Experimental and Numerical Analysis of Leakage Characteristics of Proportional Directional Valve

Marian Ledvoň[1,*], *Lumír* Hružík[1], *Adam* Bureček[1], and *Filip* Dýrr[1]

[1]VSB-Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Hydromechanics and Hydraulic Equipment, 17. listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic

Abstract. This article deals with the experimental and numerical analysis of the leakage characteristics of the proportional directional valve. These characteristics describe the flow through the directional valve in the region of the center position of the spool valve. The element under investigation is a three-position four-way directional valve with zero overlap and feedback from the valve spool position. The actual valve spool position is sensed by an inductive position sensor and processed by integrated electronics. By means of an offset on the integrated electronics, it is also possible to set the center position of the valve spool. By moving the valve spool, the size and direction of the working fluid flow in both directions can be controlled. Internal leakage occurs due to axial and radial clearances between the spool and the sleeve. The magnitude of the axial clearances that occur at the control edges is investigated. The blocked-line pressure sensitivity curve, leakage flow curve and center flow curve are determined by experimental measurements. Depending on the experimental measurement, the correction of the center position of the valve spool is then made using offset. The flow through the control edges at the center position of the valve spool was simulated using Ansys Fluent software. Subsequently, the geometry of the flow simulation model is adjusted. The adjustment is made to take into account manufacturing tolerances. Finally, the simulated dependencies including the effect of manufacturing tolerances are compared with the measured and analytically determined characteristics.

Research background: Spool valve description, mathematical equations, flow analysis through valve, radial and axial clearance.
Purpose of the article: Effect of axial clearance on leakage characteristic.
Methods: Experimental measurements, numerical simulation.
Findings & Value added: Determining the range of the center flow curve as a function of manufacturing tolerances

Keywords: *proportional directional valve; spool valve; axial clearance; leakage characteristic; numerical simulation; radial clearance*

* Corresponding author: marian.ledvon@vsb.cz

1 Introduction

In industrial applications, proportional directional valves are often used to control hydraulic motors. Proportional directional valve allows continuous control of the magnitude and direction of flow in hydraulic systems [1, 2]. From the design point of view of the control element we distinguish between spool and poppet valve. Poppet valve ensures tightness in a certain direction of fluid flow. In spool valve, leak occurs between the spool and the sleeve and internal fluid leakage occurs [3]. Fluid leakage is undesirable but unavoidable. In many applications with directional spool valve, internal leakage is an important factor affecting the design of the hydraulic system. Due to leak, fluid leakage occurs, which can affect energy losses in the system or also undesired movement of the unloaded hydraulic motor [4]. The amount of internal fluid leakage between the valve spool and the sleeve is influenced by the radial clearance and the type of spool valve overlap. The overlap size of the individual control edges of the directional valve may vary depending on the requirements of the hydraulic system [5, 6]. The actual dimensions of the radial clearance and all functional spool surfaces depend on the accuracy of the manufacturing process. The same applies to the overlap of the channels in the axial direction. Internal leakage can also be affected by surface topography errors, which include roughness, corrugation and shape error. These errors lead to an uneven gap field between the spool and the sleeve, resulting in leakage [7]. In spool valve, adhesive and abrasive wear of the functional surfaces and edges of the spool valve occurs during use. This wear causes leakage to increase [8, 9, 10]. Internal leakage can also be affected by thermal deformation of the hydraulic flow orifices caused by viscous heating [11]. Although manufacturing inaccuracies are on the order of a few microns, this can significantly affect the behaviour of the valve in the center position region of the directional valve.

2 Theoretical background

2.1 General valve analysis

The investigated element is a proportional directional valve PRL2-06-32-0-24 from Argo Hytos. This directional valve is mainly used for continuous flow control to hydraulic motors. It is a directly controlled, three-position, four-way directional valve with a sharp edge spool. The overlap of the spool in the center position is stated as zero. The control part of the directional valve consists of a linear motor. The armature of the linear motor is rigidly connected to the valve spool. An inductive spool position sensor is also part of the directional valve. The internal electrical feedback from the position of the valve spool ensures higher accuracy of the directional valve [12].

