Design of Novel Bearing-less Electromagnetic Actuator in Valve Operation

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***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.

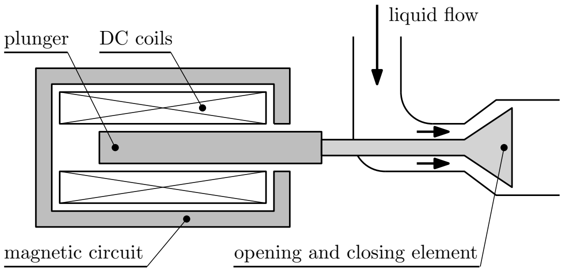

Figure 1. Classical electromagnetic valve system

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.

The valve works in two modes, closed and open. Both modes are depicted in Fig. 3. Figure 4 shows the detailed configuration of the system together with the principal dimensions of the most important parts. The permanent magnet bearings help to stabilize the movable plunger (opening and closing elements represent props for the non-magnetic shell in both described modes, open and closed). Thus, they do not support any levitation, but only the stabilisation of the plunger against optional force impacts.

The bistable mode of the valve (the plunger has only one stable position) is secured by the short magnetic circuit with permanent magnet drawn in Fig. 4. The plunger is in the closed position (stable position, see left part in Fig. 3) if the coil is without field current. The magnetic flux produced by DC field current in the long magnetic circuit demagnetizes the adjacent part of the plunger, so that the force caused by the short magnetic circuit is suppressed. The plunger starts moving to the open position (unstable position, see the right part in Fig. 3). The plunger is moved to the stable position again when the field current is switched off.

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-

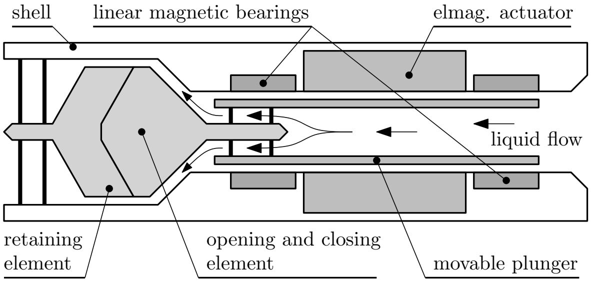

Figure 2. Basic concept of designed valve

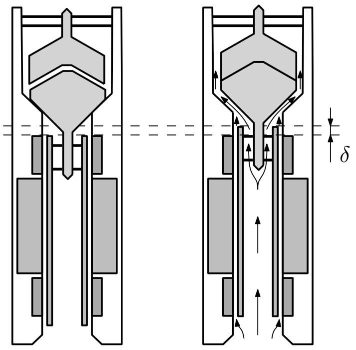

Figure 3. Operation modes (closed and open valve)

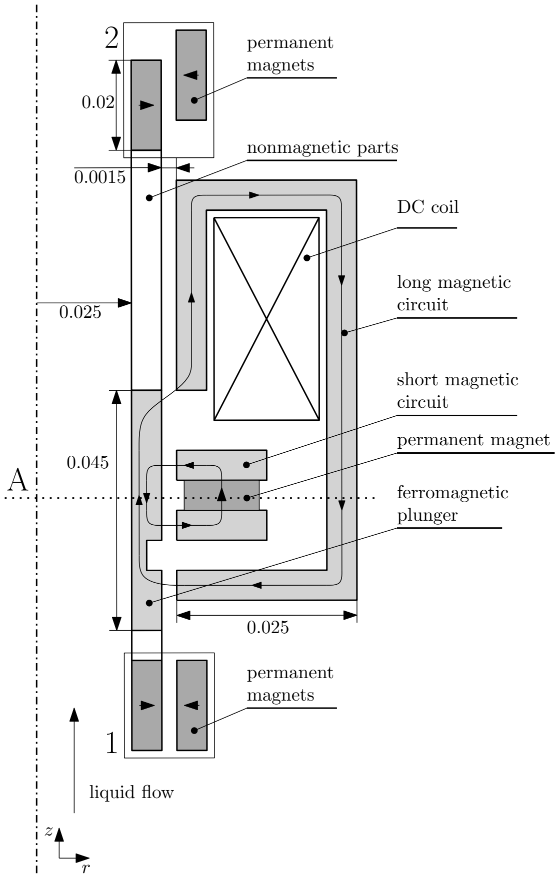

Figure 4. Magnetic circuit of designed valve with main dimensions in m

romagnetic plunger from undesirable approaching to the other magnetic parts.

