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Spool valve leakage behaviour

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A four-way axial spool servovalve has such a design that flows through its restrictions can be presented by means of a hydraulic bridge. The characteristics analytically describe the fluid flow through spool orifices in the most of working regimes. The exceptions are regimes around the null characterised by an overlap existence when internal leakages dominate. Several mathematical models for the calculation of the internal leakage flows are presented in this paper including theoretical model worked out by authors. Modelling results are compared with appropriate experimental.

Keywords: *spool valve, leakage*

1. Introduction

Theoretical, ideal stationary characteristics of spool control valves that include the following assumptions: no volumetric losses, equal and symmetrical spool orifices, turbulent flow regime through the spool orifices, equal zero lap conditions on all spool orifices are presented in detail in standard literature [1–2]. Mentioned mathematical expressions describe the characteristics of working fluid flow through axial spool valve orifices in the most of working regimes. The exceptions are the working regimes characterised by the existence of overlap where fluid flows between the spool and bushing (valve body) significantly affect the valve behaviour. In these regimes the mentioned characteristics does not precisely describe the flow of working fluid through the spool valve orifices. Therefore, models of the valve for the regimes should include additional terms for the flow of internal leakage. This internal leakage flow is one of the key parameters in designing the precise positioning of the hydraulic actuator. Due to the internal leakage, pressure difference on hydraulic load exists, which affects the behaviour of the system in several ways: crawling of a loaded actuator in open loop systems, position error of a P-controlled loaded actuator and increase of the system damping [2].

2. Mathematical models of internal leakage flow

Following equations:

$$Q_{L1} = Q_{t1} - Q_{t4} + Q_{l1} - Q_{l4}, \quad (1)$$

$$Q_{L2} = Q_{t3} - Q_{t2} + Q_{l3} - Q_{l2}, \tag{2}$$

can be written using denotes in Figure 1, where:

- Q_{L1} [m^3/s] – volumetric flow through the right actuator port,
- Q_{L2} [m^3/s] – volumetric flow through the left actuator port,
- Q_{li} [m^3/s] – internal leakage volumetric flow through i-th spool orifice, i = (1, 2, 3, 4),
- Q_{ti} [m^3/s] – volumetric flow through i-th spool orifice, i = (1, 2, 3, 4),

Volumetric flow through i-th spool orifice can be calculated as:

$$Q_{ti} = \begin{cases} Q_{ti} & x \cdot (-1)^{i+1} \geq x_{0i} \\ 0 & x \cdot (-1)^{i+1} < x_{0i} \end{cases} \text{ and } Q_{li} = \begin{cases} 0 & x \cdot (-1)^{i+1} \geq x_{0i} \\ Q_{ti} & x \cdot (-1)^{i+1} < x_{0i} \end{cases}, \tag{3}$$

where x [m] – spool displacement, x_{0i} [m] – null lap condition of i-th spool orifice.

Several mathematical models for the calculation of the internal leakage flow through a spool orifice can be found in literature [3–5]. It is necessary to know the experimental spool valve static characteristics for their use.

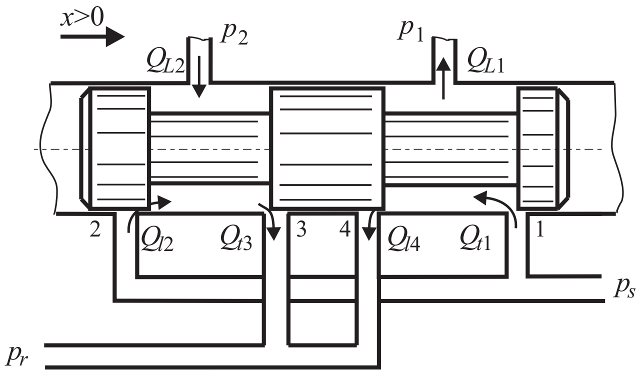

Fig. 1. Analysis of internal leakage flow through axial spool valve

Ellman & Virvalo presented the model which assumed laminar leakage flow and symmetric valve configuration [2]. The model also assumes small positive or zero overlap for each orifice. It is valid only for small positive spool displacements limited to approximately 2% of maximal spool displacement. The authors propose that internal leakage flow should be calculated according to:

