Electromagnetically controlled low-pressure hydraulic valve

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***Abstract*—Basic functions and properties of an electromagnetically controlled low-pressure hydraulic valve are investigated. The construction of the valve is described together with its principal operating regimes. A mathematical model describing its static and dynamic characteristics is proposed. The model is solved numerically by the finite element method. The obtained results are presented and discussed.**

Keywords—electromagnetically controlled valve; finite element method; force effects; operating regimes.

I. INTRODUCTION

Various technological systems in engineering, chemical manufacturing, food processing and so forth, work with hydraulic circuits with controlled fluid flow. Different kinds of valves actuated mechanically, hydraulically, pneumatically or electromagnetically may be used in this case. From the technological viewpoint, the most advantageous are the last ones - installation of electric circuitry is nowadays much easier and cheaper than, for example, installation of pipes with compressed air or other mechanical parts.

On the other hand, electromagnetically controlled valves may exhibit a disadvantage, mainly in long-term operating modes. Longer flow of electric current through the field coil of the electromagnet can cause an excessive heating of the whole system. That is why modified electromagnetic systems (actuators), based on a combination of a classical electromagnet and permanent magnet, are more promising nowadays. In such a case, only short power pulses are delivered to the field coil, while long-term force effects are realized by a permanent magnet. The paper deals with an electromagnetically controlled low-pressure hydraulic valve based on this particular principle.

II. FORMUATION OF THE PROBLEM

An electromagnetic valve is designed for a controlled dosing of a low-pressure fluid flowing through it - see Fig. 1. It is adapted to work in two arbitrarily long and recurring operation regimes "open" and "closed". Two very short transition regimes, "opening" and "closing", are between them, each of them taking only a few hundredths of a second.

A. Arrangement of the valve

The valve has two main parts – a mover and a stationary core. Its arrangement is depicted in Fig. 2 and detail A is shown in Figs. 3a and 3b.

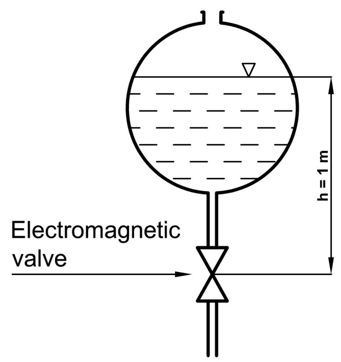

Fig. 1: Schematic arrangement of tank and valve

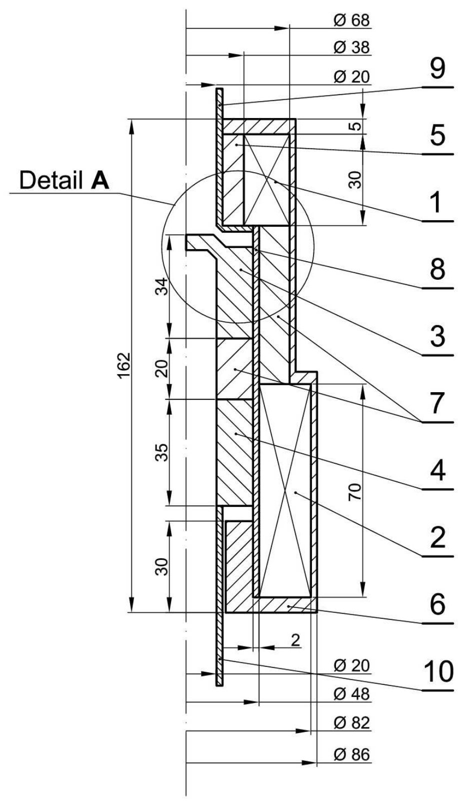

Fig.2: Arrangement of considered valve

The mover consists of two ferromagnetic tubes **3** and **4** (steel ČSN 12 040, its nonlinear characteristic $B(H)$ being shown in Fig. 4). These tubes are connected by a hollow non-ferromagnetic (nylon) insert **7**. The element **3** is a conical head of the valve, connected to the stationary core of the valve in the regime "close". This conical head contains six holes with a diameter of four millimeters, which are used for fluid flow in the regime "open". Then the fluid flows into the cavity of the valve through a nylon outlet pipe **10**, which is connected by the element **4**.

