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BOND GRAPH MODEL AND INVESTIGATION OF DYNAMICS OF A CLASS OF HYDRAULIC FLOW CONTROL VALVES

S.A.KASSEM*, G.RABIE**

ABSTRACT

Using bond graph, a model is developed for two-way pressure compensated flow control valves with pressure balancing stage perior to the throttling section. The model, which carries the physical and mathematical structures of the valve, is in a ready form to be interconnected to models of other components to get the bond graph for a global system incorporating the valve. Equations governing the valve dynamic behaviour are obtained from the bond graph in the form of assignment statements. Simulation is realized on digital computer to investigate the valve transient response to step load-pressure variation, when the valve is used in a hydraulic circuit of a meter-in mode of speed control. Results showed that at low values of resistance of the passage connecting the load to the spring chamber of compensator, the response is of high initial load flow overshoot that decreases rapidly to the steady state value. At higher resistances, initial overshoot is reduced and the response is slower and of oscillatory nature.

INTRODUCTION

Electro-hydromechanical control systems are characterised by the great number of components and subsystems composing them. Energy and information carrying media in these cases belong to different fields. Generally, the mathematical models of these systems include great number of equations and it is, in many cases, hard to determine whether it is possible to solve the obtained set of equations, in order to proceed towards system simulation, or not. The representation of the equations in a convenient pictorial form, such as a block diagram or a signal flow graph, is useful in this respect and would simplify system simulation. However, a slight modification in the studied system will necessitate repeating the whole process of derivation of equations and construction of the pictorial representation. Other techniques for modelling of systems are available. The system graph method, the method of resistances [1-4] , and the bond graph [5-9] prove to be another powerful techniques for modelling multi-port systems.

In this paper, bond graph is used to develop a model for the two-way pressure

*Associate Professor, Mechanical Design Dept., Faculty of Engineering, Cairo University, Cairo, Egypt. ** Col. Dr., Military Research Authority, Cairo, Egypt.

compensated flow control valve shown in Fig.1, which is used to admit constant flow rate irrespective to load or supply pressure variation. Simulation of the valve is realized by the exploitation of equations obtained from the bond graph by a digital computer.

Static characteristics of this class of valves are shown in [10] to yield nearly constant flow rate when the compensator spring and control port area are properly chosen. Experimental determination of a commercial valve transient response to step variation of load pressure is also quoted in [10] and shows that the flow rate exhibits overshoots and damped oscillations during the transient period.

VALVE BOND GRAPH MODEL

The bond graph technique is based on the fundamental physical considerations of energy supply, storage, dissipation, and exchange. The function of any system can be described in this technique in terms of four generalized variables; effort, flow, generalized momentum, and generalized displacement. The system is to be divided into basic simple elements, that exchange energy through identified bonds.

The bond graph model for the studied valve is shown in Fig. 2, and is developed under the following assumptions:

1. flow forces acting on the spool are neglected.
2. connecting lines within the valve are of negligible compliance and resistance to acceleration.
3. intrenal leakage across spool lands is negligible.

In the shown model, pressures p_1 and p_3 are imposed by the two sources of effort SE. The resistance of the compensator throttling section is R_2. Capacitances due to fluid compressibility in the volumes V_a, V_b, and V_c are C_{17}, C_{10}, and C_4, respectively. The spring is represented by the capacitance C_{14}. The spool inertia and viscous damping resistance are I_{12} and R_{13}. Transformation of hydraulic energy into mechanical one at the spool is ensured by the transfer elements TF. Resistance R_2 and capacitances C_{10} and C_{17} are modulated by the spool displacement x.

The valve is generally incorporated with other components in a global system. The bond graph model shown can be interconnected in this case through the bond 1 to the bond graph model of the preceeding component, and through the bond 22 to the subsequent one.

While in many practical cases neither the resistance R_i nore the resistance R_o are of appreciable values, and the bond graph is much simplified by ignoring them, investigation of valve dynamics will be carried out when R_i is present.

When p_3 is expected to be constant, the resistance R_i might be eleminated. The bond graph shown in Fig. 2 can be modified in this case by eleminating the bond 20. Further, the compressibility of fluid in the volume V_a is nill and the capacitance C_{17} can be omitted too. The resulting bond graph is thus as shown in Fig. 3 .

