EXPERIMENTAL VERIFICATION OF A MATHEMATICAL MODEL OF STATIC CHARACTERISTICS OF PILOT OPERATED PRESSURE RELIEF VALVES

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A numerical and experimental investigation of the static characteristics of pilot operated pressure relief valves is presented in this article. A mathematical model of a pressure drop depending on a flow in a pilot operated pressure relief valve is developed. A test stand is created for the experimental determination of the pressure drop depending on the flow and the obtained results are compared with theoretical ones. The results of solving the mathematical model and experimental investigation are presented in a few diagrams. A few directions for improving the static characteristics are given, especially at the moment of the main valve of the pilot operated pressure relief valves opening. Advantages and disadvantages of the static characteristics of both types of valves are presented.

Keywords: pilot operated pressure relief valve, static characteristics.

1. INTRODUCTION

The pressure relief valve is a basic component in every hydraulic system. Its function is to limit the maximal pressure in the system. There are two types of pressure relief valves depending on their construction: direct acting pressure relief valves and pilot operated pressure relief valves. Direct acting pressure relief valves are with limited application because of their pure static characteristics at high flow and pressure ranges. To avoid this disadvantage a pilot operated pressure relief valves have been introduced.

Many authors [5], [6], [7], [8] have investigated the characteristics of this type of valves and different mathematical models have been obtained, which describe their characteristics. In this article an attempt at determining the static characteristics of a specified pressure relief valve and its experimental verification has been made by means of contemporary mathematical approach.

2. PRINCIPLE OF OPERATION

A functional diagram of the specified pilot operated pressure relief valve is shown in *Fig. 1.* This valve can be observed as a system consisting of three

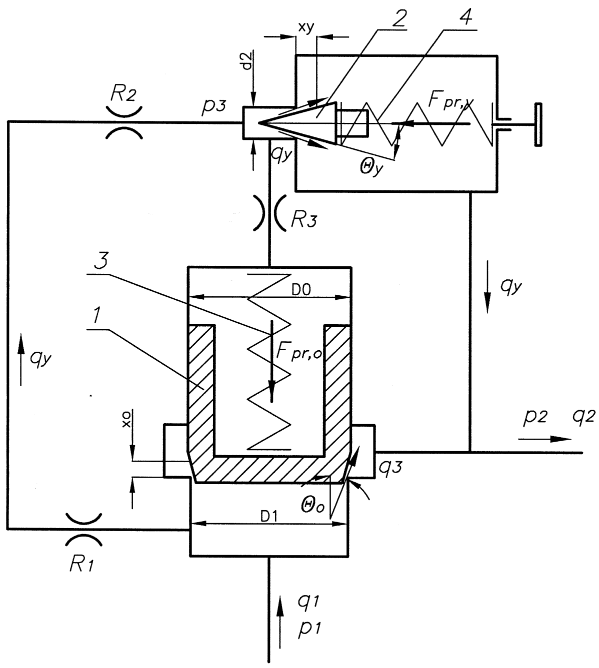

Fig. 1. Functional diagram of pilot operated pressure relief valve
Фиг. 1. Функционална диаграма на предпазно-преливен клапан
с непряко управление

subsystems: the main valve *1*, the pilot valve *2* and the fixed orifices (R_1 and R_2). In neutral position both pilot and main valves are closed under the influence of the springs *3* and *4*, and there is a balance of forces at the closing element of the main valve *1*. When inlet pressure p_1 reaches higher value than the preset spring force *4* of the pilot valve the closing element of the pilot valve 2 is opening, and through the orifices R_1 and R_2 there begins to flow a little amount of pilot flow q_y. The pressure p_3 in the upper part of the main valve is maintained approximately constant by the pilot valve. With further increase of the inlet pressure p_1 the pressure drop $p_{1,3} = p_1 - p_3$ continues to increase up to:

$$p_{1,3} = \frac{F_{pr,0}}{A_1} = \frac{c_0 \cdot h_0}{A_1}$$

at which the main valve is opening and the flow $q_1 = q_2 + q_y$ is flowing to the tank. By changing the flow q_1 the pressure drops $p_{1,2}$ and $p_{1,3}$ also change, which leads to moving the closing element of the main valve *1*. This provides constant pressure drop $p_{1,2}$, which is preset at the pilot valve. If the outlet port of the valve is directly connected to the tank, then pressure p_2 will not act at the closing element of the pilot valve *2*. In that case the pressure relief valve will provide a constant pressure at the inlet port p_1, not pressure drop $p_{1,2}$.

