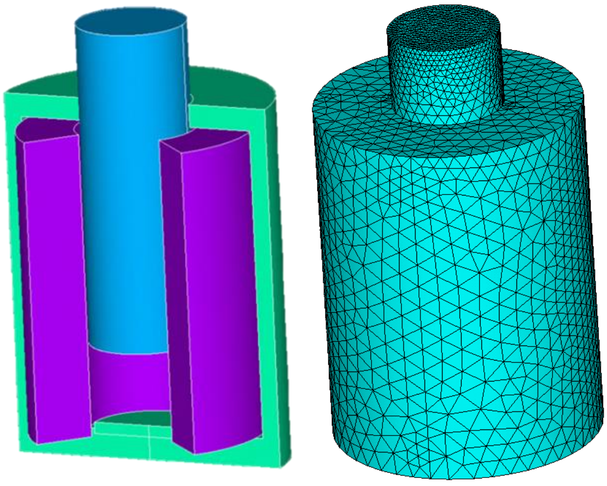
$$\mathbf{F} = \iint_S \left((\mathbf{n}\cdot\mathbf{B})\mathbf{H} - \frac{1}{2}(\mathbf{B}\cdot\mathbf{H})\mathbf{n} \right) dS \, , \qquad (2)$$

where **B**, **H, n,** S are the vector of magnetic flux density, vector of magnetic field intensity, unit vector to normal and closed surface, respectively [9, 10, 11].

IMPLEMENTATION

For solving the formulated problem finite element method by ANSYS 12.1 software is used [12]. Computations were automated using ANSYS Parametric Design Language (APDL). 3D geometrical model of electromagnetic actuator is built and shown in Fig. 2(a). In Fig. 2(b) are presented the meshed volumes. Element SOLID236 is used to solve the problem. The mesh consists of 773 557 elements.

Two models for calculation of electromagnetic force are developed. The first model is linear with ferromagnetic core and ferromagnetic plunger made of steel with magnetic permeability μ=1000. Second model is nonlinear. Material of plunger and core is carbon steel 12 040 with nonlinear material characteristic, shown in Fig. 3.



(a) *(b)*

Fig.2 *3D model of electromagnetic actuator*

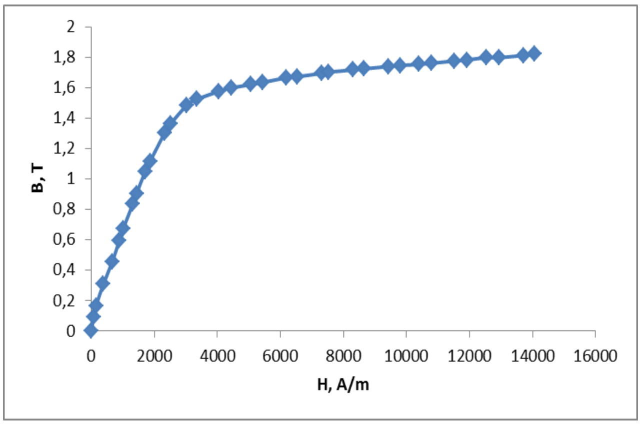


Fig.3 *B-H curve of carbon steel 12 040*

RESULTS

Distributions of magnetic flux density of the electromagnetic actuator at various values of the magnetic gap and magnetic permeability of the ferrofluid are determined.

In Fig. 4 and Fig. 5 are shown magnetic flux density distributions at d = 2.5 mm with relative magnetic permeability of the ferrofluid μ = 1 and μ = 5, respectively. The maximum value of magnetic flux density obtained with air gap and relative magnetic permeability μ = 1 is B_{max}=0.986 T and it is obtained in the plunger. The maximum value of magnetic field intensity is H_{max}=25 604 A/m and it is obtained in the air gap. But using the magnetic gap with ferrofluid and relative magnetic permeability μ = 5, B_{max}=1.71 T and H_{max}=19 515 A/m.

For the electromagnetic actuator with air gap d = 35 mm and relative magnetic permeability μ = 1 is determined the distribution of magnetic flux density, shown in Fig. 6. In

Fig. 7 is shown distribution of magnetic flux density with relative magnetic permeability of ferrofluid $\mu = 5$. The maximum value of magnetic flux density and magnetic field intensity with air gap are B_{max}=0.185 T and H_{max}=6 713 A/m. And with magnetic gap with ferrofluid are B_{max}=0.499 T and H_{max}=5 293 A/m.

