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TRANSIENT RESPONSE OF A PILOT OPERATED PRESSURE RELIEF VALVE

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Abstract: A subject of investigation was conventional design of pilot operated pressure relief valve. 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.

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 conventional design of pilot operated relief valve mostly used in industry is subject of investigation.

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.

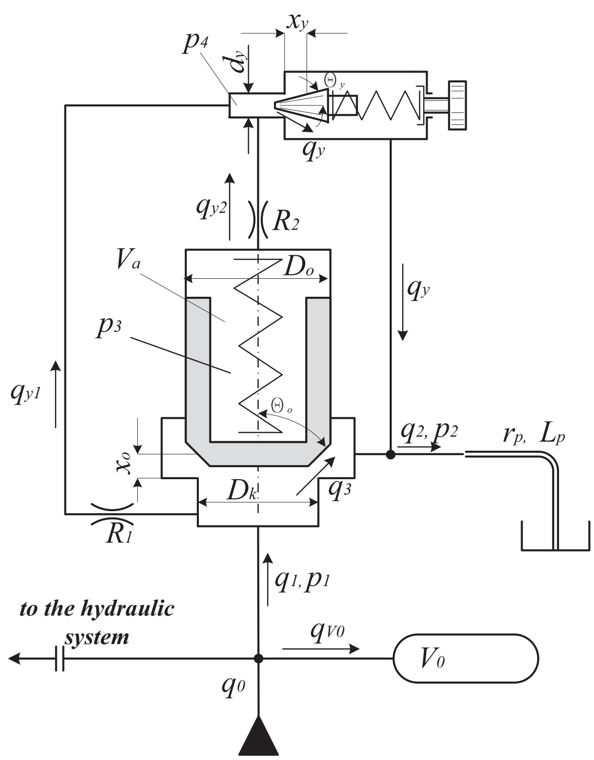


Fig.1 Functional diagram of the valve

2. NONLINEAR MATHEMATICAL MODEL OF THE VALVE

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

- *Equation of motion of the closing element of the pilot valve [4]*

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

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; $p_{4,2}$ – the pressure drop at the pilot valve; A_y - the area of the seat of the pilot valve.

- *Equation of continuity in front of the pilot valve [4]*

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

Where q_y - the flow through the pilot valve; q_{3y} - the flow through the control orifice of the pilot valve; θ_y - the angle of flowing in the pilot valve.

- *Equation of motion of the closing element of the main valve*

$$m_0 \cdot \frac{d^2x_0}{dt^2} + c_0 \cdot (h_0 + x_0) + r_0 \cdot x_0 \cdot p_{1,2} = p_1 \cdot A_k + p_2 \cdot \Delta A - p_3 \cdot A_0 \quad (3)$$

Where m_o – the mass of the closing element of the main valve; c_o- the spring constant of the main valve; h_o- 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_0 - the area of the closing element of the main valve.

- *Equation for pressure drop in the resistance R_1*

$$p_{1,4} = r_{1l} \cdot q_{y_1} + r_{1m} \cdot |q_{y1}|q_{y1} + L_1 \cdot \frac{dq_{y_1}}{dt} \quad (4)$$

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_{y_1} – the pilot oil flow.

- *Equation of compressibility in the spring chamber of the main valve*

$$q_{y_2} = A_0 \cdot \frac{dx_0}{dt} - \frac{V_a}{K} \cdot \frac{dp_3}{dt} \quad (5)$$

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 R_2*

$$p_{3,4} = r_{2l} \cdot q_{y_2} + r_{2m} \cdot |q_{y2}|q_{y2} + L_2 \cdot \frac{dq_{y_2}}{dt} \quad (6)$$

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_{y_2} – the pilot oil flow through the orifice R_2.

- *Equation of continuity in front of the valve*

$$q_0 = q_{in} + q_v + q_1 \quad (7)$$

where: $q_{in} = \left(1 - \frac{t}{t_1}\right) \mu_v \cdot \pi \cdot d_v \cdot x_v \cdot \sqrt{\frac{2}{\rho} \cdot p_1}$ -flow through the directional control valve V, which closes for time t_1; t – time; μ_v – flow coefficient through the directional control valve; $q_v = \frac{V_0}{K}\frac{dp_1}{dt}$ – flow which enters in the volume V_0; q_1 – the flow entering the valve

- *Flow equation through the main valve*

$$q_3 = \mu_0 \cdot \pi \cdot D_k \cdot sin\theta_0 \cdot x_0 \cdot \sqrt{\frac{2}{\rho} \cdot p_{1,2}} \quad (8)$$

where μ_0 - the flow coefficient of the main valve; D_k - the seat diameter of the main valve; θ_0 - the angle of flowing in the pilot valve.