- 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 $\boldsymbol{A}$ in the form

$$\operatorname{curl}\ \left(\mu(\boldsymbol{B})^{-1}\operatorname{curl}\ \boldsymbol{A}-\boldsymbol{H}_{\mathrm{c}}\right)=\boldsymbol{J}_{\mathrm{ext}}\,, \tag{1}$$

where μ denotes the magnetic permeability, $\boldsymbol{B}$ flux density, symbol $\boldsymbol{H}_{\mathrm{c}}$ stands for the coercive force and $\boldsymbol{J}_{\mathrm{ext}}$ 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 $\boldsymbol{A}=\boldsymbol{0}$.

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

$$\boldsymbol{F}_{\mathrm{m}}=\oint_{S}\boldsymbol{S}_{\mathrm{m}}\,\mathrm{d}\boldsymbol{S}\,, \tag{2}$$

where $\boldsymbol{S}_{\mathrm{m}}$ is the Maxwell stress tensor and the integration is performed over the complete boundary S of the plunger ($\boldsymbol{S}$ being the outward normal to this boundary).

The Maxwell stress tensor $\boldsymbol{S}_{\mathrm{m}}$ is given by the expression

$$\boldsymbol{S}_{\mathrm{m}}=-\frac{1}{2}(\boldsymbol{H}\cdot\boldsymbol{B})\boldsymbol{I}+\boldsymbol{H}\otimes\boldsymbol{B}\,, \tag{3}$$

where $\boldsymbol{I}$ 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 $\boldsymbol{v}$ in the steady state (partial simplification of the model) and pressure p in the form

$$\rho(\boldsymbol{v}\cdot\operatorname{grad}\ )\boldsymbol{v}=-\operatorname{grad}\ p+\eta\triangle\boldsymbol{v}+\boldsymbol{f}\,, \tag{4}$$

$$\operatorname{div}\ \boldsymbol{v}=0\,, \tag{5}$$

where ρ is the density of the liquid, η represents its dynamic viscosity and finally $\boldsymbol{f}$ 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

$$m\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t}=\boldsymbol{F}_{\mathrm{m}}+\boldsymbol{F}_{\mathrm{f}}+\boldsymbol{F}_{\mathrm{g}}\,, \tag{6}$$

$$\boldsymbol{v}=\frac{\mathrm{d}\boldsymbol{s}}{\mathrm{d}t}\,, \tag{7}$$

where $\boldsymbol{v}$ is the velocity of the plunger, t is the time, $\boldsymbol{F}_{\mathrm{m}}$ is the force produced by the magnetic field, $\boldsymbol{F}_{\mathrm{f}}$ stands for the pressure and viscous forces, $\boldsymbol{F}_{\mathrm{g}}$ is the gravity force, m denotes the mass of the plunger and, finally, $\boldsymbol{s}$ 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 $\delta = 0.125\,\mathrm{mm}$. The calculation of the force was realized by the Eggshell method [8].

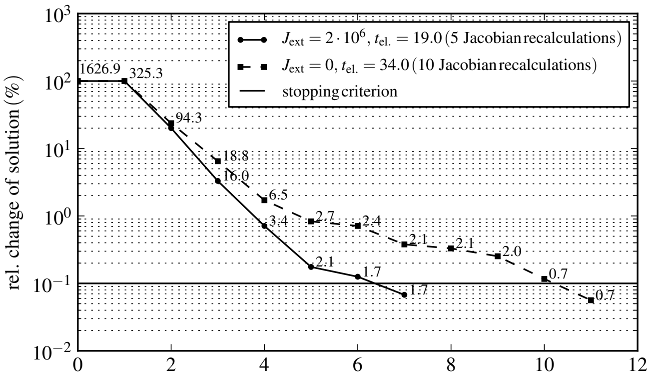

Figure 5. Convergence of the Newton solver (dependence of relative change of solution on number of iteration steps for plunger position $\delta = 0.125\,\mathrm{mm}$). The numbers at point denote residual, $t_{\mathrm{el.}}$ is the elapsed time.