$$Q_{li} = \frac{Q_{l0}}{2 \cdot p_s} \cdot \left(1 - \frac{x}{x_a} \operatorname{sgn}(x)\right) \cdot \Delta p_i, \qquad Q_{li} \geq 0, \tag{5}$$

where:

- Q_{l0} [m^3/s] – internal leakage flow at null (zero spool displacement),
- p_s [Pa] – supply pressure,
- x_a [m] – relative opening of the spool where the load pressure equals supply pressure,
- $Q_{L\max}$ [m^3/s] – nominal volumetric flow through the valve (measured at full opening – max spool displacement $x_{\max}$ and supply pressure p_s).

and where (using denotes on Figure 1) pressure difference on each spool orifice Δp_i can be written as:

$$\Delta p_{ti} = \begin{cases} p_s - p_1, & i = 1 \\ p_s - p_2, & i = 2 \\ p_2 - p_r, & i = 3 \\ p_1 - p_r, & i = 4 \end{cases}, \tag{6}$$

where:

- p_r [Pa] – atmospheric (reservoir) pressure,
- p_1 [Pa] – pressure in right actuator chamber,
- p_2 [Pa] – pressure in left actuator chamber.

According to the model, flow through i-th spool orifice is:

$$Q_{ti} = \frac{Q_{l0}}{2 \cdot p_s} \cdot \left(1 + \frac{x}{x_a} \cdot \mathrm{sgn}(x)\right) \cdot \Delta p_i + x \cdot \frac{Q_{L\max}}{\sqrt{p_s}} \cdot \sqrt{\Delta p_i}, \tag{7}$$

Values for Q_{l0}, x_a and $Q_{L\max}$ can be obtained from the valve experimental static characteristics (Figure 2).

Ellman presented an improved model that can include a valve asymmetry [1]. Unlike the previous, the model provides a ”smooth” transition from the internal leakage flow to flow through the spool orifice. According to the model, internal leakage flow can be written as:

$$Q_{li} = \frac{k_{EL2}}{2}\left[\sqrt{\left(\frac{k_{EL2}}{k_{EL1}}\right)^2 x^2 + 4\Delta p_i} - \frac{k_{EL2}}{k_{EL1}} x\right], \tag{8}$$

In addition to static pressure gain characteristic, it is necessary to know experimental curves of flow characteristics for both actuator ports to determine the parameters k_{EL1} and k_{EL2}. For obtaining the mentioned curves non-standard measurements are required and therefore this model was omitted from further analysis due its complexity for practical application.

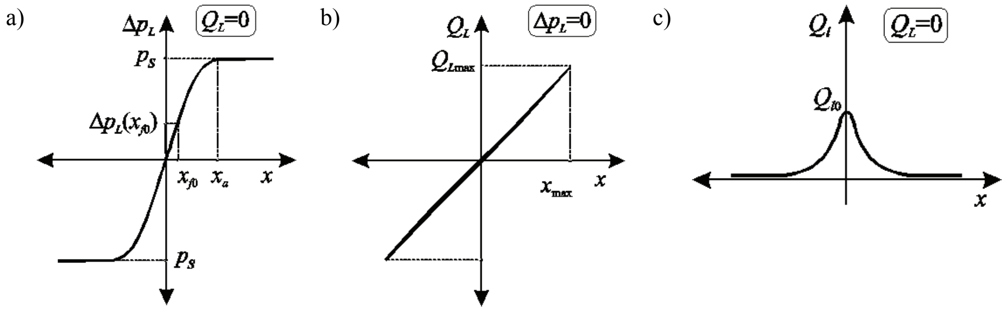

Fig. 2. Static characteristics of axial spool valve a) pressure gain characteristic, b) no-load static flow characteristic, c) internal leakage flow characteristic

