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SIMULATION USING BOND GRAPHS FOR A HYDRAULIC SYSTEM DRIVING LARGE ROTATIONAL INERTIA

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ABSTRACT

The process and results of computer simulation using bond graphs for a hydraulic system driving large rotational inertia are presented in this paper.

As the large rotational inertia and its application characteristics, control criteria of this system is not position-control nor velocity-control but appropriate acceleration, deceleration and inching ability.

All the components' nonlinear characteristics are modelled using bond graphs. The equationing and solution process is carried out by a package.

Finally it is concluded that modelling of this kind of system by bond graphs and using a software as its solver shows good approximated results to actual experimental data, and that the proposed modelling may be useful to actual design process for this kind of hydraulic system.

1. INTRODUCTION

Many of preceding works have been devouted to the hydraulic control systems which mainly consist of constant pressure supply source, servo valves, and servo actuators. Their characteristics can be summarized as follows: 1) pump discharges more flow than needed, 2) pressure control valve usually operates in open condition, and 3) the spool stroke is less than 1 mm so that its characteristics can be linearized without introducing considerable deviation. Therefore inspite of much energy loss theoretical approach is possible and the experimental result is predictable, so that the above mentioned system has been applied to fine position control systems such as military weapons, aircraft, etc.

In the hydraulic system studied in this paper, the actuator usually uses all discharge flow of pump, supplying pressure varies from zero to relief pressure and the flow through control valve may be up to hundreds of liters per minute and the system efficiency is one of the most important factors in design process.

The difficulty of theoretical analysis comes from serious nonlinearity due to this characteristic. But since early seventies many researches have been carried out in the point of energy savings and automatic control. Also, there have been reports about components design and performance. [5]

Since industrial(heavy duty) machinery, such as crane, handles large weight and its swing superstucture weighs considerably for static balancing, hydraulic power is preferred to drive the system. In such an equipment either exact position control nor velocity control is not pursued in the design concept. The strategy is that 1) it can be smoothely controlled, 2) it should have appropriate acceleration, deceleration ability ,the maxima of which are limited by extra contraints such as structural strength, dynamic balancing, 3) inching operation can be easily done. And because transferred energy through the system is very large, cut-down of energy loss is another important factor.

In this research, using bond graph description method, the authors have attempted to numerically analize the pump-valve-motor system, which is frequently applied in the industrial field. The characteristic behaviour of the given system are explained qualitatively, and some ideas for the better performance are proposed.

The authors propose that bond graphs description method be a suitable and efficient tool for the analysis and design for the hydrostatics-prevailing system.

2. CONSTRUCTION OF THE SYSTEM

Hydraulic circuit to be analyzed is shown in Fig. 1. It is basically open circuit. Displacement of the pump varies depending upon both discharge pressure and control signal which is common in industrial application for higher efficiency. The relief valve limits the maximum pressure of pump discharge. The directional control valve spool forms tandem circuit and the spool position is selected proportionally to the control signal. The motor has two kinds of accessary; make-up valve for preventing cavitation and cross-over relief valve for limiting acceleration/deceleration differential pressure.

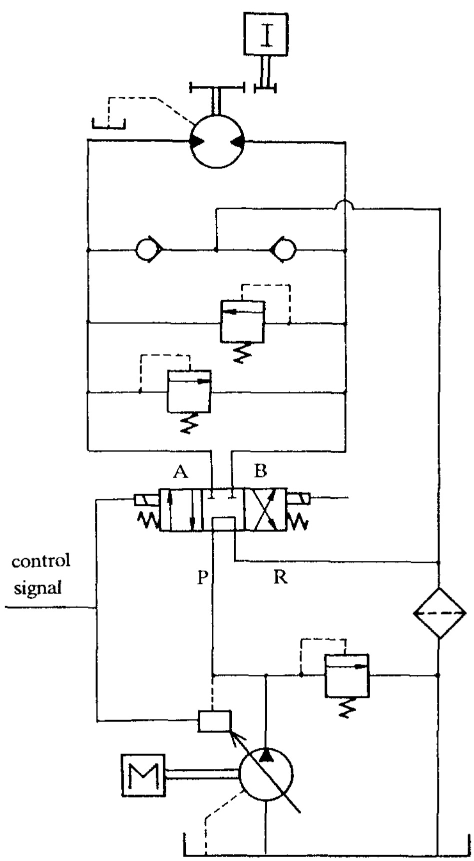


Figure 1. Hydraulic Circuit

Prime mover, driving pump, is the engine with constant speed governor. The hydraulic motor drives large rotational inertia which is connected through reduction gear trains.

