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DESIGN OF ELECTROMAGNETIC ACTUATOR AND EXPERIMENTAL VERIFICATION OF ITS PARAMETERS

FRANTIŠEK MACH

Abstract: *This work deals with the design and experimental verification of a DC linear electromagnetic actuator using power effect of the magnetic field in ferromagnetic material.*

Key words: *Electromagnetic actuator, static characteristic, dynamic characteristic*

INTRODUCTION

Actuators (also called as power transducers) are devices that transform input energy (control variable) to output mechanical work (acting variable). A special type is the electromagnetic actuator. Electromagnetic actuator transforms electric current into force interaction and its effects. The principle of such transformation is based on force interaction in a magnetic field. Electromagnetics actuators are used in many applications (from small devices for a very precise control of position to quite powerful units such as drives of rods in nuclear reactors).

The aim of this work is design and experimental evaluation of a DC linear electromagnetic actuator uses the force acting on ferromagnetic material located in magnetic field.

1 CONCEPT

The solved actuator consists of two basic parts – electric and magnetic circuits. The electric circuit is formed by a cylindrical coil wound fixed on the frame. The magnetic circuit is formed by the shell and movable core. The core is placed on the axis of the actuator and can move freely in it. To reduce the friction force between the moving core and shell as well as to prevent their mutual impact the core is placed in a nonmagnetic sliding tube. The current in the coil produces magnetic field that acts on the ferromagnetic core by the Maxwell force.

2 DESIGN

The aim of the design was the optimization of magnetic circuit dimensions with regard to the amplitude of the current density J_b in winding coil. This current density was chosen considering the available power sources in the range from 0,6 A/mm^2 to 1,9 A/mm^2. An additional goal of the work was the verification of the current density in terms of temperature rise in the actuator due to Ohmic losses in the coil.

The design of the actuator was based on the evaluation of magnetic field in it. The mathematical model of the magnetic field (supplemented with correct boundary conditions) was formulated in terms of magnetic vector potential and solved by the finite element method.

Definition area is due to the rotational symmetry of the actuator defined in the cylindrical coordinate system. Each sub-domain of the definition area is characterized by the relation based on first Maxwell's equation, which is defined in the form

$$\mathrm{rot}\frac{1}{\mu_r \cdot \mu_0}\mathrm{rot}A \quad = \quad J \,, \tag{1}$$

where $\boldsymbol{A}$ is the magnetic vector potential, μ_r relative permeability, μ_0 permeability of vacuum and $\boldsymbol{J}$ current density.

Equation (1) is valid in all sub-domains. In the coil domain, the current density $\boldsymbol{J}$ from equation (1) is equal to the current density J_b. The current density is equal zero in other sub-domains.

The magnetic circuit is made of ferromagnetic material. That is why it is necessary to take into account the relative permeability μr is not constant in these sub-domains and the B-H characteristic of the used material is non-linear. As the exact material characteristics of the material are unknown, the B-H characteristics derived from the characteristics of standard steel 12 040 have been used for the actuator design. The regions of the coil and the sliding contact are made of non-magnetic materials with relative permeability $\mu_r = 1$ and equation (1) can be considered with the permeability μr equal to permeability of vacuum μ_0.

The boundary condition on the outer surface of the actuator assumes a zero magnetic field outside the actuator and can by defined by Dirichlet boundary condition. The condition along the symmetry axis implies the antisymmetry. The equation on both parts of the boundary can be defined in the form

$$A_\varphi \quad = \quad 0\,. \tag{2}$$

Calculations were carried out by professional FEM-based code QuickField$^{\mathrm{TM}}$ supplemented with a number of single-purpose procedures and scripts. I calculated a number of different arrangements and selected the configuration that provided (from a certain point of view) the optimal static characteristic. The distribution of magnetic field is depicted in Fig. 1 and Fig. 2.

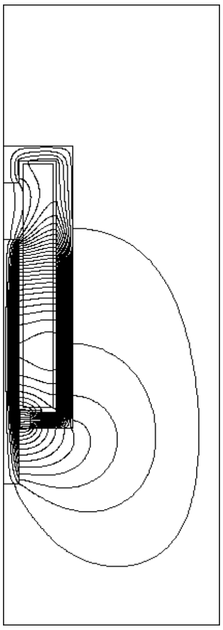

Fig. 1: Distribution of force lines in the final draft

In order to verify the amplitude of current density J_b in term of temperature rise in the actuator, a numerical model of stationary temperature field inside the actuator has been created. The definition area includes the same regions as the definition area of magnetic field and can be defined in a cylindrical coordinate system. The temperature field within the device is described by the Fourier-Kirchhoff equation

$$\mathrm{div}\lambda\mathrm{grad}T \quad = \quad -w\,, \tag{3}$$

where λ is the thermal conductivity, T is temperature and w the specific Ohmic losses. These are nonzero only within the field coil and may be expressed by relation

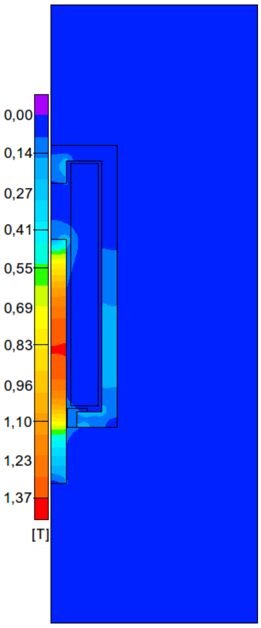

Fig. 2: Distribution of flux density ***B*** *in the final draft*

This equation again applies in all sub-area. In coil is given the power given to the concept of actuator Joule losses P_j, which are defined in the form

$$P_j \quad = \quad \frac{J_b^2}{\gamma}\,, \tag{4}$$

where γ is the specific conductivity of the coil wires.