In general, for the flow through the valve orifices is described by the orifice equation:

$$Q_{Oi} = C_D w_i x \sqrt{\frac{2}{\rho} \Delta p_{Oi}}, \tag{1}$$

where C_D is the flow coefficient, w is the area gradient of the valve, x is the spool stroke, ρ is the fluid density, Δp_O is the pressure drop across the control edges, i = 1, 2, 3, 4 is the index corresponding to the given pair of control edges, see Fig. 1.

If a positive overlap of the control edges is achieved, the equation for flow in a narrow cylindrical gap applies [13]:

$$Q_{Gi} = \frac{\pi D_{SP} s^3}{12\eta x} \Delta p_{Gi}, \tag{2}$$

where D_{SP} is the spool outer diameter, s is the radial clearance, η is the fluid dynamic viscosity, x is the spool stroke corresponding to the length of the narrow cylindrical gap and Δp_G is the pressure drop across the narrow cylindrical gap.

If the valve spool is in the center position, the following equation can be used to calculated the center flow rate [14]:

$$Q_{Ci} = \frac{\pi w_i s^2}{32\eta} \Delta p_{Ci}, \tag{3}$$

where s is the radial clearance, η the fluid dynamic viscosity, w is the area gradient of the valve and Δp_G is the pressure drop across the control edges.

After adjusting equation (3), the following equations apply to the calculation of the pressure gradient at the control edges:

$$\Delta p_{Ci} = \frac{32\eta Q_{Ci}}{\pi w_i s^2}, \tag{4}$$

This equation is then used to analytically calculate the center flow rate for comparison with experimental measurement and mathematical simulation.

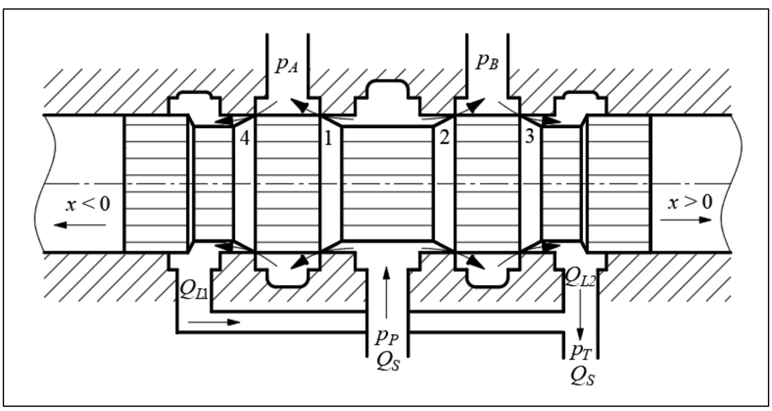


Fig. 1. Analysis of the flow through the 4/3 spool valve in center position $x = 0$.

There are several critical dimensions that must be maintained in manufacture of spool valve. These are the axial and radial clearances between the spool and the sleeve, see Fig. 2. For high performance valves, these dimensions are strictly tolerated in the range $U_{AT} = U_{PA} = (-2.54 \div 2.54)$ µm. In some cases, a range $U_{AT} = U_{PA} = (-7.62 \div 7.62)$ µm may be acceptable [14]. These tolerances significantly affect the internal leakage and pressure sensitivity around the center position. The spool outer diameter D_{SP} and the sleeve diameter D_{SL} were measured using a Metrosoft Quartis. The actual radial clearance between the spool and the sleeve is $s = 3$ µm. The amount of axial clearances that occur at the control edges is the subject of research. In the case of valves with zero overlap, the clearance is ideally zero, in reality a positive or negative overlap occurs. The amount of the overlap or underlap is determined by the manufacturing variation.

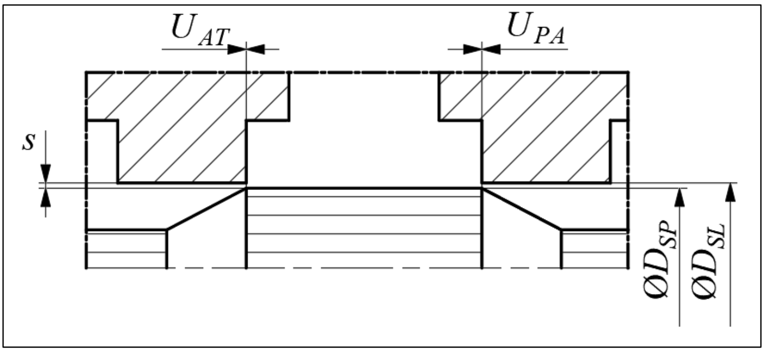


Fig. 2. Control edge geometry with zero overlap.