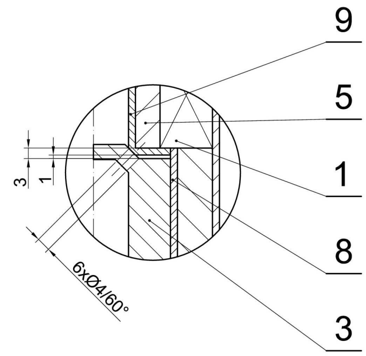

Fig.3a: Detail of conical head in regime "close"

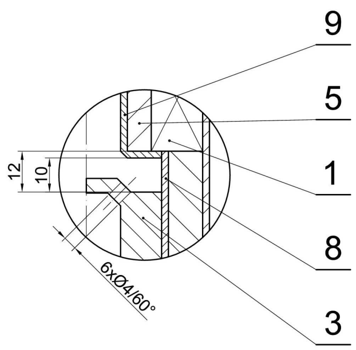

Fig.3b: Detail of conical head in regime "open"

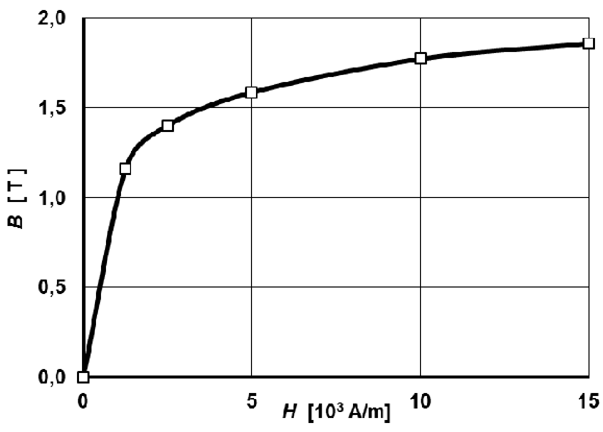

Fig.4: Nonlinear characteristic of steel ČSN 12 040

The stationary core of the valve consists of a ferromagnetic casing **6** containing a toroidal permanent magnet **5** (NEOREC 53B, μ_r=1.031, H_c=5.6×10^5 A/m [1]) and two coils **1** and **2**. The coils are connected by a non-ferromagnetic (nylon) insert **7** and a nonmagnetic steel tube **8**, which also serves as a guide track for the mover.

B. *Valve operating modes*

A current of density $\boldsymbol{J}_1$ flowing through the coil **1** in the transient mode "opening" (which ends by the stationary regime "open") produces demagnetization and reduces the impact force of magnet **5** on the ferromagnetic element **3**. At the same time, a current of density $\boldsymbol{J}_2$ flows through the coil **2**. This makes the ferromagnetic element **4** pull into that coil.

An opposite current of density $-\boldsymbol{J}_1$ flowing through the coil **1** in the transient regime "closing" (which ends by the stationary regime "close") enlarges the impact force of magnet **5** on the ferromagnetic element **3**. The current density $\boldsymbol{J}_2$ is now equal to zero.

III. MATHEMATICAL MODEL

The mathematical model of magnetic field in the whole system is generally described by the differential equation [2], [3] for the magnetic vector potential $\boldsymbol{A}$

$$\mathrm{curl}\left(\frac{1}{\mu}\left(\mathrm{curl}\,\boldsymbol{A}\right) - \boldsymbol{H}_{\mathrm{c}}\right) = \boldsymbol{J}\,. \tag{1}$$

In the cylindrical coordinates r, φ, z (the arrangement may be considered practically axisymmetric) there holds

$$\boldsymbol{J} = \mathbf{r}_0\, 0 + \mathbf{z}_0\, 0 + \boldsymbol{\varphi}_0\, J_{\varphi}\,,$$

$$\boldsymbol{A} = \mathbf{r}_0\, 0 + \mathbf{z}_0\, 0 + \boldsymbol{\varphi}_0\, A_{\varphi}\left(r, z\right).$$

