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STATIC AND DYNAMIC PERFORMANCE OF PILOT OPERATED HYDRAULIC RELIEF VALVES

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ABSTRACT

An investigation of the performance of pilot operated hydraulic relief valves has been carried out. The valve behavior is described by means of a nonlinear mathematical model, considering the nonlinear variation of the restriction areas, the nonlinear flow-pressure relations and the flow forces. The theoretical treatment is carried out by treating the developed mathematical model using a digital simulation program. The model is validated in the steady state by comparing simulation and experimental results. The transient behavior of the valve is investigated theoretically. The effect of the dimensions of the damping orifices and volume of oil filling the inlet line is predicted. The simulation program is used to predict the optimum dimensions of the damping orifices, which introduced an observable improvement in the transient response.

NOMENCLATURE

a_1 Pilot valve poppet area subjected to pressure P_2, m^2.
a_2 Pilot stage opening area, m^2.
a Main poppet opening area, m^2.
A Main poppet area subjected to pressure P, m^2.
A_1 First orifice area, m^2.
A_2 Second orifice area, m^2.
A_3 Third orifice area, m^2.
A_t Area of the throttle valve, m^2.
B Bulk modulus of oil, N/m^2.
C_{c1} Contraction coefficient.
C_{c2} Contraction coefficient.
C_d Discharge coefficient of the valve opening orifice.
C_{d1} Discharge coefficient of the first orifice.
C_{d2} Discharge coefficient of the second orifice.
C_{d3} Discharge coefficient of the third orifice.
C_{d4} Discharge coefficient of the pilot stage restriction.
D Main poppet diameter, m.
d_p diameter of the seat of pilot valve poppet, m.

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d_1 Diameter of the first damping orifice, m.
d_2 Diameter of the second damping orifice, m.
d_3 Diameter of the third damping orifice, m.
f_1 Damping factor of the pilot valve poppet, Ns/m.
f_2 Damping factor of the main poppet, Ns/m.
F_p Axial component of flow force acting on the pilot valve, N.
F_{ps} Pilot poppet seat reaction, N.
F_s Axial component of flow force acting on the main poppet, N.
F_{Rs} Main poppet seat reaction, N.
m_p Equivalent mass of moving parts of the pilot poppet, kg.
m_s Equivalent mass of moving parts of the main poppet, kg.
K_1 Pilot valve spring stiffness, N/m.
K_2 Main valve spring stiffness, N/m.
P Pressure in the inlet chamber, Pa.
P_1 Pressure in the first chamber, Pa.
P_2 Pressure in the second chamber, Pa.
P_3 Pressure in the third chamber, Pa.
P_T Return pressure, Pa.
Q_1 Flow rate through the first damping orifice, m^3/s.
Q_2 Flow rate through the second damping orifice, m^3/s.
Q_3 Flow rate through the third damping orifice, m^3/s.
Q_4 Relief flow rate of the pilot stage, m^3/s.
Q Flow rate through the main valve, m^3/s.
Q_p Pump flow rate, m^3/s.
Q_t Flow rate through the throttle valve, m^3/s.
V Volume of oil filling the inlet chamber, m^3.
V_1 Volume of oil filling the first chamber, m^3.
V_2 Volume of oil filling the second chamber, m^3.
V_3 Volume of oil filling the third chamber, m^3.
x Main valve poppet displacement, m.
x_o Precompression of the main valve spring, m.
y Pilot valve poppet displacement, m.
y_o Precompression of the pilot valve spring, m.
ρ Fluid density, kg/m^3.
α Pilot valve poppet cone angle, rad.
β Main poppet seat angle, rad.

INTRODUCTION

Pressure control valves are basic elements of hydraulic power systems. They are widely used in the hydraulic circuits to fulfill different functions such as the limitation of the maximum fluid pressure, pressure reduction, unloading of pumps after the charging of hydraulic accumulators, keeping certain sequence of operations based upon the pressure variation,..., etc. Among the pressure control valves, relief valves are ones of the utmost importance. They are used to limit the maximum pressure in the circuit, by relieving the excess fluid to tank, which makes this class of valves indispensable for the circuit protection. But, inspite of this fact, only few publications are found to deal with the dynamic behavior of these valves; [1],[2],[3]&[4].

Herein, the performance of a class or pilot operated relief valves is investigated. The study aims to point out the peculiarities of operation of these valves in the transient conditions.