The other case of eleminating R_o would result in the bond graph shown in Fig. 4 , which is obtained by cancelling the bond 7 . The two capacitances

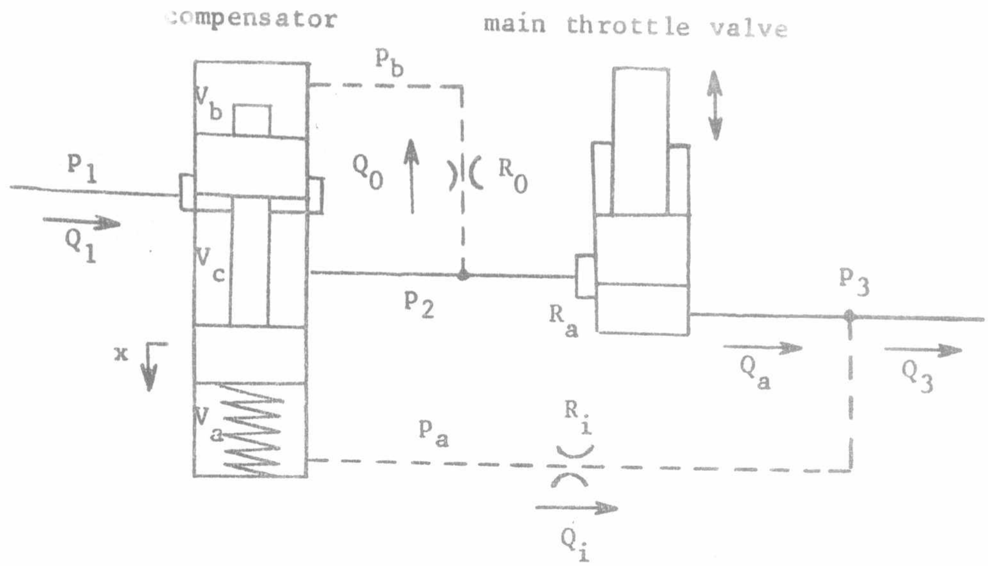

Fig.1. Layout of two-way pressure compensated flow control valve

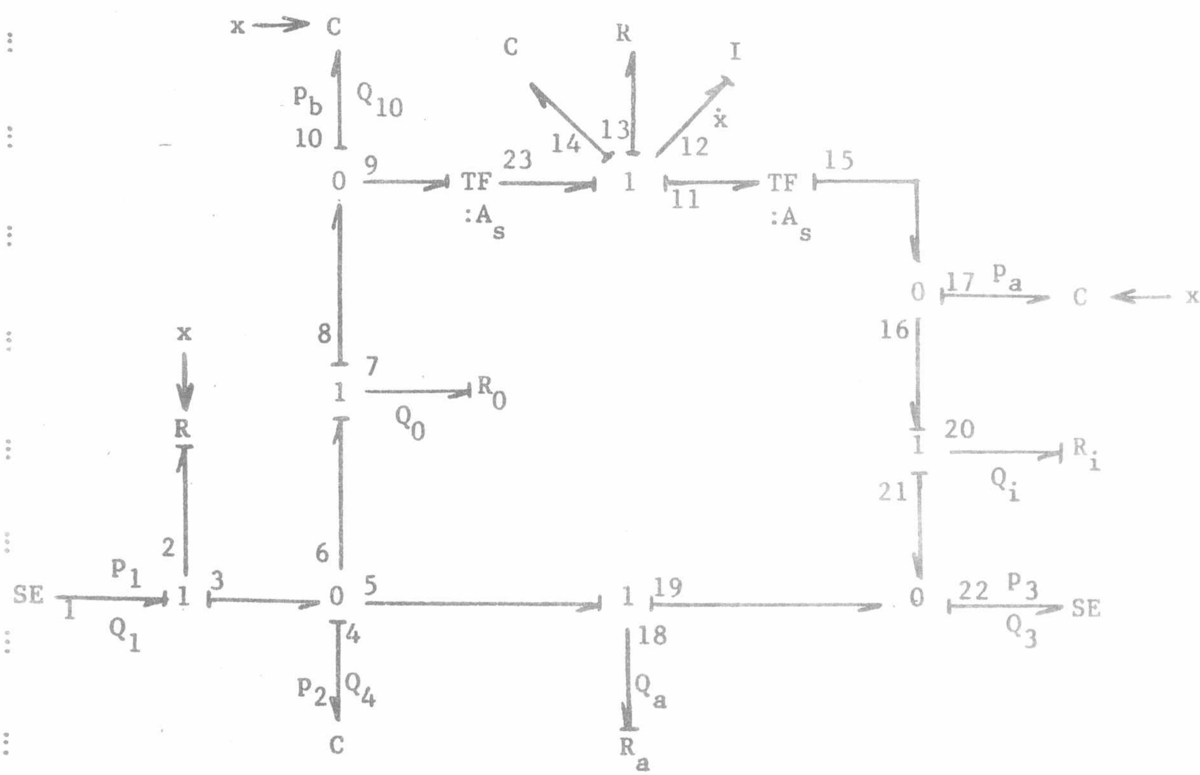

Fig.2. Bond graph model of the valve

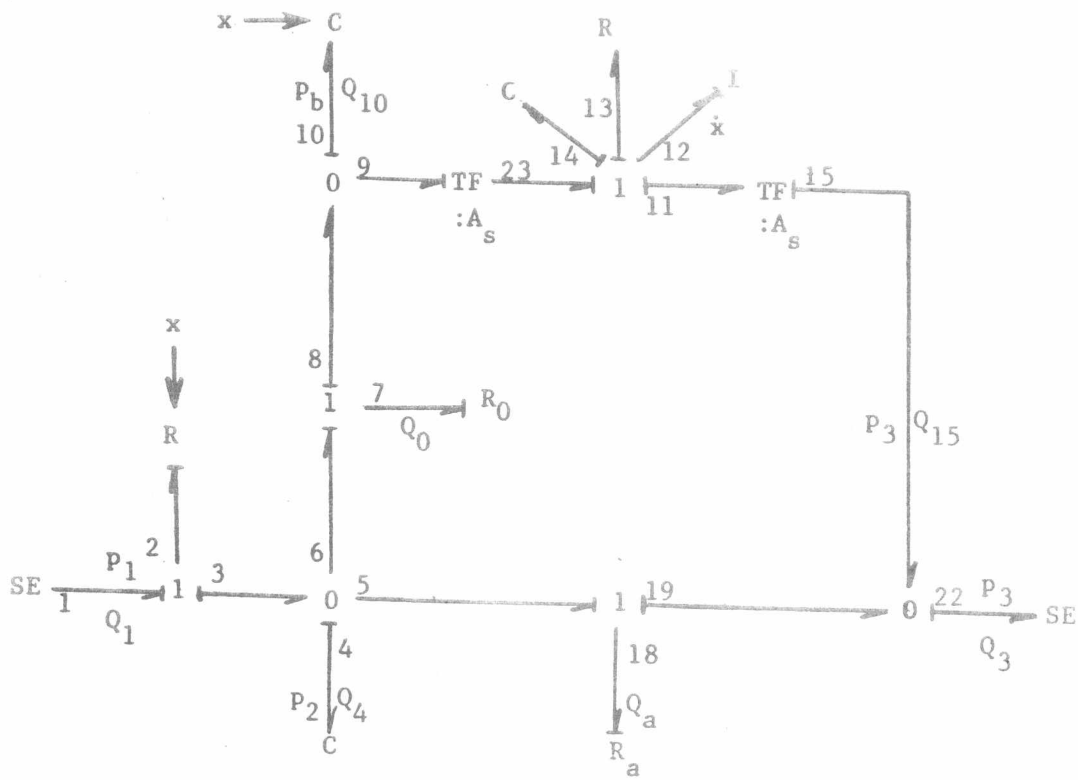

Fig.3. Bond graph model of the valve without the resistance R_i

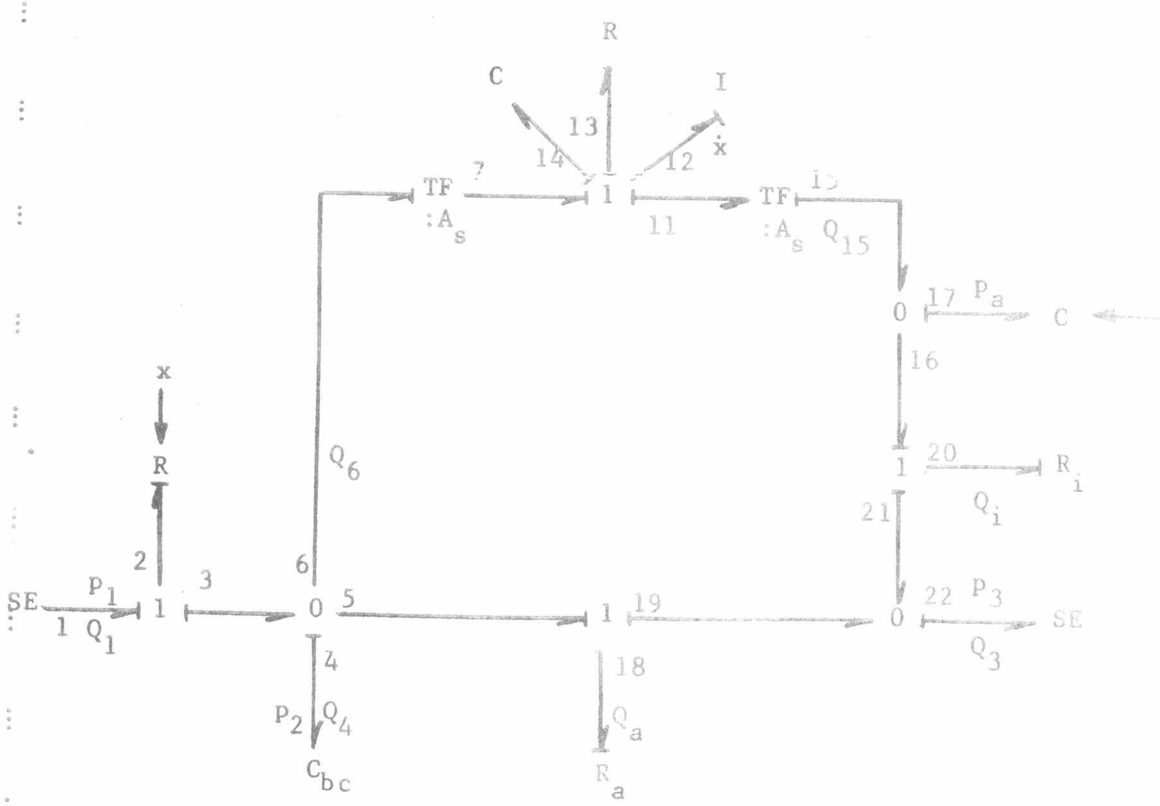

Fig.4. Bond graph model of the valve without the resistance R_0

C_4 and C_{10} are thus connected in parallel by the junction 0 and can be replaced by an equivalent capacitance $C_{bc} = C_4 + C_{10}$. The governing equations as obtained from the bond graph, in this case, are :

$$e_2 = p_1 - p_2 \quad , \quad Q_1 = C_{d1}\pi\, d(x_i - x)\sqrt{\tfrac{2}{\rho}|e_2|}\,\text{sign}(e_2) \quad ,$$