3 Experimental analysis

Three leakage characteristics are measured and subsequently evaluated in the experimental measurements. These characteristics describe the behaviour of the investigated directional valve around of the center position, when leakage occurs due to radial and axial clearance.

3.1 Experimental test stand

Fig. 3 shows the hydraulic scheme of the experimental equipment that was used to determine the leakage characteristics of the proportional directional valve. The source of pressure energy is a hydraulic unit with a constant pressure control axial piston hydrogenerator. Experimental measurements are performed on the proportional directional valve PRL2 from Argo Hytos. The proportional directional valve is connected to the system by a pressure pipe P. The load ports of valve A and B are blocked by pressure sensors S2 and S3. The load flow between ports A and B is zero. The fluid is drained back to the tank by a return pipe T. Measuring points for connecting pressure sensors S1 and S4 in front and behind of the valve are placed in the hydraulic circuit. The spool position is sensed by an integrated inductive position sensor. The flow meter S5 and temperature sensor S6 are connected in front of the proportional directional valve. The measuring instrument MS 5070 from Hydrotechnik is used to record the measurements. The working liquid is HV46 oil with kinematic viscosity $\nu = 45.3\ mm^2 \cdot s^{-1}$ at oil temperature $t_O = 40$ °C. The measuring range and accuracy of all the sensors used is given in Table 1.

Table 1. Technical parameters of individual sensors.

Sensors	Measuring range	Measuring accuracy
Pressure sensor S1	(0 ÷ 400) bar	± 0.25% of full scale
Pressure sensor S2, S3	(0 ÷ 250) bar	
Pressure sensor S4	(0 ÷ 60) bar	
Flow meter S5	(0.05 ÷ 5) $dm^3 \cdot min^{-1}$	up to ± 0.4% of reading
Temperature sensor S6	(-50 ÷ 200) °C	0.3 + 0.005 t_O °C

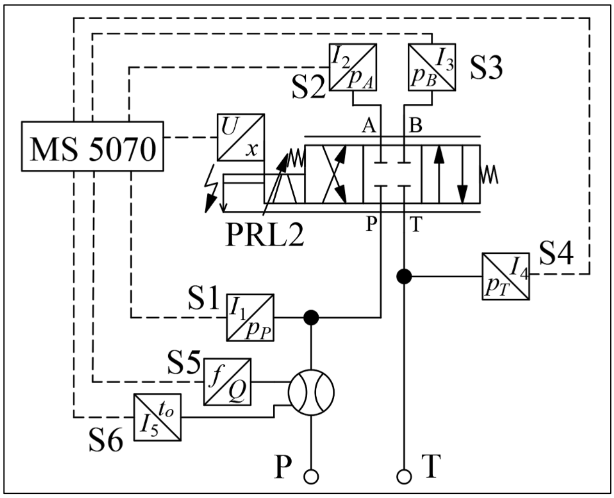


Fig. 3. Scheme of experimental equipment.

3.2 Experimental measurements

Experimental measurements to determine the leakage characteristics are performed with load ports A and B blocked, so the load flow is zero. Supply pressure p_P, pressures p_A a p_B in the load ports, return pressure p_T, flow rate Q, spool position x a working liquid temperature t_O are measured using by a MS 5070. Working liquid temperature is constant t_O = 40 °C. The supply pressure is set to a constant value p_P = 250 bar for determine the blocked-line pressure sensitivity curve a leakage curve. The spool is in the center position and the supply pressure p_P is gradually increased in the range p_P = (50 ÷ 250) bar for determine center flow curve. The measurements were first made with the manufacturer's original setting for the center position of the valve spool. The center position of the directional valve is defined as the state when the pressure difference p_A and p_B at the blocked load ports A and B is zero resp. the pressures are equal. Depending on the determined blocked-line pressure sensitivity curves, the correction of the center position of the valve spool is then performed. Subsequently, the measurements were performed again with a modified center position of the valve spool.