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

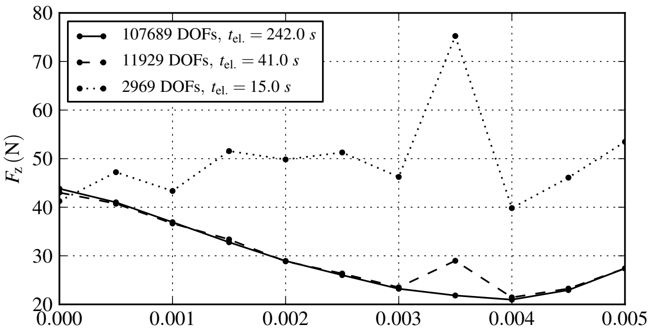

Figure 6. Convergence of static characteristics in regime opening

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 $2 \cdot 10^6\,\mathrm{A\,m^{-2}}$. 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 $B_r = 1.45\,\mathrm{T}$, relative permeability in the second quadrant $\mu_r = 1.21$ and maximum allowable temperature is $T_{\max} = 80\,^{\circ}\mathrm{C}$. For simulation of liquid flow we used water with dynamic viscosity $\eta = 0.001\,\mathrm{Pa\,s}$ and density $\rho = 10^3\,\mathrm{kg\,m^{-3}}$. For the entry part of the valve a permanent velocity of flow was prescribed, that continuously decreases to the wall of the channel.

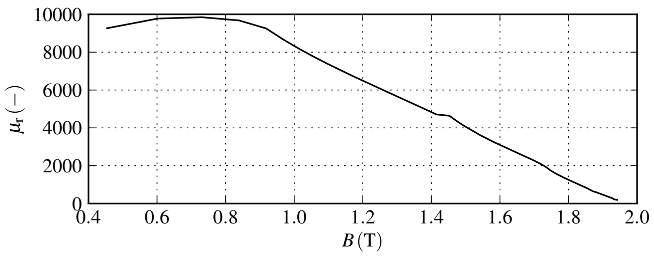

Figure 7. Relative permeability of used iron versus magnetic flux density

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.

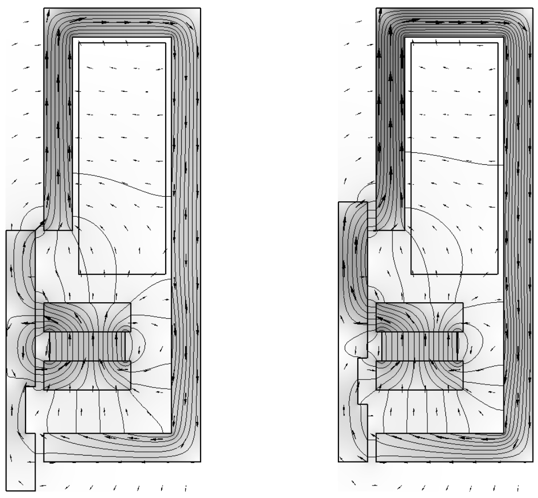

Figure 8. Opening of valve (distribution of flux density and force lines)

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

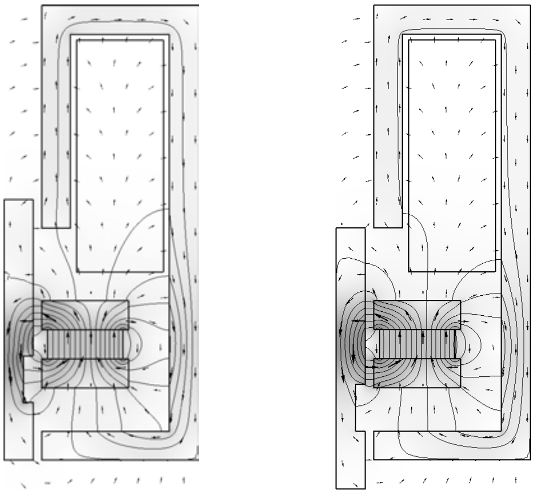

Figure 9. Closing of valve (distribution of flux density and force lines)

