CFD Simulation and Optimization of Hydraulic ON/OFF Valve for Small Volume Flow

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Abstract

High response on/off hydraulic valves with small volume flow represents in combination with digital control technique a promising approach to get higher dynamics of hydraulic drives. One of the development stages presented in the paper is CFD (Computational Fluid Dynamics) simulation and optimization of an on/off valve geometry in order to achieve the proper fluid forces in closing position and minimal fluid forces acting on the moving valve needle in the opening position independent on the needle displacement. The first part of the paper presents the theoretical determination of the influence geometry parameters. The second part of the paper includes CFD simulation and optimization method according to the predefined influence parameters. The compensated on/of hydraulic valve geometry is presented at the end as the dependence of the resultant axial fluid force on valve geometry and needle displacement.

KEYWORDS: on/off valve, fluid forces, CFD simulation

1. Introduction

One of the promising alternative approaches to replace the high dynamic servo valves over last decade is the digital hydraulics and use of several parallel connected fast switching on/off hydraulic valves /1/. To reach the servo valve dynamic performance, a high number of parallel connected high-response on/off valves with very small volume flow is needed. Miniaturization of switching on/off valves is one of the optimization methods in order to decrease the mass of movement parts and to increase the dynamic performance of the valve. Better dynamics of the valves can be achieved by using of light-weight piston materials including geometry optimization in order to optimize the static and dynamic flow forces. Optimization is necessary especially in case of using high dynamic alternative actuators /3/, /4/.

The main goal of this paper is the geometry characterisation and optimization of an on/off valve needle in order to optimize the static pressure forces and dynamic flow forces by using the CFD simulation tool.

2. Physical background

2.1. Type of flow resistors

During the development stage it is first of all necessary to define the type of flow resistor which should be used in the on/off valve. In general, sharp-edged orifices (turbulent resistors) with predominantly turbulent flow characteristics or gap-shaped laminar resistors with primarily laminar flow characteristics are used in hydraulic flow determination. Turbulent flow is dominated by inertia forces and characterised by irregular paths of the fluid particles. In laminar flow viscosity forces prevail resulting in an orderly, smooth, parallel line motion of the fluid particles /2/. **Table 1** shows the typical geometries and the corresponding relations between specific values of the volume flow (Q/Q_0), pressure difference (p/p_0) and resistor opening (h/h_0) for turbulent and laminar resistor /5/.

Туре	Figure	Relation	Initial conditions
Turbulent resistor		$\frac{Q}{Q_0} = \left(1 \pm \frac{h}{h_0}\right) \sqrt{\frac{\Delta p}{p_0}}$	$\Delta p = p_0 - p$
Laminar resistor		$\frac{Q}{Q_0} = \left(1 \pm \frac{h}{h_0}\right)^3 \frac{\Delta p}{p_0}$	$Q_0 = f(h = h_0, \Delta p = p_0)$

 Table 1: Turbulent and laminar resistor /5/.

The reference flow Q_0 represents the flow through the resistor at an opening of h_0 and at the pressure difference $\Delta p = p_0$. Specific flow (1), (2) derivative with respect to a positive specific opening yields a sensitivity of flow change due to a change in specific resistor opening:

Turbulent resistor sensitivity:

$$\frac{d(Q/Q_0)}{d(h/h_0)} = \sqrt{1 - \frac{p}{p_0}}$$
(1)

Laminar resistor sensitivity:

$$\frac{d(Q/Q_0)}{d(h/h_0)} = 3\left(1 + \frac{h}{h_0}\right)^2 \left(1 - \frac{p}{p_0}\right)$$
(2)

Sharp-edged orifices with predominantly turbulent flow characteristics are more suitable for development of an on/off hydraulic valve. Laminar resistor is characterised by higher flow sensitivity. The higher sensitivity leads to a larger volume flow and faster pressure change in the chamber. Laminar flow depends on the viscosity and, consequently, on the temperature of the fluid. Presented resistors (*Table 1*) and their sensitivities have major influence in case of using a very small hydraulic valve.

2.2. Volume flow determination

Basic orifice equation (3) of volume flow rate Q_1 can be determined as:

$$Q_1 = \alpha_D \cdot A_V \frac{2(p_{in} - p_{out})}{\rho}$$
(3)

where α_D presents the flow discharge coefficient, *A* the cross section area of volume flow, p_{in} and p_{out} the inlet and outlet pressure and ρ fluid density. Above mentioned parameters of equation (3) are the initial influence parameters of orifice.