3.2.1 Blocked-line pressure sensitivity curve

Fig. 4 shows the determined blocked-line pressure sensitivity curves in the range of spool stroke x = (-20 ÷ 20) %. For a greater spool stroke in both directions, the pressures p_A and p_B remain constant. From the waveforms of the determined characteristics with the original settings from the manufacturer, it is found that the center position of the valve spool is reached at the input voltage U_x = 0.11 V. Depending on the determined input voltage for the center position, the correction of the center position of the valve spool was then using offset. From the evaluation of the determined characteristics after correction it can be seen that the pressures p_A and p_B are equal at zero spool stroke. The difference in spool stroke before and after correction corresponds to 1.4% of the maximum spool stroke. In the center position of the valve spool, the load ports have the same pressure, which corresponds to 58% supply pressure. It can be said that the pressure drop at the control edges PA and AT is not the same. The difference of pressure drops can be caused by axial clearances on individual control edges that are affected by manufacturing tolerances.

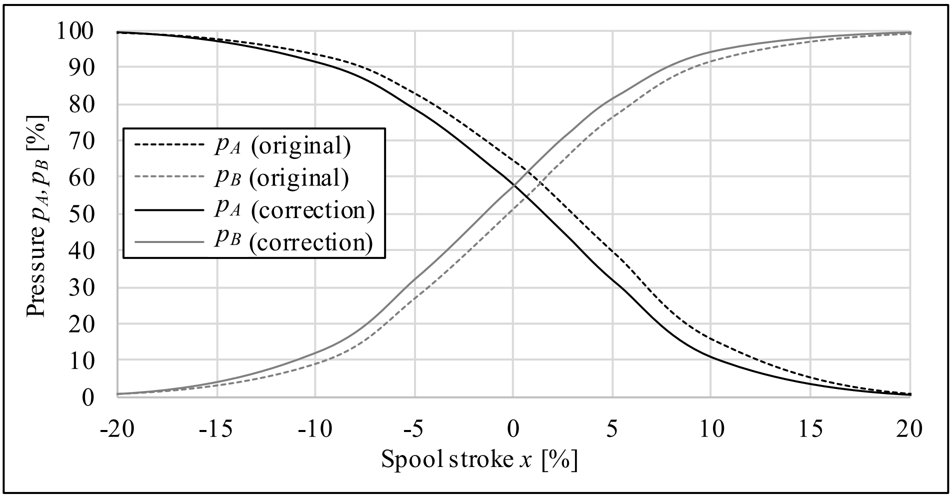


Fig. 4. Blocked-line pressure sensitivity curves.

3.2.2 Leakage flow curve

The leakage curves for the original and adjusted settings of the center position of the valve spool using the correction are shown in Fig. 5. It is clear from the graph that in the center position of the valve spool, the leakage flow Q_L is maximum and decreases rapidly with spool stroke x in both directions. The decrease is due to the increasing length of edge overlap corresponding to the spool stroke.

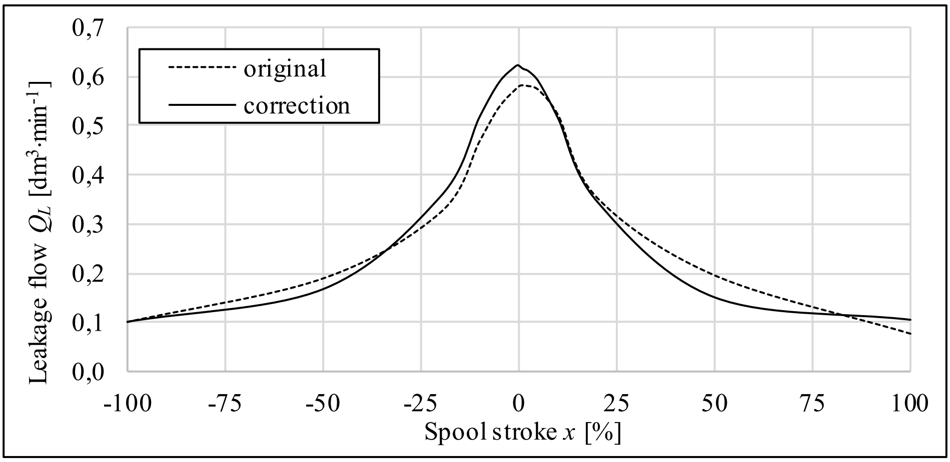


Fig. 5. Leakage curves.

