Optimization of parameters of the pressure regulator with variable characteristic

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Abstract. When designing a variable capacity pressure regulator, it is necessary to select parameters that meet certain criteria. In this article optimization of regulator parameters by LPτ search method is considered. The mathematical model of the regulator is made, a possible set of quality criteria is given, dependent criteria are established and the majority of approximate effective points are found. Setting of criteria restrictions is performed in the dialog mode. The methods described in the article allow to obtain an optimal design of the pressure regulator with variable characteristic.

Introduction
The use of pumps with a pressure regulator is a widespread way to increase the energy efficiency of hydraulic systems. Improving the performance of hydraulic systems is an urgent task [1–4]. In many hydraulic systems operating at constant pressure, there is a need to change the pressure itself. There are circuits with a variable characteristic in which, at a constant load, a change in the characteristic causes a transition to a new static state with a new pressure value.

Choosing the parameters of a pressure regulator is a complex multi-criteria task [5–9]. Choosing a set of quality criteria is also not an easy task. It is necessary to determine a set of quality criteria, which, on the one hand, reflects as much information as possible about the operation of the system, and on the other hand, is minimal for solving the optimization problem.

There are various methods for solving optimization problems [10–13]. We will optimize the parameters of a pressure regulator with a variable characteristic by the LPτ search method, which is widely used and underlies many other methods [14–19].

The mathematical model of the regulator.
The schematic diagram of the controller is presented in Fig. 1.

The principle of operation and the mathematical description of the equilibrium of this regulator is given in [20]. Consider the dynamics equations of the regulator.

Spool movement equation:

$$m_1 \cdot \frac{d^2}{dt^2} x + k_{f1} \cdot \frac{d}{dt} x + c_1 (x_0 + x) + p_{ext} \cdot A_{cf} = p_d \cdot A_{sf} \quad (1)$$

Where m_1 — reduced mass of the spool,

t— Time

x — Spool offset from neutral,

k_{f1} — reduced damping coefficient of the spool,

c_1 — The stiffness of the spring acting on the spool,

x_0 — initial spring preload,

p_{ext} — external pressure

A_{cf} — the area affected by external pressure,

p_d — is the discharge pressure

A_{sf} — The area of the end face of the spool.
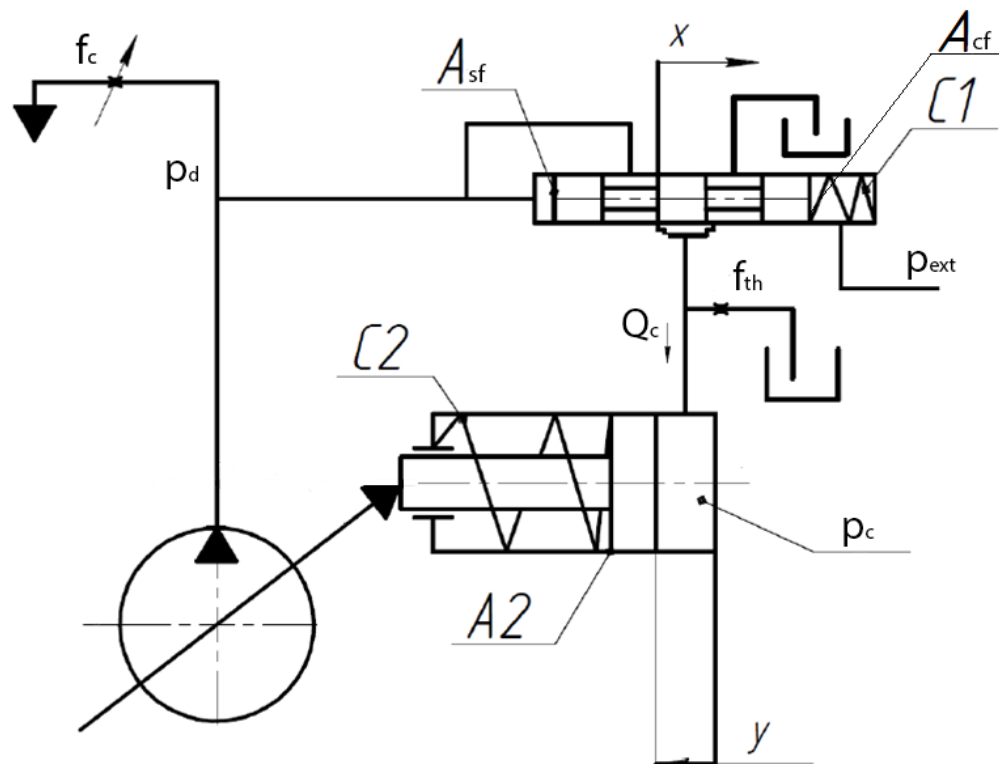
Fig. 1. Schematic diagram of the controller.