DESCRIPTION OF THE STUDIED VALVE

The investigated pilot operated hydraulic relief valve is drawn schematically in Fig.1. The valve consists of two stages; a pilot stage and a main stage. The pilot stage includes a conical poppet (5) loaded by a spring (4). The main stage incorporates the main poppet (7) which is loaded by a spring (6). The pressure P in the inlet chamber, of volume V, affects the main poppet, while the pressure P_2 in the second chamber, of volume V_2, affects the pilot valve poppet. Pressures P_2 and P_3 are limited by the pilot stage through the initial compression of spring (4). The valve inlet chamber is communicated to the pilot stage through two orifices (1) and (2). If the pressure P, at the inlet of valve is smaller than the value necessary to open the pilot stage, the pilot valve remains closed and the pressure P_3, together with the spring force (6), keep the main poppet seated in the closing position. When the pressure P is higher than the value preset at the pilot stage, the pilot valve poppet moves to an opening position. This causes the limitation of the pressures P_2 and P_3. When the inlet pressure P exceeds this limit by about 0.4 MPa the main poppet gets open to dump the excess fluid to tank.

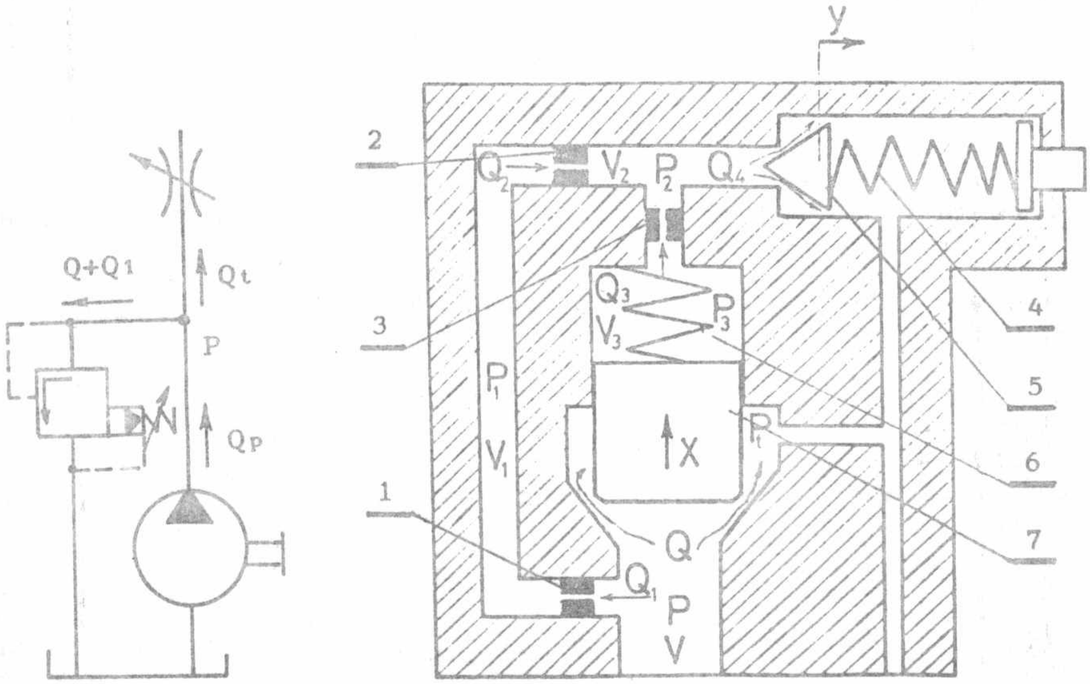


Fig.1. Scheme of the studied pilot operated hydraulic relief valve and its connection.

