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HIGHER-ORDER MODEL OF ELECTROMAGNETIC VALVE FOR CONTROL OF LIQUID FLOW

An electromagnetic valve for control of flow of electrically non-conductive liquids is proposed and modeled. The device contains only one movable part (a cylindrical plunger) whose movement is controlled by a secondary magnetic circuit with a high-parameter permanent magnet and current in the field coil. The paper presents its mathematical model that is solved numerically. For computations we used our own code Agros2D based on a fully adaptive higher-order finite element method. The static characteristics of the device are calculated using a modified version of the Eggshell method in order to avoid undesirable peaks and oscillations. The principal results are evaluated and discussed.

KEYWORDS: electromagnetic actuator, numerical modeling, higher-order finite element method, magnetic field, static characteristic.

1. INTRODUCTION

The control of fluid flow is nowadays realized mostly by valves whose operation is based on numerous physical principles (electromagnetic, mechanical, pneumatic, hydraulic, etc.) [1–3]. These devices, however, usually contain more movable elements (drag-bars, plungers, springs and others), which deteriorates their reliability.

Even many types of electromagnetic valve actuators (EMVA) are typical by their rather complicated structures, although researchers pay much attention to designing devices that allow valve timing and lifting without cams and other similar elements. Examples of more complicated solenoidal EMVAs can be found in [1] or [4] and information about hybrid (also rather complicated) EMVAs are in [5] or [6].

The authors present a simple EMVA for food industry (for dosing beverages), where another important condition is easy cleaning of its interior. The valve has only one movable part – a cylindrical plunger – that is controlled by current in the field coil and a permanent magnet in an auxiliary magnetic circuit. The device is modeled numerically in order to evaluate its operation parameters and characteristics. The computations are performed by own code Agros2D based on a fully adaptive higher-order finite element method. The results of analysis are evaluated and discussed.

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2. FORMULATION OF TECHNICAL PROBLEM

The principal arrangement of the designed valve is depicted in Fig. 1. The EMVA consists of a classic magnetic actuator with an auxiliary magnetic circuit with permanent magnet, two magnetic bearings, hollow cylindrical plunger, shell, and action element for opening and closing the valve. A more detailed view of the body of actuator (together with the main dimensions in meters) is in Fig. 2