3. BOND GRAPHS MODELLING OF THE COMPONENTS

Bond graphs description is a method which emphasis the relations of each componenet and the description has analogous form to actual circuit.[1], [2]

Fig. 2 shows the modularized elements and their relations on the basis of system circuit. Each module exchanges energy or power through identifiable connections or ports(bond). Therefore modelling of the system can be achieved by synthesizing element-level modelling.

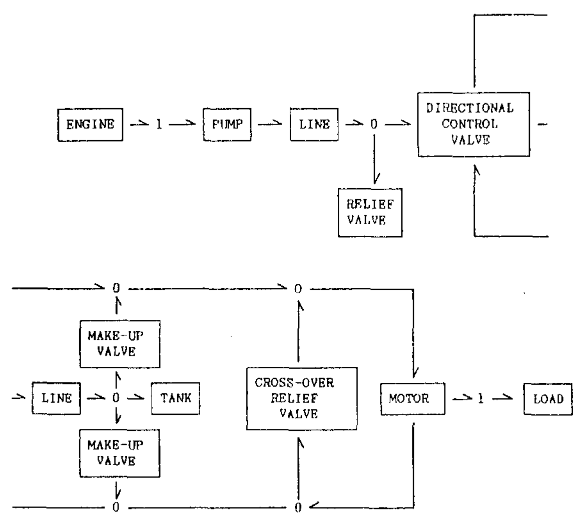
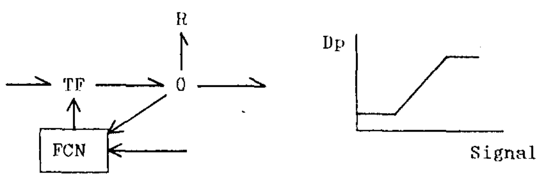


Figure 2. Modularized Element and Their Relation

3.1 Variable Displacement Pump

External leakage is considered to be laminar flow. Actually the amount of internal leakage is small in comparison with external leakage and frictional loss does not effect the hydraulic system behaviour but slightly increases the engine torque, so that they are ignored. And inertia of rotating parts of pump is ignored.

For the large corner horse power and energy saving, the displacement is assumed to be pressure-compensated and to increase proportionally to control signal. Displacement of pump is calculated in FCN block.



(a) (b)

Figure 3. Bond Graph of Pump

3.2 Directional Control Valve Spool

In Fig. 1, the spool opens or closes the valve ports; P to A, P to B, P to R, A to R, and B to R. So five resistor element appears in bond graph at five corresponding locations respectively.[4]

All resistor element equations are defined as

$$Q = C_d A_i \sqrt{2\Delta P/\rho}$$
$$= K\, Ai \sqrt{\Delta P}$$

where C_d : discharge coefficient, A_i : orifice area

ΔP : differential pressure, ρ : density

$K : (= C_d \sqrt{2/\rho})$

All the orifice areas are function of spool stroke and are calculated in corresponding FCN blocks.

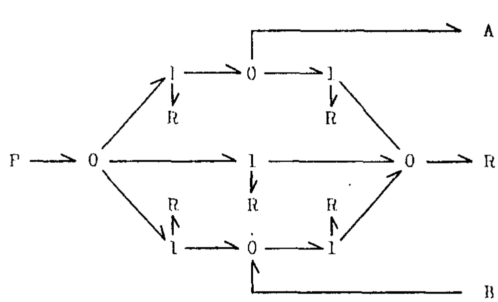


Figure 4. Bond Graph of Directional Control Valve

3.3 Fixed Displacement Motor

External leakage is considered to be laminar flow, internal leakage is ignored and frictional loss is assumed to be Coulomb type and to be included in load friction.