Equation of piston movement:

$$m_2 \cdot \frac{d^2}{dt^2}y + k_{f2} \cdot \frac{d}{dt}y + c_2 \cdot y = p_c \cdot A_2 \quad (2)$$

Where m_2 — the reduced mass of the piston,

y — The coordinate of the piston position,

k_{f2} — The reduced damping coefficient of the piston,

c_2 — The stiffness of the control piston spring,

p_c — The control pressure

A_2 — The area of the end face of the control piston.

The equation of the balances of the costs of the pump - throttle simulating the load:

$$Q_d + Q_{com1} = Q \quad (3)$$

Where Q_d — flow rate on the throttle simulating the load,

Q_{com1} — Flow rate for fluid compression in the discharge line,

Q — pump feed.

We replace the input quantities with the expressions for their calculation.

$$\mu \cdot f_d \cdot \sqrt{\frac{2 \cdot p_d}{\rho}} + \frac{V_{lin}}{B} \frac{dp_d}{dt} = Q_{max} - k_c y \quad (4)$$

Where μ — flow rate

f_d — flow area of the throttle simulating the load,

ρ — Fluid density,

V_{lin} —discharge line volume (assumed constant),

B — Reduced volume modulus of elasticity of the working fluid,

Q_{max} — Maximum pump flow.

$$k_c = \frac{Q_{max}}{y_{max}} \quad (5)$$

Where y_{max} — maximum movement of the control piston.

The equation of the balance of expenses:

$$Q_{fs} = Q_{com2} + Q_{ds} + Q_c + Q_{th} \quad (6)$$

Where Q_{fs} — flow rate through the filling gap,

Q_{com2} — Fluid compression rate in the control cavity,

Q_{ds} — Flow rate through the drain slot

Q_c — control flow,

Q_{th} — flow on the throttle.

Replace the incoming values with expressions to calculate them.

$$\mu b X_f \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_d - p_c} = \frac{V_c}{B} \frac{dp_y}{dt} + \mu b X_d \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_c} + A_2 \frac{dy}{dt} + \mu \cdot f_{th} \cdot \sqrt{\frac{2 \cdot p_c}{\rho}} \quad (7)$$

Where b — the total width of the dispenser windows,

V_c — Volume of the control cavity (assumed constant),

f_{th} — Throttle bore area,

The following spool geometry model is adopted:

$$X_f = -2R + \sqrt{(\delta + 2R)^2 + 0,25 \cdot \left(S + 2R + x + |S + 2R + x|\right)^2} \quad (8)$$

$$X_d = -2R + \sqrt{(\delta + 2R)^2 + 0,25 \cdot \left(S + 2R - x + |S + 2R - x|\right)^2} \quad (9)$$

Where R — spool edge radius

δ — Spool radial clearance,

S —spool edge overlap.

Mathematical Modeling Results

A program was written in the Python programming language that allows the entire optimization process to be performed for this device. It includes an LPτ sequence generator, subroutines that accept a list of variable parameters and return a list of criteria corresponding to it, a dialog algorithm for specifying criteria constraints, and a generator of a set of approximately effective points. To calculate transients was used the scipy.integrate.solve_ivp function from the scipy library, which allows to find a solution to systems of ordinary differential equations. The integration method BDF is used (an implicit multi-step method of variable order (from 1 to 5) based on the backward differentiation formula). To work with data arrays, the numpy library is used.