3.2.3 Center flow curve

The center flow curves for the original and adjusted settings of the center position of the valve spool using the correction are shown in Fig. 6. It is clear from the graph that the center flow Q_C as a function of supply pressure p_P increases almost linearly. The center flow Q_C for the maximum supply pressure p_P corresponds to the maximum leakage flow Q_L in Fig. 5.

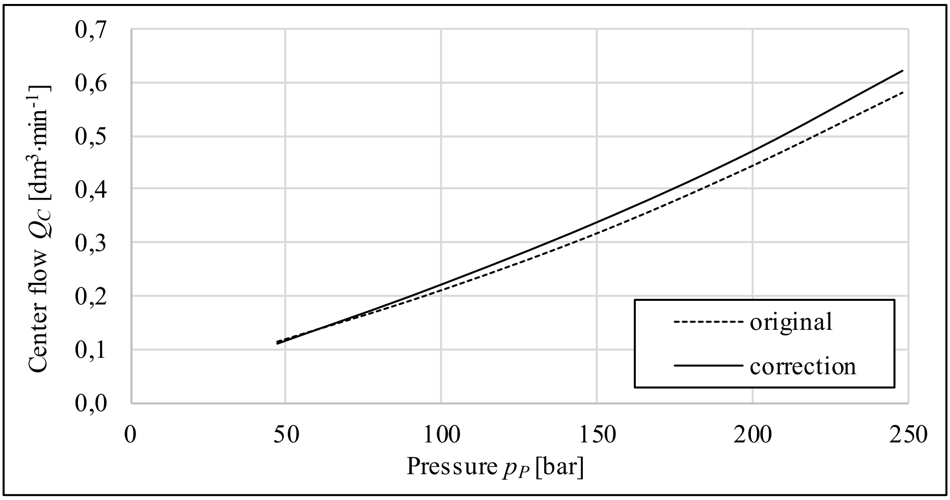
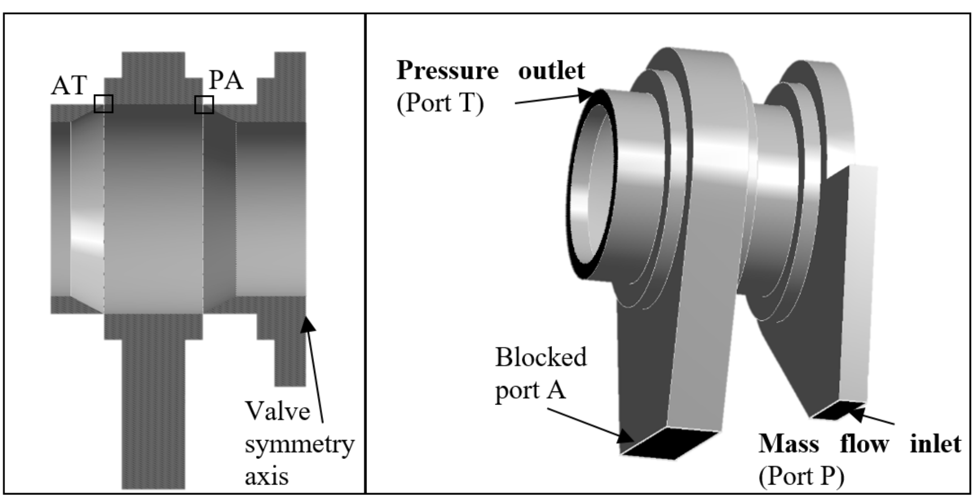


Fig. 6. Center flow curves.

4 Numerical simulation

The simulations of the flow through the directional valve with the valve spool in the center position and with the load ports blocked were carried out. The inverse geometry of the solved region is created in ANSYS Design Modeler. To simplify the calculation, half of the directional valve with spool for channel A is modelled, see Figure 7a. The mesh is created in ANSYS Mesher, see Figure 8. The mesh is refined in the area of the narrowest cross-section. The mesh was subsequently adapted according to the velocity gradient to refine the calculation. The monitored parameter in the mesh adaptations was the pressure drop at the control edges. Further refinement of the mesh at the control edges is achieved by adapting the mesh. The number of elements after the adaptations is approximately 15 million. The definition of each boundary condition is shown in Fig. 7b.



(a) (b)

Fig. 7. (a) Cross-section of modelled region for channel A, (b) boundary conditions.