Eryilmaz & Wilson presented the model where the internal leakage flow is turbulent, whereby the cross-section area is inversely proportional to the length of the overlap between the spool and the body of the valve [3]. The model only assumes valve with zero overlap in null and it is valid for all possible spool positions. The authors suggest that the internal leakage flow can be calculated by:

$$Q_{li} = K_{EWi} \cdot \sqrt{\Delta p_i} \cdot \frac{x_{f0i}^2}{x_{f0i} + k_{EWi} \cdot x}, \tag{9}$$

where the flow through the orifice is:

$$Q_{ti} = K_{EWi} \cdot \sqrt{\Delta p_i} .(x_{f0i} + x), \tag{10}$$

where the term x_{f0i} [m] denotes "fictive overlap" of i-th orifice. This parameter takes into account turbulent leakage flow at zero spool displacement. It should be mentioned that x_{f0i} corresponds to a spool displacement that would result in the same amount of flow in a non-leaking valve as the leakage flow rate in a leaking valve with zero lap at null.

For valves with symmetric and matched spool orifices, parameters K_{EWi}, k_{EWi} and x_{f0i} are equal for all orifices so subscript i can be omitted. In this case, the parameters can be determined from the experimental static characteristics (Figure 2) according to:

$$K_{EW} = \frac{Q_{L\max} \cdot \sqrt{2}}{\sqrt{(p_s - p_r)} \cdot x_{\max}}, \tag{11}$$

3. Theoretical mathematical model of internal leakage flow

The authors of the paper propose usage of a mathematical model in which all parameters are physical quantities. The model is based on theoretical analysis performed by Mookherjee et al. [6]. This model includes pressure-flow relations for the following orifices: short (based on inflow and outflow along the spool edge), intermediate (based on boundary layer analysis of steady, incompressible developing flow) and long (based on fully developed steady laminar flow through an annular orifice). As a result, the group of implicit equations for internal leakage flow determination is obtained [4]:

$$\begin{aligned}
&q\cdot Q_{li}^{2}=\Delta p_{i} \quad \text{for } \left|x\cdot(-1)^{\mathrm{i}}+x_{0i}\right|<(q/s)^{2}\cdot Q_{li},\\
&s\cdot\left|x\cdot(-1)^{\mathrm{i}}+x_{0i}\right|^{1/2}\cdot Q_{li}^{3/2}=\Delta p_{i} \quad \text{for } (q/s)^{2}\cdot Q_{li}\le\left|x\cdot(-1)^{\mathrm{i}}+x_{0i}\right|<x_{tli},\\
&s\cdot x_{tli}^{1/2}\cdot Q_{li}^{3/2}+w\cdot\left(\left|x\cdot(-1)^{i}+x_{0i}\right|-x_{tli}\right)\cdot Q_{li}=\Delta p_{\mathrm{i}} \quad \text{for } \left|x\cdot(-1)^{\mathrm{i}}+x_{0i}\right|\ge x_{tli},
\end{aligned} \tag{14}$$

where:

- $q=\dfrac{\rho}{2\cdot K_{ti}^{2}\cdot f^{2}\cdot(\sqrt{(\delta+h)^{2}+h^{2}}-h)^{2}\cdot\delta^{2}}$,
- $s=\dfrac{23\cdot(\rho\cdot\eta)^{1/2}}{f^{3/2}\cdot\delta^{5/2}}$, and $w=\dfrac{12\cdot\eta}{f\cdot\delta^{3}}$,

and where:

- ρ [kg/m^3] – fluid density,
- η [Pa·s] – fluid dynamic viscosity,
- K_{ti} [–] – flow coefficient of *i*-th spool orifice,
- f [m] – spool valve area gradient,
- δ [m] – spool in bushing radial clearance,
- h [m] – sum of radiuses of bushing and spool control edges.

