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## TRANSIENT RESPONSE OF A PILOT OPERATED PRESSURE RELIEF VALVE WITH COMPENSATING CONTROL PISTON

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**Abstract:** A subject of investigation was pilot operated pressure relief valve with compensating control piston. Non linear mathematical model of the valve was developed. Theoretically and experimentally the transient response of the valve has been investigated. Using advance measurement equipment experimentally has been shown the opening of the main valve before the pilot valve, i.e. opposite of the static characteristic.

**Keywords:** valve, compensating control piston, non-linear mathematical model

### 1. INTRODUCTION

Influence of different design modification of the pilot line and different locations of the resistances in the pilot line to the transient response of the valve are investigated in [1]. Theoretically has been shown [2] that in the transient response the main valve open first, than pilot valve opens. It limits increasing of the pressure in the system and the transient response is much smoother than the transient response of the direct operated pressure relief valve. In this paper a modified conventional design of pilot operated relief valve mostly used in industry is subject of investigation. New feature of this valve is built-in compensating control piston in the pilot line. This control piston can improve static characteristic at the beginning of opening of the valve [5]. But higher diameter of the control piston can cause unstable work of the valve. A transient response with different diameter of the control piston is investigated in this paper.

At fig. 1 a functional diagram of the pilot operated pressure relief valve with compressible volume of oil at its inlet and return pipeline at its outlet has been shown.

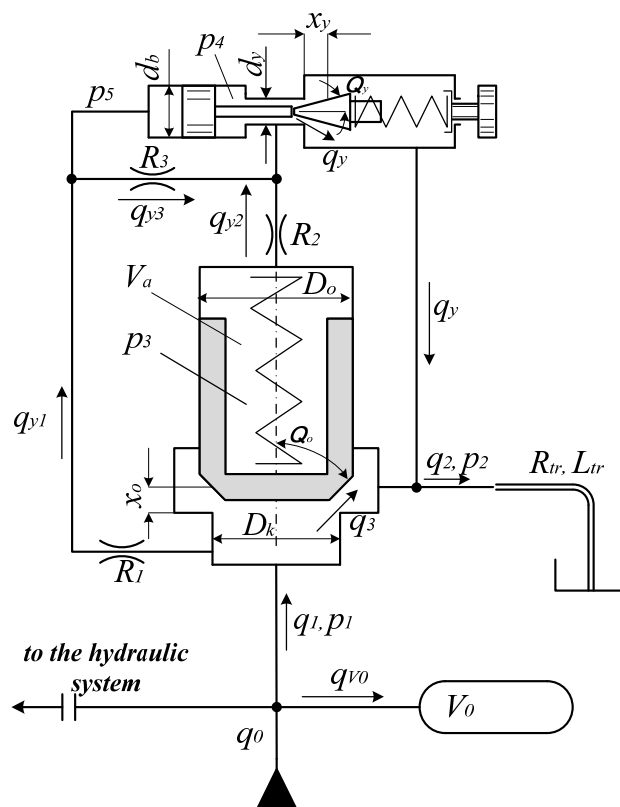


Fig.1. Functional diagram of the valve

## 2. NONLINEAR MATHEMATICAL MODEL OF THE VALVE

The mathematical model of the pilot operated pressure relief valve with compensating control piston is described by the following equation:

Equation of motion of the closing element of the pilot valve

$$m_y \cdot \frac{d^2 x_y}{dt^2} + c_y \cdot (h_y + x_y) + r_y \cdot x_y \cdot p_{4,2} = p_{5,4} \cdot A_b + p_{4,2} \cdot A_y \quad (1)$$

where  $m_y$  - the mass of the cone of the pilot valve;  $c_y$  - the spring constant of the pilot valve;  $h_y$  - previews spring deformation of the pilot valve;  $x_y$  - the displacement of the pilot valve;  $r_y$  - the coefficient of the hydrodynamic force of the pilot valve;  $p_{5,4}$  - the pressure drop at the orifice R3;  $p_{4,2}$  - the pressure drop at the pilot valve;  $A_y$  - the area of the seat of the pilot valve;  $A_b$  - the area of the control piston.