This leads to a specific form of the equations describing the magnetic field in every element of the considered valve. For example:

a) Coils **1** and **2**:

$$\frac{\partial^2 A_{\varphi}}{\partial r^2} + \frac{1}{r}\frac{\partial A_{\varphi}}{\partial r} + \frac{\partial^2 A_{\varphi}}{\partial z^2} = -\mu_0 J_{\varphi,1,2}\,. \tag{2}$$

b) Ferromagnetic elements **3**, **4** and core **6**:

$$\frac{\partial}{\partial r}\left(\frac{1}{\mu r}\frac{\partial}{\partial r}\left(r A_{\varphi}\right)\right) + \frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A_{\varphi}}{\partial z}\right) = 0\,, \tag{3}$$

where $\mu = \mu(B)$ (this curve can easily be derived from the magnetization characteristic in Fig. 4).

c) Permanent magnet **5**:

$$\frac{\partial^2 A_{\varphi}}{\partial r^2} + \frac{1}{r}\frac{\partial A_{\varphi}}{\partial r} + \frac{\partial^2 A_{\varphi}}{\partial z^2} - \boldsymbol{H}_{\mathrm{c}} = 0 \tag{4}$$

where $\mu = \mu_r \mu_0$, μ_r=1.031, H_c=5.6×10^5 A/m .

d) Non-ferromagnetic elements **7**, **8**, **9**, **10** and ambient air:

$$\frac{\partial^2 A_{\varphi}}{\partial r^2} + \frac{1}{r}\frac{\partial A_{\varphi}}{\partial r} + \frac{\partial^2 A_{\varphi}}{\partial z^2} = 0\,, \tag{5}$$

where $\mu = \mu_0$.

The unambiguousness of the solution of these equations is provided by the correct boundary conditions in the form:

- $A_{\varphi}\left(\Gamma_{\infty}\right) = A(0, z) = 0$, where Γ_{∞} is an artificial boundary simulating the infinity. These conditions respect the fact that the electromagnetic field is axisymmetric and that the system has finite dimensions.
- the conditions at the interfaces of two arbitrary sub-domains (i, j) of the considered valve satisfy the following relations:

$$\mu_i \frac{\partial A_{\varphi,i}}{\partial n_{i,j}} = \mu_j \frac{\partial A_{\varphi,j}}{\partial n_{i,j}}, \quad A_{\varphi,i} = A_{\varphi,j}.$$

The vector of the electromagnetic force $\boldsymbol{F}_{\mathrm{m}}$ acting on the mover (in fact, on its ferromagnetic elements **3** and **4**) is given by the integral

$$\boldsymbol{F}_{\mathrm{m}} = \frac{1}{2}\oint_S \left[\boldsymbol{H}(\boldsymbol{n}\cdot\boldsymbol{B}) + \boldsymbol{B}(\boldsymbol{n}\cdot\boldsymbol{H}) - \boldsymbol{n}(\boldsymbol{H}\cdot\boldsymbol{B})\right]\mathrm{d}S, \qquad (6)$$

where S is the surface of the mover (in fact, of its ferromagnetic elements **3** and **4**)

IV. NUMERICAL SOLUTION

The numerical solution of the mathematical model of the considered electromagnetically controlled valve was carried out FEM program Agros2D [5] and QuickField 5.0 [4]. All nonlinearities of the permanent magnet NEOREC 53B [1] and carbon steel 12 040 were respected in the course of the calculations.