$$Q_4 = Q_1 - Q_a - Q_6 \quad , \quad p_2 = p_2(0) + \frac{1}{C_{bc}}\int Q_4\, dt \quad ,$$

$$Q_6 = A_s\dot{x} \quad , \quad e_7 = A_s p_2 \quad ,$$

$$e_{13} = R_{13}\,\dot{x} \quad , \quad e_{14} = e_{14}(0) + \frac{1}{C_{14}}\int \dot{x}\, dt \quad ,$$

$$e_{11} = A_s p_a \quad , \quad \dot{x} = \dot{x}(0) + \frac{1}{I}\int e_{12}\, dt \quad ,$$

$$x = x(0) + \int \dot{x}\, dt \quad , \quad Q_{15} = A_s\dot{x} \quad ,$$

$$e_{12} = e_7 - e_{11} - e_{13} - e_{14} \quad , \quad Q_{17} = Q_{15} - Q_i \quad ,$$

$$p_a = p_a(0) + \frac{1}{C_{17}}\int Q_{17}\, dt \quad , \quad e_{20} = p_a - p_3 \quad ,$$

$$Q_i = \frac{1}{R_i}\sqrt{|e_{20}|}\,\text{sign}(e_{20}) \quad , \quad e_{18} = p_2 - p_3 \quad ,$$

$$Q_a = C_{da}\, wy\sqrt{\tfrac{2}{\rho}|e_{18}|}\,\text{sign}(e_{18}) \quad , \quad Q_3 = Q_a + Q_i$$

where,

$$C_{bc} = \beta\,(V_b + V_c + A_s x)\ , \quad C_{14} = \frac{1}{K}\ , \quad \text{and } C_{17} = \beta\,(V_a - A_s x)$$

VALVE DYNAMICS

The dynamic performance of the valve can be obtained theoretically by solving the set of governing equations simultaneously, provided that the valve parameters and initial conditions are known. Solution is carried out on a digital computer, for the case in which the valve is used in a hydraulic circuit with meter-in mode of speed control. In this case the inlet pressure p_1 is maintained constant at the value preset at the relief valve, while the outlet pressure p_3 might vary as it depends on the external load. The model shown in Fig. 4 represents this case, and the above equations govern the valve dynamic behaviour. Possible improvement of valve transient response to step variations in p_3 is investigated, by studying the effect of the resistant R_i on the response. The variation of R_i can be achieved in practice by changing the diameter of the connecting passage or inserting a fixed throttle in it.

