FLUID FLOW MODELING IN THE SPOOL AND SLEEVE OF AN ELECTRO-HYDRAULIC POWER AMPLIFIER

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Abstract

This article deals with the initial data for modeling a spool valve. It describes the volumetric solid model of the flowing part of the high precision spool pair layouts in the electro-hydraulic power amplifier; the generation of the finite-element mesh of the solid model; the physical and mathematical model of the fluid flow process; and the estimations and their analysis. The pressure characteristics of the spool valve under different load are calculated. 3D modeling of fluid flow through the annular clearance between the spool and sleeve in the electro-hydraulic power amplifier (fluid leak modeling) is performed.

Keywords: electro-hydraulic power amplifier, spool and sleeve, fluid leak modeling, computational fluid dynamics

I. Introduction

The precision and efficiency of modern industrial hydraulic systems are due to the use of automation and servo control elements. One such element is the electro-hydraulic power amplifier (EHPA), which regulates the speed and power of the hydraulic drive. However, the increasing demands on the performance of hydraulic drives require an increase in the accuracy of design calculations, including those for spool-type EHPAs [1-4]. The simulation of fluid flow through the annular clearance between the sleeve and spool of an EHPA is effective for optimizing valve performance and estimating leak rates. Modeling results can be used to make informed decisions on valve design and tuning and to improve overall system performance.

II. Modeling of valve hydrodynamics

The EHPA model under study includes a housing and a high-precision spool and sleeve valve. The other valve components such as the linear motor, position sensor, fasteners and seals were removed from the model as they do not contribute to the study of the fluid dynamics of the device. The high-precision spool and sleeve valve consists of a fixed sleeve and a spool; the latter is mounted inside the sleeve and can move along the longitudinal axis. The spool and sleeve are installed in the central groove of the housing. The spool is shaped to ensure the required connections of the hydraulic lines.

A volumetric solid model of the P-A and B-T valve flow paths was designed in Autodesk Inventor software from a 3D model of the valve. The P-B and A-T paths are of the same geometry as P-A and B-T because of the symmetry of the spool and valve housing. Therefore, it is reasonable to limit the analysis to the P-A and B-T paths only.

The 3D model of the hydraulic amplifier is simplified and adapted for hydrodynamic calculations. We made the following assumptions: there is no radial clearance between the sleeve and the rod, and the radial grooves and the unloading line of the spool end surfaces are excluded. The 3D model was formed at different spool positions: 5%, 10%, 25%, 50%, 75% and 100% of X_{max}. We applied the Ansys Meshing preprocessor to build the computational mesh [5, 6].

The modeling of the valve hydrodynamics revealed the pressure characteristics of a high-precision spool valve. We determined the volumetric flow rate through the valve and the pressure drop at different spool movements.

Figure 1 shows the characteristics of the EPHA, represented by the dependence of the hydraulic fluid flow rate on the spool movement at four pressure drops ΔPAB.