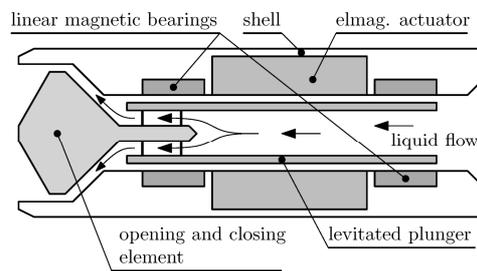


Fig. 1. Basic arrangement of designed EMVA

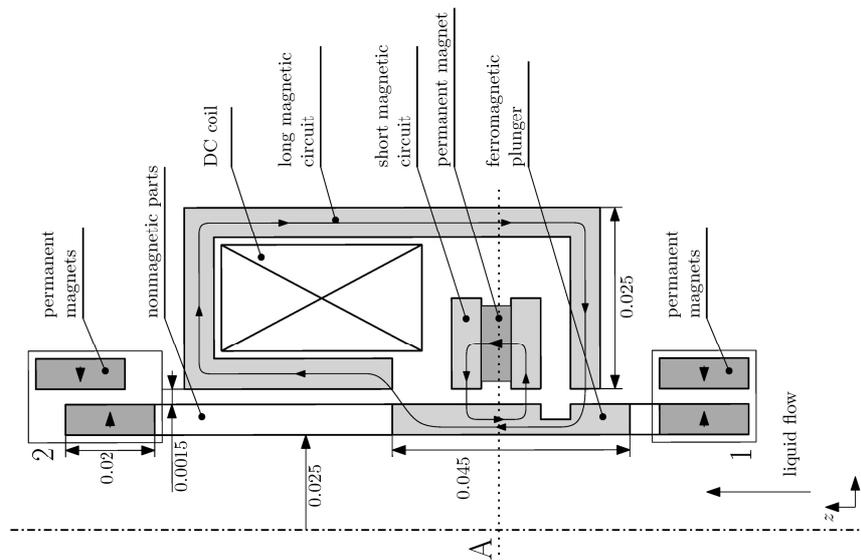


Fig. 2. Detailed view of actuator

The plunger is in the closed position if the coil carries no field current. In this case, the principal role is played by the short (auxiliary) magnetic circuit with a strong permanent magnet that keeps the plunger in the position depicted in Fig. 3, left part. The process of opening is started by connecting the field coil to the source of sufficiently high direct current. The magnetic flux produced by the coil in the

long magnetic circuit demagnetizes the plunger, so that the force caused by the short magnetic circuit is suppressed. Now the plunger starts moving (in Fig. 2) to the left. The position “open” is shown in Fig. 3, right part. Of course, all parts of the actuator must be proposed appropriately as for the materials and dimensions. The same holds for the magneto-motive force of the field coil.

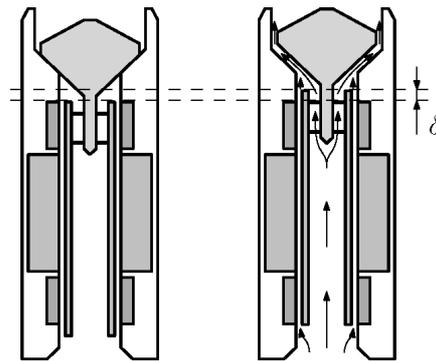


Fig. 3. Operation modes of valve: left-valve is closed, right-valve is open

The presented structure has a number of advantages with respect to the solutions mentioned in the introduction. Mentioned can be, for example:

- The process of opening and closing the valve can be fully controlled by the cooperation of permanent magnet and field coil.
- The valve has only one movable element.
- The permanent magnet is not demagnetized in the course of the process (local demagnetization of the plunger is used instead), which contributes to the safety and reliability of the valve.
- Cleaning of the valve is very easy.
- The plunger is axially stabilized by the magnetic bearings, which prevents the valve from leaking during the steep changes of pressure in the connected pipe.

3. MATHEMATICAL MODEL

The principal quantities to be determined are the static and dynamic characteristics of the device. The computation of the dynamic characteristics, however, requires knowledge of liquid flow in the system, which will be the topic of further work in the domain. In this stage of research we will deal just with the principal functionality of the valve and its static characteristics.

The basic condition is to find the distribution of magnetic field in the system for a series of positions of the plunger. In our case, its distribution is given by the partial differential equation for the distribution of the magnetic vector potential A in the form

$$\operatorname{curl} \left(\left(\frac{1}{\mu} \operatorname{curl} \mathbf{A} \right) - \mathbf{H}_c \right) = \mathbf{J}_{\text{ext}} \quad (1)$$

where μ denotes the magnetic permeability, \mathbf{H}_c is the coercive force (just in the domain of the permanent magnets) and \mathbf{J}_{ext} is the vector of the external direct current density in the inductor. The conditions along the axis of the device and artificial boundary placed at a sufficient distance from the system are of the Dirichlet type ($\mathbf{A} = \mathbf{0}$).

The total magnetic force acting on the movable plunger may be determined from the Maxwell Stress Tensor σ_M given by the relation

$$\sigma_M = -\frac{1}{2}(\mathbf{H} \cdot \mathbf{B})\mathbf{I} + \mathbf{H} \otimes \mathbf{B}, \quad (2)$$

where \mathbf{H} and \mathbf{B} are the field vectors, \mathbf{I} denotes the unit diagonal matrix, and symbol \otimes stands for the dyadic product. The axial magnetic force \mathbf{F}_M acting on the body (plunger) is now given by the integral

$$\mathbf{F}_M = \iint_S \sigma_M \, d\mathbf{S}, \quad (3)$$

where \mathbf{S} denotes the outward unit normal vector to the boundary S of the plunger.