MODELLING OF THE VALVE

Considering the geometry of the main and pilot poppet valves, shown in Fig.2, the throttling areas of these valves and the areas subjected to pressure forces are given by the following relations.

$$A = \pi D^2/4 \qquad (1)$$

$$a = (\pi D \cos \beta)\, x + (\pi \sin \beta \cos^2 \beta)\, x^2 \qquad (2)$$

$$a_1 = \pi d_p^2/4 - (\pi d_p \cos \alpha \sin \alpha)\, y + (\pi d_p \cos^2 \alpha \sin^2 \alpha)\, y^2 \qquad (3)$$

$$a_2 = (\pi d_p \sin \alpha)\, y - (\pi \sin^2 \alpha \cos \alpha)\, y^2 \qquad (4)$$

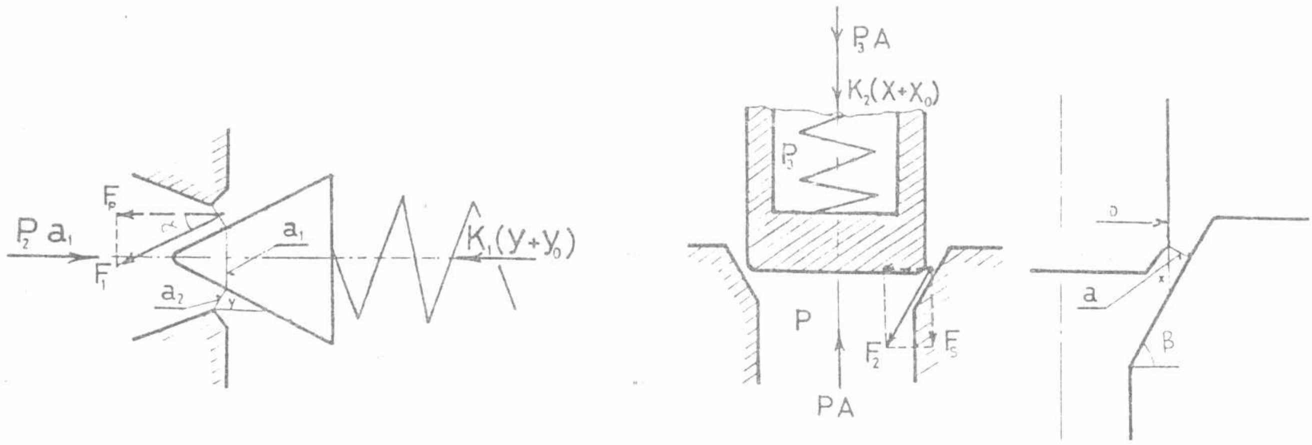


Fig.2. Basic dimensions of the main and pilot poppet valves.

The dynamic behavior of the valve can be described by the following relations.

$$Q = C_d\, a \sqrt{2\,(P - P_T)/\rho}\; \mathrm{sign}(P - P_T) \qquad (5)$$

$$Q_1 = C_{d1}\, A_1 \sqrt{2\,(P - P_1)/\rho}\; \mathrm{sign}(P - P_1) \qquad (6)$$

$$Q_2 = C_{d2}\, A_2 \sqrt{2\,(P_1 - P_2)/\rho}\; \mathrm{sign}(P_1 - P_2) \qquad (7)$$

$$Q_3 = C_{d3}\, A_3 \sqrt{2\,(P_3 - P_2)/\rho}\; \mathrm{sign}(P_3 - P_2) \qquad (8)$$

$$Q_4 = C_{d4}\, a_2 \sqrt{2\,(P_2 - P_T)/\rho}\; \mathrm{sign}(P_2 - P_T) \qquad (9)$$

$$Q_t = C_d\, A_t \sqrt{2\,(P - P_T)/\rho}\; \mathrm{sign}(P - P_T) \qquad (10)$$

$$Q_p - Q - Q_1 - A\, dx/dt - [(V + Ax)/B]\, dP/dt = 0 \qquad (11)$$

$$Q_1 - Q_2 - (V_1/B)\, dP_1/dt = 0 \qquad (12)$$

$$Q_2 + Q_3 - Q_4 - a_1\, dy/dt - (V_2/B)\, dP_2/dt = 0 \qquad (13)$$

$$A\, dx/dt - Q_3 - [(V_3 - Ax)/B]\, dP_3/dt = 0 \qquad (14)$$

$$m_s\, d^2x/dt^2 + f_2\, dx/dt + K_2(x + x_o) = (P - P_3)A - F_s + F_{Rs} \qquad (15)$$

$$m_p\, d^2y/dt^2 + f_1\, dy/dt + K_1(y + y_o) = (P_2 - P_T)a_1 - F_p + F_{Rp} \quad (16)$$

$$F_s = \rho Q^2 \sin(\beta)/(C_{c1}\, a) \quad (17)$$

$$F_p = \rho\, Q_4^2 \cos(\alpha)/(C_{c2}\, a_2) \quad (18)$$

$$F_{Rs} = \begin{cases} 0 & \text{for } x \geq 0 \\ K_R\, x + f_R\, dx/dt & \text{for } x < 0 \end{cases} \quad (19)$$

$$F_{Rp} = \begin{cases} 0 & \text{for } y \geq 0 \\ K_R\, y + f_R\, dy/dt & \text{for } y < 0 \end{cases} \quad (20)$$