Equation of continuity in front of the pilot valve

$$q_{y2} + q_{ys} + A_b \cdot \frac{dx_y}{dt} = q_{3y} + A_y \cdot \frac{dx_y}{dt} = \mu_y \cdot \pi \cdot d_y \cdot \sin \theta_y \cdot \sqrt{\frac{2}{\rho} \cdot p_{4,2}} + A_y \cdot \frac{dx_y}{dt} \quad (2)$$

where  $q_y$  - the flow through the pilot valve;  $q_{3y}$  - the flow through the control orifice of the pilot valve;  $\theta_y$  - the angle of flowing in the pilot valve.

Equation of motion of the closing element of the main valve

$$m_o \cdot \frac{d^2 x_o}{dt^2} + c_o \cdot (h_o + x_o) + r_o \cdot p_{1,2} = p_1 \cdot A_k + p_2 \cdot \Delta A - p_3 \cdot A_o \quad (3)$$

where  $m_o$  - the mass of the closing element of the main valve;  $c_o$  - the spring constant of the main valve;  $h_o$  - the previews spring deformation of the main valve;  $x_o$  - the displacement of the main valve;  $r_o$  - the coefficient of the hydrodynamic force of the main valve;  $p_{1,2}$  - the pressure drop at the main valve;  $A_k$  - the area of the main valve seat;  $A_o$  - the area of the closing element of the main valve.

Equation for pressure drop in the resistance

$$p_{1,5} = r_{1l} \cdot q_{y1} + r_{1m} \cdot |q_{y1}| q_{y1} + L_1 \cdot \frac{dq_{y1}}{dt} \quad (4)$$

where  $r_{1l}$  - the linear resistance in the orifice  $R_1$ ;  $r_{1m}$  - the local resistance in the orifice  $R_1$ ;  $L_1$  - the inertial resistance in the orifice  $R_1$ ;  $q_{y1}$  - the pilot oil flow.

Equation for pressure drop in the resistance

$$p_{5,4} = r_{3l} \cdot q_{y3} + r_{3m} \cdot |q_{y3}| \cdot q_{y3} + L_3 \cdot \frac{dq_{y3}}{dt} \quad (5)$$

where  $r_{3l}$  - the linear resistance in the orifice  $R_3$ ;  $r_{3m}$  - the local resistance in the orifice  $R_3$ ;  $L_3$  - the inertial resistance in the orifice  $R_3$ ;  $q_{y3}$  - the pilot oil flow through the orifice  $R_3$ .

Equation of compressibility in the spring chamber of the main valve

$$q_{y2} = A_o \cdot \frac{dx}{dt} - \frac{V_a}{K} \cdot \frac{dp_3}{dt} \quad (6)$$

where  $V_a$  - volume of oil in the spring chamber of the main valve;  $K$  - bulk modulus of the oil.

Equation for pressure drop in the resistance

$$p_{3,4} = r_{2l} \cdot q_{y2} + r_{2m} \cdot |q_{y2}| q_{y2} + L_2 \cdot \frac{dq}{dt} \quad (7)$$

Where  $r_{2l}$  - the linear resistance in the orifice  $R_2$ ;  $r_{2m}$  - the local resistance in the orifice  $R_2$ ;  $L_2$  - the inertial resistance in the orifice  $R_2$ ;  $q_{y2}$  - the pilot oil flow through the orifice  $R_2$ .

Equation of continuity in front of the compensating control piston

$$q_{y1} = q_{y3} + \frac{V_b}{K} \cdot \frac{dp_5}{dt} + A_y \cdot \frac{dx_y}{dt} \quad (8)$$

Where  $V_b$  - the volume of oil in front of the compensating control piston;  $p_5$  - the pressure in front of the compensating control piston.

Equation of continuity in front of the valve

$$q_0 = q_{in} + q_v + q_1 \quad (9)$$

where:  $q_{in} = \left(1 - \frac{t}{t_1}\right) \cdot \mu_v \cdot \pi \cdot d_v \cdot x_v \cdot \sqrt{\frac{2}{\rho} \cdot p_1}$  - flow through the directional control valve V, which

closes for time  $t_1$ ;  $t$  - time;  $\mu_v$  - flow coefficient through the directional control valve;  $q_v = \frac{V}{K} \cdot \frac{dp_1}{dt}$

- the flow which enters in the volume  $V_0$ ;  $q_1$  - the flow entering the valve.