3. MATHEMATICAL MODELLING STATIC CHARACTERISTIC

The static characteristic of a pressure relief valve shows changing of the control parameter (pressure drop $p_{1,2}$) depending on the inlet parameter (inlet flow q_1). The static characteristics of the pilot operated pressure relief valves are described by the following equations [2], [3]:

- *Flow equation across the pilot valve*

$$q_y = \mu_y \cdot d_2 \cdot \pi \cdot x_y \cdot \sin(\theta_y) \cdot \sqrt{\frac{2}{\rho} \cdot p_{3,2}}, \tag{1}$$

where: q_y $\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$ is the flow across the pilot valve; μ_y is the flow coefficient of the pilot valve; d_2 [m] is the seat diameter of the pilot valve; x_y [m] is the displacement of the closing element of the pilot valve; θ_y [°] is the angle of oil flowing at the pilot valve; ρ $\left[\frac{\mathrm{kg}}{\mathrm{m}^2}\right]$ is the oil density; $p_{3,2} = p_3 - p_2$ [Pa] is the pressure drop in the pilot valve.

- *Balance of forces acting on the closing element of the pilot valve*

$$c_y \cdot (h_y + x_y) = p_{3,2} \cdot A_2 - r_y \cdot x_y \cdot p_{3,2}$$

or

$$x_y = \frac{p_{3,2} \cdot A_2 - c_y \cdot h_y}{c_y + r_y \cdot p_{3,2}}, \tag{2}$$

where: A_2 [m^2] is the area of the seat of the pilot valve; c_y $\left[\frac{\mathrm{N}}{\mathrm{m}}\right]$ is the spring constant of the pilot valve; h_y [m] is the previous deformation of the spring of the pilot valve; $r_y = 2 \cdot \mu_y \cdot \pi \cdot d_2 \cdot \cos(\theta_y)$ [m] is the hydrodynamic force coefficient of the pilot valve.

If we solve the equations (1) and (2), the static characteristic of the pilot valve there will be obtained:

$$q_y = \mu_y \cdot d_2 \cdot \pi \cdot \sin(\theta_y) \cdot \sqrt{\frac{2}{\rho} \cdot p_{3,2}} \cdot \frac{p_{3,2} \cdot A_2 - c_y \cdot h_y}{c_y + r_y \cdot p_{3,2}}. \tag{3}$$

- *Pressure drop at the fixed orifices*

$$p_{1,3} = R_{1l} \cdot q_y + R_{1m} \cdot q_y^2 + R_{2l} \cdot q_y + R_{2m} \cdot q_y^2 \tag{4}$$

$$p_{1,2} = (R_{1l} + R_{2l}) \cdot q_y + (R_{1m} + R_{2m}) \cdot q_y^2 = R_l \cdot q_y + R_m \cdot q_y^2,$$

where: $p_{1,3} = p_1 - p_3$ [Pa] is the pressure drop at the pilot chain, $R_l = R_{1l} + R_{2l} = \dfrac{128 \cdot v \cdot \rho \cdot l_1}{\pi \cdot d_{dr_1}^4} + \dfrac{128 \cdot v \cdot \rho \cdot l_2}{\pi \cdot d_{dr_2}^4} \left[\dfrac{\text{Pa} \cdot \text{s}}{\text{m}^2}\right]$ is the linear hydraulic resistance in the orifices R_1 and R_2; $R_m = R_{1m} + R_{2m} = \xi_1 \cdot \dfrac{\rho}{2 \cdot A_{dr_1}^2} + \xi^2 \cdot \dfrac{\rho}{2 \cdot A_{dr_2}^2} \left[\dfrac{\text{Pa} \cdot \text{s}}{\text{m}^2}\right]$ is the local quadratic resistance in the orifices R_1 and R_2; $A_{dr} = \dfrac{d_{dr}^2 \cdot \pi}{4[m^2]}$ is the area of the orifice R_1 or R_2; d_{dr_1} [m] is the diametar of the orifice R_1; l_1 [m] is the length of the orifice R_1; d_{dr_2} [m] is the diametar of the orifice R_2; l_2 [m] is the length of the orifice R_2; $v \left[\dfrac{\text{m}^2}{\text{s}}\right]$ is the oil viscosity.

- *Pressure drop at the main valve*

$$p_{1,2} = p_{1,3} + p_{3,2}, \tag{5}$$

where: $p_{1,2} = p_1 - p_2$ [Pa] is the pressure drop at the main valve.