VALVE SIMULATION

This study is applied to the pilot operated hydraulic relief valve type DB 30/10/315 produced by REXROTH, Germany [5]. A summery of the numerical parameters of the valve is given in the following.

K_1 = 290000 N/m	K_2 =11500N/m
d_p = 5 mm	D = 22 mm
α = 26°	β = 60°
m_s = 0.014 kg	m_p= 0.07 kg
d_1 = 1.1 mm	d_2= 0.75 mm
d_3 = 1.1 mm	P_{max} up to 315 bar

The theoretical analysis of the valve static and dynamic behavior is carried out by simulating its function using the TUTSIM simulation program,[6]&[7]. The simulation by this program includes the representation of the governing equations in the form of a block diagram using the TUTSIM mathematical operator blocks. The developed block diagram is presented in Fig.3.

ANALYSIS OF RESULTS

The steady state relation between the relief flow and the input pressure of the main stage and the pilot operated relief valve is evaluated experimentally and predicted theoretically using the simulation program. Figure 4 shows the results of the static characteristics investigations. This figure shows a good agreement between the theoretical and experimental results. The main stage presents constant relief pressure of about 0.4 MPa. A relatively small override pressure is observed in the pilot operated valve characteristics.

The transient response of the pressure at the valve inlet chamber to sudden closure of the exit throttle valve is predicted using the simulation program for different values of the preset relief pressure. The predicted transient response is plotted in Fig 5(a). The transient response of the main poppet displacement at the same conditions is also calculated and the results are plotted in Fig. 5(b). These results show the nonlinear behavior of the valve. The valve presents shorter settling time for higher preset relief pressures associated with transient oscillations in the pressure