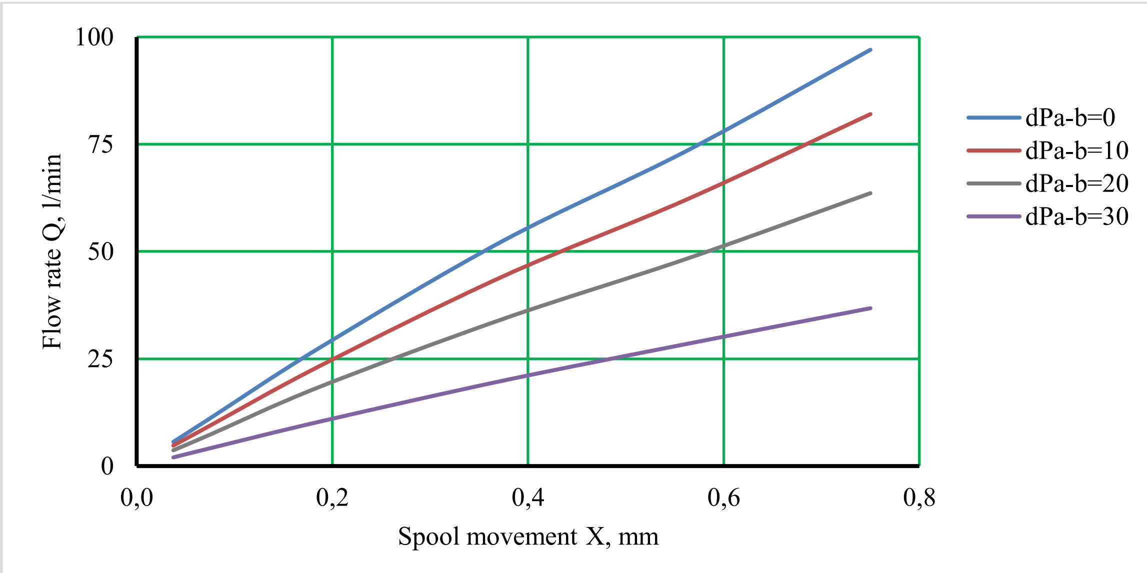

Figure 1: *Dependence of the spool movement on the hydraulic fluid flow rate through the valve (nominal flow rate 40 l/min)*

III. Calculation of the generalized characteristic of the EHPA.

The spool-sleeve system in the EHPA is a system of controlled restricting openings, combined in one structure (Fig. 2).

The fluid flow with flow rate Q_p and pressure p_p enters the sleeve, then the goes around the spool and enters the hydraulic motor operating cavities with flow rate Q_m and pressure p_1. The fluid flow goes back from the hydraulic motor to the operating cavity of the spool at the same flow rate Q_m and pressure p_2 and then to the output in the drainage pipeline at a flow rate Q_{dr} and pressure p_{dr}. Flow rates Q_3 and Q_4 must be taken into account due to the internal fluid leakage through the gaps.

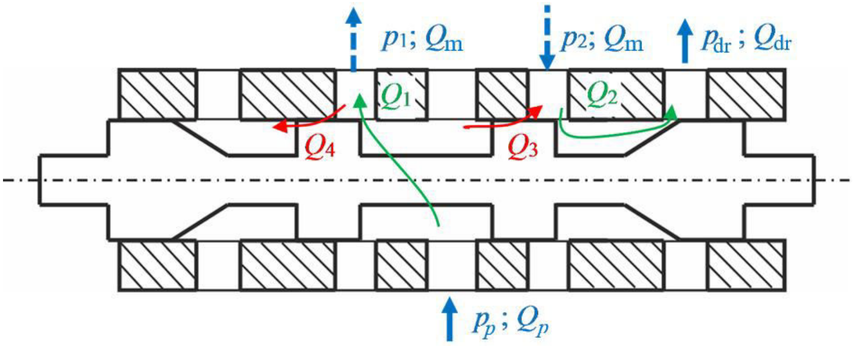

Figure 2: *Calculation of the sleeve-spool system*

The system of equations describing the physical fluid flow through the EHPA-hydraulic motor system, includes the following continuity equations and Bernoulli equations:

$$Q_1 = \mu_1 \cdot S_{or1} \cdot \sqrt{\frac{2\cdot(p_p - p_1)}{\rho}} \tag{1}$$

$$Q_2 = \mu_2 \cdot S_{or2} \cdot \sqrt{\frac{2\cdot(p_2 - p_{dr})}{\rho}} \tag{2}$$

$$Q_3 = \mu_3 \cdot S_{or3} \cdot \sqrt{\frac{2\cdot(p_p - p_2)}{\rho}} \tag{3}$$

$$Q_4 = \mu_4 \cdot S_{or4} \cdot \sqrt{\frac{2\cdot(p_2 - p_{dr})}{\rho}} \tag{4}$$

$$Q_m = Q_1 - Q_4 \tag{5}$$

$$Q_m = Q_2 - Q_3 \tag{6}$$

$$P_m = p_1 - p_2 \tag{7}$$

where p_m is pressure drop on the hydraulic motor; p_1, p_2 are pressures in the operating cavities of the hydraulic motor; Q_m is liquid flow rate entering the hydraulic motor; Q_i is liquid flow rate through the i-th restricting opening; μ_i is the flow coefficient of the liquid flow through the i-th restricting opening; $S_{or\text{-}i}$ is the cross-sectional area of the i-th restricting opening.
Flow coefficients μ_i are determined by the results of computational modeling presented in Table 1.

