DETERMINATION OF VALUES FOR FLOW COEFFICIENTS OF FIRST STAGE ORIFICES IN TWO-STAGE ELECTROHYDRAULIC SERVOVALVES

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Resume

The first stage of hydraulic amplification of two-stage electrohydraulic servovalve is usually flapper-nozzle valve with two nozzles. This is the combination of four orifices (two with constant and two with variable areas) that form hydraulic bridge. It is usual to add a constant orifice in return line of the first stage in order to reduce volumetric losses and to eliminate cavitation. Usually, it is assumed that flow coefficients of these orifices take constant values in equations for volumetric flows calculation regardless working fluid flow regimes. Variations of Reynolds numbers and for these values calculated flow coefficients of analyzed orifices in transient regimes of a servovalve for step input current are analyzed.

***Keywords**: servovalve, flapper-nozzle valve, flow coefficient*

1. INTRODUCTION

Flapper-nozzle valve with two nozzles is the most frequently used as the first stage of hydraulic amplification of two stage electrohydraulic servovalve. It is combination of four orifices (restrictors) (two constant - *oL* and *oD* and two variable - *mL* and *mD*), connected in form of hydraulic bridge. A constant orifice - *oR* is usually placed in return line of the first stage (drain orifice) in order to reduce volumetric losses and to eliminate cavitation.

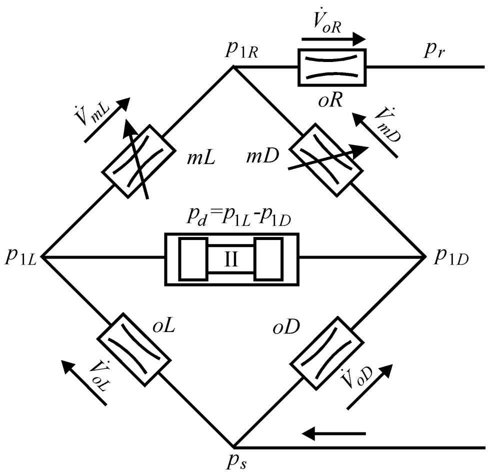

Figure 1 *Scheme of the first stage of hydraulic amplification oL & oD – left and right constant orifice, oR – drain orifice, mL & mD – left and right variable orifice, II – second stage of hydraulic amplification*

Relation between working fluid volumetric flow and pressure drop at any orifice can be defined as:

$$\dot{V} = K \cdot A \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{\Delta p}\ , \quad (1)$$

where:

- $\dot{V}$ [m^3/s] - volumetric flow through orifice,
- K [-] - flow coefficient,
- A [m^2] - orifice flow area,
- ρ [kg/m^3] - working fluid density,
- Δp [Pa] - pressure drop at orifice.

Flow coefficient depends on type (shape) of orifice and flow regime defined with Reynolds number - Re [-].

If we observe labels on scheme at figure 1 and use equation (1), following equations for volumetric flows through constant orifice can be written as:

$$\dot{V}_{oL} = K_{oL} \cdot \frac{d_{oLD}^2 \cdot \pi}{4} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_s - p_{1L}}\ , \quad (2)$$

$$\dot{V}_{oD} = K_{oD} \cdot \frac{d_{oLD}^2 \cdot \pi}{4} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_s - p_{1D}}\ , \quad (3)$$

$$\dot{V}_{oR} = K_{oR} \cdot \frac{d_{oR}^2 \cdot \pi}{4} \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_{1R} - p_r}\ , \quad (4)$$

where:

- $\dot{V}_{oL}$ [m^3/s] - volumetric flow through left constant orifice,

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- $\dot{V}_{oD}$ [m³/s] - volumetric flow through right constant orifice,
- $\dot{V}_{oR}$ [m³/s] - volumetric flow through drain orifice,
- K_{oL} [-] - flow coefficient of left constant orifice,
- K_{oD} [-] - flow coefficient of right constant orifice,
- K_{oR} [-] - flow coefficient of drain orifice,
- p_s [Pa] - working fluid supply pressure,
- p_{1L} [Pa] - working fluid pressure in left nozzle,
- p_{1D} [Pa] - working fluid pressure in right nozzle,
- p_{1R} [Pa] - working fluid pressure in the drain compartment,
- p_r [Pa] - working fluid pressure at drain orifice exit which is approximately equal to tank pressure,
- d_{oLD} [m] - left, i.e. right constant orifice diameter,
- d_{oR} [m] - drain orifice diameter.