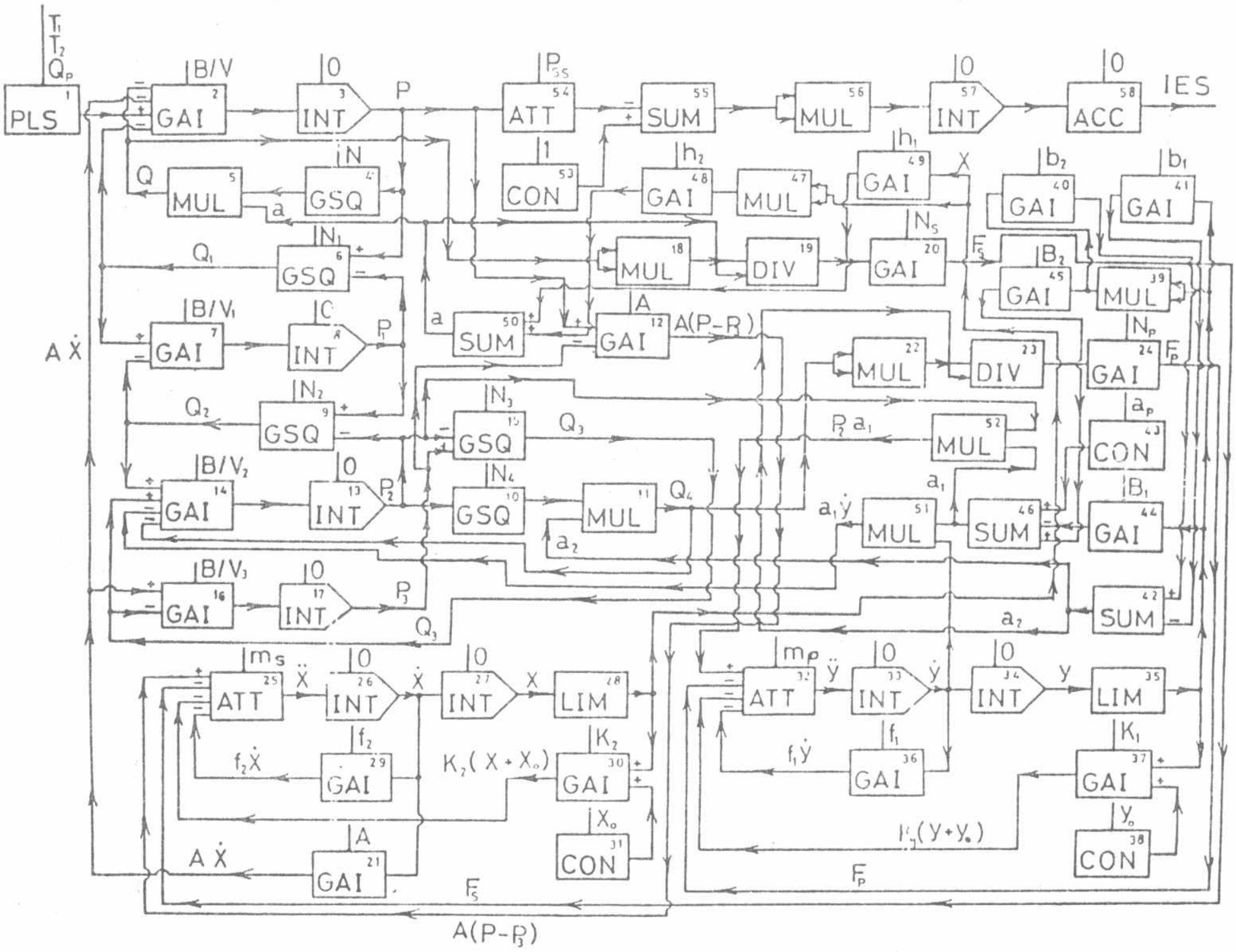
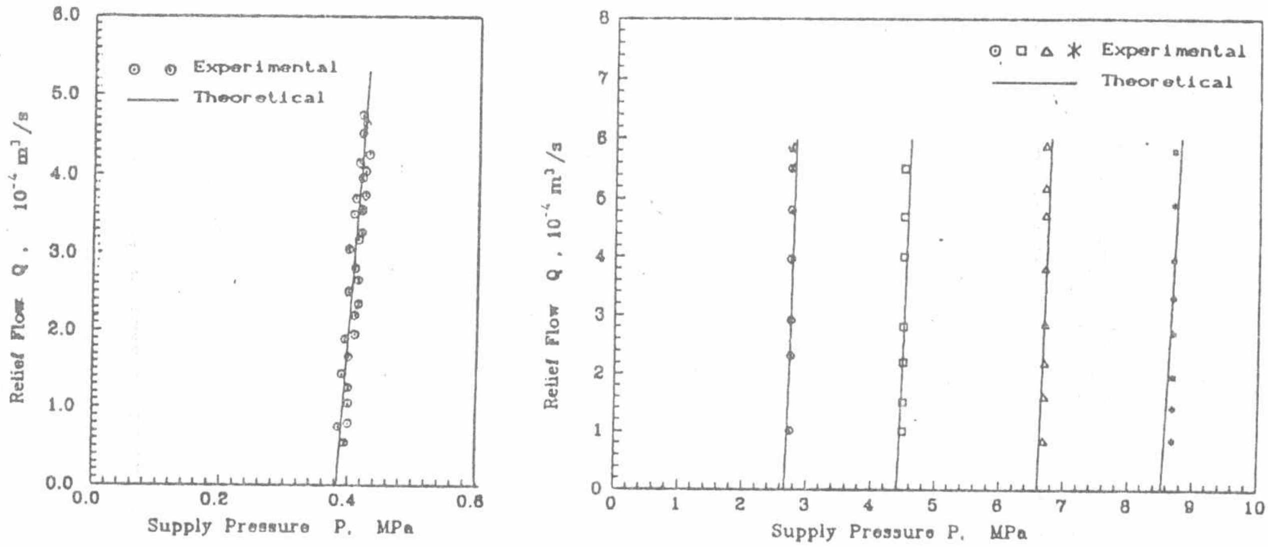


Fig.3. TUTSIM block diagram of the studied pilot operated hydraulic relief valve.



(a) Main poppet valve.

(b) Pilot operated relief valve.

Fig.4. Steady state relation between the inlet pressure and flow rate.

and main poppet displacement. For small values of the relief pressure, considerable percentage overshoot appears associated with longer settling time.