In Equation (14) the term x_{tli} [m] denotes large transition length. It presents the distance from the entrance at which boundary layers on spool and bushing meet at the mid-plane. It can be obtained as:

$$x_{tli}=\frac{0.075\cdot\delta\cdot Q_{li}}{\pi\cdot d_{s}\cdot\nu}, \tag{15}$$

where ν [m^2/s] is fluid kinematic viscosity nad d_s [m^2/s] is spool diameter.

Considering the spool in bushing radial clearance, round corners of control edges and lapping conditions of spool orifices the volumetric flow through *i*-th spool valve orifice can be written as:

$$Q_{ti}=K_{ti}\cdot f\cdot\sqrt{(\delta+h)^{2}+[(x-x_{0i}\cdot(-1)^{i+1})+h]^{2}}-h)\cdot\sqrt{\frac{2}{\rho}}\cdot\sqrt{\Delta p_{i}}. \tag{16}$$

4. Comparative analysis of the models

In order to determine the accuracy of proposed models for internal leakage flow calculation, the results of numerical calculation should be compared with appropriate experimental results. Estimation of model accuracy was done by comparing the numerical results obtained using the software package Matlab, with experimental pressure gain and internal leakage flow characteristics of servovalve B.31.210.12.1000.U2V, produced by PPT, Trstenik, Serbia (Figure 3).

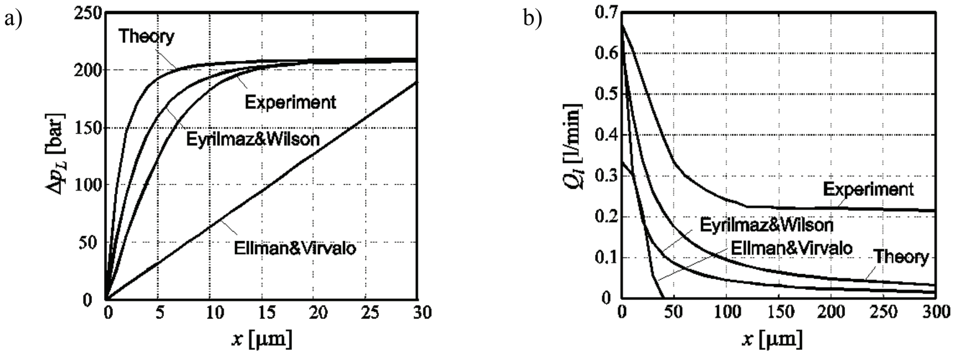

Fig. 3. Comparative review of a) pressure gain and b) internal leakage characteristics

The values of quantities and parameters used in numerical simulation are presented in Table 1.

Table 1. Initial date for numerical calculations

Symbol	Value	Unit
p_s	210	bar
p_r	0	bar
ρ	871	kg/m^3
ν	$14\cdot10^{-6}$	m^2/s
η	0,012	Pa s
d_s	4,62	mm
f	2·2.4	mm
h	20	μm
δ	4	μm

Symbol	Value	Unit
x_{0i}	0	mm
K_t	0.611	–
Q_{l0}	0.672	l/min
x_a	33	μm
Q_{Lmax}	12	l/min
x_{max}	0.5	mm
K_{EW}	$1.237\cdot10^{-4}$	m^2·s^{-1}·Pa$^{-0.5}$
k_{EW}	2.793	–
x_{f0}	0.7	μm

Static experimental analyses of the servovalve were performed on the standard servovalve testing equipment MOOG-PLOTTERSTAND D046-030 (Figure 4).

It can be noticed that pressure gain characteristic calculated by the Ellman & Virvalo model by its trend completely deviates from the experimentally determined characteristic. Pressure gain characteristic determined with proposed theoretical model gives somewhat higher values then values obtained by Eryilmaz &Wilson model and experimental until saturation.