Since the directional valves of flapper-nozzle type have flapper at relatively small distance from two equal nozzles, it can be assumed that working fluid flow through the variable orifice is determined with cylindrical envelope flow area. In this way, using the equation (1) and presumption that flapper displacement to the left side is denoted as positive, following equations for volumetric flows through variable orifices can be written:

$$\dot{V}_{mL} = K_{mL} \cdot d_m \cdot \pi \cdot (x_0 - x) \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_{1L} - p_{1R}}\,, \qquad (5)$$

$$\dot{V}_{mD} = K_{mD} \cdot d_m \cdot \pi \cdot (x_0 + x) \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{p_{1D} - p_{1R}}\,. \qquad (6)$$

where:

- $\dot{V}_{mL}$ [m³/s] - volumetric flow through the left variable orifice (nozzle),
- $\dot{V}_{mD}$ [m³/s] - volumetric flow through the right variable orifice (nozzle),
- K_{mL} [-] - flow coefficient of left variable orifice,
- K_{mD} [-] - flow coefficient of right variable orifice,
- d_m [m] - nozzle diameter,
- x_0 [m] - equilibrium distance from the top of the flapper to nozzle,
- x [m] - displacement of the top of the flapper from the equilibrium position.

2. DETERMINATION OF FLOW COEFFICIENTS

2.1. Determination of flow coefficient of constant orifices

Constant orifices have circular cross section. Since the volumetric flows of the first stage of hydraulic amplification are relatively small, diameters of constant orifices are small, too. So, it would be hard to justify use of constant orifices with sharp edges since their production is relatively expensive. Therefore constant orifices are produced as short tubes orifices, with adequate ratio of orifice length l_o and orifice diameter d_o. In case of cavitationless working fluid flow through this type of orifices, variation of flow coefficient K_o as a function of Reynolds number Re_o, that is defined with:

$$\mathrm{Re}_o = \frac{4 \cdot \dot{V}_o}{d_o \cdot \pi \cdot \nu \cdot K_o} = \frac{d_o \cdot \sqrt{\frac{2}{\rho}} \cdot \sqrt{\Delta p}}{\nu}\,, \qquad (7)$$

where:

- Re_o [-] - Reynolds number through the constant orifice,
- $\dot{V}_o$ [m³/s] - volumetric flow through constant orifice,
- K_o [-] - flow coefficient of constant orifice,
- d_o [m] - orifice diameter,
- ν [m²/s] - kinematic viscosity of working fluid,

and ratio l_o/d_o, obtained by Lichtarowitz [3], is shown at figure 2.

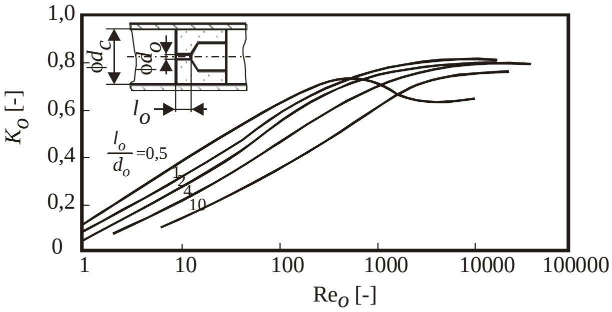

Figure 2 *Experimentally determined functional dependence of flow coefficient and flow regime for short pipe orifice [3]*

According to obtained results, author concludes:

1. avoid orifices with $l_o/d_o<1{,}5$ since K_o varies rapidly with l_o/d_o,
2. for $2<l_o/d_o<10$, flow coefficient K_o (signed as K_{oc}) is constant for $\mathrm{Re} > 2 \cdot 10^4$. It can be calculated as:

$$K_{oc} = 0{,}827 - 0{,}0085 \cdot \frac{l_o}{d_o}\,, \qquad (8)$$

3. for $10<\mathrm{Re}<2\cdot 10^4$, K_o is calculated as:

$$\frac{1}{K_o} = \frac{1}{K_{oc}} + \frac{20 \cdot (1 + 2{,}25 \cdot \frac{l_o}{d_o})}{\mathrm{Re}_o} - \frac{0{,}005 \cdot \frac{l_o}{d_o}}{1 + 7{,}5 \cdot (\ln 0{,}00015 \cdot \mathrm{Re}_o)^2}\,. \qquad (9)$$

In case of existence of low local pressure behind the orifice that can provoke cavitation, flow coefficient has somewhat different values.