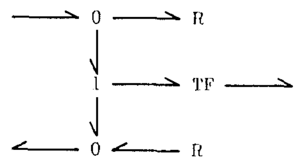
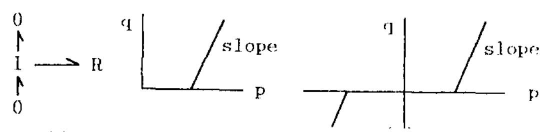


Figure 5. Bond Graph of Motor

3.4 Relief Valve Cross-over Relief Valve and Make-up Valve

The bond graphs of them are the same, shown in Fig. 6 (a), but the equations of them are different. (b) shows those of relief valve and make-up valve and (c) shows that of cross-over relief valve.



(a) (b) (c)

Figure 6. Bond Graph of Valves

3.5 Lines

The resistance of tube is relatively small to that of control valve spool, so ignored. But the minor resistance of return line cannot be ignored, for it builds boost pressure for make-up. And the compressibility of the fluid and the compliance of the tube is considered to form an equivalent capacitor.

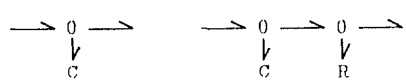


Figure 7. Bond Graph of Lines

3.6 Engine and Reduction Gear Train & load

The constant speed governor of industrial engine does not keep exactly constant speed. The speed varies a little according to the load torque. In this system, the load torque is assumed to be less than designed rated torque.

The modelling of varying speed are shown in Fig.8 (b). The inertia of moving parts of engine is neglected which is the same assumption as in the case of pump. FCN block sends load torque signal to the engine(TF), shown in (a).

The characteristic aspect of this system is large rotational inertia which is larger than $1.0 \, x \, 10^4 Kgf \, M \, sec^2$. As for the friction term, the rotation speed is very low, less than 1.5 rad/sec. So Coumomb friction is assumed which includes all the friction of hydraulic motor, reduction gear train, and large bearing. And it is compacted into one R element. The modelling of load is shown in (c), Fig. 8.

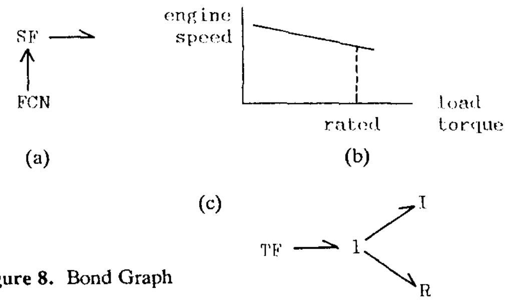


Figure 8. Bond Graph of Engine, Gear Train & Load

4. SIMULATION USING BOND GRAPHS

All the modularized modelling which is constructed in section 3 are synthesized into one bond graph of total system. The obtained bond graph is entered through keyboard input on graphic terminal through dialogue between operator and computer.

Care must be giben to selected units because the system considered is a mixture of mechanical and hydraulic subsystems, and the order of numbers in computer calculation should be adjusted to avoid instability of numerical solution. Pressure unit in bar, flow unit in cc/sec and inertia unit in hundredth of $Kgf \, M \, sec^2$ are used.

5. SIMULATION RESULT AND DISCUSSION

Fig. R1 is the simulation result of an assumed system, all parameters of which are based upon the arbitraily selected fictious hydraulic system and will be called standard parameters. The control signal is a step function, shown in (a).

Fig. R1 (e) shows typical pressure trend of large rotational inertia system combined with pressure compensated pump. Relief pressure builds up very rapidly at stepwise control input and kept on during relief valve is open. Then pressure decreases. Pressure decreasing interval is divided into two step. During the first step, it decreases slow due to the increase of