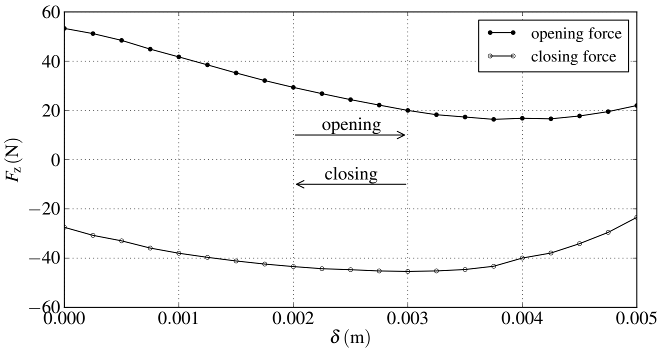

Figure 10. Static characteristics of actuator

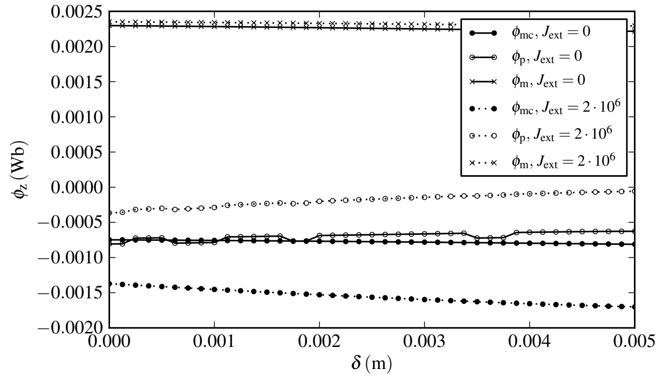

Figure 11. Magnetic fluxes in long magnetic circuit (ϕ_{mc}), plunger (ϕ_{p}) and permanent magnet of short magnetic circuit (ϕ_{m}). All fluxes are calculated in cut A (see Fig. 4)

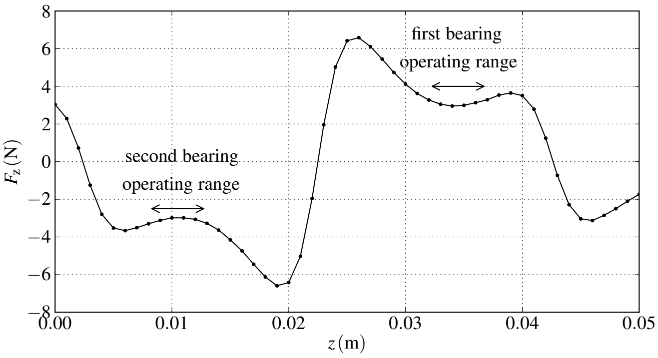

Figure 12. Static characteristic of bearing

conveniently be used for the control of the valve due to uniform dynamic characteristics for its opening and closing.

The short notch in the ferromagnetic part of the plunger allows increasing of the force effect of the short magnetic circuit, which is important for reaching a sufficient downforce of the closed valve and prevention of leakage.

Figure 11 shows the magnetic fluxes in several parts of the magnetic circuit for both excited ($J_{\mathrm{ext}} = 0$) and unexcited ($J_{\mathrm{ext}} = 2 \cdot 10^6\,\mathrm{A} \cdot \mathrm{m}^{-2}$) coils. From the comparison of both states it is clear, that the magnetic flux produced by the DC coil reduces the local magnetization of the plunger and magnetic flux in permanent magnet. This means that the force produced by the short magnetic circuit is reduced and the force produced by the coil makes the plunger mover.

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 δ 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 ($t < 11\,\mathrm{ms}$).

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

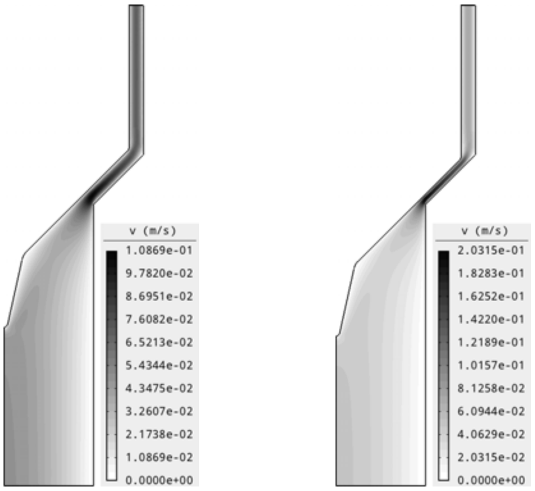

Figure 13. Distribution of liquid velocity for plunger position $\delta = 0.005\,\mathrm{m}$ (open valve) and $\delta = 0.0025\,\mathrm{m}$

