INVESTIGATION OF PERFORMANCE OF A DIRECT OPERATED HYDRAULIC PRESSURE REDUCER, APPROACH BY BLOCK BOND GRAPH

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ABSTRACT

The steady state and transient behaviour of a direct-operated hydraulic pressure reducer of spool type is investigated herein. The studied valve is equipped with a relief arrangement limiting the maximum pressure in the exit port. A block bond graph of the valve is developed, taking into account the nonlinear relations describing the basic elements. The simulation is carried out, on the basis of the bond graph, using the TUTSIM simulation program. The steady state behaviour of the pressure reducer is evaluated experimentally and compared with simulation results. The transient response of the valve, when operating as a reducer or as a relief valve is predicted theoretically, presented and discussed.

NOMENCLATURE

A_i Inlet throttling area, m^2.
A_o Damping orifice area, m^2.
A_r Relief restriction area, m^2.
A_s Inner spool area, m^2.
A_t Exit throttle area, m^2.
B Bulk modulus of oil, Pa.
C Capacitance.
C_d Discharge coefficient,-.
C_{14} Hydraulic capacitance, m^3/Pa.
d_s Inner spool diameter, m.
D Spool diameter, m.
D_o Damping orifice diameter, m.
I Inertia.
k Spring stiffness, N/m.
P_e Exit pressure, P_a.
P_{ess} Steady state exit pressure, P_a.
P_i Inlet pressure, P_a.
P_n Exit pressure at zero flow,P_a.
P_s Pressure in the spool inner chamber, P_a.
P_t Return pressure, P_a.
Q_e Exit flow, m^3/s.
Q_i Input flow, m^3/s.
Q_l Leakage flow from the inner spool chamber, m^3/s.
Q_r Relief flow, m^3/s.
Q_s Flow through damping orifice, m^3/s.
R Resistance.
SE Source of effort.
t time, s.
TF Transformer.
V_s Volume of spool inner chamber, m^3.
X Spool displacement, m.
X_o Initial spring compression distance, m.
ρ Density of oil, kg/m^3.

INTRODUCTION

Nowadays, the hydraulic and electrohydraulic systems play an indispensable role in the engineering field. They are widely applied for power transmission and control of both industrial machines and aerospace vehicles. The performance of these systems should satisfy strict requirements during the transient and steady state modes of operation, due to the required (high) precision and stability.

These systems operate in transient condition most of the time. Therefore, a special effort should be paid to investigate their dynamic behaviour. This investigation is usually based upon a detailed study of the performance of their basic components, mainly the control valves, transmission lines and motors.

There are three main groups of valves controlling the pressure, flow rate and direction. Among the pressure control valves, one can distinguish the pressure reducers, designed to deliver oil at reduced pressure, corresponding to their exit flow rate.

This paper deals with the study of the static and dynamic characteristics of a direct-operated pressure reducer of spool type. The studied valve acts also as a relief valve limiting the maximum pressure in the exit line. The study of such element is usually based upon the development of a mathematical model describing the studied valve and the numerical solution of this model by means of a computer simulation program {1}. In the last decade, the bond graph is widely applied as an alternative method for dynamic systems' modelling, replacing the mathematical relations and their pictorial representation {2}&{3}. From the bond graph, a set of linear differential and algebraic equations, describing the system can be deduced systematically. These equations are obtained in the form of assignment statements convenient for many of the known computer simulation programs. But when using the TUTSIM program, there is no need for the deduction of any equations, as it accepts the bond graph as a structure entry.

In the case of nonlinear systems, the nonlinear relations can be introduced in the bond graph by the addition of convenient TUTSIM functional blocks. The resulting graph, called block bond graph{5}, together with the TUTSIM program represent a powerful tool for the simulation of the nonlinear dynamic system {6}. Herein, a block bond graph of the pressure reducer is developed and used to simulate the valve by the TUTSIM simulation program. The static behaviour of the valve is evaluated theoretically and experimentally. The transient characteristics of the valve are investigated on the basis of simulation results.

Description of the Studied Valve

The studied pressure reducer is drawn schematically in Figure (1).