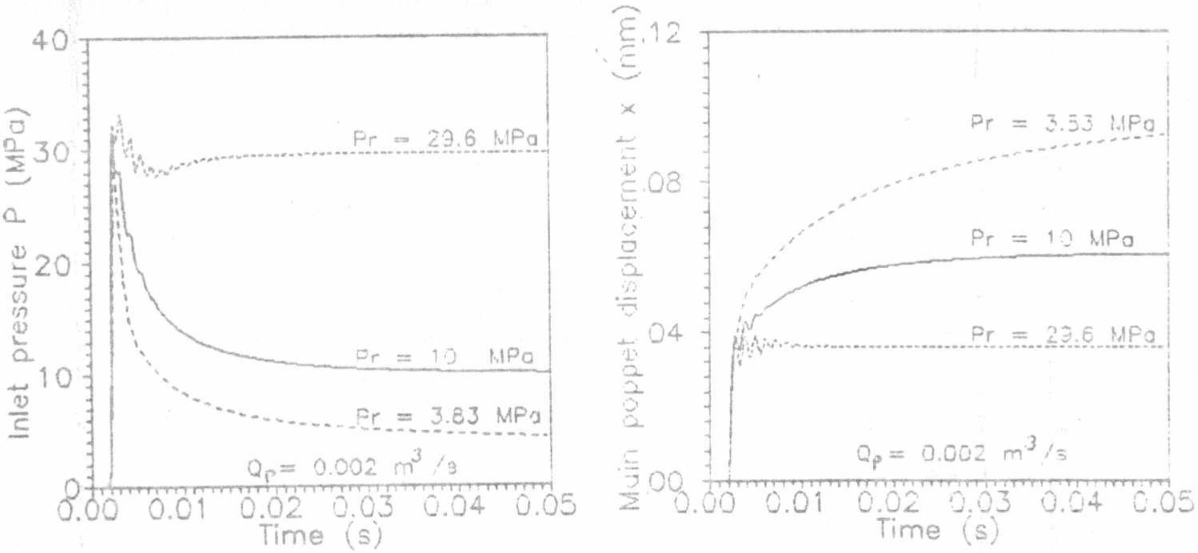


Fig.5.Transient response of the inlet pressure and main poppet displacement to sudden closure of the exit throttle valve.

In the previous analysis, the effect of the fluid compressibility in the connecting hydraulic line is not taken into consideration. Only the effect of the small volume of oil (10 cm^3) at the valve inlet chamber is considered, which explains the observed shorter time of response and the high percentage overshoot. Usually, the effect of the transmission line is considered separately when studying a system behaviour. But the response of the relief valve is highly affected by the volume of fluid in the inlet chamber. Therefore, the valve transient response to sudden closure of the throttle valve is calculated considering different values of inlet chamber volume. Figure 6 shows the calculation results considering a relief pressure of 10 MPa and a constant pump flow rate of 0.002 m^3/s. This figure shows that the increase of the inlet volume decreases the maximum percentage overshoot and increases the settling and rise times.

The first two damping orifices;(1 & 2 ,Fig.1) affect both of the static and dynamic behavior of the valve, while the third orifice has its effect only on the valve dynamic behavior. These orifices can be sized to give the best valve response, according to a selected criterion. When changing the diameters of the first and third orifices, an observable improvement of the response appears. The transient response of the valve pressure and main poppet displacement, with the valve equipped with the original and the proposed orifices, is calculated and presented in Fig.7. The valve time of response is not practically affected by this variation in the orifices dimensions while the transient oscillations are rapidly damped.

The developed simulation program can be used for further investigations concerning the effect of the valve transient behavior of the overall system performance. More analysis of the effect of the valve constructional and operational parameters on the valve behavior can be also carried out.