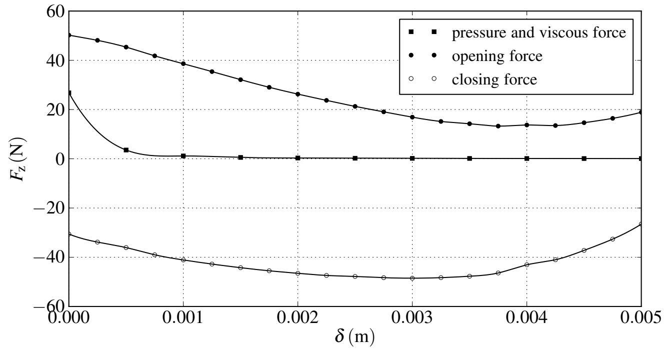

Figure 14. Static characteristics of actuator with magnetic bearing and pressure and viscous force acting to opening and closing element

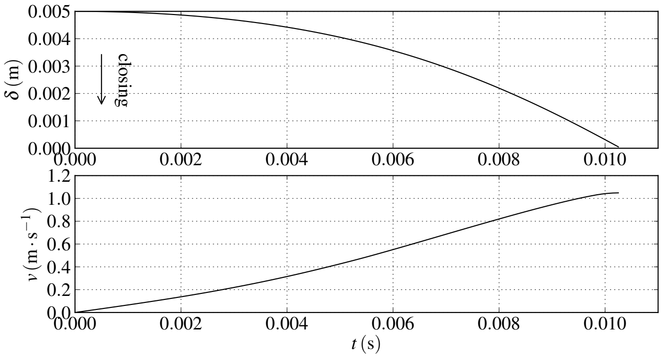

Figure 15. Dynamic characteristics of valve with respecting pressure and viscous force acting to movable plunger

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

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REFERENCES

[1] Yee-Pien, Y., Jieng-Jang, L., Da-Hau, Y., Yi-Ruei, C., Pai-Hsiu, L.: Multiobjective Optimal Design and Soft Landing Control of an Electromagnetic Valve Actuator for a Camless Engine, Transactions on Mechatronics, 2013, Volume 18, Issue 3, pp 963– 972

[2] Albert, J., Banucu, R., Hafla, W., Rucker, W.M.: Simulation Based Development of a Valve Actuator for Alternative Drives Using BEM-FEM Code, IEEE Transactions on Magnetics, 2009, Volume 45, Issue 3, pp 1744–1747

[3] Baoping, C., Yonghong, L., Xiaojie, T., Zelu, W., Fei, W., Hang, L., Renjie, J.: Optimization of Submersible Solenoid Valves for Subsea Blowout Preventers, IEEE Transactions on Magnetics, 2010, Volume 47, Issue 2, pp 451–458

[4] Parlikar, T.A., Chang, W.S., Qiu, Y.H., Seeman, M.D., Perreault, D.J., Kassakian, J.G., Keim, T.A.: Design and experimental implementation of an electromagnetic engine valve drive, Transactions on Mechatronics, 2005, Volume 10, Issue 5, pp 482 –494

[5] Parlikar, T.A., Chang, W.S., Qiu, Y.H., Seeman, M.D., Perreault, D.J., Kassakian, J.G., Keim, T.A.: Design and experimental implementation of an electromagnetic engine valve drive, Transactions on Mechatronics, 2005, Volume 10, Issue 5, pp 482–494

[6] Karban, P., Mach, F., Kůs, P., Pánek, D., Doležel, I.: Numerical solution of coupled problems using code Agros2D, Computing, 2013, Volume 95, Issue 1, pp 381–408

[7] Solin, P., Cerveny, J., Dolezel, I.: Arbitrary-Level Hanging Nodes and Automatic Adaptivity in the hp-FEM, Math. Comput. Simul., 2008, Volume 77, pp 117–132

[8] Henrotte, F., Felden, M., Vander, G. M., Hameyer, K.: The eggshell approach for the computation of electromagnetic forces in 2D and 3D, COMPEL, 2004, Volume 23, Issue 4, pp 996–1005