Flow equation through the main valve

$$q_3 = \mu_0 \cdot \pi \cdot D_k \cdot \sin \theta_0 \cdot x_0 \cdot \sqrt{\frac{2}{\rho} \cdot p_{1,2}} \quad (10)$$

where  $\mu_0$  - the flow coefficient of the main valve;  $D_k$  - the seat diameter of the main valve;  $\theta_0$  - the angle of flowing in the pilot valve.

Equation of continuity in front of the main valve

$$q_1 = q_3 + q_{y2} + A_k \cdot \frac{dx_0}{dt} \quad (11)$$

Flow equation through outlet pipeline

$$p_2 = r_{1p} \cdot q_2 + r_{mp} \cdot |q_2| q_2 + L_p \cdot \frac{dq_2}{dt} \quad (12)$$

where  $r_{1p}$  - the linear in the outlet pipeline;  $r_{mp}$  - local resistance in the outlet pipeline;  $L_p$  - inertial resistance in the outlet pipeline;  $p_2$  - the pressure drop through the outlet pipeline;  $q_2$  - the flow through the outlet pipeline.

As can be seen of the above consideration, the mathematical model of the pilot operated pressure relief valve with compensating control piston is described by large system of nonlinear differential and algebraic equation.

### 3. TRANSIENT RESPONSE OF A PILOT OPERATED PRESSURE RELIEF VALVE

The subject of investigation was Denison pressure relief valve type R4V 06, shown on fig.2 [4].

The parameters of the valve are:

$$d_y = 5mm, c_y = 250N/mm, d_b = 5.5mm, d_{dr1} = d_{dr3} = 0.8mm, d_{dr2} = 0.6mm, \\ l_{dr1} = l_{dr2} = l_{dr3} = 1mm, D_k = 28.5mm, D_0 = 28mm, c_o = 7N/mm, h_o = 16.5mm,$$

The parameters of the oil are:  $\nu = 34cSt$ ,  $\rho = 890kg/m^3$ , and  $K = 1.45 \cdot 10^9 N/m^2$  and working flow is 30 l/min. The valve outlet was connected with the tank by the pipeline with diameter 20 mm and length 1.5 m.

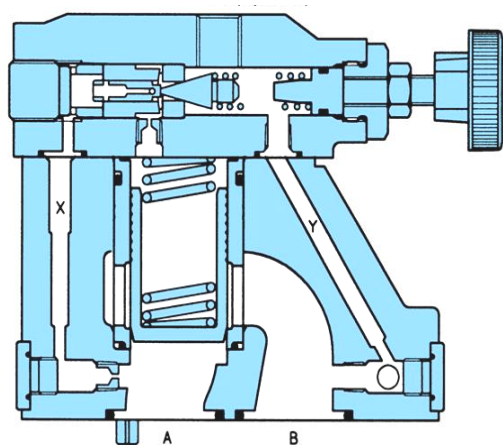


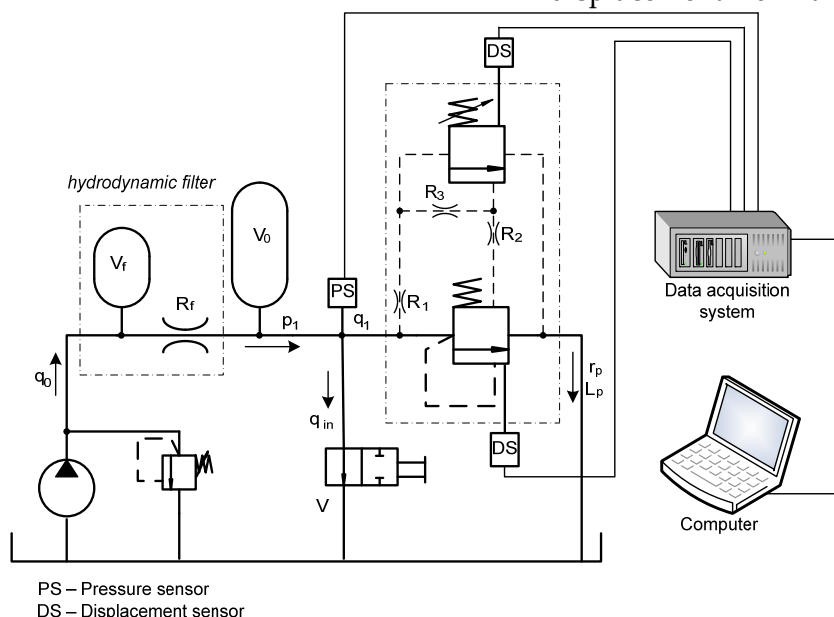
Fig.2 The analyzed valve type R4V 06-Denison [4]