- *Equation of continuity in front of the main valve*

$$q_1 = q_3 + q_{y_1} + A_k \cdot \frac{dx_0}{dt} \quad (9)$$

- *Flow equation through outlet pipeline*

$$p_2 = r_{lp} \cdot q_2 + r_{mp} \cdot |q_2| \cdot q_2 + L_p \cdot \frac{dq_2}{dt} \quad (10)$$

where r_{lp} - 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 is described by large system of nonlinear differential and algebraic equation.

3. TRANSIENT RESPONSE OF A PILOT OPERATED PRESSURE RELIEF VALVE

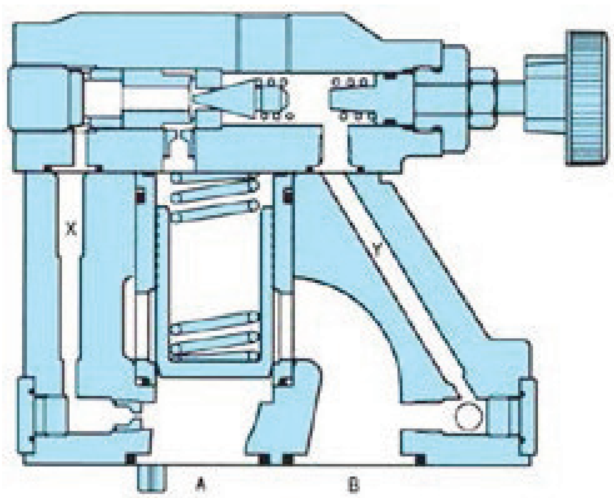


Fig.2 The analyzed valve type R4V 06-*Denison* [4]

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

The parameters of the valve are: $d_y = 5\,mm$, $c_y = 250\,\frac{N}{mm}$, $d_b = 5.5\,mm$, $d_{dr1} = 0.8\,mm$, $d_{dr2} = 0.6\,mm$, $l_{dr1} = l_{dr2} = 1\,mm$, $D_k = 28.5\,mm$, $D_o = 28\,mm$, $c_o = 7\,\frac{N}{mm}$, $h_o = 16.5\,mm$, the parameters of the oil are: $\nu = 34\,cS$, $\rho = 890\,\frac{kg}{m^3}$ 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*.

