Energy Conversion and Management 123 (2016) 15–28

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

CFD analysis of the characteristics of a proportional flow control valve with an innovative opening shape

Edward Lisowski *, Grzegorz Filo

Cracow University of Technology, al. Jana Pawła II 37, 31-864 Kraków, Poland

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form 23 May 2016
Accepted 8 June 2016
Available online 16 June 2016

Keywords:
Proportional flow control valve
Flow characteristics
Jet angle
Simulation
CFD analysis

ABSTRACT

The main objective of this article is to analyse the flow characteristics of a proportional flow control valve and to improve its characteristics by means of geometrical modifications of the valve spool. As the first step, a geometrical model of the valve was built in a CAD system and flow analyses were carried out using CFD methods. Two types of openings in the spool were tested: a round and a triangular one. Simulations were conducted with various values of throttle gap width, flow rate and input pressure. Based on the obtained results, the jet angle was determined as a function of throttle gap width for both types of openings. Then, a mathematical model of the valve was formulated. Based on the mathematical model, a simulation model was built in Matlab/Simulink. The results of the simulation results showed that the use of triangular openings in a throttle valve spool instead of standard round openings increased the proportional operating range of the valve by approximately 40%. The obtained simulation results were verified experimentally on a test bench.

1. Introduction

Flow control valves are offered by most hydraulic equipment manufacturers. Valves of this type can be adjusted manually or automatically using sensors, controllers and actuators. The primary function of a flow control valve is to maintain a constant flow rate, regardless of the pressures prevailing at the inlet and outlet of the valve. Presently, industrial as well as scientific centres are mostly interested in flow control valves with proportional solenoids, because they allow for a smooth adjustment of the flow rate in a feedback loop. Proportional flow regulators are produced by many well-known world wide companies like Bosch-Rexroth, Vickers, Brevini, PQS Technology and PONAR Wadowice.

Proportional flow control valves are usually designed as compact constructions, which contain a mechanical part and an electronic controller in a single module. As regards the mechanical part, at least two valve components can be distinguished inside the flow controller body: a throttle valve and a pressure compensation valve. Due to the high-scale integration, the flow paths can take complex shapes with multiple fluid stream bends, including places where the stream is split or multiple streams are merged together. Moreover, the fluid flows around moving parts, which results in the generation of flow forces. The flow forces may interfere with the controller and thus decrease its accuracy. As a result, it is difficult to obtain an exactly proportional relationship between the control signal value and the volumetric flow rate in a wide range of the flow rate. Thus, flow control valve manufacturers usually propose solutions dedicated to a narrow range of flow rates. For example, Bosch-Rexroth [1] offers eight versions of DN6 size flow controllers, dedicated respectively to the nominal flow of $1.0, 2.0, 8.0\ \mathrm{dm^3/min}$ (linear) and $3.0, 6.0, 10.0, 16.0, 25.0\ \mathrm{dm^3/min}$ (progressive) and differential valve pressure $\Delta p = 1.0$ MPa. Similarly, the PQS Technology DN6 size flow regulators [2] are available in four versions, with the nominal flow of $5.0, 8.0, 15.0$ and $30.0\ \mathrm{dm^3/min}$, wherein $\Delta p = 1.0$ MPa. Brevini also offers four versions of the DN6 flow regulator [3], with the nominal flow of $3.0, 10.0, 15.0$ and $18.0\ \mathrm{dm^3/min}$ and $\Delta p = 0.5$ MPa. The necessity to manufacture and apply different versions of the valves with a narrow operating range is disadvantageous to producers as well as to designers of hydraulic systems. Hence, the improvement of the valve characteristics, including the extension of the operating range, is currently being undertaken by leading research centres. Studies of this type are mainly carried out using CFD methods, and may include different aspects,such as the improvement of the characteristics by adjusting valve geometry, the application of advanced sensors, controllers and control algorithms or the appropriate use of flow forces.

* Corresponding author.
E-mail addresses: lisowski@mech.pk.edu.pl (E. Lisowski), filo@mech.pk.edu.pl (G. Filo).

http://dx.doi.org/10.1016/j.enconman.2016.06.025
0196-8904/

Nomenclature

Indices

p, L	pump, leakage
r	relief valve
T	return line
$2, 3, 4$	flow control valve channel
$s1, s2$	spool number
$g1, g2$	throttle gap number