A functional diagram of the test stand for experimental determination of the transient response is shown on fig.3. For real behavior of the valve in the stand as in a system, it is assumed that there is volume of oil in front of the valve  $V_0$  and downstream pipeline with resistance  $r_p$  and inertial resistance  $L_p$ . To isolate the oil compressibility between the pump and the valve and for reducing pressure pulsation after the pump, it is included a hydrodynamic filter. The hydrodynamic filter is composed of volume of oil  $V_f$  and high inertial resistance  $R_f$ .

A pressure sensor  $PS$  for pressure measurement in front of the valve and two displacement sensors  $DS$  for displacement of the pilot and the main valve displacement measurement are built-in at the stand.

Analog signals from the sensors, through appropriate cables, are transfer to the Data Acquisition System where they are converted to digital ones. The Data Acquisition System, through USB cable, is connected to the computer and using specially programmed software the measured parameters are displayed in graphical form.

A rapid closure of the directional control valve  $V$  creates a transient response.



PS – Pressure sensor  
DS – Displacement sensor

Fig. 3. Functional diagram of the experimental test stand

Pump flow  $q_0$  enters in the inlet volume  $V_0$  and the inlet pressure  $p_1$  is increasing. Because of high local resistance at the orifices  $R_1$ ,  $R_2$  and  $R_3$  always the main valve first opens. The spool of the main valve is moving up and compresses oil volume in the spring chamber of the main valve (fig.1). The pilot valve opens after reaching the set pressure at it. After opening the pilot valve, balance of forces acting to the closing element of the main valve is impaired and the main valve is fully opening. Previews fast opening of the main valve decreases high pressure overload at beginning, typical for direct operated pressure relief valves [3].

Transient responses of the pilot operated pressure relief valve with volume of oil in front of the valve  $V_0 = 480 \text{ cm}^3$  and the diameter of the compensating piston  $d_b = 5.5 \text{ mm}$  are shown on fig.4. On fig. 4 - a the pressure in front of the valve and the displacement of pilot and the main valve for pressure setting of 60 bar is shown. On fig.4 - b the pressure in front of the valve and the displacement of pilot and the main valve for pressure setting of 100 bar is shown.

Transient responses of the pilot operated pressure relief valve with volume of oil in front of the valve  $V_0 = 480 \text{ cm}^3$  and the diameter of the compensating piston  $d_b = 6 \text{ mm}$  are shown on fig.5. On fig. 5 - a the pressure in front of the valve and the displacement of pilot and the main valve for pressure setting of 60 bar is shown. On fig.5 - b the pressure in front of the valve and the displacement of pilot and the main valve for pressure setting of 100 bar is shown.