Table 1: *Flow coefficients*

Spool position, mm	Pressure drop ΔP_{AB}=0 MPa		Pressure drop ΔP_{AB}=10 MPa		Pressure drop ΔP_{AB}=20 MPa		Pressure drop ΔP_{AB}=30 MPa	
	Flow rate Q, l/min	Flow coefficient	Flow rate Q, l/min	Flow rate Q, l/min	Flow rate Q, l/min	Flow coefficient	Flow rate Q, l/min	Flow coefficient
0.04	5.4	1	4.6	2.0	2.0	1	2.0	1
0.08	11.1	0.96	9.4	4.2	4.2	0.96	4.2	0.96

0.19	27.8	0.92	23.5	10.4	10.4	0.93	10.4	0.91
0.38	52.7	0.86	44.5	19.9	19.9	0.86	19.9	0.86
0.56	73.9	0.8	62.4	28.6	28.6	0.8	28.6	0.82
0.75	97.5	0.79	82.4	36.8	36.8	0.79	36.8	0.79

The following formulae have been applied to calculate the areas:

$$S_i = \begin{cases} n \cdot b \cdot \sqrt{(X_з - G_i)^2 + \delta^2} \text{ при } (X_з - G_i) > 0 \\ n \cdot b \cdot \delta \text{ при } (X_з - G_i) \le 0 \end{cases}; \quad (8)$$

where n = 4 is the number of restricting openings; b = 5.2; 3.5; 1.8 mm are the opening widths; $X_з$ is spool movement; G_i are the overlaps of corresponding restricting openings.

When testing, the fluid flow is poured through the EHPA unloaded, when the hydraulic lines connecting the EHPA to the hydraulic motor are connected to each other. In this case, the pressures in the hydraulic lines controlling the hydraulic motor are equal to $p1 = p2$.

To determine the unified characteristics, Equations (1–8) were calculated. These establish the relationship between the spool X_{sp} positions, fluid flow and load, indirectly characterized by the pressure difference in the operating chambers of the hydraulic motor ($p_p = p_1$-p_2) for the pressure drop at the valve $\Delta p = 35$ *MPa.*

The results of 3D modeling allow us to determine the flow coefficients μ at the restricting openings. For this purpose, the coefficients $\mu_1$and μ_2 are set using the MathCad computer program by successive approximations. The results of Equations (1–8) in the form of flow rates are compared with the results of 3D modeling. The coefficients of flow rates μ were determined with a relative error of flow rates Q_i not exceeding 1%.

Figs. 3 and 5 show characteristics for three EHPA models in dimensional and dimensionless coordinates. Here $dP = p_1 - p_2$ is the pressure drop in the operating chambers; $X = X_{sp} / X_{max}$ is a dimensionless coordinate of the spool position at X_{max} = 0.75 mm; $\overline{Q_m} = Q_m / Q_{max}$ is a dimensionless flow rate at maximum flow rate Q_{max}, when the spool takes position 0,75 mm, and $dP = 0$; $\overline{p_m} = dP / p_p - p_{or}$ is dimensionless pressure difference in operating chambers of the hydraulic motor at $p_p - p_{or}$= = *35 MPa.*