2.2. Determination of flow coefficient for variable orifices

More complicated geometry influences that it is more difficult to obtain values of flow coefficients of the first stage variable orifices K_m than values of flow coefficients of constant orifices K_o. According to Lichtarowitz [2], two types of fluid flow can exist in flapper-nozzle valve as the function of ratio of distance from flapper to nozzle - x_m and δ (figure 3). This is the reason why two different functional relations between flow coefficient K_m and Reynolds number Re_m exist. In case of narrow and long gaps ($x_m/\delta<0,2$), working fluid is reattached (figure 3). Flow coefficient increases slowly with the increase of Reynolds number until it reaches maximum value of 0,8÷0,9. When the gaps are longer ($x_m/\delta>1$), different flow patterns exist. After the initial variation with Re_m number, K_m settles to a constant and somewhat lower value (around 0,6). In intermediate range ($0,2<x_m/\delta>1$), K_m changes rapidly with both valve opening and Re_m. Variations of K_m as a function of Reynolds number Re_m, defined as:

$$Re_m = \frac{2 \cdot x_m \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}}{\nu}, \qquad (10)$$

where:

- x_m [m] - distance from flapper to nozzle,

for mentioned working fluid flow regimes are shown in figure 3.

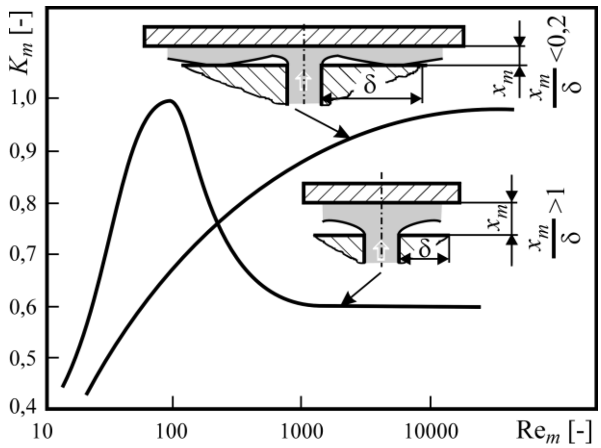

Figure 3 *Flow coefficient of variable orifices (flapper- nozzle type) as a function of flow regime and orifice geometry [2]*

In paper [2] Bergadà also determined values of flow coefficient K_m. His work is very significant because he experimentally determined K_m values for the most frequent working fluid flow regimes through flapper-nozzle servovalve (figure 4). This figure shows that working fluid flows with relatively small Re_m numbers in usual regimes.

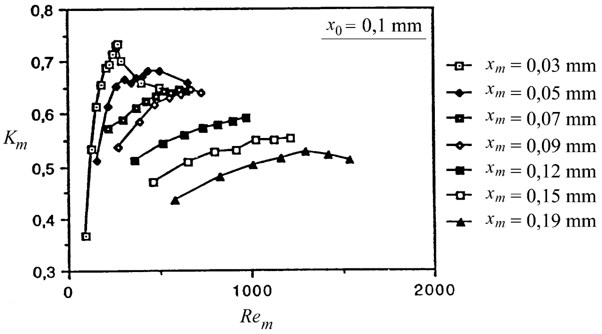

Figure 4 *Experimentally determined flow coefficient of variable orifice (flapper-nozzle type) as a function of flow regime and orifice geometry [2]*

3. VALUES OF FLOW COEFFICIENT

It is usual to neglect variation of flow coefficient with Reynolds number in equations (2)-(6) when we numerically determine static and dynamic characteristics of a servovalve. Researchers consider that flow coefficients of left, right and drain constant orifice are the same. They are taking value of flow coefficient for turbulent regime determined with (Re_o>10.000) for their values. They also consider that flow coefficients of left and right variable orifice are the same. It is usual to take value of flow coefficient for regime when flapper is neutral position for their values.

In following part of the paper justification of these presumptions will be analyzed. In order to perform this analysis, time responses of servovalve (labeled B.31.210.12.1000.U2V manufactured by PPT – Trstenik) for step input current signal (magnitude of 25% of rated current i_{max}) are numerically modeled. This level of input current signal was chosen because it practically covers the whole possible range of flapper movement (x goes over 80 %$\cdot x_o$) [1].

As a part of mentioned analysis, Reynolds numbers and for these values calculated flow coefficients of the first stage of hydraulic amplification orifices are shown in figures 5÷7.

4. RESULTS ANALYSIS AND CONCLUSION

Significant variations of Reynolds number in variable orifices (flapper–nozzle type) can be noticed in analyzed transient response. These have influence on significant deviation of calculated from presumed values of flow coefficient (figure 5). For instance, when the flapper displacement is maximal, deviation of flow coefficients is 16÷17% for both variable restrictors. Therefore, this variation of flow coefficient values with flapper movement should be taken into account if possible. "Unusual" shape of flow coefficient K_{mL} time dependence curve is consequence of extrapolation of data from figure 4.