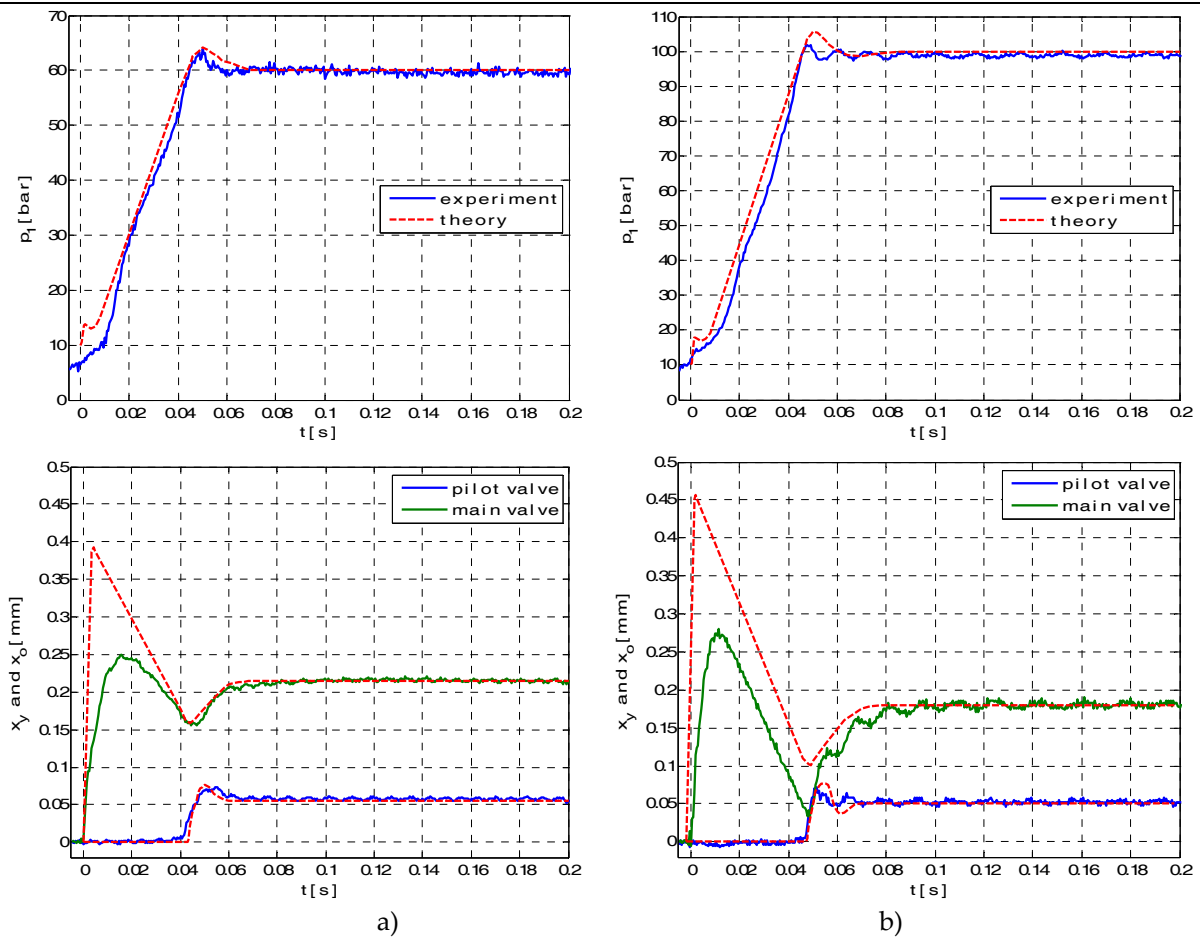


Fig.4 Transient response of a pilot operated pressure relief valve with  $db=5.5$  mm and  $V_o=480$  cm<sup>3</sup>