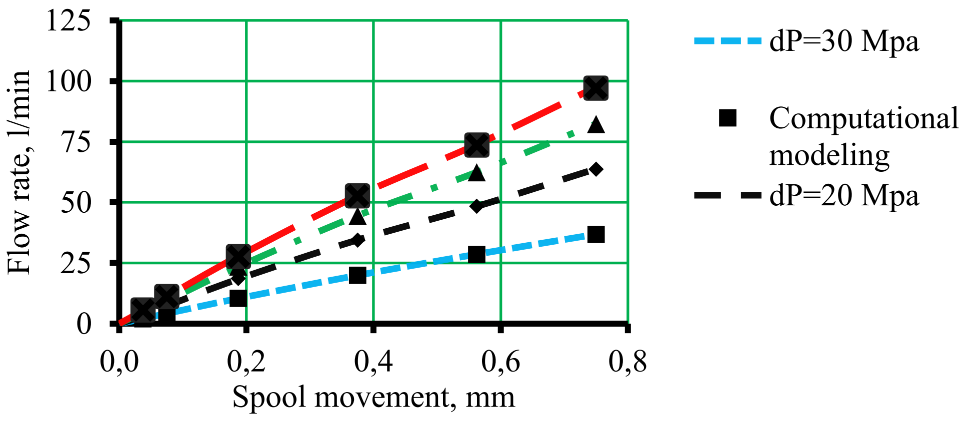

Figure 3: *Influence of spool position on the flow rate through EHPA with a nominal flow rate of 40 l/min at different pressure drops in channels* $dP = p_1 - p_2$

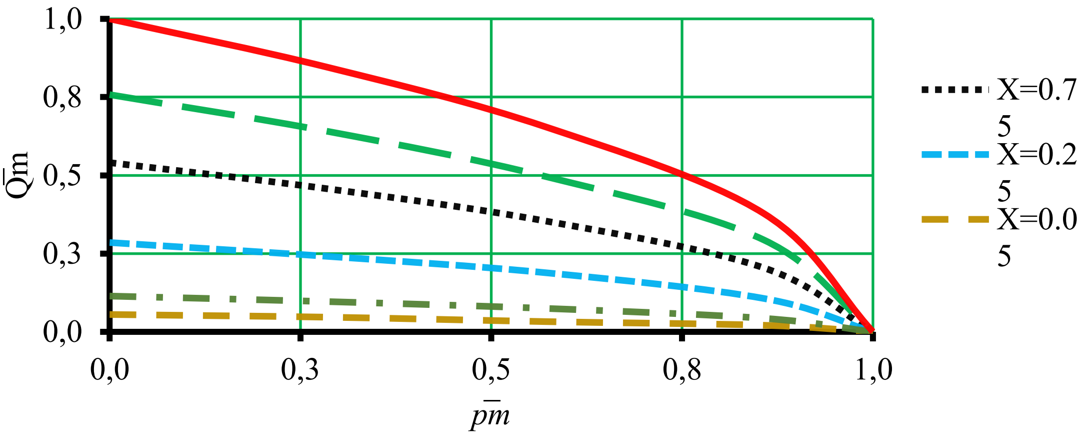

Figure 4: *Characteristics of the EHPA with a nominal flow rate of 40 l/min at Q_{max} = 97.5 l/min*

The pressure distributions show that an increase of the open flow area of the spool leads to increase in the liquid flow rate and the irregularity of the pressure distribution in the opening of the flowing part of the valve. This includes an increase in the irregularity of the velocity accompanied by local vortex and a decrease in hydrostatic pressure.

IV. Modeling fluid leaks in the valve

The operation of the EPHA results in fluid leak in the annular clearance. The annular clearance is the area between the sleeve and the spool that carries the fluid flow. Leaks depend on the fluid properties, pressure drop, and the clearance shape. The geometric parameters of the annular clearance have been determined according to the design documentation. The outer diameter of the ring is D = 8.058 mm, the inner diameter is d = 8.052 mm. The clearance widths for four spool positions 5%, 10%, 50%, and 100% of X_{max}, are 0.04 mm, 0.08 mm, 0.38 mm, and 0.75 mm, respectively.

The mathematical model of fluid flow through the valve annular clearance is based on the equations of the continuity of flow and impulse. We adopted the laminar model of fluid flow through the annular clearance. The inlet pressure is set on the inlet of the calculation area. The static pressure is accepted on the outlet. The wall condition is defined on the opening housing surfaces. We carried out calculations at three values of pressure drop on the annular clearance, respectively: 17.5 MPa, 7.5 MPa, and 2.5 MPa.

According to the results of hydrodynamics modeling through the annular clearance of the valve, we determined the values of the pressure drop and the flow rate of liquid (Fig. 5).