To determine the optimal parameters of the controller, the following variable parameters were identified:

$a_1 = A_2$ —end face of the control piston,

$a_2 = c_2$ —control piston spring stiffness,

$a_3 = A_{sf}$ —Spool end face,

$a_4 = c_1$ — The stiffness of the spring acting on the spool,

$a_5 = f_{th}$ —throttle bore area,

$a_6 = b$ — The total width of the dispenser windows,

$a_7 = S$ — overlapping spool edges,

$a_8 = k_c$ — Coefficient of influence of piston movement on pump flow,

$a_9 = k_{f1}$ — reduced damping coefficient of the spool,

$a_{10} = k_{f2}$ —Reduced piston damping coefficient.

The parameters were varied using an LPτ sequence generator based on an arithmetic algorithm. At the output of the generator, we have an LPτ sequence in a unit cube, which is then recalculated for any given parallelepiped P. The accepted number of points in the sequence is N=256.

The value calculation A_{cf}, x_0 is made separately for each selected point in the space of variable parameters so that the static characteristics set has the same value of the regulation start pressure, which is the initial value for design.

Variable parameters are sought in the multidimensional parallelepiped P, which is determined by the inequalities:

$$a_i^* \leq a_i \leq a_i^{**} \ (i = 1, 2 \ldots 10) \ (10)$$

Where a_i^* — the restriction on the ith criterion from below,

a_i^{**} —restriction on the ith criterion from above.

Before solving the optimization problem, a_i^0 — the values of the parameters corresponding to some prototype. And found $\Phi_\vartheta^0 \ (\vartheta = 1, 2 \ldots 16)$ — values of the quality criteria for the prototype.

Tab. 1. Values of parametric restrictions on the values of the parameters of the prototype

i	1	2	3	4	5	6	7	8	9	10
a_i^* / a_i^0	0,56	0,67	0,56	0,90	0,88	0,83	0,80	0,82	0,61	0,75
a_i^{**} / a_i^0	1,27	3,06	1,59	1,10	1,32	1,17	1,50	1,36	1,46	1,25

The following quality criteria were assigned as optimality criteria for the regulator.
Group I (criteria related to the static characteristic).

$$\Phi_1 = \frac{1}{k_{Qp1}}$$

Where k_{Qp1} —gain flow pressure at a flow rate of $\frac{Q_{max}}{2}$ and at maximum p_{ext}.

$$\Phi_2 = Q_{fs01}$$

Where Q_{fs01} — flow rate through the filling gap at the flow rate point $\frac{Q_{max}}{2}$ and at maximum p_{ext}.

$$\Phi_3 = \frac{1}{k_{Qp2}}$$

Where k_{Qp2} —the pressure gain of the flow rate at the point with the flow rate $\frac{Q_{max}}{2}$ and at maximum p_{ext}.

$$\Phi_4 = Q_{fs02}$$

Where Q_{fs02} — flow rate through the filling gap at the flow rate point $\frac{Q_{max}}{2}$ and at maximum p_{ext}.

Group II (criteria related to the dynamics of the regulator).

For each selected point in the space of variable parameters, the following system responses are constructed $p_d(t)$.

1) System response to step increase p_{ext}. Initially, the system is in equilibrium at a point with a flow rate of $\frac{Q_{max}}{2}$ with a minimal p_{ext}. The magnitude of the step effect at the input is chosen such that the change in p_d is $\frac{1}{3}$ of the original value.

2) System response to step increase p_{ext}. Initially, the system is in equilibrium at a point with a flow rate of $\frac{Q_{max}}{2}$ with a maximal p_{ext}. The magnitude of the step effect at the input is chosen such that the change in p_d is $\frac{1}{3}$ of the original value.

3) System response to step increase f_d. Initially, the system is in equilibrium at a point with a flow rate of 0 with a minimal p_{ext}. The magnitude of the step effect at the input is chosen such that the flow rate varies from 0 to $\frac{Q_{max}}{2}$.

4) System response to step increase f_d. Initially, the system is in equilibrium at a point with a flow rate of 0 with a minimal p_{ext}. The magnitude of the step effect at the input is chosen such that the flow rate varies from Q_{max} to $\frac{Q_{max}}{2}$.

5) System response to step increase f_d. Initially, the system is in equilibrium at a point with a flow rate of 0 with a maximal p_{ext}. The magnitude of the step effect at the input is chosen such that the flow rate varies from 0 to $\dfrac{Q_{max}}{2}$.