The calculations brought a lot of results. First, we investigated the convergence of the numerical solution, i.e. the effect of the size of the minimum $\delta_{\min}$ and maximum $\delta_{\max}$ dimensions of the used FEM discretization mesh in on the force acting on the ferromagnetic elements **3** and **4**, respectively, on the movable core of the valve, both in the "closed" and "open" regimes. The relevant results are summarized in Tab. 1. It can be seen that in the case with $\delta_{\min} = 2.5\times10^{-4}$ m and $\delta_{\max} = 1.25\times10^{-3}$ m (which corresponds to a mesh with about 140 thousand nodes) the inaccuracy in the calculation $F_{\mathrm{m},34}$ is less than 1 % of the nominal value, which is technically quite acceptable. All further computations were then performed on such meshes.

regime "close" :

$\delta_{\min}$ (m)	$\delta_{\max}$ (m)	nodes	$F_{\mathrm{m}3,4}$ (N)
1×10^{-3}	5×10^{-3}	8816	–28.239
5×10^{-4}	2.5×10^{-3}	34578	–28.316
2.5×10^{-4}	1.25×10^{-3}	140493	–28.326

regime "open" :

$\delta_{\min}$ (m)	$\delta_{\max}$ (m)	nodes	$F_{\mathrm{m}3,4}$ (N)
1×10^{-3}	5×10^{-3}	8786	195.00
5×10^{-4}	2.5×10^{-3}	33745	198.90
2.5×10^{-4}	1.25×10^{-3}	140757	200.94

Tab.1: Numerical convergence of the solution - regimes "closed" and "open"

The distribution of magnetic force lines in the "closed" position is depicted in Fig. 5 and in the "open" position in Fig. 6. It is clear that:

a) in the regime "closed" (Fig. 5), the permanent magnet **5** acts on the movable core of the valve through the ferromagnetic element **3**, and against the direction of axis z ;
b) in the regime "open" (Fig. 6), the coil **2** acts on the movable core of the valve through a ferromagnetic element **4**, in the direction of axis z ;

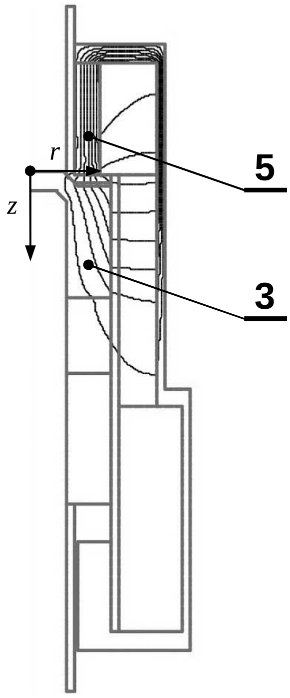

Fig.5: Distribution of magnetic field lines in the regime "closed" – ($J_1 = 0$, $J_2 = 0$)

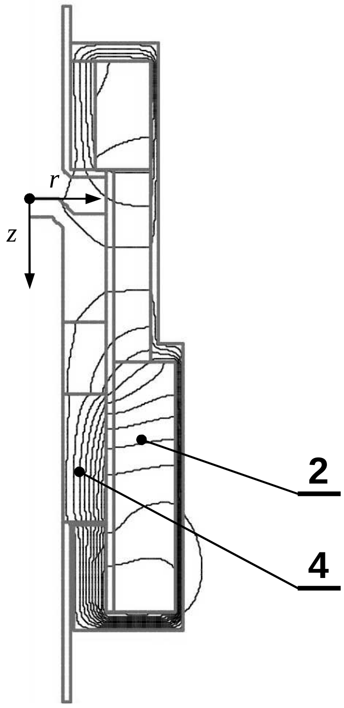

Fig.6: Distribution of magnetic field lines in the regime "open" – ($J_1 = 0$, $J_2 = 3\times10^6$ A/m^2)

Similarly the distribution of magnetic force lines can be mentioned for the regime "closing" (Fig. 7) and for the regime "opening" (Fig. 8). From here it is evident that:

a) The permanent magnet **5** acts on the mover through the ferromagnetic element **3** again against the direction of axis z in the regime "closing" (Fig. 7), while its effect is amplified appropriately oriented current $J_1 = -1.5\times10^7$ A/m^2 in the coil **1**;

The coil **2** acts on the mover through the ferromagnetic element **4** again in the direction of axis z in the regime "opening" (Fig. 8), while the effect of the permanent magnet **5** is weakened by the opposite oriented current J_1 = 1.5×10^7 A/m^2 in the coil **1**;