Although the relations (2) and (3) are correct, their numerical computation is problematic. In case of high nonlinearities the computation is relatively slow, convergence of the result is rather poor and accuracy is often insufficient. Therefore, we offer an alternative technique based on a higher-order Eggshell method whose algorithms are implemented in our codes Agros2D and Hermes.

The Eggshell method [7] is based on introducing a thin shell over the surface of the body (see Fig. 4) and an appropriate function γ satisfying the conditions $\gamma = 0$ along the external boundary of the shell and $\gamma = 1$ along its internal boundary. Then the magnetic force acting on the body is

$$\mathbf{F}_M = \int_V \sigma_M \cdot \operatorname{grad} \gamma \, dV, \quad (4)$$

where V is the volume of the eggshell. Function γ can be chosen in more ways.

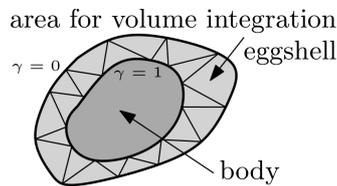


Fig. 4. Principal scheme of Eggshell method

In our implementation, we use the solution of the Laplace equation in the eggshell domain obtained using higher-order finite elements. These bring additional smoothness to the solution and we can choose their orders arbitrarily. Since the eggshell domain is covered with very few elements, the additional computational cost caused by increasing the element order is quite negligible.

4. NUMERICAL SOLUTION

The task was solved by our own code Agros2D [8] based on a fully adaptive higher-order finite element method [9]. The problems with strong nonlinearities were overcome by our effective implementation of the Newton algorithm.

The code representing a powerful preprocessor and postprocessor cooperates with the library Hermes [10] that includes the most advanced numerical algorithms based on a fully adaptive higher-order finite element method and also discontinuous Galerkin method. Both packages written in C++ are freely distributable under the GNU General Public License. The code exhibit quite unique features, for example:

- Solution of multiphysics problems with multimesh technology (every physical field can be calculated on a different mesh generally varying in time).
- Advanced implementations of the Newton and Picard solvers for the solutions of problems described by nonlinear PDEs.
- Full space h -, p - and hp -adaptivity) and also time adaptivity.
- Triangular, quadrilateral and curved elements with hanging nodes of any level.
- Advanced optimization techniques using the genetic algorithms (simulated annealing, NSGA II and several others).
- Higher-order methods of particle tracing, higher-order Eggshell Method for computation of forces acting in nonlinear magnetic fields.

5. ANALYSIS OF VALVE

5.1. Input data

The main dimensions of the valve are indicated in Fig. 2. The field coil of the actuator contains 600 turns wound by a copper conductor. The field current density changes from 0 to 6 A/mm². The ferromagnetic parts of the magnetic circuit are manufactured of special iron whose saturation curve is depicted in Fig. 5. The auxiliary permanent magnet VMM10 in the system is of type NdFeB and its manufacturer provides the following parameters: remanence $B_r = 1.45$ T and relative permeability in the second quadrant $\mu_r = 1.21$.

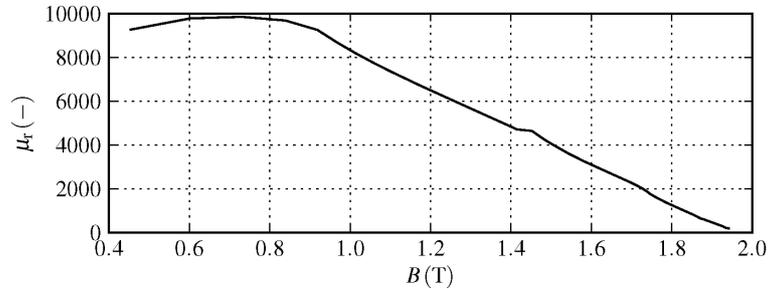


Fig. 5. Relative permeability of used iron versus magnetic flux density

5.2. Selected results

The static characteristics of the device obtained for varying field currents are depicted in Fig. 6. Their shapes are similar and may be considered "almost" linear, which is due to the cooperation of the long and short magnetic circuits indicated in Fig. 2. This fact may conveniently be used for the control of the valve.