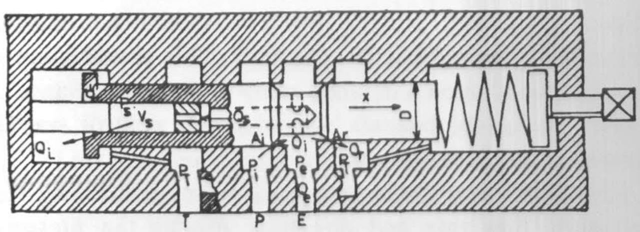

Figure 1. Scheme of the pressure reducer

The high pressure oil is fed to the valve through the input port P, and the oil at reduced pressure exits through the port E. If the pressure in the line E is lower than the preset valve, the spool displaces to the left allowing the oil at higher pressure to flow to the valve exit. When reaching the required reduced pressure, it acts on the spool in the direction to close partially the area A_i, keeping the pressure P_e constant. If this pressure continues to increase, due to an increase in the load of the driven motor, the spool displaces further to the right closing A_i and connecting the exit line to tank; relief operation.

In this study, the external load is represented by a throttling element of area A_t , Figure (2).

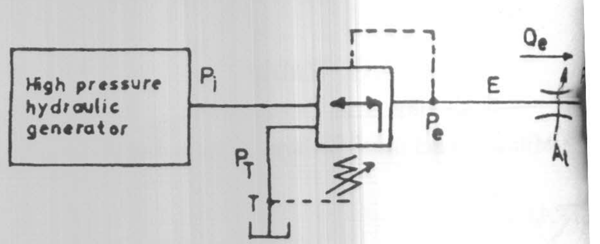

Figure 2. Connection of the pressure reducer.

Bond Graph Of The Valve

Figure (3) shows the bond graph developed to desc the function of the pressure reducer. In this graph, energy dissipating effect of valve restrictions of areas and A_r as well as that of spool radial clearance introduced by the resistors R(2) and R(9). These resist are modulated by the spool displacement x to introduce effect on the throttling areas. The resistance R represents the effect of the exit throttle valve. T pressures P_i, P_l and P_t are imposed by the sources effort SE (1), (10) and (11). The effect of fl compressibility in the exit line is represented by capacitor C(4) while that of the spool central chambe considered by the modulated capacitance C (14).

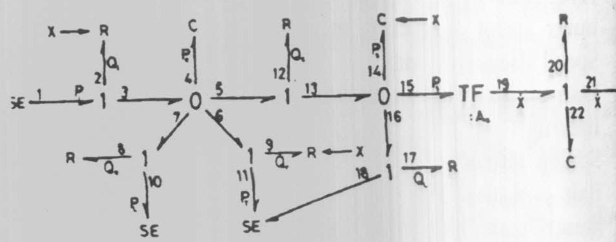

Figure 3. Bound graph of the pressure reducer.

The resistance R(12) and R(17) represent the dam orifice and the resistance to radial clearance leakage.

The transformation of hydraulic power to mechar power needed for the spool motion is ensured by transformer TF (15). The inertia of the moving spring stiffness and viscous friction are represented b elements I(21), C (22) and R (20).

The jet reaction forces are found to be of no signifi effects on the valve behaviour, therefore these forces neglected.

Assuming that the return pressure is null, the bond and 18 can be eliminated as they transmit zero po Then by the assignment of causality, one gets augmented bond graph in Figure (4).

This bond graph can be applied directly for the simulation of the valve, assuming linear relations.

$$Q_i = A_i(x)\sqrt{(P_i - P_e)/(\rho/2C_d^2)} \qquad (1)$$

$$Q_e = A_t \sqrt{(P_e - P_L)/(\rho/2C_d^2)} \qquad (2)$$

$$Q_r = A_r(x)\sqrt{P_e/(\rho/2C_d^2)} \qquad (3)$$

$$Q_s = \sqrt{(P_e - P_s)/(\rho/2C_d^2 A_o^2)} \qquad (4)$$

$$P_s = \frac{B}{(V_s + A_s x)} \int \left(Q_s - Q_L - A_s \frac{dx}{dt} \right) dt \qquad (5)$$

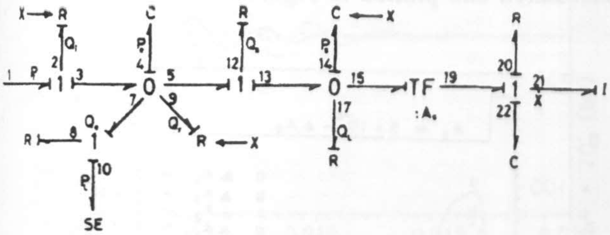

Figure 4. Augmented bound graph of the pressure reducer.