- *Balance of forces acting on the closing element of the main valve*

$$p_{1,2} \cdot A_0 - p_{1,2} \cdot \Delta A = c_0 \cdot (h_0 + x_0) + r_0 \cdot x_0 \cdot p_{1,2}$$

or

$$x_0 = \frac{p_{1,3} \cdot A_0 - p_{1,2} \cdot \Delta A - c_0 \cdot h_0}{c_0 + r_0 \cdot p_{1,2}}, \tag{6}$$

where: A_0 [m^2] is the area of the closing element of the main valve; ΔA [m^2] is the unbalanced area at the closing element of the main valve; h_0 [m] is the previous deformation of the spring of the main valve; x_0 [m] is the displacement of the closing element of the main valve; $r_0 = 2 \cdot \mu_0 \cdot \pi \cdot D_1 \cdot \sin(\theta_0) \cdot \cos(\theta_0)$ [m]is the hydrodynamic force coefficient of the main valve; μ_0 is the flow coefficient of the main valve; D_1 [m] is the seat diameter of the main valve; θ_0 [°] is the angle of oil flowing at the pilot valve.

- *Flow across the main valve*

$$q_2 = \mu_0 \cdot D_1 \cdot \pi \cdot x_0 \cdot \sin(\theta_0) \cdot \sqrt{\frac{2}{\rho} \cdot p_{1,2}}, \tag{7}$$

where: q_2 $\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]$ is the flow across the main valve.

- *Flow through pilot chain*

$$q_1 = q_2 + q_y. \tag{8}$$

The static characteristics of the pilot operated pressure relief valves are fully described by the equations from (1) to (8).

The specified pressure relief valve shown in *Fig. 2* has the following parameters:

- the seat diameter of the pilot valve $d_2 = 5$ [mm],
- the seat diameter of the main valve $D_1 = 24.3$ [mm],
- the closing element diameter of the main valve $D_0 = 25$ [mm],
- the spring constant of the pilot valve $c_y = 61$ $\left[\frac{\mathrm{N}}{\mathrm{mm}}\right]$,
- the spring constant of the main valve $c_0 = 15$ $\left[\frac{\mathrm{N}}{\mathrm{mm}}\right]$,
- the fixed orifices diameter $d_{dr} = 1$ [mm],
- the oil viscosity $v = 46$ [cSt]

The numerical static characteristic is shown in *Fig. 3.*

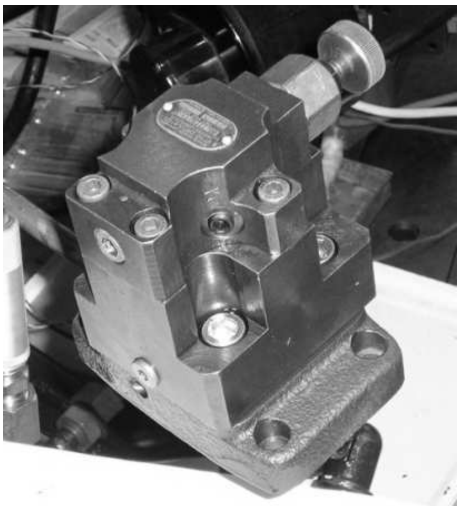

Fig. 2. Specified pilot operated pressure relief valve
Фиг. 2. Определен предпазно-преливен клапан с непряко управление

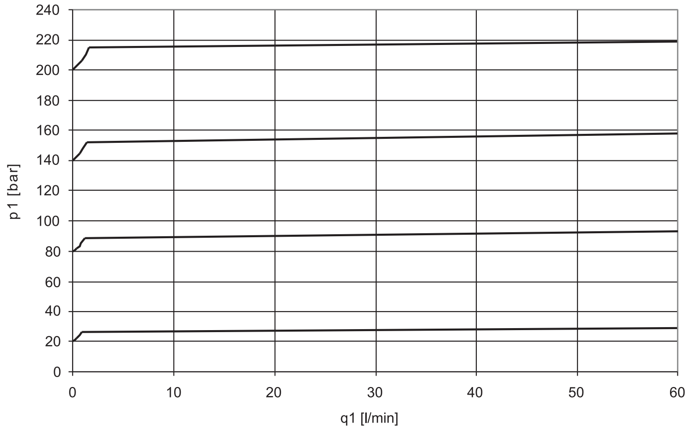

Fig. 3. Numerical static characteristic of a pilot operated pressure relief valve
Фиг. 3. Числени статични характеристики на регулиращ предпазен вентил

4. EXPERIMENTAL RESULTS

The basic aim of this investigation is to determine the true static characteristic of the pilot operated pressure relief valves, and to compare it with the numerical characteristic. The diagram of the *Fig. 4* shows the experimental static characteristic of the specified valve. In the diagram mentioned above the approximately identical numerical and experimental pressure vs flow depending