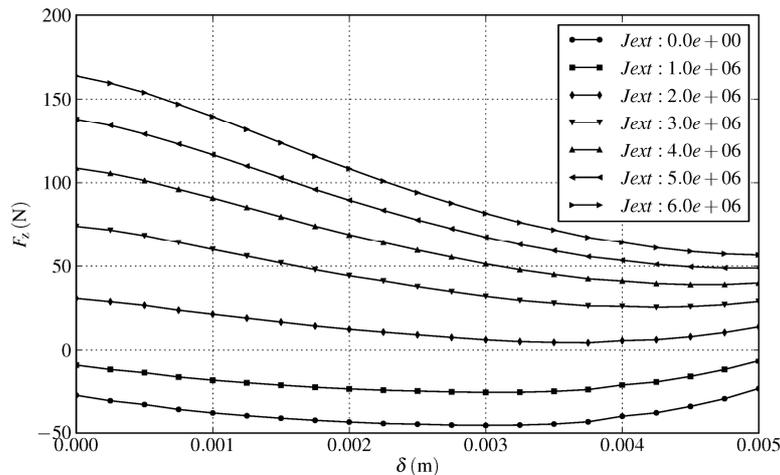


Fig. 6. Static characteristics for different field currents

The characteristic for zero field current corresponds so the regime of closing the valve. The "opening" characteristic must be positive everywhere and must be chosen with respect to the flow resistances in the system given by the velocity and pressure of the liquid.

Very important is the distribution of magnetic fluxes passing through the wall of the long magnetic circuit (ϕ_c), plunger (ϕ_p) and permanent magnet in the short magnetic circuit (ϕ_m) for different field current densities.

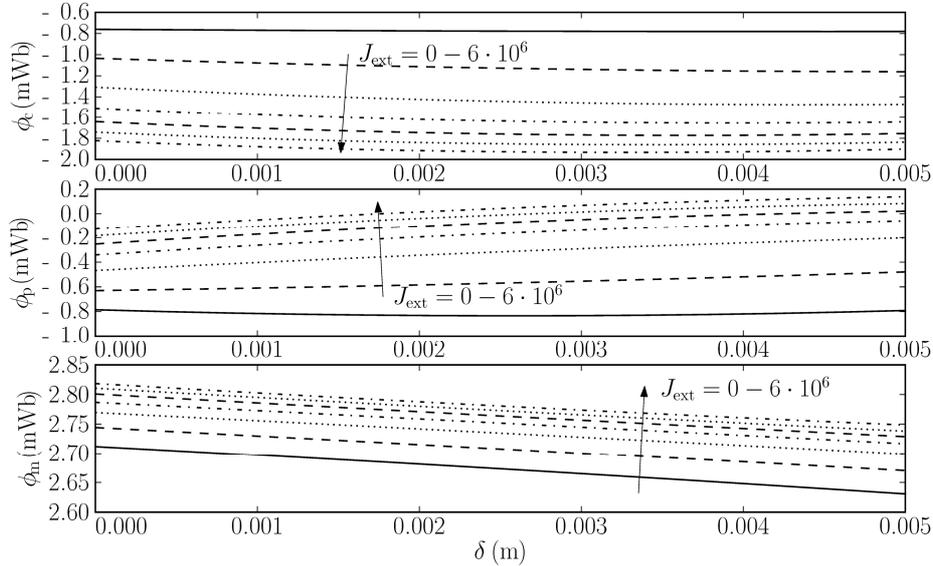


Fig. 7. Distribution of magnetic fluxes (for different field current densities) through the wall of the long magnetic circuit (ϕ_c), plunger (ϕ_p) and permanent magnet in the short magnetic circuit (ϕ_m)

It is clear that the magnetic flux through the permanent magnet changes only in a very small range, which means that its demagnetization in the process of opening is low. This very significantly contributes to the stability of the system.

6. CONCLUSION

Even when the presented work only shows the first design of the valve, the device exhibits very good parameters, promising for numerous industrial applications. In the next steps the important elements of the device will be optimized and then the complete valve will be built and experimentally tested at various parameters of flow (velocity, pressure).

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