6) System response to step increase f_d. Initially, the system is in equilibrium at a point with a flow rate of 0 with a maximal p_{ext}. The magnitude of the step effect at the input is chosen such that the flow rate varies from Q_{max} to $\dfrac{Q_{max}}{2}$.

A stepwise action is defined by an exponential sigmoid. Operating points, if necessary, are found by the half-division method. For each i-th transient, the transient time t_i and the amount of overshoot are determined by $\Delta h_i\ (i = 1, 2 \ldots 6)$.

Then

$$\Phi_{2i+3} = t_i, (11)$$

$$\Phi_{2i+4} = \Delta h_i. (12)$$

Total we have 16 quality criteria.

After the values of the quality criteria were obtained for each selected point from the space of variable criteria, the correlation coefficients between the criteria were found. The exclusion of dependent criteria was carried out as follows: criteria that were desired to be maintained ($\Phi_1, \Phi_2, \Phi_{15}, \Phi_{16}$), those criteria that had a correlation coefficient with these criteria greater than 0.9 were excluded from consideration. As a result, the set of criteria considered has decreased ($\Phi_1, \Phi_2, \Phi_7, \Phi_{15}, \Phi_{16}$). Test tables were compiled for each of these criteria, based on which criteria limitations were set. Taking into account the criteria constraints, a set of admissible points D was formed, and the criteria constraints were entered in the interactive mode with the subsequent verification of the set D for emptiness.

From the set D, points are selected that form the set of approximately effective ones. An analysis of the table containing the parameters and quality criteria of approximately effective points made it possible to select the final set of parameters.

Tab. 2. Values of the selected parameters relative to the values of the parameters of the prototype.

$\dfrac{a_1}{a_1^0}$	$\dfrac{a_2}{a_2^0}$	$\dfrac{a_3}{a_3^0}$	$\dfrac{a_4}{a_4^0}$	$\dfrac{a_5}{a_5^0}$	$\dfrac{a_6}{a_6^0}$	$\dfrac{a_7}{a_7^0}$	$\dfrac{a_8}{a_8^0}$	$\dfrac{a_9}{a_9^0}$	$\dfrac{a_{10}}{a_{10}^0}$
1,230	1,313	0,916	0,900	0,948	0,868	1,257	1,253	1,287	0,881

Tab. 3. Values of the quality criteria of the selected option relative to the values of the quality criteria of the prototype.

$\dfrac{\Phi_1}{\Phi_1^0}$	$\dfrac{\Phi_2}{\Phi_2^0}$	$\dfrac{\Phi_3}{\Phi_3^0}$	$\dfrac{\Phi_4}{\Phi_4^0}$	$\dfrac{\Phi_5}{\Phi_5^0}$	$\dfrac{\Phi_6}{\Phi_6^0}$	$\dfrac{\Phi_7}{\Phi_7^0}$	$\dfrac{\Phi_8}{\Phi_8^0}$
0,999	0,875	0,997	0,875	1,009	0	0,857	0,773
$\dfrac{\Phi_9}{\Phi_9^0}$	$\dfrac{\Phi_{10}}{\Phi_{10}^0}$	$\dfrac{\Phi_{11}}{\Phi_{11}^0}$	$\dfrac{\Phi_{12}}{\Phi_{12}^0}$	$\dfrac{\Phi_{13}}{\Phi_{13}^0}$	$\dfrac{\Phi_{14}}{\Phi_{14}^0}$	$\dfrac{\Phi_{15}}{\Phi_{15}^0}$	$\dfrac{\Phi_{16}}{\Phi_{16}^0}$
1,453	0	1,067	0	0,758	0,168	1,194	0,034

Conclusions.

A lot of approximately effective points are obtained. The point selected from this set, according to the results of expert evaluation and the selected quality criteria, is the best compared to the point corresponding to the original prototype, and meets the specified requirements. The same calculation can be performed for a larger number of points. In the presented model, a number of assumptions are made, in particular, it was assumed that the moment on the inclined disk changes slightly.

Reference

[1]   Semenov, S., Kulakov, D. Mathematical modeling of the mechanisms of volumetric hydraulic machines (2019) IOP Conference Series: Materials Science and Engineering, 492 (1), № 012042,

[2]   Semenov, S.E. Mathematical modeling of the electro-hydraulic actuation systems of the machines with tree-like kinematic structure (2015) Proceedings of 2015 International Conference on Fluid Power and Mechatronics, FPM 2015, № 7337184, pp. 583–592.