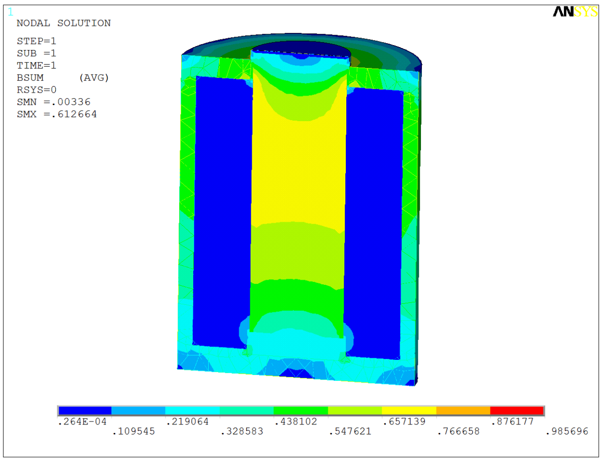


Fig.4 *- Distribution of magnetic flux density, d = 2.5mm, μ = 1*

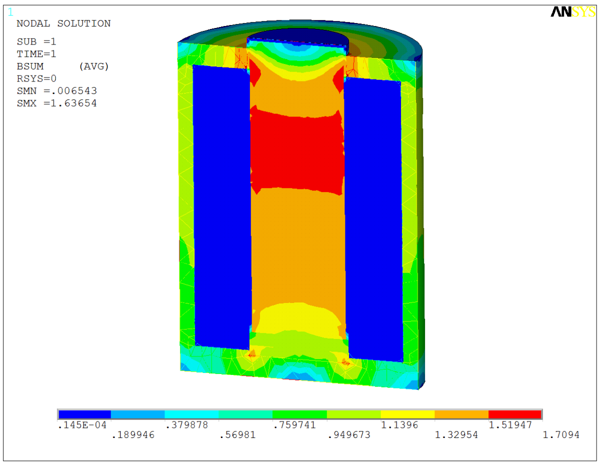


Fig.5 *- Distribution of magnetic flux density, d = 2.5mm, μ = 5*

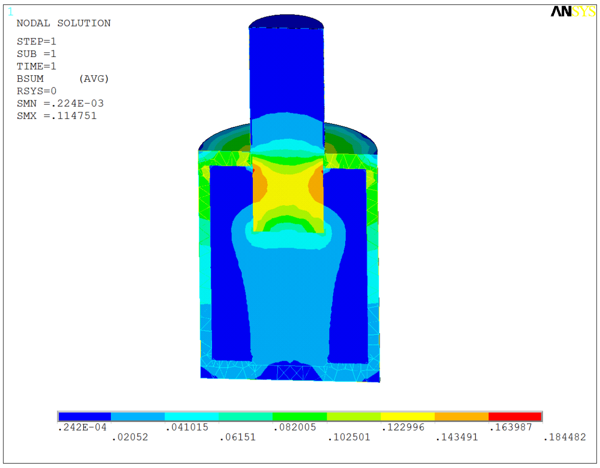


Fig.6 *- Distribution of magnetic flux density, d = 35mm, μ = 1*

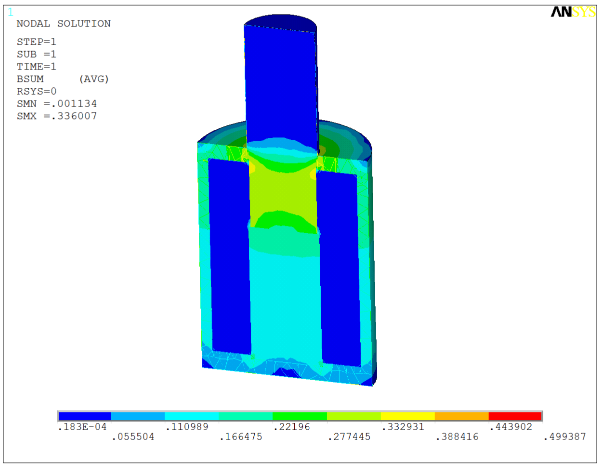


Fig.7 *- Distribution of magnetic flux density, d = 35mm, μ = 5*

The linear problem is solved with different relative magnetic permeability of the ferrofluid, $\mu = 1, 2, 5, 10, 50$. The results for electromagnetic force are shown in Fig. 8, where it is seen that with higher magnetic permeability of the ferrofluid is obtained greater electromagnetic force and electromagnetic characteristics are shifted. The maximum value of electromagnetic force is F_{max}=73.252N and it is obtained with $\mu = 50$ at gap d=2.5mm.