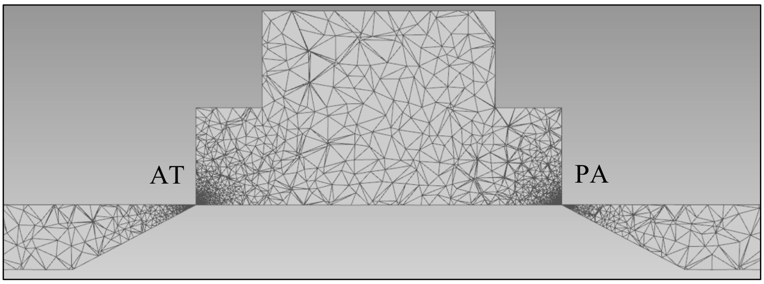


Fig. 8. Mesh of solved region.

Mathematical simulations are performed for geometries directional valve where $U_{AT} = U_{PA} = -2.54$ µm (underlap tolerance), $U_{AT} = U_{PA} = 0$ µm (null tolerance) and $U_{AT} = U_{PA} = 2.54$ µm (overlap tolerance). Symmetric tolerance is considered in the simulations where $U_{AT} = U_{PA}$. The first null tolerance simulation is performed for an ideal directional valve geometry with zero overlap. Underlap and overlap simulations are performed for directional valve geometries that take into account manufacturing tolerances. The RANS model *k*-*ω* (SST) is used for the numerical simulations. Constant boundary conditions were considered for all simulations performed. The inlet boundary condition is defined by the mass flow rate Q_m and the outlet boundary condition is defined by the outlet pressure p_{outlet}. The mass flow rate is set to half the mass flow rate to simulate flow through only channel A. The settings of the input and output boundary conditions including the fluid parameters are shown in Table 2.

Tab. 2. Boundary conditions and fluids parameters

	Q_m	p_{outlet}
	[kg·s^{-1}]	[Pa]
1.	0.000199	0
2.	0.000398	0
3.	0.000667	0
4.	0.001008	0
5.	0.001363	0
6.	0.001732	0
7.	0.002144	0
8.	0.002599	0
9.	0.003081	0
10.	0.003593	0
11.	0.004402	0
ρ_o	852	[kg·m^{-3}]
η_o	0.0385	[Pa·s]

5 Results

Center flow curves determined by mathematical simulations for individual directional valve geometries are shown in Fig. 9. The overlap and underlap tolerances define the range of centre flows that are affected by the size of the axial clearances. The range of centre flow resp. axial clearances is defined for the maximum permitted manufacturing tolerances. In the graph are compared the mathematically simulated dependencies and the experimentally and analytically determined center flow curves. Equation (4) was used for the analytically determined curve. The parameters used for the analytical calculation correspond to the parameters defined for the mathematical simulation. The experimentally determined curve corresponds to the analytically determined curve and is within the defined range.

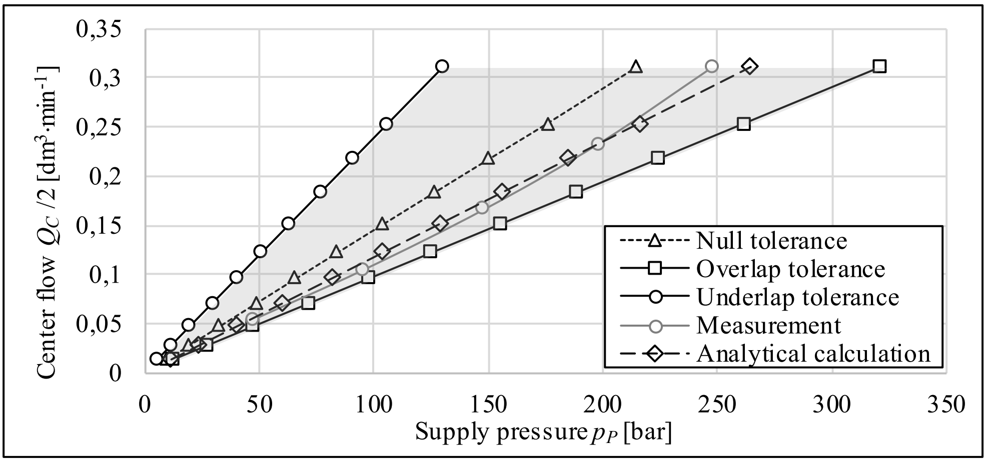


Fig. 9. Mathematically simulated, experimentally and analytically determined center flow curve.