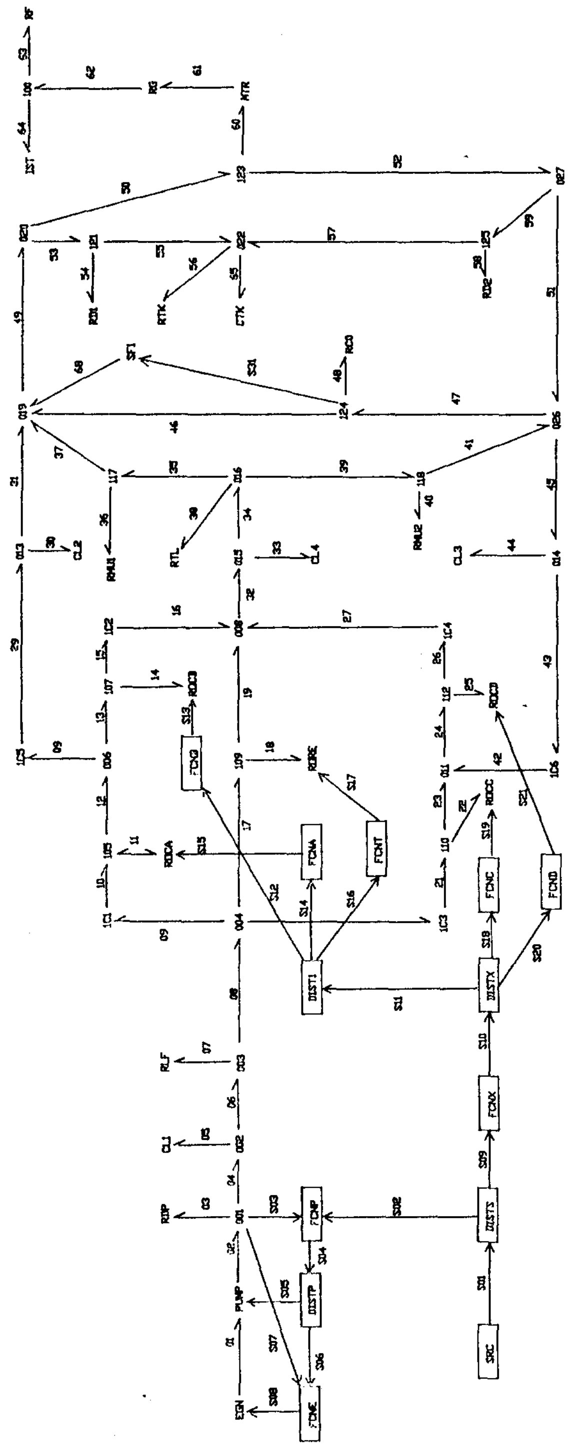


Figure 9. Full Bond Graph Of the System

the pump discharge discharge and then ,the second step, pump keeps on maximum discharges flow and the pressure decreases rapidly to reach steady state around 5 sec. Swing velocity starts to increase uniformly and reaches constant speed about 5 sec.

If the relief flow which occurs for about 2 sec can be eliminated or decreased by controlling pump flow, effective energy saving can be achived.

Fig. R2 is the same case of maximum accelation as that of Fig. R1. But stiffnesses of capacitor elements are decreased to 1/20 of standard parameters. This situation can be interpreted as the case when air bubble exists in working fluid. Fig. R2 shows that air bubble in working fluid results in fluctuation in pressure (overshoot) before getting steady state.

As for Fig. R3 and R4, all parameters are assigned to a set of values different from the previous case. And both of them are concerned with deceleration. C-elements and I-element were given initial values which can be obtained in steady state rotation.

In Fig. R3, where maximal deceleration is simulated hydraulic brake pressure builds at the instant of abrupt valve closing, and high outlet pressure is kept on for about 3 second and then two pressures oscillate up and down. It affect the swing velocity to oscillate a little.

But the pressure trends does not agree to the experimental data. Now another assumption is introduced. That is, new volume of fluid is created in the closed circuit. This can be validated by mentioning that as pressured oil passes through cross-over relief valve, static pressure suddenly decreases to nealy zero, this makes the air, dissolved in the fluid, form bubble and also relief energy dissipating in heat raises fluid temperature. Air volume dissolved in fluid and fluid temprature vary according to fluid history and the number of operation. This explains indirectly the reason why the same pressure curves is not obtained.

In order to implement the new assumption, SF1 element is added at the port of cross-over relief valve element. Fig. R3 is the case that SF1 element function is constant at zero, that means no SF1 element. Fig. R4 assumes that air volume of one fifteenth of relief flow be created and that stiffness of C-element decrease to one tenth. The simulation result agrees well to the experimental data. That is, low pressure curve forms sudden decrease, smooth rise and fall,then oscillation. Swing velocity oscillation appears too.

