Abstract

Appearance of the new generation nano-ferrofluid materials dramatically improves the operational characteristics of electromagnetic systems and devices. In this work new performance of solenoid type electromagnetic actuator with nano-ferrofluid is investigated and analyzed. Theoretical approach based on 3D multiphysics model of the actuator is developed for fields, processes and phenomena analysis as well as for determination of actuator operational characteristics and parameters. The model couples together electromagnetic field analysis, electric circuit analysis, fluid dynamics analysis and mechanical movement analysis. Transient mode of switching on the electromagnetic actuator is modeled. Measurement system for experimental determination of static and dynamic characteristics of the electromagnetic actuator with ferrofluid is built. Operational electromagnetic characteristics of the actuator are obtained and compared with and without ferrofluid presence in the working gap. Measured results are presented, analyzed and compared with those obtained by developed theoretical model. The developed theoretical and experimental models and investigation approaches could be used in design, optimization and investigation of new effective electromagnetic actuators and devices.

INTRODUCTION

The electromagnetic actuators are widely used in industry [1-5], because of their operational advantages including excellent performance, high reliability, long lifetime, minimal maintenance, etc. They are part of various electromechanical devices, controlling different mechanisms and systems. An electromagnetic actuator with solenoid type electromagnet is utilized in electromagnetic valve actuation systems, fuel injection actuation, exhaust gas recirculation systems, refrigerators, washing machines, etc. [1-4].

The static characteristics are necessary for interoperability of electromagnet operation and counteractions, such as reaction of spring or mass of the armature, etc. The dynamic characteristics are very important because they describe completely performance of the actuator. The static and dynamic characteristics are very sensitive to core shape, electric elements, mechanical elements and magnetic elements. In order to obtain accurate dynamic characteristics of the electromagnetic actuator, it is necessary to perform a transient analysis. To take into account all physical phenomena, it is necessary to coupled electromagnetic field analysis, electric circuit analysis, fluid dynamics analysis and mechanical movement [5, 6].

In recent years, growing interest attracts electromagnetic systems with ferrofluid nanoscale materials [7-11]. These systems have many advantages. Electromagnetic actuators with ferrofluid in the working gap are characterized with better operational characteristics compared with those with air gaps, such as reduced energy consumption, compact in size, etc. 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. 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 diversity of ferrofluids with different properties could be created [12, 13]. Modeling of electromagnetic field distributions in electromagnetic actuators with ferrofluid in its construction must be handled by modern coupled field numerical methods covering all specific properties of modeled applications. Finite element method (FEM) is a powerful numerical method capable to solve such complex problems taking into account all characteristics and special features. Recent achievements of the FEM give possibilities to model fully three-dimensional, nonlinear, inhomogeneous, or anisotropy fields and multi-joint systems.

In this work two investigation approaches are applied for analysis of electromagnetic systems with nano-ferrofluid. First one is theoretical approach for multiphysics problem modeling; second one is experimental approach realized via a sophisticated computer aided measurement system.

In this work new performance of solenoid type electromagnetic actuator with nano-ferrofluid is investigated and analyzed. 3D multiphysics model of the actuator is developed for fields, processes and phenomena analysis as well as for determination of actuator operational characteristics and parameters. The model couples together electromagnetic field analysis, electric circuit analysis, fluid dynamics analysis and mechanical movement analysis. Magnetic field distribution is analyzed by finite element method. Electromagnetic force over the actuator armature is calculated by Maxwell stress tensor method. Dynamic behavior of electromagnetic actuator in transient mode is numerically modeled. Measurement system for experimental determination of static and dynamic characteristics of the electromagnetic actuator with ferrofluid is built.

Electromagnetic force and operational characteristics of solenoid type actuator is measured by laboratory measurement system. Operational electromagnetic characteristics are determined for armature moving in ferrofluid in the working gap and they are compared with the characteristics of electromagnet without ferrofluid.