Calculated values of flow coefficients of left and right constant orifice do not deviate more then 4 % from the equilibrium values (figure 6). Therefore it is justified presumption that flow coefficients of left and right variable orifice are equal. Variations of Reynolds number and flow coefficient of drain orifice are also minimal (figure 7), so we will not make big mistake if we assume that this flow coefficient is constant in analysis.

Nevertheless we should be careful with the choice of values for flow coefficients of constant orifices. For all three orifices values for Reynolds numbers are in the range 1.000-2.500. From this range, values of flow coefficient must be chosen for analyzes instead for usual values of Reynolds numbers.

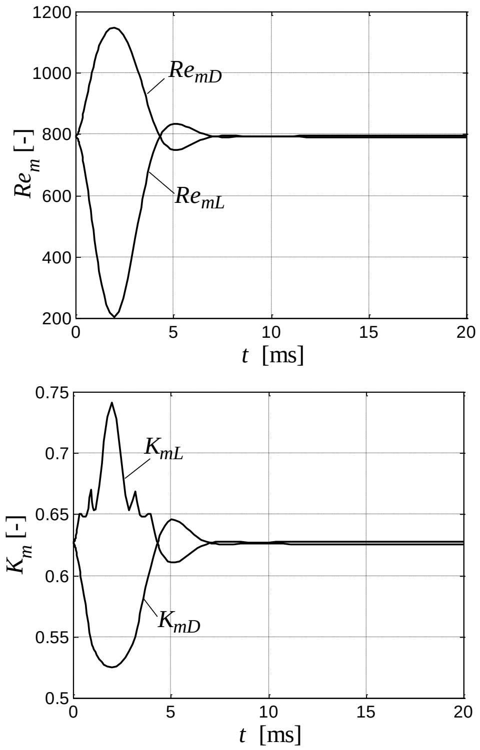

Figure 5 *Time dependences of Reynolds number and flow coefficient of left and right variable orifice (flapper – nozzle type)*

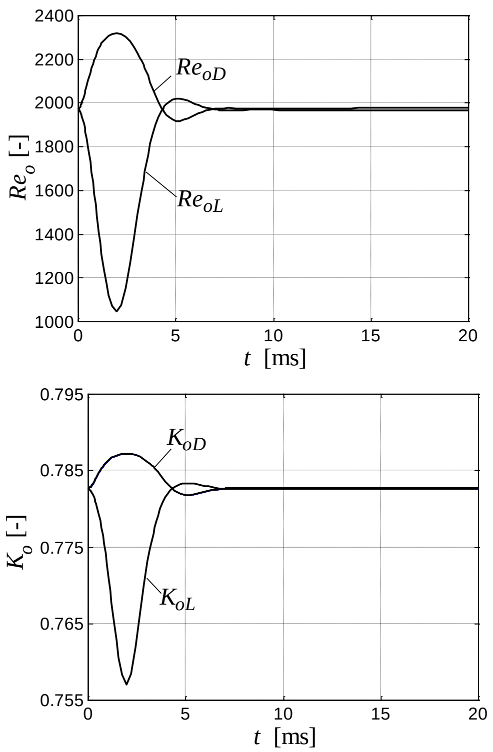

Figure 6 *Time dependences of Reynolds number and flow coefficient of left and right constant orifice*

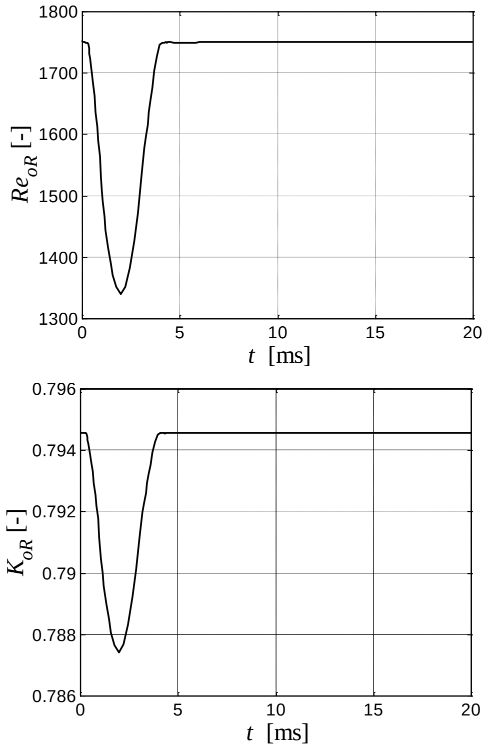

Figure 7 *Time dependences of Reynolds number and flow coefficient of drain orifice*

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