Governing equations can be reduced to dimensionless form by introducing the following reference quantities;

$$L_r = y\ ,\ p_r = p_1\ ,\ Q_r = C_{d1}\pi\, d\, x_i(2p_1/\rho)^{\frac{1}{2}}\ ,\ t_r = 1\text{ ms}\ ,\ A_r = Q_r t_r/L_r\ ,$$

$$R_r = p_r/Q_r^2\ ,\ C_r = Q_r t_r/p_r\ ,\ I_{sr} = A_r p_r t_r^2/L_r\ ,\ R_{sr} = A_r p_r t_r/L_r\ ,$$

and $C_{sr} = L_r/(A_r p_r)$.

I_{sr}, R_{sr}, and C_{sr} are the reference quantities for the spool parameters.

The following dimensionless constants are also defined,

$\alpha = L_r/x_i$ and $\lambda = C_{d1}\, d/(\,C_{da}\, w)$

and used to obtain the set of governing equations in dimensionless form. This is a straight forward process, and the resulting equations will not be presented again for convenience.

The dimensionless parameters of the class of valves studied might be,

$\alpha = 8.865$, $\lambda = 0.21$, $I^* = 0.156$, $R^*_{13} = 0.1$, $C^*_{14} = 0.05$, $A^*_s = 2.4$,

and $C^*_{bc} = C^*_{17} = 0.05$.

These would be typical parameters for a valve that allows a flow rate of 40 1/min at a supply pressure of 5 Mpa when the load pressure is 3.7 Mpa , the pressure difference across the control opening ($p_2 - p_3$) being 0.3 Mpa in the steady state. The value of R^*_i is varied over a practical range.

The variation of the load flow rate with time, when the load pressure is decreased by 25%, is shown in Fig. 5.a and b. The figure shows that the load discharge Q^*_3 gets an instantaneous rise with load pressure drop, then it decreases to a steady state value which differs, but slightly , from the initial load discharge (0.447 in this case). For a 7 mm diameter passage, $R^*_i = 1$ and the settling time (based on 2% band) is 1.9 , while for $R^*_i = 10$ (corresponding to a passage diameter of about 3 mm) the settling time is 3.8 , and it is 10 when $R^*_i = 100$ and the diameter is about 1.5 mm. The variation of load flow with time during the initial stages of response is shown in Fig. 5.a . For $R^*_i = 1$, the load discharge is shown to attain high initial rise, then it decreases monotonically in a fast rate. Decreasing the resistance to 0.5 has but very slight effect on the speed of response, and increases considerably the initial overshoot. When the resistance is 10 the initial overshoot is shown to decrease. With the further increase of R^*_i to 100, the merit of considerable decrease of overshoot is accompanied by an oscillatory slower response. The same tendency of results is seen in Fig. 6 where the load pressure step decrease is 50% and in Fig. 7 showing the response to step drop of 75%. Fig. 6 shows the effect of increasing the resistance to 1000. With such an increase no considerable effect on the discharge initial overshoot is detected, but more sluggish and oscillatory response is evident. With load pressure step increase, the same nature of results is observed (results are not presented).

It can be concluded that, for the class of valves with the parameters given, the value of the resistance R^*_i is to be taken in the range $10 < R^*_i < 100$ in order to avoid the high initial overshoot occuring at resistances less than 10, and the sluggish and oscillatory response occuring at resistances higher than 100. Further, if the valve is to be used in a system subjected to slight load variations, the resistance is better chosen around 10 as the initial overshoot would be reasonable and the speed of response is high. Systems subjected to severe load variation should be equipped with valves of resistance around 100 to limit the load flow rate overshoot, if the oscillatory response is accepted.

Variation of the resistance in the range obtained can be achieved in practice by producing a standard base valve of passage diameter of 3 mm or more, and threading this passage to accept inserting a throttle of suitable diameter