[3]   Kulakov, D.B., Semenov, S.E., Kulakov, B.B., Shcherbachev, P.V., Tarasov, O.I. Hydraulic Bipedal Robots Locomotion Mathematical Modeling (2015) Procedia Engineering, 106, pp. 62–70.

[4]   Kulakov, D., Kulakov, B. Study of the dynamics of an electro-hydraulic servo drive physical model on FESTO learning system (2019) IOP Conference Series:

[5]   Fulbright, N.J., Van De Ven, J.D. Dynamic response of pressure compensated variable displacement linkage pump (2018) BATH/ASME 2018 Symposium on Fluid Power and Motion Control, FPMC 2018, .

[6]   Henke, R.W. UNDERSTANDING PRESSURE-COMPENSATED PUMPS. (1985) Hydraulics and Pneumatics, 28 (11), pp. 80–83.

[7]   Baz, A. OPTIMIZATION OF THE DYNAMICS OF PRESSURE-COMPENSATED AXIAL PISTON PUMPS. (1983) Journal of Fluid Control, 15 (2), pp. 64–81.

[8]   Jenkins, R.P., Ivantysynova, M. Investigation of instability of a pressure compensated vane pump (2016) 9th FPNI Ph.D. Symposium on Fluid Power, FPNI 2016

[9]   Pery, Arie EXPLANATION OF LOW FREQUENCY PEAK IN PRESSURE COMPENSATED PUMPS DISCHARGE PRESSURE FREQUENCY SPECTRUM. (1984) Proceedings of the National Conference on Fluid Power, Annual Meeting, 38, pp. 119–125.

[10]   Rao, R.V. Rao algorithms: Three metaphor-less simple algorithms for solving optimization problems (2020) International Journal of Industrial Engineering Computations, 11 (1), pp. 107–130.

[11]   Li, J., Lu, C., Zhang, H. A modified SSDP method for nonlinear semidefinie programming (2020) Journal of Computational Analysis and Applications, 28 (5), pp. 836–847.

[12]   Meneses, A.A.D.M., da Silva, P.V., Nast, F.N., Araujo, L.M., Schirru, R. Application of Cuckoo Search algorithm to Loading Pattern Optimization problems (2020) Annals of Nuclear Energy, 139, № 107214, .

[13]   Wang, Y., Chen, X. Hybrid quantum particle swarm optimization algorithm and its application (2020) Science China Information Sciences, 63 (5), № 159201, .

[14]   Jordanov, I., Georgieva, A. Neural network learning With global heuristic search (2007) IEEE Transactions on Neural Networks, 18 (3), pp. 937–942.

[15]   Antonova, G.M. Analysis of real-time-systems by means of simulation and optimization in LPτ -search with averaging (2017) Horizons in Computer Science Research, 15, pp. 69–100.

[16]   Tynchenko, V.V., Pavlenko, A.A., Bukhtoyarov, V.V., Tikhonenko, D.V., Tynchenko, S.V., Tsvettsykh, A.V. Formation of initial point of initialization methods for optimization algorithms (2019) Journal of Physics: Conference Series, 1353 (1), № 012115, .

[17]   Pavlenko, A.A., Kukartsev, V.V., Tynchenko, V.S., Mikhalev, A.S., Chzhan, E.A., Lozitskaya, E.V. Optimal parameters selection of the genetic algorithm for global optimization (2019) Journal of Physics: Conference Series, 1353 (1), № 012105, .

[18] Stupina, A.A., Pavlenko, A.A., Tikhonenko, D.V., Tynchenko, V.V., Bukhtoyarov, V.V., Tynchenko, S.V. Study of the point scattering uniform algorithms in R40 space (2019) Journal of Physics: Conference Series, 1353 (1), № 012112, .

[19] Antonova, G.M., Makarov, V.V. Recognition of nonlinear functions for estimating region of efficiency in LP τ-search with averaging (2015) Pattern Recognition and Image Analysis, 25 (2), pp. 193–200.

[20] Kolodin, I., Ryabinin, M. Mathematical representation of pressure regulator with variable characteristic (2019) IOP Conference Series: Materials Science and Engineering, 589 (1), № 012018.