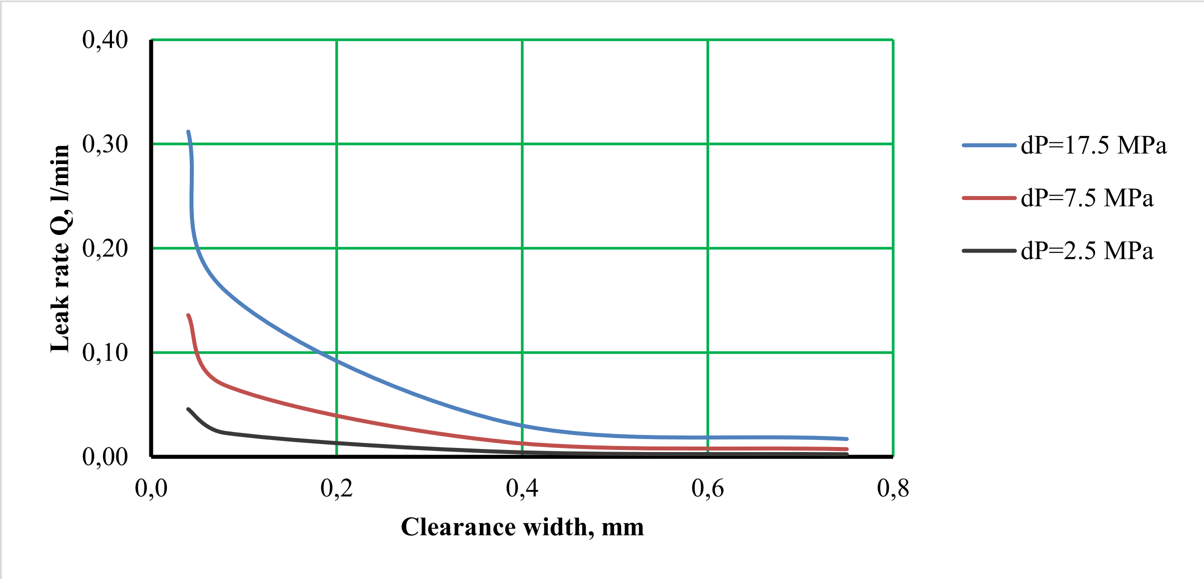

Figure 5: *Dependence of leak rate on the clearance width*

Figure 5 shows that an increase in the pressure drop across the spool and the width of the annular clearance leads to a significant increase in fluid leak.

The modeling provides a reasonable estimate of the leak rate through the annular clearance between the spool and sleeve. This helps to understand how flow affects the valve and to improve the valve performance.

V. Acknowledgments

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References

[1] E. Lisowski, W. Czyzycki, J. Rajda Three Dimensional CFD Analysis and Experimental Test of Flow Force Acting on the Spool of Solenoid Operated Directional Control Valve. Energy Conversion and Management. 2013. 70. P. 220–229. DOI: 10.1016/j.enconman.2013.02.016

[2] H. Chattopadhyay, A. Kundu, B.K. Saha, T. Gangopadhyay Analysis of flow structure inside a spool type pressure regulating valve. Energy Convers Manage, 2012, 53.

[3] J.R.Valdes, M.J. Miana, J.L. Nunez, T. Putz Reduced Order Model for Estimation of Fluid Flow and Flow Forces in Hydraulic Proportional Valves. Energy Conversion and Management. 2008.

49, 6. P. 1517–1529. DOI: 10.1016/j.enconman.2007.12.010.

[4] S.X. Karimov, F.S. Hajiyeva, S.V. Ismayilova. Calculation of the structure of the column of the rods of the deep pump installations for separate operation of two layers. “Machine-building and Energy: New Concepts and Technologies” International Scientific-practical Conference materials, December 2-3, 2021, AzTU, Baku, Azerbaijan. Pp. 140-143

[5] Ansys Fluent 19 Theory Guide. Ansys Inc.

[6] Ansys Fluent 19 User Guide. Ansys Inc.