**PROBLEM FORMULATION**

To take into account all physical phenomena that take place in the actuator construction, it is necessary to coupled electromagnetic field analysis, electric circuit analysis, fluid dynamics analysis and mechanical movement analysis. For determination of the dynamic characteristics of the electromagnetic actuator, a multiphysics coupled electromagnetic field – fluid dynamics – dynamic movement model is established. The fields distributions inside the electromagnet working gap region depends on the ferrofluid presence there as well as on the electric circuit and kinematics of the device.

**Magnetic field modeling**

Magnetic field distribution in electromagnet actuator is described by the magnetic vector potential formulation

\[
\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) - \nabla \times \left( \frac{\mu_0 M}{\mu} \right) = J ,
\]

where \( A, M, J \) and \( \mu \) are the magnetic vector potential, magnetization vector, the source current density and the magnetic permeability, respectively.

Homogeneous Dirichlet’s boundary conditions are imposed over the boundary of buffer zone surrounding the actuator.

Magnetic force acting on armature is calculated by Maxwell stress tensor method

\[
F_{\mu} = \int_S \left( n \cdot B \right) H - \frac{1}{2} \left( B \cdot H \right) n \, ds ,
\]
where \( \mathbf{B}, \mathbf{H}, \mathbf{n}, s \) are the vector of magnetic flux density, vector of magnetic field intensity, unit vector to normal and closed surface, respectively [15]. Magnetic inductance \( L \) is calculated by stored magnetic field energy – \( W \) expressed by

\[
W = \frac{1}{2} Li^2, \tag{3}
\]

where \( i \) is the coil current.

**Fluid dynamics modeling**

The effect of magnetic field on the magnetic nanoparticles volume concentration is governed by the Navier–Stokes equation for fluid velocities \( \mathbf{v} \) and pressure \( p \)

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \nabla \mathbf{v} \right) = \nabla p + \eta \nabla^2 \mathbf{v} + \mathbf{F}_M, \tag{4}
\]

where \( \rho \) and \( \eta \) are the density and viscosity of ferrofluid, respectively. Equation (4) is solved with suitable boundary conditions specifying the contact between the fluid and the domain walls, \( \mathbf{v} = 0 \), and zero traction force at the outflow, \( (p_n - \mathbf{v}_n) = 0 \) on the fluid domain cross-section.

**Dynamic modeling**

Dynamic characteristics of electromagnetic actuator system are determined in switching - transient mode. The system of equations which describes the process of switching on the electromagnetic actuator is composed of the electric circuit equation of the actuator coil and motion equation

\[
\begin{align*}
U &= Ri + \frac{d\psi}{dt}, \\
F_M &= m \frac{d^2 x}{dt^2} + kx + F_{fr} + F_{ff}
\end{align*}, \tag{5}
\]

where in the electric circuit equation \( U, R, \psi, x \) are supply voltage, resistance of the coil, flux linkage and displacement of the armature, respectively. In the motion equation \( m, k, F_M, F_{fr}, F_{ff} \) are mass of the armature, stiffness coefficient of the spring, electromagnetic force, friction force with core and resistive force of ferrofluid, respectively [15, 18]. Magnetic flux linkage is determinate by the coil inductance, depending on coil current and armature gap.

The system is solved by Euler method, which is first-order numerical procedure for solving ordinary differential equations. For each time step of the integration procedure the current values of electromagnetic force and coil inductance are acquired by the FEM magnetic field model.

**COMPUTER AIDED MEASUREMENT SYSTEM**

Computer measurement laboratory test system is developed for determination of static electromagnetic and dynamic characteristics of electromagnetic solenoid type actuator. In Fig. 1 is shown block diagram with main elements of the developed measurement system.

Computer measurement system is composed of test bench/fixture, measurement sensors and transducers, controllable power supply, data acquisition measurement module and computer unit with LabVIEW software, shown in Fig.2.
Fig. 1 Block diagram of the experimental computer measurement system.

Fig. 2 Computer measurement system.