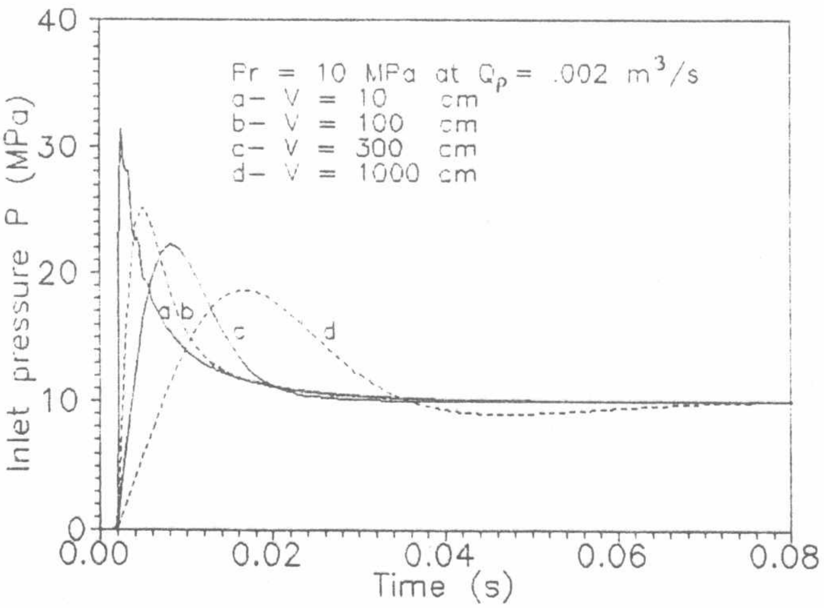


Fig.6. Effect of the volume of the valve inlet chamber on its transient response to sudden closure of the exit throttle valve.

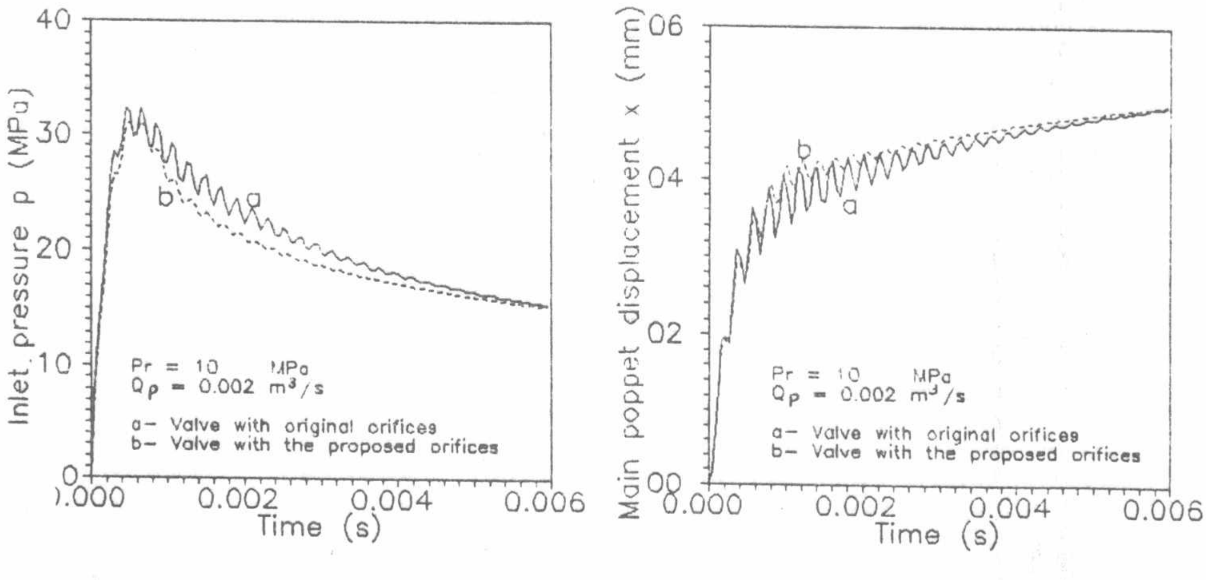


Fig.7. Effect of the damping orifices diameters on the transient response of the main poppet displacement and inlet pressure.

CONCLUSION

This paper deals with the evaluation of the static and dynamic characteristics of a pilot operated hydraulic pressure relief valve. A nonlinear mathematical model is developed for the valve. The deduced model is applied to simulate the valve using a digital simulation program. The proposed model is validated in the steady state by comparing simulation and experimental results. The transient response of the valve, predicted by using the simulation program, pointed out the nonlinear character of the studied relief valve. By increasing the volume of oil at the valve inlet chamber, considering the effect of oil compressibility in connected hydraulic lines, a remarkable reduction in the maximum percentage overshoot is observed, associated with an increase in the response time. The transient pressure oscillations could be improved by the correct sizing of the damping orifices.

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