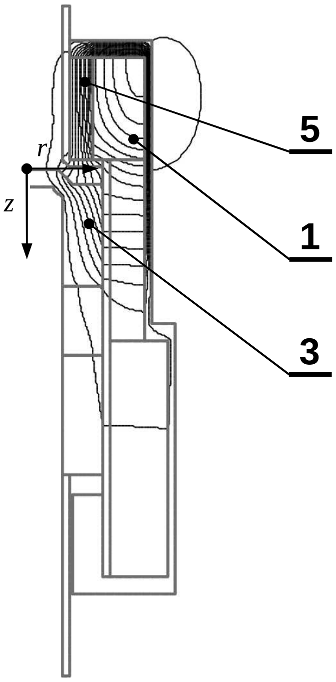

Fig.7: Distribution of magnetic field lines in the regime "closing" – (J_1 = -1.5×10^7 A/m^2, J_2 = 0 A/m^2)

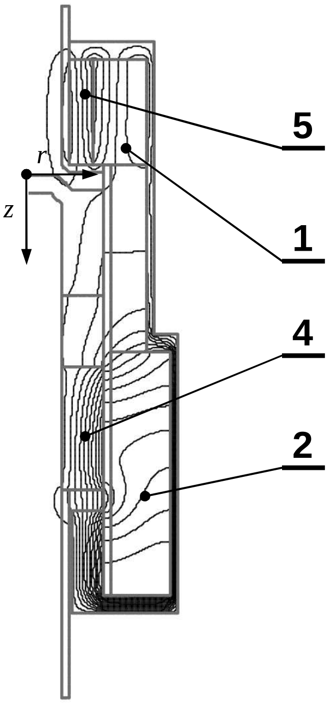

Fig.8: Distribution of magnetic field lines in the regime "opening" – (J_1 = +1.5×10^7 A/m^2, J_2 = 3×10^6 A/m^2)

V. RESULTS AND THEIR DISCUSSION

Specific practical features of the electromagnetically controlled valve are described:

a) The static characteristic (defining the force conditions in the considered valve) that determines the permissible hydrostatic pressure of fluid whose flow is controlled by the valve, both in the regime "closed" and in the regime "open";

b) The dynamic characteristic which defines the transient states of "opening" and "closing" of the valve that can help to assess the accuracy of dosing transported fluid by the valve.

A more detailed presentation of those characteristics is given in the following text.

A. Static characteristics

The static characteristic is described by the partial differential equation (1) and formula (2). Their numerical solutions for different positions of the mover within the interval $z \in \langle 3, 12 \rangle$ mm with ferromagnetic elements **3** and **4** located against the stationary core of the valve (see Fig. 1) provided the distribution of the static forces $F_{\mathrm{m}3,4}$ in the regimes

- “opening”, $J_1 = +1.5\times10^7$ A/m^2, $J_2 = 3\times10^6$ A/m^2,
- “closing”, $J_1 = -1.5\times10^7$ A/m^2, $J_2 = 0$.

The results are depicted in Fig. 9.

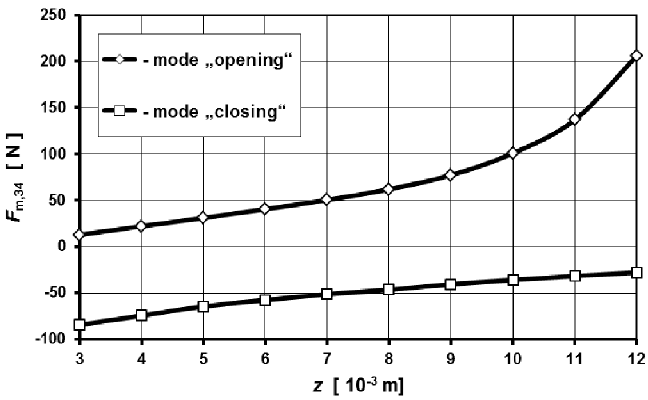

Fig.9: Static characteristics for modes “opening” and “closing”

Here it is obvious that the intended maximum hydrostatic pressure must reach such a value that the induced force acting on the inner face of the element **3** is smaller than $F_{\mathrm{m},34} \approx 28$ N (regime „closed“, $z = 12$ mm) in absolute value. The effects of the hydrodynamic pressure are ignored - their influence is not discussed in this paper.