6 Conclusion

This article deals with the experimental and mathematical analysis of leakage characteristics of proportional directional valve. Blocked-line pressure sensitivity curve, leakage flow curve and center flow curve were successively measured and evaluated. As part of the experimental analysis, the correction of the central position of the valve spool was performed. Subsequently, numerical simulations of the flow with the valve spool in the center position are performed for different directional valve geometries taking into account manufacturing tolerances. The determined overlap tolerance and underlap tolerance curves define the range of center flow that is affected by the maximum permitted manufacturing tolerance. Subsequently, the dependencies determined by simulation are compared with experimentally and analytically determined center flow curves.

This work was supported by the European Regional Development Fund in the Research Centre of Advanced Mechatronic Systems project, project number CZ.02.1.01/0.0/0.0/16_019/0000867 within the Operational Programme Research, Development and Education.

This work has been supported by The Ministry of Education, Youth and Sports of the Czech Republic from the Specific Research Project SP2022/32 (Numerical modeling of transient fluid flow problems with the support of experimental research)

References

1. Hružík, L., Bureček, A., Vašina, M. (2017). Effect of Oil Viscosity on Pulsating Flow in Pipe. *Mechanisms and Machine Science*, 44, 137-143.
2. Soon, C. C., Ghazali, R., Jaafar, H. I., Hussien, S. Y. S., Sam, Y. M., Rahmat, M. F. (2016). The Effects of Parameter Variation in Open-Loop and Closed-Loop Control Scheme for an Electro-Hydraulic Actuator System. *International Journal of Control and Automation*, 9(11), 283-294.

3. Gordić, D., Babić, M., Milovanović, D., Savić, S. (2011). Spool valve leakage behaviour. *Archives of civil and mechanical engineering,* 11(4), 859-866.
4. Mao, X., Wu, C., Ding, H., Li, B., & Liu, Y. (2020). Effect Analysis of Leakage in the Middle Position and Improvement of an O-type 3-position-4-way Directional Valve with the Spool Structure. *IOP Conference Series-Earth and Environmental Science*, 508, 012160.
5. Lu, Z., Zhang, J., Xu, B., Wang, D., Su, Q., Qian, J., Yang, G., Pan, M. (2019). Deadzone compensation control based on detection of micro flow rate in pilot stage of proportional directional valve. *ISA transactions*, 94, 234-245.
6. Zhang, L., Fu, W., Yuan, X., Meng, Z. (2020). Research on Optimal Control of Excavator Negative Control Swing System. *Processes*, 8(9), 1096.
7. Tang, W., Xu, G., Zhang, S., Jin, S., & Wang, R. (2021). Digital twin-driven mating performance analysis for precision spool valve. *Machines*, 9(8), 157.
8. Chen, Y., Gong, W., & Kang, R. (2016). Coupling behaviour between adhesive and abrasive wear mechanism of aero-hydraulic spool valves. *Chinese journal of aeronautics*, 29(4), 1119-1131
9. Liu, X., Ji, H., Min, W., Zheng, Z., Wang, J. (2020). Erosion behaviour and influence of solid particles in hydraulic spool valve without notches. *Engineering Failure Analysis*, 108, 104262.
10. Fang, X., Yao, J., Yin, X., Chen, X., & Zhang, C. (2013). Physics-of-failure models of erosion wear in electrohydraulic servovalve, and erosion wear life prediction method. *Mechatronics*, 23(8), 1202-1214.
11. Chen, Q., Ji, H., Zhao, H., Zhao, J. (2020). Optimization Algorithm and Joint Simulation to Micro Thermal Deformation Using Temperature Measurement in the Orifice of Hydraulic Valve. *Processes*, 8(9), 1136.
12. Ledvoň, M., Polášek, T., Bureček, A., Hružík, L. (2019). Modeling and Dynamic Analysis Directional Valve. *AIP Conference Proceedings*, 2118, 030026
13. Manring, N. D. (2005). *Hydraulic control systems*. John Wiley & Sons, Inc.
14. Merritt, H. E. (1967). *Hydraulic control systems*. John Wiley & Sons, Inc.