Constructed test bench/fixture is shown in Fig. 3. The main elements of the test bench are force/strain gauge, holder for fixing armature, injector for ferrofluid. A force/strain gauge for measuring the strength/pressure at range ± 30N with accuracy of 0.001 N is used. The computer measurement system is supplied by DC electric power supply HY3005D [17]. Automation of the measurement process is done by using the program LabVIEW [17].
The electromagnetic actuator under consideration is solenoid type construction and consists of a stationary ferromagnetic core, a movable cylindrical ferromagnetic part (armature) with cone end, magnetic gap filled with ferrofluid, opening spring and supporting elements. In Fig. 4 are shown the cross-section with dimensions of electromagnetic actuator.

The material of core and armature is electrical steel with non-linear B-H characteristic [3]. The air gap is filled with ferrofluid and is considered as a magnetic gap. The coil consists of 600 turns, copper wire with diameter 1mm is used. Average current density at coil region is $J = 7 \times 10^6 \text{ A/m}^2$. The mass of the armature is $m = 0.042 \text{ kg}$. The used spring is with stiffness coefficient $k = 300 \text{ N/m}$. The ferrofluid is with relative magnetic permeability $\mu = 1.21$; saturation flux density $B_s = 44 \text{ mT (± 10%)}$; magnetization $M = 107 \text{ kA/m}$; viscosity $< 6 \text{ mPa}\cdot\text{s}$; density $1.1 \text{ g/cm}^3$; boiling point $230 \text{ °C (± 10 %)}$ [14]. The electric power of the coil energize the magnetic circuit. Magnetomotive force (mmf), determined by the rated current $I = 1.66\text{A}$ and number of turns $w$, creates magnetic flux. Magnetic flux creates electromagnetic force attracting the armature. Ferrofluid is used to reduce the dissipation of magnetic flux in the working gap of the electromagnet.
IMPLEMENTATION

For solving the electromagnetic problem finite element method by ANSYS 12.1 software is employed [16]. 3D geometrical model of electromagnetic actuator (Fig. 4 – c) is built and implemented for determination of static and dynamic characteristics. For determination of dynamic characteristics are coupled magnetic, electric and motion equations. Computational process uses iterative technique, the time is divided into subintervals equal to 0.001s. In each time step are calculated the current of the coil, velocity and displacement of the armature. Values of electromagnetic force and inductance of the coil are obtained from magnetic problem by finite element method. The results from current step are used to obtain the solution in next time step. The initial conditions used for dynamic characteristics calculations at \( t_0=0 \) are \( \delta_0=\delta_{in} \), \( x_0=0 \), \( i_0=0 \), \( U=6V \), \( R=3.7\Omega \). The calculations are made for different initial working gaps \( \delta_{in}=6\div18 \) mm. Computations were automated using ANSYS Parametric Design Language (APDL).

Electromagnetic actuator is investigated in static and dynamic mode. Static electromagnetic force is calculated at working gap \( \delta=1\div18 \) mm. Dynamic characteristics are obtained at various working gaps. Distributions of magnetic flux density of the electromagnetic actuator at several values of the magnetic gap are determined.

In Fig. 5 – a, b, c, d are shown magnetic flux density distributions for electromagnet with air gap and with ferrofluid at \( \delta=1 \) mm and \( \delta=18 \) mm. The maximum value of magnetic flux density obtained with ferrofluid at working gap \( \delta=1 \) mm is \( B_{max}=1.75 \) T and with air gap \( B_{max}=1.74 \) T. At working gap \( \delta=18 \) mm the maximum value of magnetic flux density with ferrofluid is \( B_{max}=1.020 \) T and with air gap \( B_{max}=0.97 \) T.
In Fig. 6 – a, b are given the dynamic characteristics of the current changing with time in switching mode of the electromagnet. The calculation are made for electromagnet with air gap and with working gap filled with ferrofluid. In Fig. 7 are shown characteristics of electromagnetic force changing with time and in Fig. 8 are shown characteristic of inductance changing with time.
The presence of ferrofluid in electromagnet leads to increasing of the magnetic force acting on the armature at greater working gaps. Moreover, the value of ferrofluid permeability affects on the shape of the corresponding curve, the characteristic becomes flatter. In switching on mode the current in electromagnet with ferrofluid is lower than in electromagnet with air gap (Fig. 6). The coil inductance is higher when the electromagnet operates with ferrofluid. The switching time of solenoid almost not influenced. These results are experimentally investigated [17].
EXPERIMENTAL INVESTIGATION