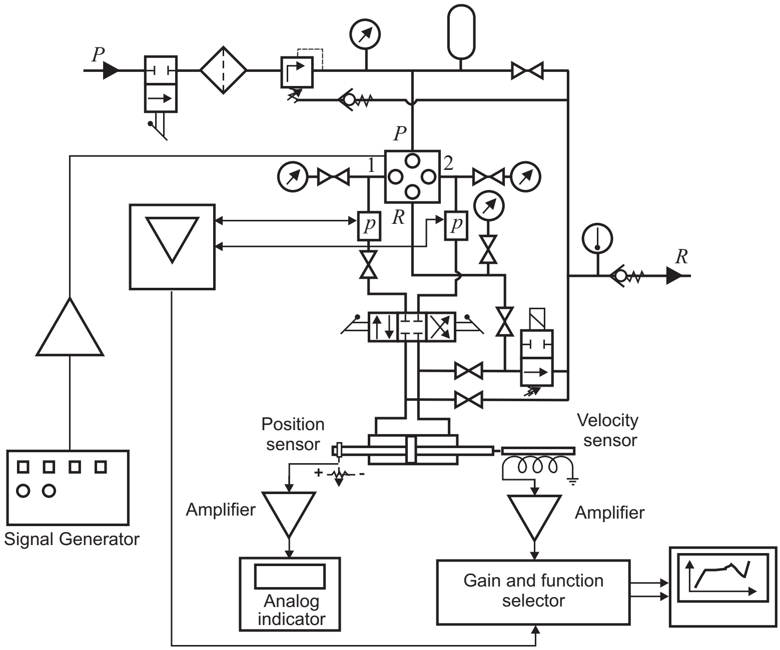

Fig. 4. Experimental test stand for static experimental analyses

Internal leakage characteristics obtained using Ellman & Virvalo model qualitatively follows experimentally obtained curve for small positive spool displacements limited to approximately 2% of maximal spool displacement as it was denoted in chapter 2. For bigger spool displacements it has negative values. This interval was not shown in Figure 3 because of compliance with graphical presentations of other methods. Internal leakage characteristics obtained using Eyrilmaz & Wilson model and the theoretical one by its trend correspond to experimental. They have the same values as experimental at null, but for other possible spool positions they had lover values. It is important to emphasize that in regimes with relative big spool displacements orifice flows dominates instead of leakage flows, so the mentioned difference does not have significant influence on valve flow characteristics.

5. Conclusion

Fluid flows between the spool and bushing (internal leakage flows) in working regimes characterised by the existence of overlap principally affect the valve behaviour. Several models for the calculation of internal leakage flow in axial spool valve can be found in relevant literature. The use of these models is limited to the knowledge of experimental static characteristics of a valve. The best result compared to experimental characteristics provides the model proposed by Eryilmaz and Wilson. The theoretical model presented in the paper, based on the valve geometry and physical properties of working fluid, correctly predicts the internal leakage flow rates. It may present a good basis for predicting the behaviour of axial spool valve in regimes close to spool zero position. Since all its parameters are easily determinable physical quantities it can be a useful design tool.

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Model teoretyczny wyznaczania wewnętrznych przecieków w rozdzielaczu hydraulicznym

Czterodrogowy rozdzielacz hydrauliczny ma budowę, w której przepływ przez jego kanały może być przedstawiony (opisany) za pomocą tzw. mostku hydraulicznego. Z reguły charakterystyki zaworu opisują przepływ cieczy przez szczeliny dla większości stanów jego pracy. Wyjątkiem są stany pracy, w których dominują wewnętrzne przecieki. W pracy przedstawiono modele matematyczne do obliczeń wewnętrznych przecieków. Przedstawiono propozycję modelu teoretycznego opracowanego przez autorów. W pracy przedstawiono również porównanie wyników badań symulacyjnych z odpowiednimi badaniami eksperymentalnymi.