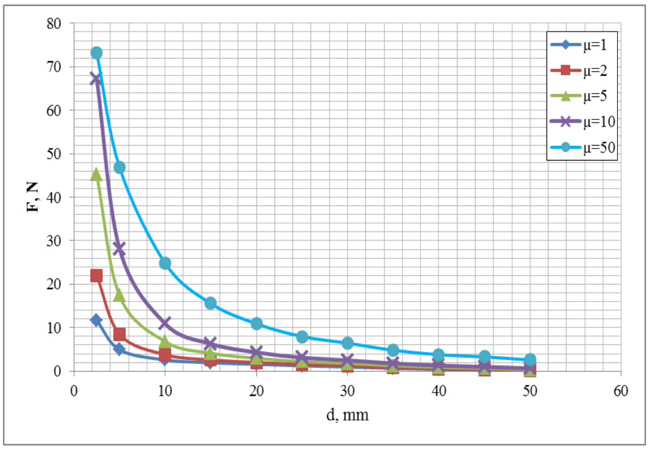


Fig.8 *- Calculated force characteristics for the linear formulation.*

The nonlinear problem is solved with different relative magnetic permeability of the ferrofluid, $\mu = 1, 2, 5, 10$ and 50. The results for electromagnetic force are shown in Fig. 9. It could be seen that with higher magnetic permeability of the ferrofluid is obtained greater electromagnetic force. The electromagnetic characteristics at relative magnetic permeability $\mu = 10$ and $\mu = 50$ cross the other. This effect is due to reduction of the magnetic energy in the working gap and increase of the magnetic energy in the plunger and core. The maximum value of electromagnetic force F_{max}= 28.995 N is obtained with μ =5 at gap d=2.5mm.

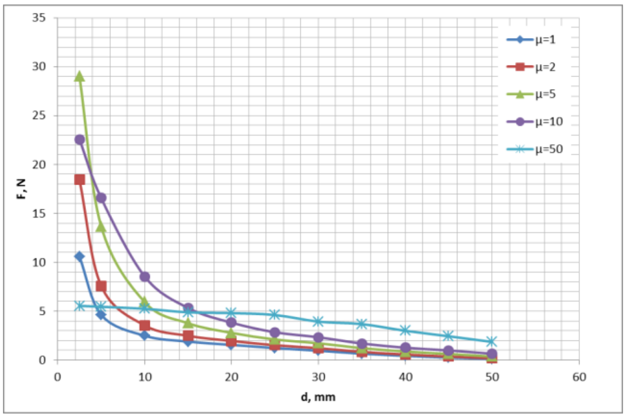


Fig.9 *- Calculated force characteristics for the non-linear formulation.*

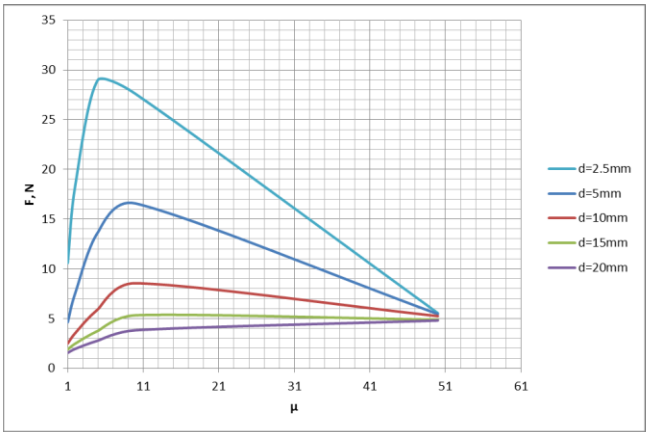


Fig.10 *– Electromagnetic force as a function of the relative magnetic permeability of ferrofluid for nonlinear problem*

For nonlinear problem in Fig.10 are shown characteristics of electromagnetic force according to relative magnetic permeability of ferrofluid at different working gaps. In small gaps electromagnetic force is increasing significantly at range of relative magnetic permeability from 1 to 5. With higher relative magnetic permeability, electromagnetic force is decreasing. But at large gaps the change of the electromagnetic force is low.

CONCLUSION

Computer modelling using finite element method applied for solenoid construction of electromagnetic actuator with ferrofluid is presented. The magnetic problem is formulated. Linear and nonlinear magnetic field models of the investigated actuator are built. The finite element method with magnetic vector potential formulation is used for modelling of electromagnetic processes and for determination of different characteristics as electromagnetic force and magnetic flux density distributions. The results obtained from computer modelling are presented and analysed.

Developed model can be used for accurate determination of the characteristics of such electromagnetic devices. Also it will be applied for constructional optimal design using different optimal criteria and parameters. Further investigation will be focused on synthesis of 3D coupled field magnetic-fluid dynamics model.

ACKNOWLEDGEMENTS

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