Of course, the static and dynamic characteristics of the designed electromagnetic valve presented in this article can be modified both qualitatively and quantitatively as needed.

The quantitative character of the static characteristic can be influenced by the:

- Values of the current densities J_1 and/or J_2. These values are in the case of J_1 (short current pulse), however, limited by the size the competent demagnetization field $H_{\mathrm{demag}}(r, z)$, which is created by coil **1** and acts on the permanenet magnet **5**. To prevent this magnet from irreversible deteriorating, the condition $H_{\mathrm{demag}} < |H_{\mathrm{c}}|$ must be satisfied. The value of the current density J_2 is only limited by the temperature, whose excessive growth could lead to the damage of the coil **2**.

- Use of different permanent magnet **5**, with higher H_{c} and B_{r}, or changing its dimensions;
- Ferromagnetic materials used for manufacturing the valve parts **3**, **4** and **6**. Suitable $B(H)$ characteristics would provide higher values of μ_{r} influencing particular operating regimes.

The qualitative character of the static characteristic can be affected by the length and value of the current density J_1 and J_2. The value of the current density J_2 is limited only by the temperature, whose excessive growth could lead to a serious damage the coil **5** again.

The change of the static characteristic causes differences in the dynamic characteristics (as is apparent from (7), (8)). Therefore, different curves for velocities $v(t)$ and trajectories $z(t)$ for the considered valve are shown in Figs. 10 and 11. The operating modes of the valve are obviously affected. The opening time (an also closing time) of the valve and accuracy of dosing the liquid are changed.

Of course, the above changes can be realized by a change of dimensions and possibly also structural arrangement of the valve. The considered low-pressure valve can be modified on a high-pressure valve by changing these parameters. It is possible to design a valve with hydrostatic pressure of the order of tens of meters of the water column. The electromagnetically operated low-pressure valve designed in this paper, is designed for the hydrostatic pressure corresponding to several meters of the water column (see Fig 1).

B. Dynamic characteristic

The dynamic characteristics in this case are described by the differential equations

$$m\frac{\mathrm{d}v}{\mathrm{d}t} = F_{\mathrm{m,34}} + F_{\mathrm{G}} + F_{\mathrm{H}} \ , \tag{7}$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = v \, , \tag{8}$$

where m is the weight of the mover. The symbols v and z are the instantaneous values of the speed and position of the mover, $F_{\mathrm{m,34}}$ is the electromagnetic force acting on the mover, F_{G} is the weight of the mover (in our case $F_{\mathrm{G}} = 6.209\ \mathrm{N}$) and F_{H} stands for the hydrostatic force acting on the closing cone **3**, which is connected with the mover. In our case $F_{\mathrm{H}} = 9.708\ \mathrm{N}$ (determined for H_2O, whose column is 1 m high, see Fig. 1). The dynamic characteristics of the regimes "opening" and "closing" are shown in Fig. 10 and 11.

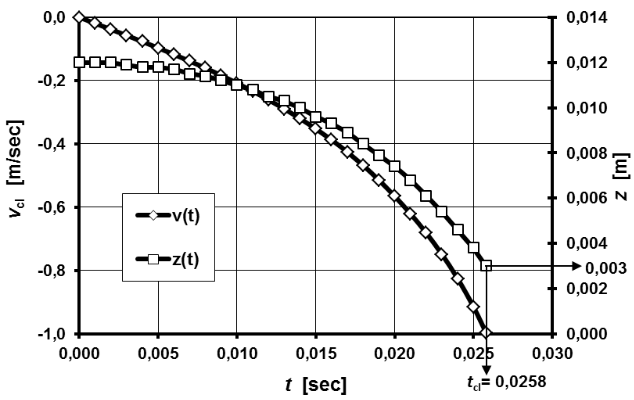

Fig.10: Dynamic characteristic for mode “closing”