Symbols

P, T	inlet port, return port
A, B	connection ports
k, ϵ	parameters (m^2/s^2, m^2/s^3)
G_k, G_b, Y_M	$k-\epsilon$ components (J)
$C_{1\epsilon}, C_{2\epsilon}, C_{3\epsilon}$	$k-\epsilon$ constants (–)
s_k, s_ϵ	Prandtl numbers (–)
μ_t	turbulent viscosity (–)
I	turbulence intensity (–)
ℓ	turbulence length scale (mm)
D_H	hydraulic diameter (mm)
$p_p, p_2–p_4, p_T$	pressure (*MPa*)
X, Y	pump leakage coefficients (–)
$Q_p, Q_1–Q_4$	flow rate (dm^3/min)
x_r, x_{s1}, x_{s2}	spool position (mm)
x_{g1}, x_{g2}	throttle gap width (mm)
α	fluid stream jet angle (°)
μ_d	fluid dynamic viscosity (Pa s)
ρ	fluid density (kg/m^3)
B	bulk modulus (MPa)
μ	flow coefficient (–)
S_i, S_{g_i}	spool area, gap area (mm^2)
D_{si}	spool diameter (mm^2)
m_{si}	spool mass (kg)
$V_p, V_2–V_4$	volume (mm^3)
k_r, k_{s1}, k_{s2}	spring stiffness (N/mm)
φ	viscous friction coeff. (N s/m)
Δ	increment or range
U	voltage control signal (V)
K_{el}	electromagnet constant (N/V)
F_{hs_2}	hydrostatic force (N)
F_{t_i}	viscous friction force (N)
F_{hd_i}	flow force (N)
F_{s_i}	spring force (N)
F_{el}	electromagnet force (N)

Research on spool control valve geometry was carried out by Ye et al. [4]. Ye investigated the influence of the spool groove shape on the valve flow characteristics using both CFD and experimental investigations. U-shaped, spheroidal and triangular grooves were studied. The results provide effective guidance for spool valve design by indicating that the triangular groove has the highest throttling stiffness, while the spheroidal has the lowest stiffness. Similarly, Borghi in [5] presented theoretical and experimental results of studies on the influence of the shape and number of spool notches on the discharge characteristics of a spool control valve. On the other hand, Bing in [6] provides several guidelines for modifying three-stage directional spool valve geometry in order to obtain a faster response and thus larger transient flow, while Simic in [7] optimised the spool and housing geometry of a small hydraulic seat valve in order to reduce axial flow forces. The optimisation of spool geometry in a double-nozzled flapper servo valve was also carried out by Peng et al. [8]. However, in that case the main purpose of the optimisation was to reduce the probability of occurrence of cavitation.

Research on the application of advanced control methods in hydraulic proportional valves was carried out by Amirante et al. [9]. Amirante presented an innovative open loop control technique based on pulse width modulation (PWM), which was characterised by a higher response rate than more expensive closed-loop regulators mounted on the valves by default. On the contrary, the modification of a closed-loop control system of a proportional directional control valve using an input shaping filter was proposed by Lee et al. [10].

The determination of hydraulic valve flow characteristics, including the flow force evaluation using CFD methods, is a recurrent research topic. A fluid flow model with the estimation of flow forces in a hydraulic proportional valve based on the classical incompressible flow theory and numerical simulations was developed by Valdés et al. [11]. Valdés showed that the proposed method correctly estimates and predicts valve parameter values and characteristics as long as the main geometry features are maintained. An evaluation of flow forces on a direct (single stage) proportional spool valve by means of CFD methods was performed by Amirante et al. [12], while Herakovič in [13] carried out a similar analysis for a sliding-spool valve. An interesting CFD analysis of the flow structure inside a pressure-regulating spool valve using the $k-\epsilon$ turbulence model was conducted by Chattopadhyay et al. [14], while related research on a flapper-nozzle pilot valve was carried out by Aung et al. [15]. Although a direct CFD method is usually used in research, Wu in [16] proposed an innovative indirect CFD method to simulate the flow-pressure characteristics of a pressure spool valve for the automotive fuel supply system. Saha et al. in [17] presented the methodology and results of flow process dynamic modelling inside spool-type valves by means of CFD methods.

Earlier studies conducted by the authors of this article also concerned the CFD flow analysis of a solenoid-operated directional spool control valve [18] as well as a multi-section proportional directional control valve [19]. This article presents the results of further studies which concern the possibility of increasing the range of linear flow regulation. In order to achieve the assumed objective, modifications were made to the valve spools. In particular, the shapes of the throttling gaps were changed. The flow characteristics calculation process was performed in such a way that at the beginning five fixed positions of each valve spool were selected. A CFD analysis was then carried out for each fixed spool position with different values of parameters such as the flow rate and pressure. The results of the CFD analysis were used to determine such parameters as pressure loss and jet angle of the liquid stream flowing through the throttling gaps. Next, a simulation model was created and adjusted using the obtained parameters. Simulations of the valve were carried out and the results were verified on a test bench.

2. Working principle of selected valve and proposed opening shape

The subject of the analysis is a proportional flow control valve of UDRDE6 type, manufactured by PONAR Wadowice. It consists of three main components shown in Fig. 1, i.e. a hydraulic valve block 1, a proportional solenoid 2 and a displacement transducer 3.