By miniaturization of the hydraulic valve the chamfered or fillet control edge can be determined as laminar resistor with dependence on the fluid viscosity. The volume flow can be determined as leakage flow Q_2 , as presented in equation (4):

$$Q_2 = \frac{\pi \cdot d \cdot \Delta r^3}{12 \cdot \eta \cdot (y_0 - y)} (p_{in} - p_{out})$$
(4)

where *r* presents the gap between the needle and control edge, $y_0-y=l$ presents the length of laminar resistor area (in case of chamfered control edge) and η dynamic viscosity of the fluid.

2.3. Pressure and flow forces

To achieve the best dynamics of the valve, it is important to identify the fluid forces which act on the needle of an on/off valve due to fluid flow and pressure.

Hydraulic on/off valve geometry and fluid flow forces acting on the valve needle are shown in *Figure 1 a) and b)*. Spring force is shown as F_{spring} . The size of the spring force is defined by taking into account the maximal force of the actuator.



Figure 1: Hydraulic on/off valve: a) design, b) fluid forces.

Resultant of axial fluid force F_3 can be determined using equation (5):

$$F_1 + F_2 - F_{tok} = F_3 \tag{5}$$

$$F_{1} = \frac{\pi \cdot \left(d_{1}^{2} - d_{4}^{2}\right)}{4} p_{out}$$
(6)

$$F_2 = \frac{\pi \left(d_1^2 - d_2^2 \right)}{4} p_{in} \tag{7}$$

$$F_{tok} = 2\alpha_D^2 \cdot A \cdot (p_{in} - p_{out}) \cos \alpha$$
(8)

$$A = \pi \cdot x \cdot \sin \alpha \cdot (d - x \cdot \sin \alpha \cdot \cos \alpha) \tag{9}$$

where F_1 presents the axial static pressure force depended on the diameter d1-d4 and outlet pressure p_{out} , F_2 presents the axial static pressure force depended on diameter d3-d2 and inlet pressure p_{in} acting on needle surface and the spring force $F_{spring}=20N$. Flow force F_{tok} is presented with equation (8). The parameter A presents the cross sectional area of the fluid flow for conical needle.

3. CFD modelling and simulation

For calculation of pressure and flow characteristics the CFD simulation tool Ansys 12 is used. The entire simulation procedure consists of creating the fluid model, meshing and setting up the fluid parameters, choosing the calculation method/simulation model and finally analyzing the results. The goal of CFD simulation is to optimize the valve needle geometry in order to get the dynamic component of the fluid flow force with its value around 0 N and the resultant axial fluid force of 15-18N. This force must act in the opposite direction to the spring force. At the same time the condition is followed throughout the research, that the minimal closing force on the needle must always be bigger then 2N.

3.1. CFD modelling

The fluid model of an on/off valve is presented in *Figure 2*. *Figure 3* shows the fluid model with variable parameters written in *Table 2*. The increase of the diameter *d2* leads to the decrease of the surface *A1*. Therefore the static pressure force and the dynamic flow force are changed. High dynamic control demands optimized and constant fluid force independent on needle position. Optimization of the inlet and outlet angle is not considered in this paper.

Variable parameter		Value			
Valve needle diameter d_2	[mm]	4,5	4,65	4,75	5
Opening gap <i>x</i>	[mm]	0	0,025	0,05	0,1

Table 2: Variable parameters considered in CFD simulation.





Figure 2: 3D model of the fluid.

Figure 3: Variable parameters *d*₂ and *x*.

The meshing and settings of the fluid parameters of the simulation model are described in *Table 3*.

Mesh	irregular mesh (tetrahedrons, prisms, pyramids), fine resolution at surface and control edge of orifice opening gap, approx. 1 000 000-1 300 000 elements
Fluid parameters:	single-phase flow
	mineral oil ISO VG 32 at 40°C (density = 840 kg/m ³ , dynamic viscosity = 0.0277 Ns/m ² , specific warm capacity = 2100 J/(kg K), molar mass = 495.5 g/mol)
Boundary conditions:	pressure at inlet and outlet p_{in} = 200 bar, p_{out} =175bar, Δp =25bar
	volume fraction of oil at inlet = 1
Turbulence model:	k-ω based shear-stress-transport (SST) model
Simulation type:	steady-state simulation at discrete needle openings x

 Table 3: Settings of CFD fluid model.