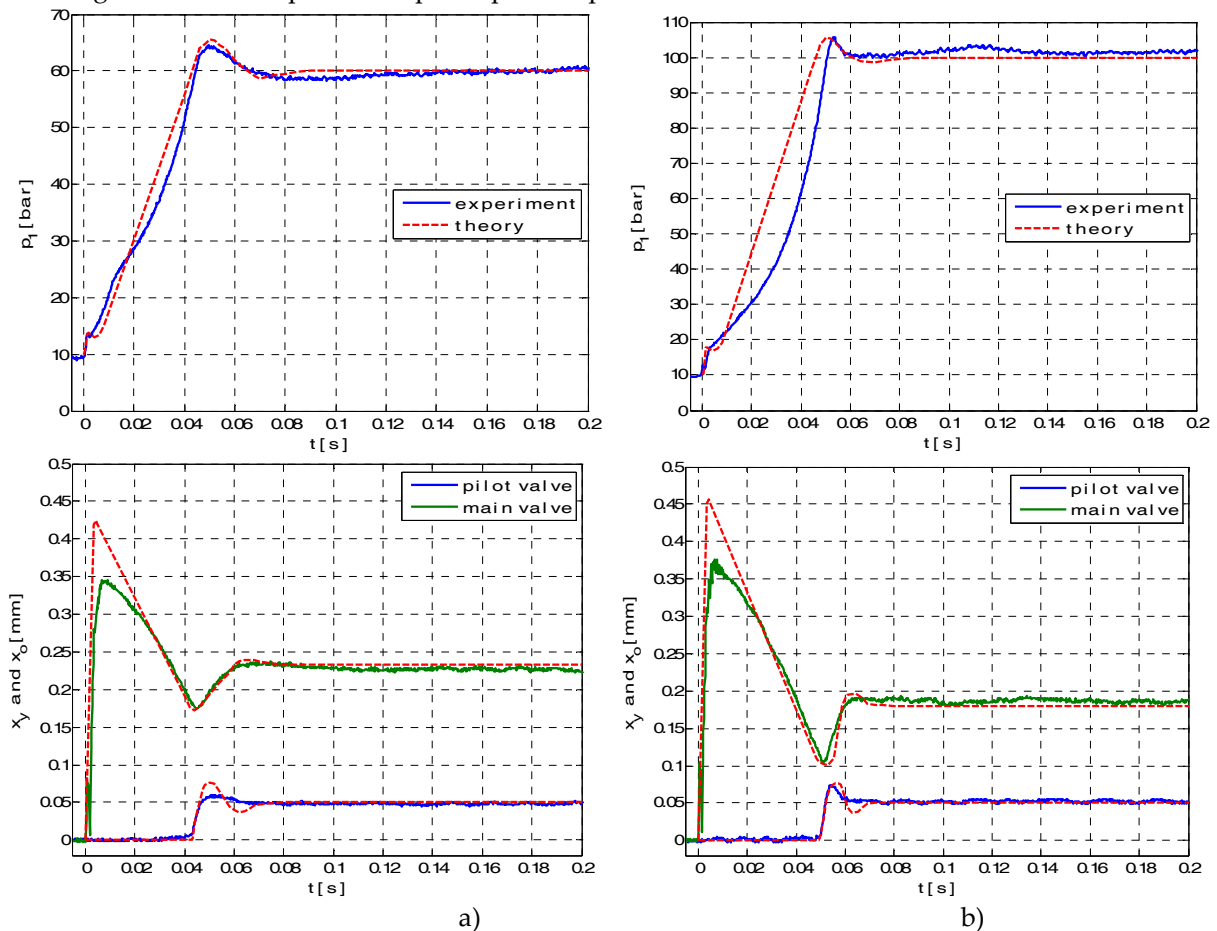


Fig.5 Transient response of a pilot operated pressure relief valve with  $db=6$  mm and  $V_o=480$  cm<sup>3</sup>

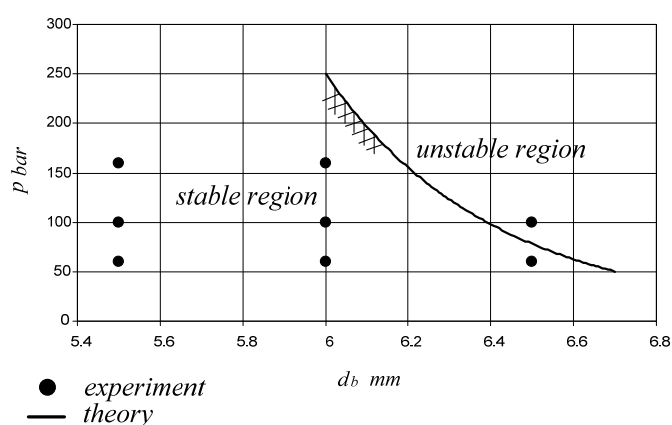


Fig.6. The area of stability of the valve

depending of the working system pressure and the diameter of the compensating control piston is presented on fig.6 [6].

#### 4. CONCLUSION

Mathematical model of a pilot operated pressure relief valve with compensating control piston is described by large system of nonlinear differential equations. The obtained theoretical results are confirmed by the experiments. Following the rapid opening of the main valve before the pilot, it is avoided the system overload from the pressure increase at the beginning. For this reason many companies offer application of pilot operated pressure relief valves for lower flows. Influence of the compensating control piston diameter to the transient response is investigated, too. Experiments have shown that proper work of the valve is limited by the compensating piston diameter. At certain value of the compensating piston diameter, the valve turns to work unstable.

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