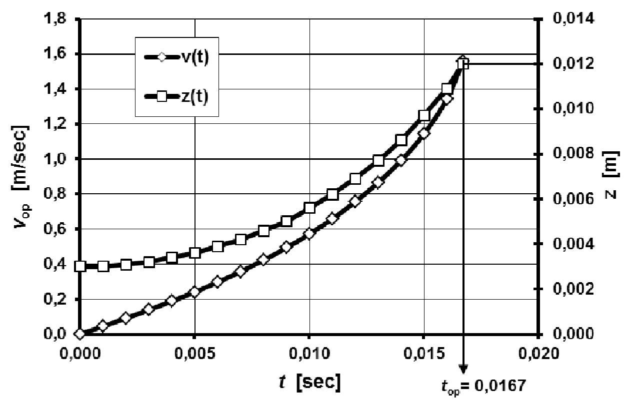

Fig.11: Dynamic characteristic for mode “opening”

The dynamic characteristics of the operating regimes "opening" and "closing" provided the time intervals $t_{\mathrm{op}} = 0.0167\ \mathrm{s}$ and $t_{\mathrm{cl}} = 0.0258\ \mathrm{s}$, for which the regimes "opening" and "closing" run and for which, therefore, current density $J_1 = \pm 1.5 \times 10^7\ \mathrm{A/m^2}$ in the coil **1** must be applied.

The dynamic characteristics shown before in Figs. 10 and 11 are obtained by the numerical solution (method Runge-Kutta) of equations (7) and (8), that respect the forces $F_{\mathrm{m,34}}$, F_{G}, F_{H} (explained previously).

These force relations are simplified and acceptable only for the considered electromagnetic valve - which is the aim of this paper.

In the course of the calculation of the dynamic characteristics it is necessary to consider also the hydrodynamic effects, if the valve should be used for controlling the flow of specific liquid in a particular hydraulic circuit. These effects can be:

- The hydrodynamic force effects (hydrodynamic resistance) of the liquid at a flow rate of six holes of diameter four millimeters, see detail A of element **3** in Fig. 3b;
- The similar force effects for the flow rate through the inner hole with diameter twenty millimeters in the mover (see Fig. 2);

- The friction between the mover and non-magnetic steel tube **8**, which also serves as a guide way for the movement of the valve core (see also Fig. 2). The calculation must respect the friction influenced by the fact that the inner surface of the pipe **8** is wetted by the flowing fluid.

It is obvious, that the first two force effects will accelerate the mover in the regime "opening", while in the regime "closing" they will slow down its motion. The third of these effects will only slow down mover in both regimes.

The calculation of these hydrodynamic force effects must be based on knowledge of the following quantities:

- The considered amount of liquid in the hydraulic circuit necessary for determination of the distribution of velocity of that fluid in each internal space of the reference valve;
- The dynamic viscosity of the investigated fluid and its dependence on the velocity and temperature;
- The weight of the considered liquid and its temperature dependence.

It is clear that the complete hydrodynamic problem is beyond the scope of this paper. In particular specific technical applications, however, it should be analyzed in more detail, because it really exists.

VI. Conclusion

This paper describes one possible design of the electromagnetically controlled low-pressure hydraulic valve. Presented are here its

a) Static characteristics which define the power conditions in the considered valve and determine the allowable hydrostatic pressure of the liquid in it;
b) Dynamic characteristics which define the transient states of "opening" and "closing" of the valve that can help to assess the accuracy of dosing the transported fluid.

The term "low-pressure valve" is here understood as a valve which admits hydrostatic pressures on the order of meters of the water column. However, a simple design change (adding one more coil and, of course, an appropriate dimensioning of the outer shell) can be used for obtaining a "high-pressure" valve, which would allow growing hydrostatic pressure up to tens of meters of the water column.

ACKNOWLEDGMENT

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