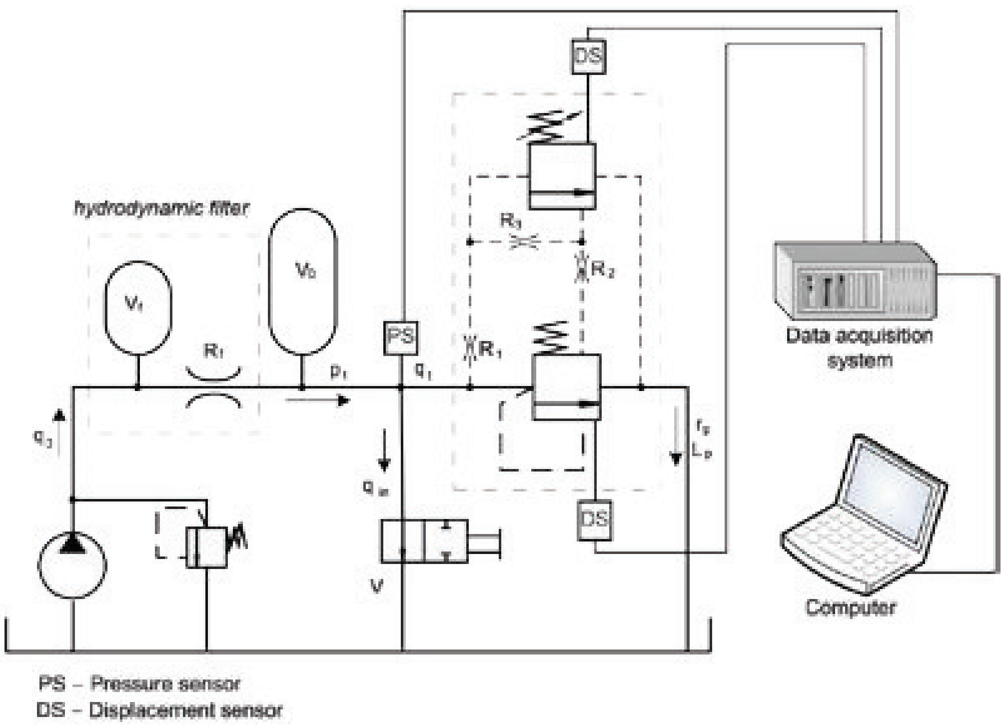


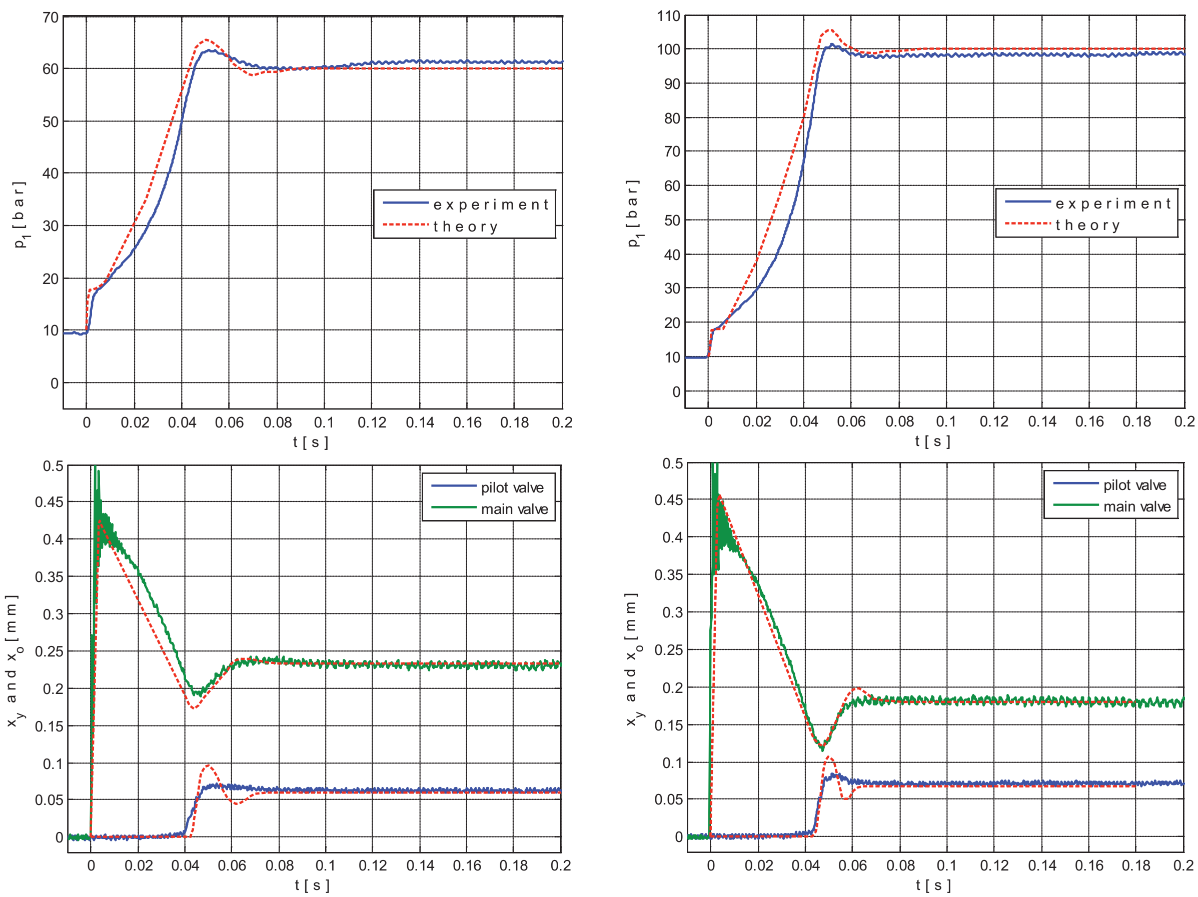
Fig. 3 Functional diagram of the experimental test stand

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_o 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. 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 and R_2 always the main valve first opens. The spool of the main valve is moving up and compresses oil volume V_a 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].

