Design of Novel Bearing-less Electromagnetic Actuator in Valve Operation
František Mach, Pavel Karban, Ivo Doležel
University of West Bohemia, Univerzitní 26, 306 14 Pilsen, Czech Republic, {fmach, karban, idolezel}@kte.zcu.cz

Abstract—A new bistable electromagnetic actuator is designed and modelled. The actuator with a magnetically moved plunger represents the main part of a valve intended for control of flow of electrically non-conductive liquids. Presented is the basic concept of the valve together with its mathematical model that is solved numerically by the code Agros2D developed by the authors. The aim of the work is to verify the functionality of the device and find its basic operation characteristics.

I. INTRODUCTION
One of the main problems of existing valves is their structural complexity. In many cases they use various drag-bars for the transfer of force effects and other movable elements, which reduces the safety and reliability of their operation. Even more complicated is the situation when the valve should work in a controllable bistable regime (which is secured, for example, by return springs representing further movable parts). In the food, chemical and other industries with extremely high demands on the cleanliness of operation, effective cleaning of such valves is also an issue of principal importance.

The existing solutions to the problem abound, but most of them are technologically rather complicated [1]–[5], see Fig. 1. The goal of this paper is to design a structurally very simple valve for operation in a bistable regime, verify its functionality and find its basic operation characteristics.

Advantages of the new concept:
• Bistable regime secured by the permanent magnets.
• The permanent magnets are 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.
• The valve does not contain any further movable elements such as drag-bars or springs and its cleaning is very easy.
• The valve saves energy due to local demagnetization of the plunger.
• The plunger is stabilized by the magnetic bearing. This measure prevents the valve from leaking at pressure jumps in the connected pipe. It also prevents the fer-

Figure 1. Classical electromagnetic valve system

II. BASIC CONCEPT
Figure 2 shows the principal arrangement of the designed valve. The device consists of an electromagnetic actuator, two linear magnetic bearings made of permanent magnets, hollow cylindrical plunger, shell, and element opening or closing the flow of liquid through the valve.

Figure 2. Basic concept of designed valve
The process of opening and closing the valve can be fully controlled by DC field coil current.

III. MATHEMATICAL MODEL

The investigated valve was studied by numerical simulation of magnetic field, incompressible flow field and also dynamics of the movable plunger.

A. Model of magnetic field

The distribution of magnetic field in the system (for any position of the plunger) is described by the equation for magnetic vector potential $A$ in the form

$$\text{curl } (\mu(B)^{-1}\text{curl } A - H_c) = J_{\text{ext}},$$

where $\mu$ denotes the magnetic permeability, $B$ flux density, symbol $H_c$ stands for the coercive force and $J_{\text{ext}}$ denotes the density of the field current in the field coil.

The model is solved as a 2D axi-symmetric problem. The solution area is closed by the Dirichlet boundary condition in the form $A = 0$.

Important in the first step of modelling are the static characteristic of the device both when closing and opening the valve, i.e., the dependences of the axial force acting on the plunger on its position in the system. The force can be determined from the actual distribution of the magnetic field and can be expressed using the formula

$$F_m = \int_S S_m \, \text{d}S,$$

where $S_m$ is the Maxwell stress tensor and the integration is performed over the complete boundary $S$ of the plunger ($S$ being the outward normal to this boundary).

The Maxwell stress tensor $S_m$ is given by the expression

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

where $I$ is the unit diagonal matrix and symbol $\otimes$ denotes the dyadic product.

B. Model of incompressible flow

The incompressible flow in the working area of the valve is described by the Navier-Stokes equation for liquid velocity $v$ in the steady state (partial simplification of the model) and pressure $p$ in the form

$$\rho(v \cdot \text{grad } v) = -\text{grad } p + \eta \Delta v + f,$$

$$\text{div } v = 0,$$

where $\rho$ is the density of the liquid, $\eta$ represents its dynamic viscosity and finally $f$ denotes the internal forces (for example gravitational force).