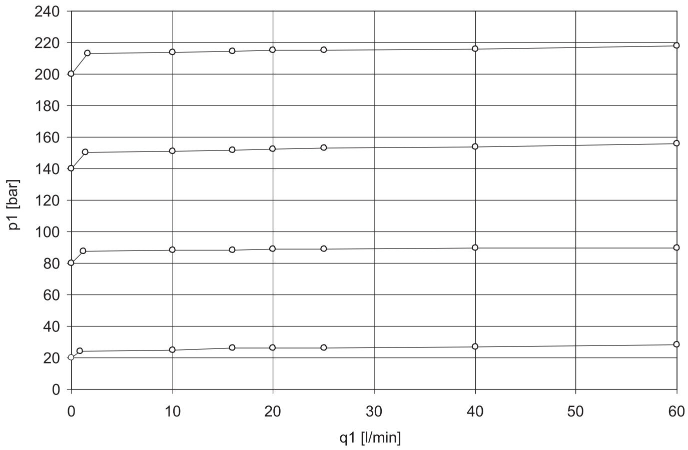

Fig. 4. Experimental static characteristic of a pilot operated pressure relief valve
Фиг. 4. Експериментални статични характеристики на предпазно-преливен клапан с непряко управление

is notable. By this fact, the applied mathematical methodology for calculation of static characteristics of pilot operated pressure relief valves is verified.

A test stand for experimental determination of the true static characteristic of the specified pressure relief valve is shown in *Fig. 5.*

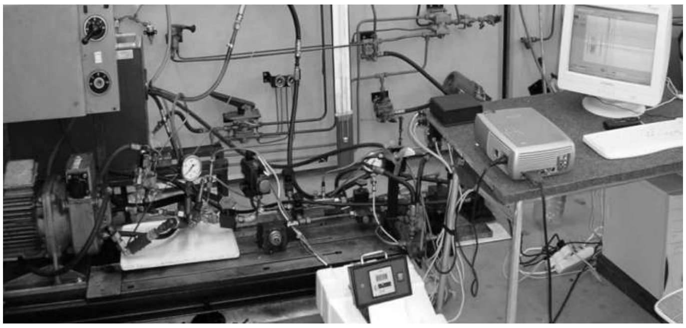

Fig. 5. Experimental test stand
Фиг. 5. Стенд за експериментално тестване

5. CONCLUSION

The experimental static characteristic has confirmed the proposed methodology for numerical obtaining of the static characteristic. However, the diagrams generally show some features of the static characteristics of pressure relief valves.

The main advantage of the pilot operated pressure relief valves is its low slope, or low statism at higher flow and pressure ranges from the moment of opening the main valve, compared with the direct acting pressure relief valves. This low statism primarily is due to low spring constant of the main valve. But, the main disadvantage of these valves is their high (relative) error of the control value (pressure p_1) at the beginning, to the moment of opening of the main valve. From both the diagrams we can notice the difference between the moment of opening of the pilot valve and the moment of opening of the main valve. An appropriate designing modification on some details of the valve like orifice diameter and seat diameter of the pilot valve can reduce the pressure difference of the opening of the pilot and the main valve, but to keep good dynamic characteristics yet. It is important to say that some modification can improve static characteristics, but at the same time it can influence negative to dynamic characteristics. So, static and dynamic characteristics are usually investigated simultaneously in order to get optimal performance of the valve.

As inlet pressure p_1 (or pressure drop $p_{1,2}$) increases, the pilot flow q_y also increases. Usually for different designs of pilot operated pressure relief valves, the pilot flow q_y moves around $0.5 - 1.6 \left[\frac{\text{l}}{\text{min}}\right]$.

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ЕКСПЕРИМЕНТАЛНА ВЕРИФИКАЦИЯ НА МАТЕМАТИЧЕН МОДЕЛ НА СТАТИЧНИТЕ ХАРАКТЕРИСТИКИ НА ПРЕДПАЗНО–ПРЕЛИВЕН КЛАПАН С НЕПРЯКО УПРАВЛЕНИЕ

Сашко Димитров, Симеон Симеонов, Славчо Цветков

Р е з ю м е

В настоящата статия е представено числено и експериментално определяне на статичните характеристики на предпазно–преливен клапан с непряко управление. Разработен е математичен модел на спада на налягането в зависимост от дебита в клапана. Създаден е стенд за експериментално определяне на спада на налягането в зависимост от дебита и получените резултати са сравнени с теоретичните. Резултатите от решаването на математичния модел и от експерименталното изследване са показани в няколко диаграми. Дадени са няколко насоки за подобряване на статичните характеристики, особено в момент на отваряне на основния клапан на предпазно–преливен клапан с непряко управление. Представени са предимствата и недостатъците на статичните характеристики на двата типа клапана.

Ключови думи: предпазно–преливен клапан с непряко управление, статични характеристики.

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