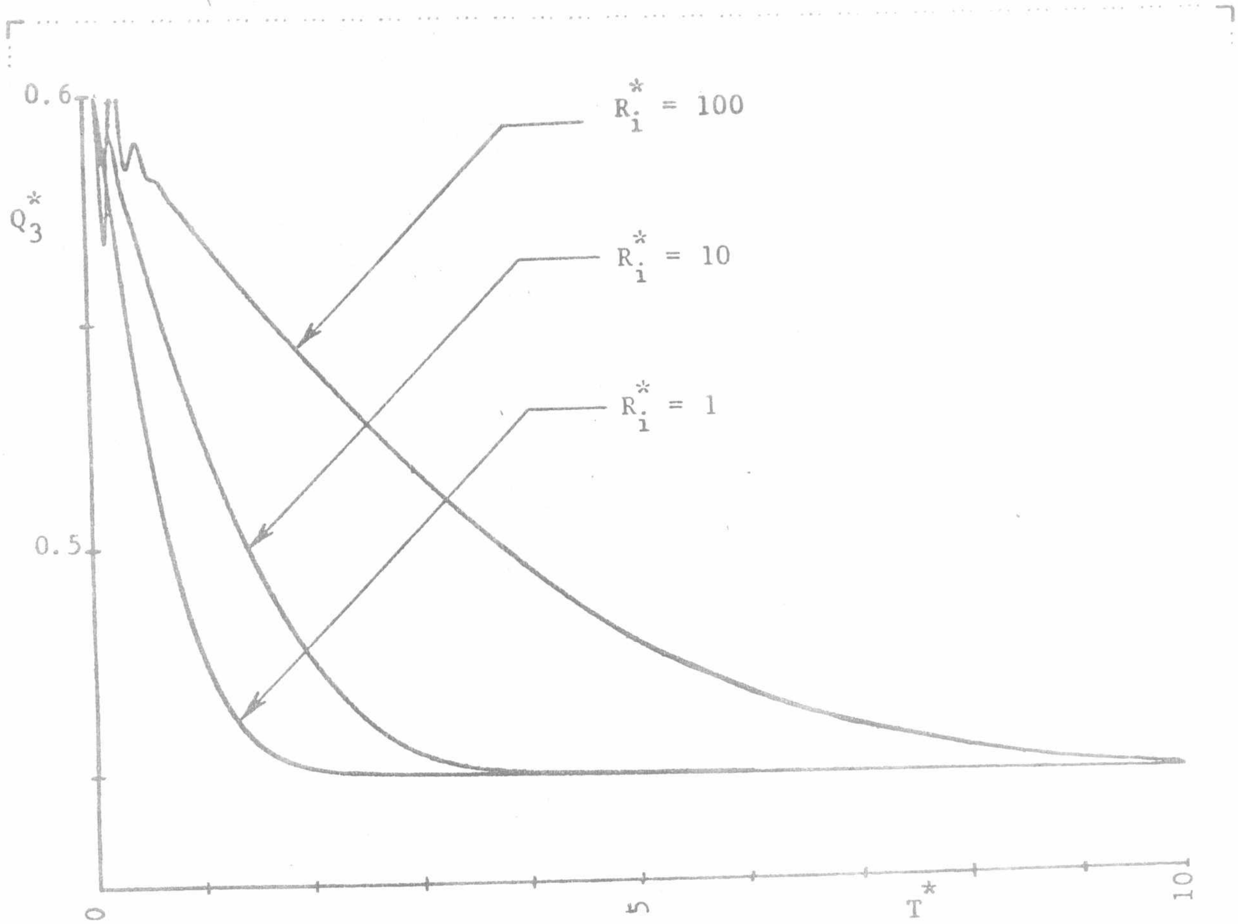

Fig.5a. Variation of load flow rate with time for 25% load pressure drop

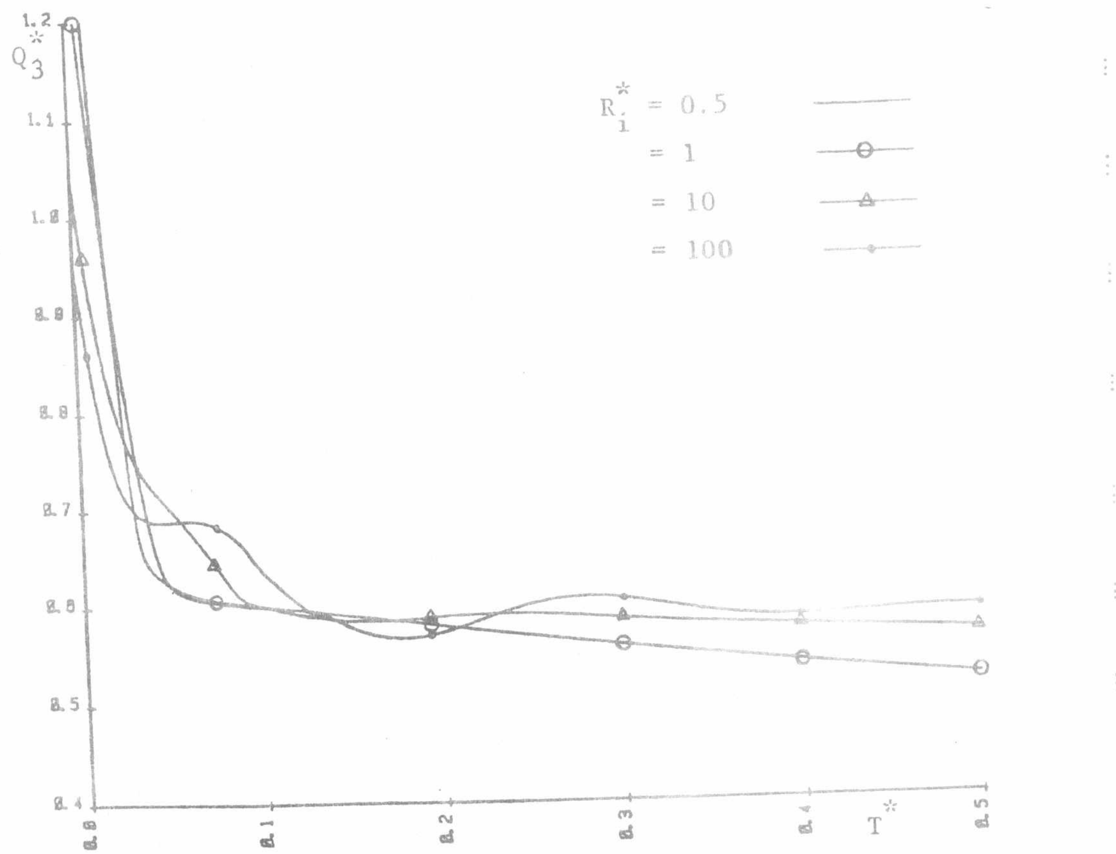

Fig.5b. Variation of load flow rate with time for 25% load pressure drop

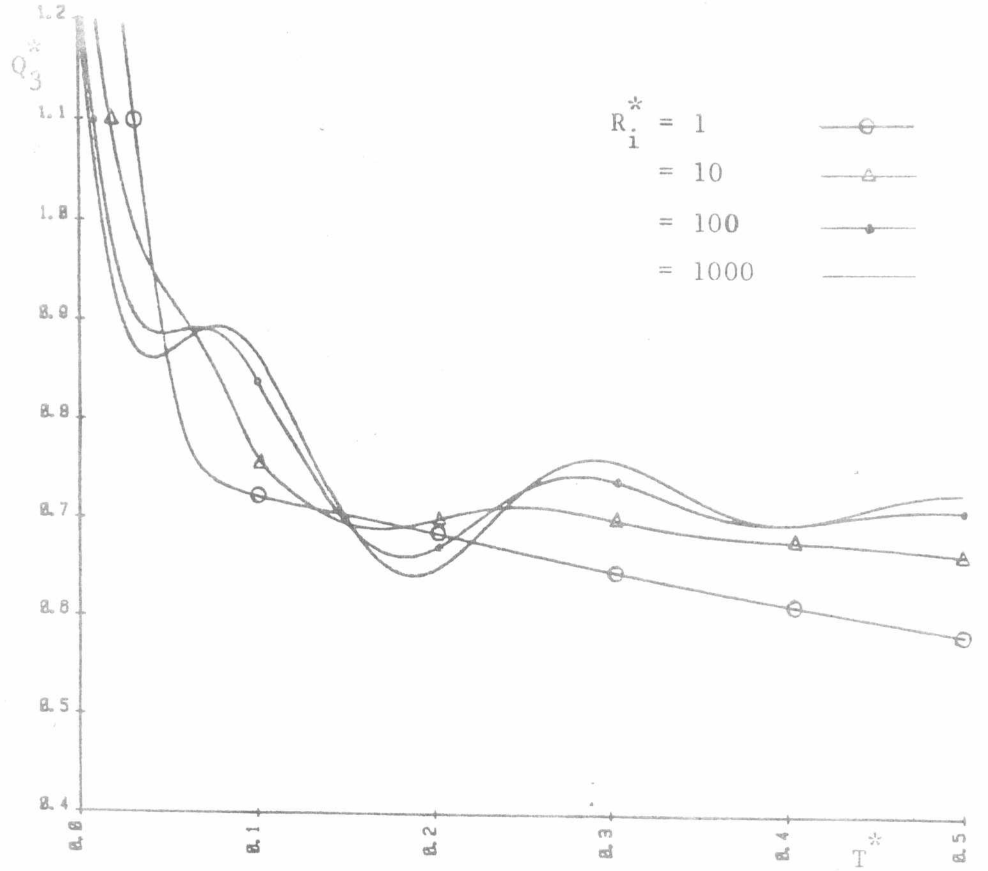

Fig.6. Variation of load flow rate with time for 50% load pressure drop

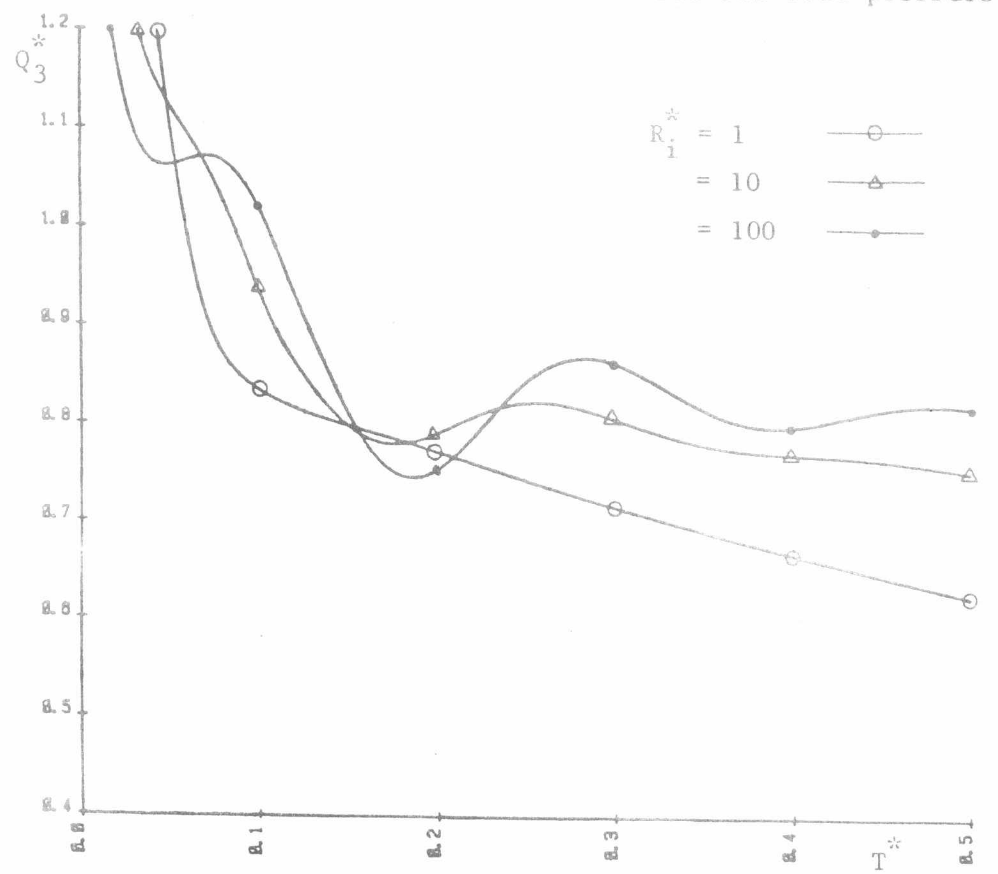

Fig.7. Variation of load flow rate with time for 75% load pressure drop

to render the required value of the resistance R_i^*.

CONCLUSION

The bond graph model of a global system incorporating a two-way pressure compensated hydraulic flow control valve can be obtained by connecting the model of the valve, developed in this paper, with the models of the other system components. Valve simulation can be realized through the exploitation of the valve mathematical model, as obtained from the bond graph, by a digital computer. The simulation of set of valves working under constant inlet pressure