Provided that the body of the actuator is placed in the air, the boundary condition on its outer surface may be expressed as

$$\lambda\frac{\partial T}{\partial n} \quad = \quad \alpha\left(T - T_{env}\right), \tag{5}$$

where α is the coefficient of heat transfer to surrounding air and T the ambient temperature.

The boundary conditions on the axis of symmetry assume an antisymmetric condition introducing the derivative of the temperature in the normal direction to zero. The boundary condition reads

$$\lambda\frac{\partial T}{\partial n} \quad = \quad 0\,. \tag{6}$$

Numerical simulations were carried out by professional code QuickField$^{\mathrm{TM}}$. The distribution of temperature is depicted in Fig. 3.

Based on the simulation results I prepared the technical documentation necessary for the construction of the actuator. This documentation was created by the help of SolidWorks software. The magnetic circuit was produced by company KLIMA a. s. Other parts of the actuator were produced at the Department of Theory of Electrical Engineering and Department of Technologies and Measurement FEE UWB in Pilsen.

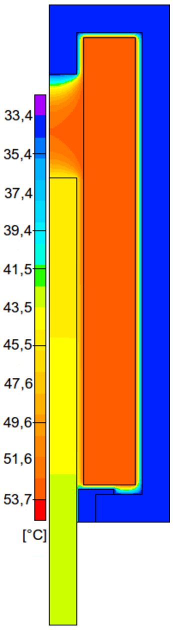

Fig. 3: Distribution of temperature in the final draft

Fig. 4: Photo of the produced actuator

3 EXPERIMENTAL VERIFICATION

The aim of the experimental verification was the functionality verification of produced actuator. For experimental verification I measured the static characteristics of the device. This characteristic represents the dependence of the force acting on the core on its position (at a given current). For this measurement I prepared a mechanical construction that allowed the motion of the measuring apparatus and actuator as well as the change of position of the movable core. The measurement results are shown in Fig. 5.

Fig. 5 shows that the results of measurement and calculation are qualitatively equal. At higher saturation of the magnetic actuator circuit, the values of the calculated and measured values are slightly different. This difference can be caused by the used B-H characteristic, which seems to be different from the actual characteristics of the material at higher values of magnetic field.

The results of measurements were then used for derivation of the dynamic characteristic. The dynamic characteristic reflects the dependence of the instantaneous velocity and position of the movable core on time. Their calculation was performed using the scripting language GNU Octave.

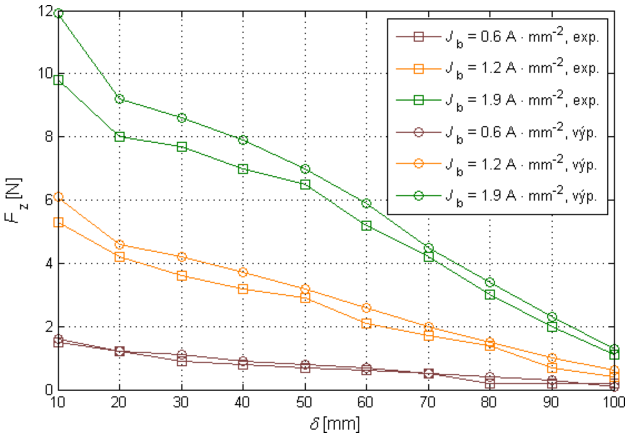

Fig. 5: Calculated and measured static characteristics

Dynamic characteristic are characterized by a differential equation in form

$$m \cdot \frac{dv}{dt} = F_z + F_G , \qquad (7)$$

where m denotes the mass of the moving core, v the velocity, F_z the force acting on the core and F_G is the weight. Dynamic behavior of the system can be described as follows

$$\frac{ds}{dt} = v , \qquad (8)$$

where s is the distance over which the core actuator moves. The results of calculations are shown in Fig. 6 and Fig. 7.

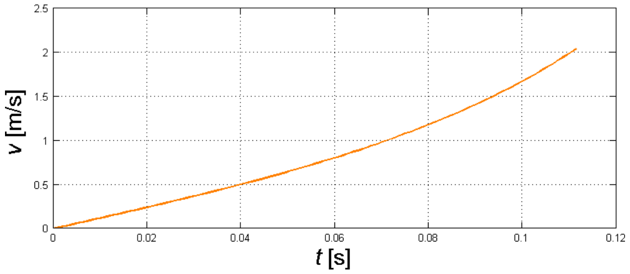

Fig. 6: Dependence of velocity of the movable core on time

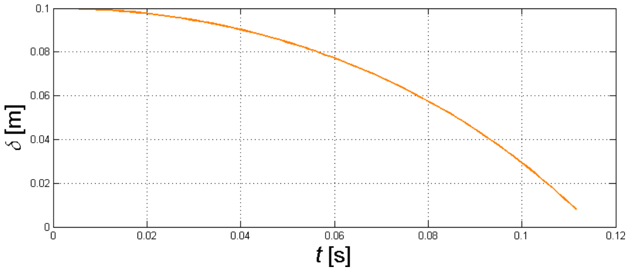

Fig. 7: Dependence of position of the movable core on time

4 CONCLUSION

The experiment results show that the design of the actuator has been done correctly. Differences between measured and calculated values at high saturation of magnetic circuit are most probably caused by inaccurate values of material properties used for calculation. Unfortunately, it was not possible to find more precise characteristics of the material during the work.

The actuator solved in this work is currently used at the Department of Theory of Electrical Engineering, FEE UWB in Pilsen as a physical model for the application in experiments. It is also used as an aid (instrument) for teaching relevant subjects.

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