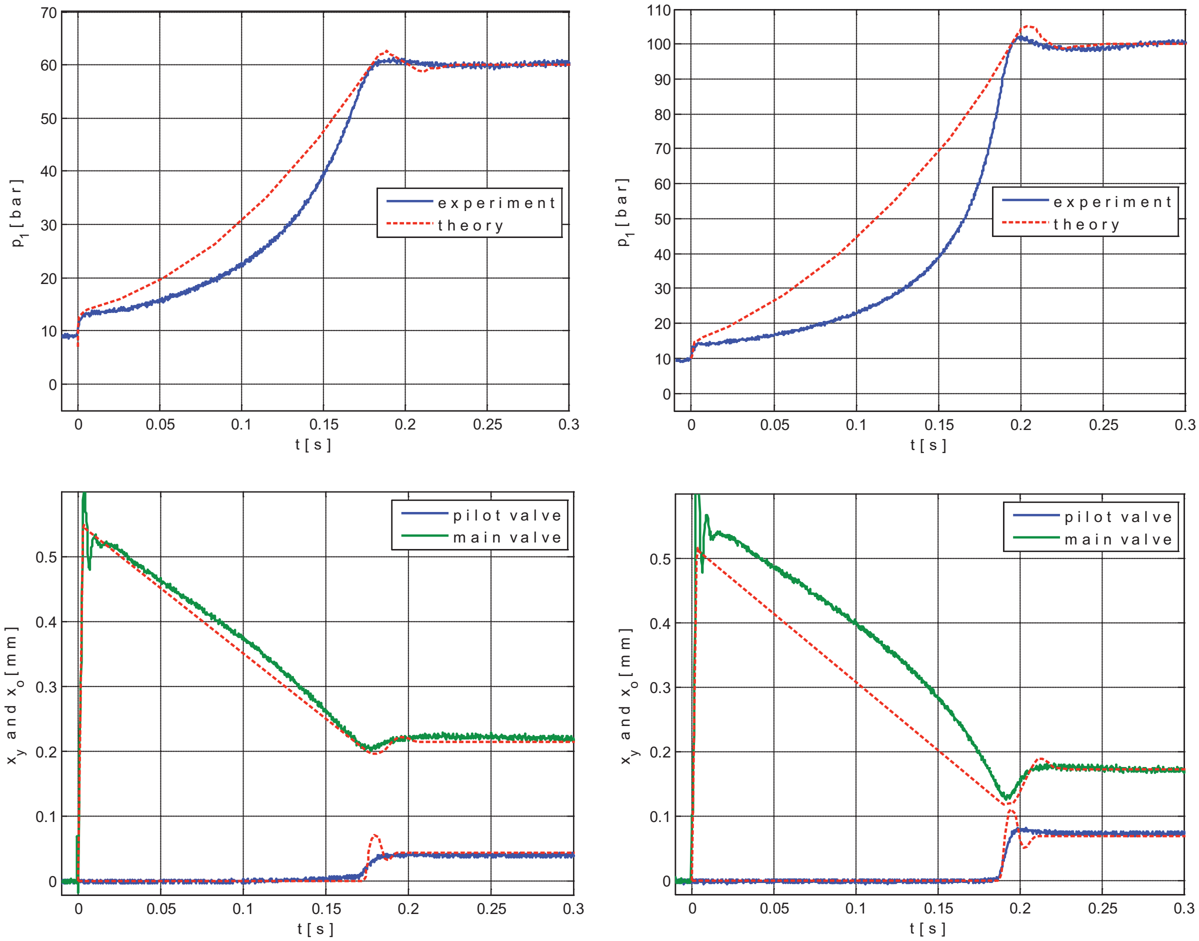


a) b)

Fig.4 Transient response of a pilot operated pressure relief valve with $V_o = 52\ cm^3$

Transient responses of the pilot operated pressure relief valve with volume of oil in front of the valve $V_o = 52\ cm^3$ 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 $V_o = 480\ cm^3$ 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.



a) b)

Fig.5 Transient response of a pilot operated pressure relief valve with $V_o = 480\ cm^3$

4. CONCLUSION

Mathematical model of a pilot operated pressure relief valve 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, too.

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