The spool radial clearance is taken into consideration when calculating the nonlinear dependence of areas A_i and A_r on the spool displacement x. The block bond graph of the valve, Figure (5), is obtained by introducing equations 1 to 5 in the augmented bond graph using the convenient TUTSIM functional blocks.

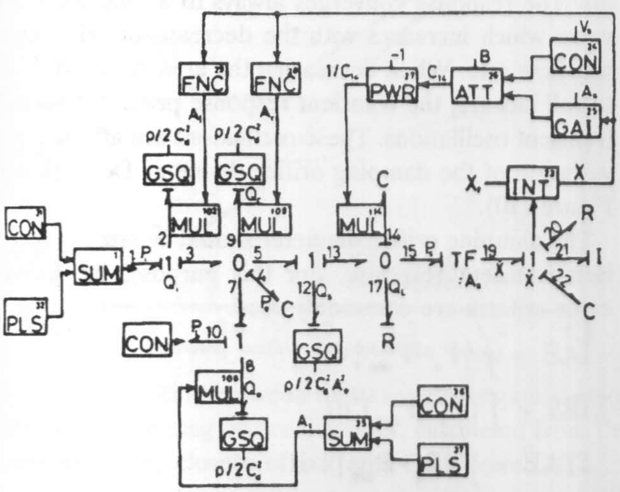

Figure 5. Block bound graph of the pressure reducer.

Simulation Of The Valve

This study is applied to the pressure reducer type DR10DP produced by Rexroth, Germany, having the following specifications:

Maximum input pressure	=	31,5	MPa
Maximum exit pressure	=	21	MPa
Maximum drain pressure	=	15	MPa
Maximum flow rate	=	50	L/min

The parameters of the valves are found in the producer's data sheets {7} and by direct measurements of the real valve parts.

The simulation is carried out using the TUTSIM program on the basis of the block bond graph. The developed simulation program is given in appendix A.

SIMULATION RESULTS

1- *Static Characteristics Of The Valve*

The steady state performance of the valve has been predicted by the simulation program, mainly the effect of load flow Q_e and input pressure P_i on the exit pressure and the performance of the valve when operating as a pressure relief valve.

Effect of the load flow on the exit pressure

The relation between the load flow and exit reduced pressure has been evaluated theoretically and experimentally. The results are plotted in Figure (6), which shows a good agreement between them. This figure shows also that the exit pressure changes considerably with the exit flow.

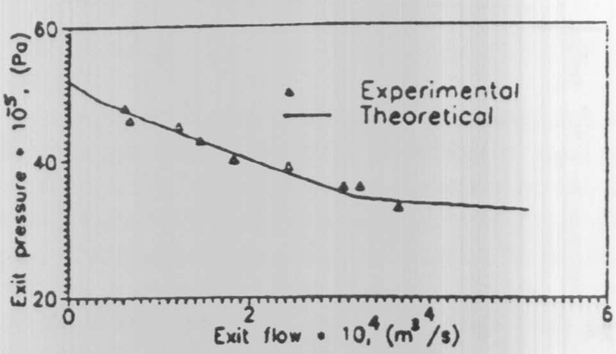

Figure 6. Effect of the exit flow on the exit pressure when $P_i = 10$ MPa, $P_n = 5{,}2$ MPa& $P_L = P_t = 0$

Effect of the inlet pressure

The effect of variation of input pressure P_i on the valve exit pressure P_e is calculated for two different valves of exit area A_t. Figure (7) gives the results of these calculations. For input pressures higher than the no flow preset reduced pressure P_n, the variation of exit pressure is about 10% of input pressure change.