showed that the transient response to step variation of outlet pressure depends considerably on the value of the resistance of the passage leading from the outlet section to the spring chamber of the compensator. At low resistances, the outlet flow rate attains high initial value that decreases rapidly to the steady state, when the outlet pressure is decreased. At high resistances, the merit of reduced initial overshoot is accompanied by an oscillatory and sluggish response.

It is concluded that there is a certain range in which this resistance should be chosen to obtain a suitable response regarding outlet flow rate overshoot, oscillations, and settling time. Valves of this type are recomended to be produced with the passage, leading from the outlet section to the spring chamber, allowing to insert fixed throttles in it to get the required resistance that suits each application.

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NOMENCLATURE

A_s	spool cross sectional area
C	capacitance
C_{d1}	discharge coefficient of compensator throttle
C_{da}	discharge coefficient of main throttle valve
d	spool diameter
e	effort variable
K	spring constant
I, I_{12}	inertia of spool
P	pressure
P_1, P_2, P_3	inlet, intermediate, and outlet pressures respectively
Q	flow rate
Q_3	outlet flow rate
R	resistance
R_s, R_{13}	linearized frictional resistance of spool
R_i	resistance of passage connecting outlet section to compensator spring chamber
R_o	resistance of passage connecting the intermediate section to the other compensator chamber
V_a, V_b, V_c	volume of spring, intermediate, and upper chambers respectively
w	port width of main throttle valve
x_i	initial opening of compensator throttle
$x, \dot{x}$	spool displacement and velocity
y	main throttle valve opening
ρ	fluid density
β	fluid compressibility coefficient
α, λ	dimensionless constants
R_i^*, I^*, ..etc	dimensionless resistance, inertia, ..etc
L_r, t_r, ..etc	reference length, time, ..etc