3.2. Simulation results

As shown in an example of one simulation step (*Figure 4*) in all simulation models the pressure distribution (*Figure 4a*), velocity profile (*Figure 4b*) and the flow (*Figure 4c*) are analyzed.





The simulation result presents the resultant axial fluid force acting on the valve needle which consists of static pressure force and dynamic flow force. By knowing the pressure distribution along the needle surface the pressure force can be calculated analytically. Dynamic force is then calculated by knowing the resultant axial force and static pressure force.

3.2.1. Dependence of the diameter d_2 on the axial fluid force

Figure 5 presents the valve geometry characteristics used in the simulation model. The varied parameter d_2 at the opening gap x=0,1 mm and all other parameters are presented in *Table 4*. ISO VG 32 fluid is used.



The initial fluid model is compensated in terms of static pressure force by the geometry of the valve needle: d1=d2 and d3=d5. The increase of the diameter d2 leads to the increase of the resultant fluid force as presented in the *Figure 6*. The negative value of the force at the diameter $d_2=4,5$ mm presents the flow force.



Figure 6: Dependence of the resultant axial fluid force on the diameter d_2 .

The static pressure force, depended on the geometry parameters, is presented in *Figure 7* and the dynamic part of the fluid flow force is presented in *Figure 8*.







3.2.2. Dependence of the opening gap x on the axial fluid force

The geometry parameters presented in *Table 5* are set to compensate the static fluid force. The resultant force of the simulation presents directly the dynamic flow force at the pressure difference $\Delta p=25$ bar.



Figure 9: Geometry characteristic of an on/off valve.

Table 5: The characteristics of the simulation parameters.

Figure 5 presents the dependence of the axial fluid force on the opening gap size *x*. Very high dynamics is achieved when axial fluid force is independent on the valve needle position. Simulation results in the *Figure 10* show almost the constant dynamic flow force. The deviation value is around 1,3N from gap size of 0,025mm to 0,1mm.



Figure 10: Dependence of the axial fluid force on the gap size x.

3.2.3. Dependence of the diameter d_2 and the opening gap x on the axial fluid force

Compensation of the static and dynamic flow force can be achieved by the deviation of the diameter d2 of the needle. Dependence of the resultant fluid force on the diameter and the opening gap x is presented in *Figure 11*. The proper diameter depends on the size of internal force such as spring force and maximal actuating force in our case.



Figure 11: Dependence of the diameter d_2 and the opening gap x on the axial fluid force.

Taking into consideration the spring force $F_{spring}=20N$ which acts in the opposite direction of the resultant fluid force, the compensated diameter is approximately 4,75 mm. In this case the axial resultant force of fluid flow force and spring force is presented in *Figure 12*.



Figure 12: Dependence of the resultant fluid force and the spring force.

4. Conclusions

Determination of the influence geometric parameters of an on/off hydraulic valve by using the CFD simulation has an important role in early design stage. Reduction of axial fluid forces increases the dynamic performance of valve and enables the use of alternative actuators with very low actuation force and low consumption energy.

The simulation result shows that turbulent flow is achieved by using a proper hydraulic needle of the on/off valve. Axial static pressure forces and axial flow forces can be reduced with optimal geometry of the valve which is defined by using the CFD simulation method. The axial static pressure forces have much more influence on valve needle than flow forces. The flow forces are independent on the valve diameter *d2* and on the opening gap *x* if the geometry of the control edge is optimized. The combination of static pressure force optimization and dynamic flow force optimization gives the axial resultant of the fluid force approximately $F_R=0$ N.

5. Bibliographical References

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6. Symbols

Q ₁ , Q ₂	volume flow	l/min
a _D	outlet flow coefficient	/
A	cross section area	mm ²
p _{in}	inlet pressure	bar
p _{out}	outlet pressure	bar
ρ	fluid density	kg/m ³
r	leakage gap	mm
η	dynamic viscosity	kg/ms
y ₀ -y=I	overlap, length of laminar resistor	mm
F ₁ , F ₂ , F ₃ ,	static pressure forces	Ν
F _{tok}	flow force	Ν
FR	Resultant axial force	Ν
d	Valve, needle diameter	mm
x	opening gap	mm