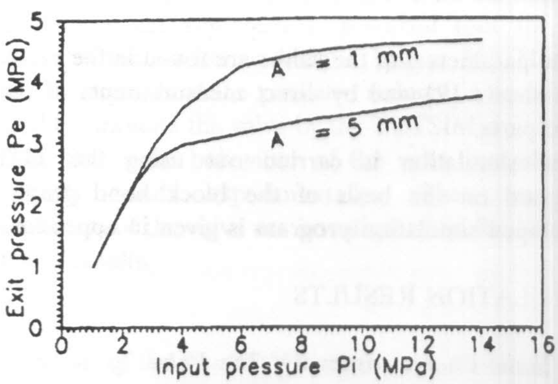

Figure 7. Effect of input pressure on the exit pressure for different throttle valve openings. $P_n = 5$ MP_a, $P_t = P_l = 0$.

Static Characteristics of the relief valve

Increasing the load pressure P_l, Figure (2) due to excessive motor loads for example, may lead to the increase of exit pressure P_e to valves greater than the no load flow P_n. In this case, the valve operates as a relief valve. The effect of increase of P_e on the relieved flow rate is calculated. This relation is plotted in Figure (8), which shows that the relief valve presents a permanent leakage of about 1 L/min.

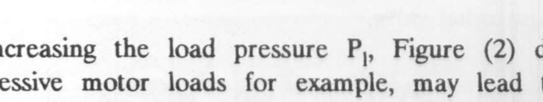

Figure 8. Static characteristics of relief arrangement $P_i = 10$ MP_a, $P_n = 5$ MP_a and $P_t = 0$

The relief pressure is about 7.5 MP_a; 2.5 MP_a h than the preset no-flow pressure P_n. This diffe depends on the spool dimensions and spring stiffnes can not be changed by any adjustment. It is also impo to point out the non negligible over-ride pressure, a 1,3 MP_a at $Q_r = 18$ L/min.

2- Transient Response of the Valve

Transient response of the pressure reducer

The transient response of the valve to step variatio exit orifice area of different magnitudes has b calculated and plotted in Figure (9).

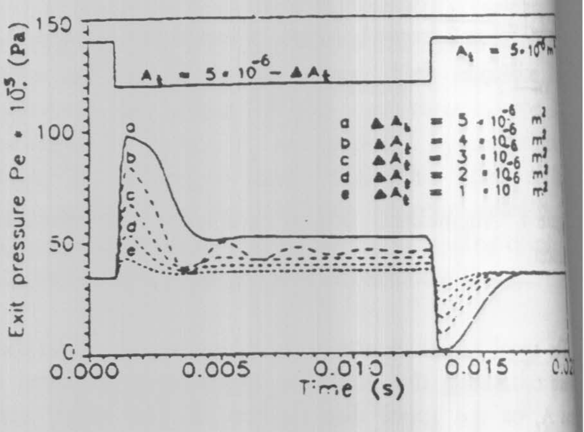

Figure 9. Transient response of the pressure reducer step variation of exit orifice area. $P_i = 10$ MP_a, $P_n = 5$ MP & $P_l = P_t = 0$.

The settling time of the transient response is less than ms. The response converges always to a final steady sta value which increases with the decrease of exit area a exit flow rate. When decreasing the area A_t to values ne to full closure, the transient response presents observa transient oscillations. These oscillations are affected by variation of the damping orifice diameter Do as shown Figure (10).

The damping orifice diameter should be sized to give best transient response. For this purpose, the follow error criteria are commonly used.

$$IAE = \int |P_e - P_{ess}| \, dt$$

$$IES = \int (P_e - P_{ess})^2 dt$$

$$ITAE = \int |P_e - P_{ess}| \, t \, dt$$

The optimum value of diameter Do is that w minimizes the chosen error criterion. The relation between each of the three error criteria and diameter Do, is calculated and plotted Figure (11). This figure shows that the optimum value of Do lies in the range 0,65mm ≤ Do ≤ 0,95mm. The studied commercial valve has a damping orifice of 0,75 mm diameter.