C. Dynamics of the plunger

The dynamics of the movable plunger is described by the motion equations

$$m \frac{dv}{dt} = F_m + F_f + F_g,$$

$$v = \frac{ds}{dt},$$

where $v$ is the velocity of the plunger, $t$ is the time, $F_m$ is the force produced by the magnetic field, $F_f$ stands for the pressure and viscous forces, $F_g$ is the gravity force, $m$ denotes the mass of the plunger and, finally, $s$ represents the trajectory of the plunger.
IV. NUMERICAL ANALYSIS

The numerical solution of the problem is realized by a fully adaptive higher-order finite element method whose algorithms are implemented into the codes Agros2D [6] and Hermes [7]. Both codes have been developed in our group for a couple of years. The codes are intended for monolithic numerical solution of systems of generally non-linear and non-stationary second-order partial differential equations and their principal purpose is to model complex physical problems in the hard coupled formulations. Both codes are freely distributable under the GNU General Public License.

Figure 5 shows the convergence of the Newton method for two cases (excited and unexcited DC coil) for the position of plunger $\delta = 0.125$ mm. The calculation of the force was realized by the Eggshell method [8].

![Figure 5. Convergence of the Newton solver (dependence of relative change of solution on number of iteration steps for plunger position $\delta = 0.125$ mm). The numbers at point denote residual, $t_{el}$ is the elapsed time.](image)

Figure 6 shows the convergence of the static characteristic in the regime “opening”. The computations are performed for ten uniformly distributed points.

![Figure 6. Convergence of static characteristics in regime opening](image)

V. ILLUSTRATIVE EXAMPLE

A. Input data

The field coil of the actuator contains 600 turns wound by a thin copper conductor. The field current density is $2 \cdot 10^6$ A m$^{-2}$. The ferromagnetic parts of the magnetic circuit are manufactured of iron whose saturation curve is depicted in Fig. 7. The permanent magnets VMM10 in magnetic bearings are of NdFeB type and their manufacturer provides the following parameters: remanence $B_r = 1.45$ T, relative permeability in the second quadrant $\mu_r = 1.21$ and maximum allowable temperature $T_{max} = 80^\circ$C. For simulation of liquid flow we used water with dynamic viscosity $\eta = 0.001$ Pa s and density $\rho = 10^3$ kg m$^{-3}$. For the entry part of the valve a permanent velocity of flow was prescribed, that continuously decreases to the wall of the channel.

![Figure 7. Relative permeability of used iron versus magnetic flux density](image)

B. Selected results

Figures 8 and 9 show the distributions of flux density and force lines at the beginning and end of both processes - opening and closing of the valve.

![Figure 8. Opening of valve (distribution of flux density and force lines)](image)

Both static characteristics depicted in Fig. 10 are of similar shapes and may be considered “almost” linear. These shapes were reached thanks to the cooperation of the long and short magnetic circuits indicated in Fig. 4. This fact may
opening

The operation regime of the bearing is defined in the linear part of the static characteristics. This allows stabilizing the plunger in the axial direction because the force effects secure that the plunger keeps the bearing inside the actuator. This can also be seen in Fig. 12 with the indicated ranges of operations of both bearings: the peaks push the bearings to the corresponding local minimums.

Figures 13 show the distributions of the liquid velocity in the valve for two different positions of the plunger. The pressure

and viscous forces acting on the opening and closing element are depicted in Fig. 14 together with the static characteristic of the valve (superposition of the magnetic force acting to the plunger and axial force acting on the magnetic bearing). The operation of the valve closing is characterized by a considerable increase of the velocity of flow in the closing channel, which results in the pressure and viscous forces pressing on the valve. This phase is critical for error-less closing of the valve and it is necessary to produce a sufficient force acting on the plunger.

Dynamics of the movable plunger was computed with respecting pressure and viscous forces. The time-dependent characteristic of plunger position \( \delta \) and plunger velocity \( v \) are shown in Fig. 15.

From the above figures it is clear that the valve is able to close the flow despite a considerable growth of the pressure force on the closing-up element at the increasing velocity of flow through the valve. The action is, moreover, very fast and time of closing very low (\( t < 11 \text{ ms} \)).

VI. CONCLUSION

The paper presents basic design of the novel valve. The simulations show that the system exhibits very good parameters that allows wide industrial applications. Further work in the
domain will be aimed at optimizing the whole system and also in building the physical model of the device and experimental verification of the theoretical results.

VII. ACKNOWLEDGEMENTS

This work was supported by the European Regional Development Fund and Ministry of Education, Youth and Sports of the Czech Republic (project No. CZ.1.05/2.1.00/03.0094: Regional Innovation Center for Electrical Engineering - RICE), by the project P102/11/0498 (Grant Agency of the Czech Republic) and project SGS-2012-039.

REFERENCES