The dynamic characteristics of the electromagnetic actuator are measured by the developed computer measurement system. Dynamic characteristics are determined in switching - transient mode for electromagnet’s armature. For this purpose the holder device for fixing actuator armature in the stationary position has been replaced by spring mechanism.

In Fig. 9 are given the dynamic characteristics of the current changing with time in switching mode of the electromagnet. Rated current of the solenoid type electromagnet is 1.66 A.

![Fig. 9 Dynamic characteristics of the actuator at various gaps at supply current of I=1.66A - a) and I = 2.075A – b)](image)

The dynamic characteristics of the electromagnet is determined also at current 25% higher than rated one (I = 2.075 A). The results obtained for transient process are shown in Fig.9-b. The response time of the electromagnet for air gap δ = 6 mm with current I = 1.66A is t = 0.041s and with current I = 2.075A, t = 0.036s. For air gap δ = 16 mm and I=1.66 A the response time is t = 0.134 s and for I = 2.075A, t =0.079 s.

It is seen that for larger air gaps with increasing current by 25%, the response time of the electromagnet decreases almost by half.

CONCLUSIONS

Investigation approach for solenoid type electromagnetic actuator with nano-ferrofluid is developed and performed. 3D multiphysics model of the actuator is developed and applied for operational characteristics determination. Operational electromagnetic characteristics are determined for armature moving in ferrofluid in the working gap and they are compared with the characteristics of electromagnet without ferrofluid. Computer measurement system for experimental determination of static and dynamic characteristics of the electromagnetic actuator with ferrofluid is built. The developed and implemented computer measurement system is characterized with simplicity, with easy operation and with high accuracy according to force measurements (0.001 N), distance measurements (0.1 mm) and electric voltage measurement (1.47 mV). Measurement process could be further improved by applying more sophisticated virtual instrument and accurate sensors. Developed computer measurement system is suitable for investigation of electromagnetic actuators as well as for scientific and educational research.

Developed model can be applied for explorations of the characteristics of such electromagnetic devices. The developed theoretical and experimental models and investigation approaches could be used in design and optimization of new effective electromagnetic devices.
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References

ЕЛЕКТРОМАГНИТНИ СИСТЕМИ И УСТРОЙСТВА С НАНО ФЕРОФЛУИДИ

Илиана Маринова, Валентин Матеев, Анелия Терзова

Катедра „Електрически апарати“, Технически Университет - София
бул. Климент Охридски №8, бл. 12, 1756 София

Резюме
Появата на нови нано-ферофлуидни материали подобрява значително работните характеристики на електромагнитните системи и устройства. В тази статия е изследвания работата на соленоиден електромагнитен изпълнителен механизъм с нано-ферофлуид. Формулирана е задачата за моделиране на работните характеристики на електромагнитния изпълнителен механизъм с ферофлуид. Разработен е 3D модел на изследвания електромагнит, използващ метода с крайни елементи, за изследване на свързаните физични полета на системата. Преходният процес на включване на електромагнита е моделиран и изследван посредством прецизна компютърна измерителна система за експериментално определяне на електромагнитните работни характеристики на устройството. Моделираните и експериментално измерени работни характеристики, със и без ферофлуид, са сравнени и анализирани. Разработените и разгледани модели, измерителна система формират обобщен изследователски подход, който може да се използва при проектирането и оптимизацията на нови ефективни електромагнитни устройства и изпълнители механизми.