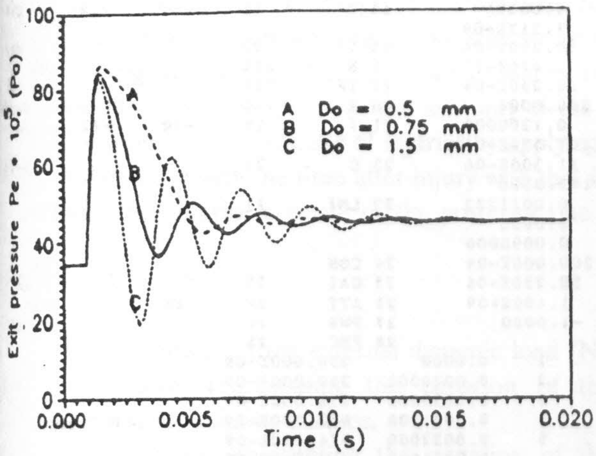

Figure 10. Transient response of the pressure reducer to sudden variation of exit orifice area from 5mm^2 to 1mm^2 for different values of damping orifice diameter.

$P_i = 10MP_a$, $P_n = 5MP_a$ & $P_t = P_l = 0$

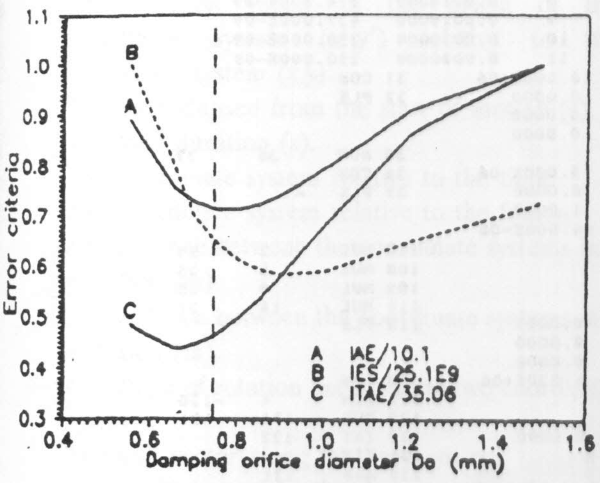

Figure 11. Realtion between the transient response error criteria and damping orifice diameter, calculated from the response to step closure of exit area from 5mm^2 at:

$P_i = 10MP_a$, $P_n = 5MP_a$ & $P_L = P_t = 0$

Transient response of the relief arrangement

When increasing the load pressure P_L, the exit line is protected by the valve relief arrangement. The transient response of the valve to step variation of pressure P_L of different magnitudes is calculated and plotted in Figure (12).

The transient response presents considerable overshoot which reaches the value of the applied P_L step. The duration of this great overshoot is very small. In the case if this time is considerably long, the valve is to be equipped with a check valve allowing the exit line to discharge in the inlet one. A flat part is seen at the maximum overshoot. This corresponds to the time period during which the spool is moving in the overlapping zone. In this zone, the exit line is not connected neither to the pressure nor to the return lines. The settling time of the relief valve response is about 5ms.

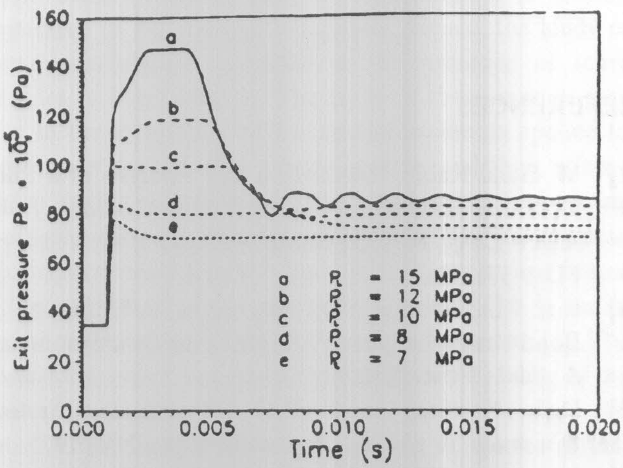

Figure 12. Transient response of the relief arrangement to step increase in the load pressure P_1 at $P_i = 10$ MP_a, $P_n = 5mp_a$, $P_t = 0$ andA_t $5mm_2$.

CONCLUSION

In this paper, the static and dynamic characteristics of a direct operated hydraulic pressure reducer of spool type are studied. This valve operates as a pressure reducer and a relief valve at the same time. A block bond graph of the valve is developed taking into consideration the nonlinear relations describing the valve elements. The simulation is carried out by the exploitation of the block bond graph using the TUTSIM simulation program

The static behaviour of the valve has been evaluated theoretically and showed a good agreement with experimental results. The investigation of the valve static characteristics pointed the following results

- The exit pressure drops considerably below the preset no-flow pressure with the increase of the load flow.
- The variation of input pressure has a significant effect on the valve of exit reduced pressure.
- A permanent leakage exists due to the spool radial clearance.
- The relief arrangement presents an important over-ride pressure.
- The pressure reducer presents a transient response of about 5 ms settling time with considerable overshoot.
- The relief arrangement presents a short time of response with great overshoot equalling the applied load pressure during most of the transient period.
- The valve delivers the oil at a nearly constant exit pressure only when the inlet pressure and exit flow are kept within a narrow zone of variation.

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[7] Rexroth Data Sheet RE26581, Mannes mann Rexroth, Germany, April 1985, pp 1-4.

Appendix A

TUTSIM program simulating the hydraulic pressure reducer

```
                 1 SUM     31     32          ;Pi
 1.161E+03       2 GSQ      1     -4          ;Qi/A
 7.000E-15       4 C      102   -109    -12   ;Pe
                         -108
 3.457E+06
 1.161E+03       8 GSQ      4   -115          ;Qe/A
 1.161E+03       9 GSQ      4                 ;Qr/A
 2.868E+15      12 GSQ      4   -114          ;Qs
 1.0000         14 C       12    -17    -15   ;Ps C
 1.317E-09
 50.250E-06     15 TF      21                 ;As
 1.870E-15      17 R      114                 ;QL
 50.250E-06     19 TF     114                 ;Ps A
200.0000        20 R       21                 ;f dx
 0.1200000      21 I       19    -20    -22   ;dx/dt
107.556E-06
 11.300E-06     22 C       21                 ;k(x
173.3320
 0.0011233      23 LMI     21                 ;x
 0.0000
 0.0090000
500.000E-09     24 CON                        ;Vs
 50.250E-06     25 GAI     23                 ;x A
 1.400E+09      26 ATT     24     25          ;C14
 -1.0000        27 PWR     26                 ;1/C
                28 FNC     23
   1    0.0000       250.000E-09
   2    0.0029000    250.000E-09
   3    0.0030000    250.000E-09
   4    0.0031000    437.700E-09
   5    0.0032000    874.800E-09
   6    0.0036000      2.619E-06
   7    0.0040000      4.335E-06
   8    0.0041000      6.620E-06
   9    0.0042000     10.500E-06
  10    0.0050000     50.200E-06
  11    0.0080000    200.000E-06
                29 FNC     23
   1   -0.0010000    100.500E-06
   2    0.0000        50.190E-06
   3  600.000E-06     20.660E-06
   4  800.000E-06     10.900E-06
   5  900.000E-06      6.620E-06
   6    0.0010000      4.340E-06
   7    0.0014000      2.620E-06
   8    0.0018000    874.800E-09
   9    0.0019000    437.000E-09
  10    0.0020000    250.000E-09
  11    0.0090000    250.000E-09
 10.000E+06     31 CON
 0.0000         32 PLS
 0.0000
 0.0000
                35 SUM     36     37          ;At
 5.000E-06      36 CON
 0.0000         37 PLS
 1.0000
 -4.000E-06
               102 MUL      2     29          ;Qi
               108 MUL      8     35          ;Qe
               109 MUL      9     28          ;Qr
               114 MUL     14     27          ;Ps
 0.0000        115 PLS                        ;Pl
 0.0000
 0.0000
 4.530E+06     120 CON                        ;Pe
               121 SUM      4   -120          ;Pe-
               122 MUL    121    121    124
 0.0000        123 INT    122                 ;IT
               124 TIM
               125 ABS    121
 0.0000        126 INT    125                 ;IA
               127 MUL    121    121
 0.0000        128 INT    127                 ;I
```