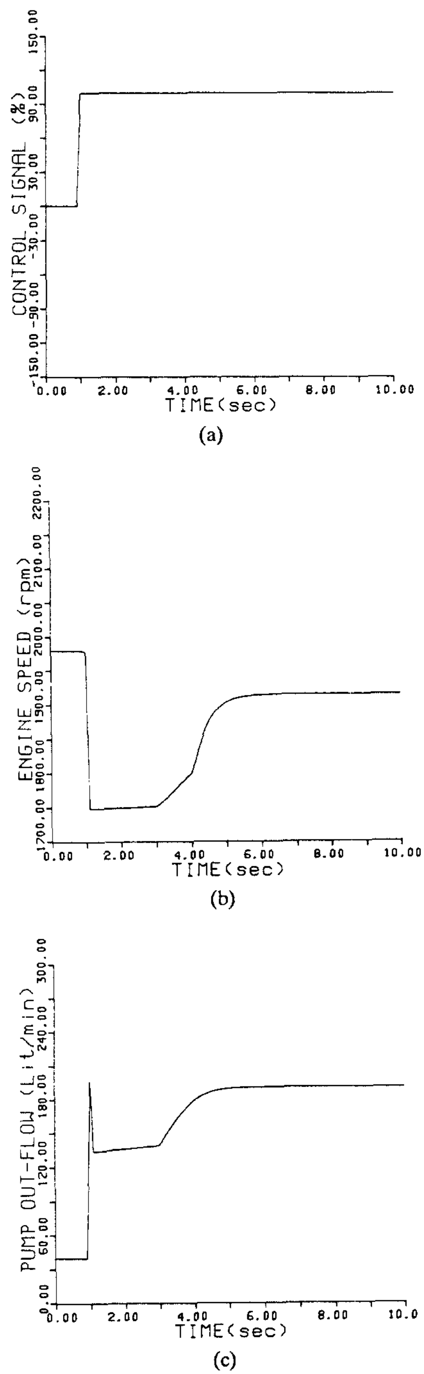
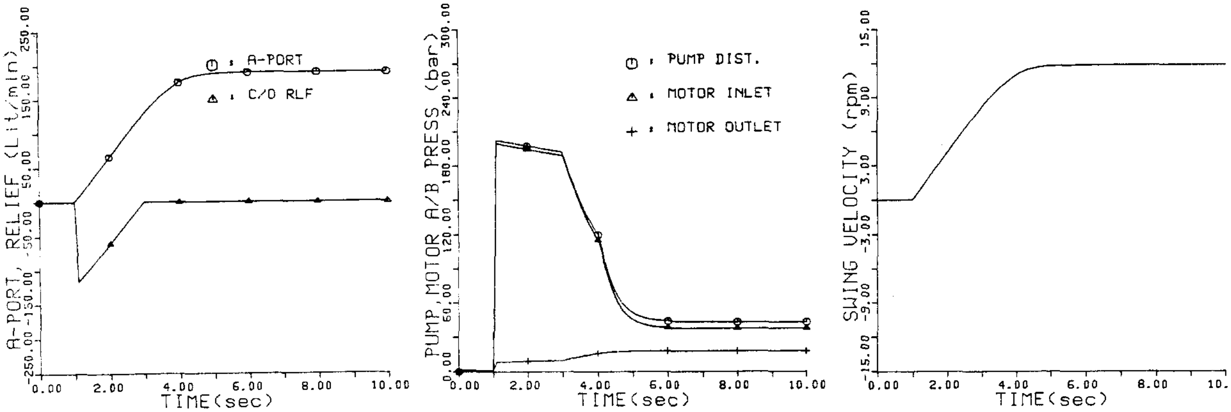


FIG. R1



(d) (e) (f)

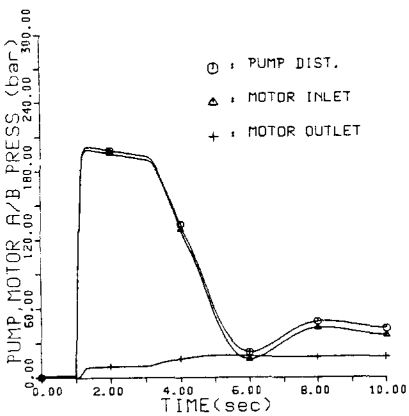


FIG. R2

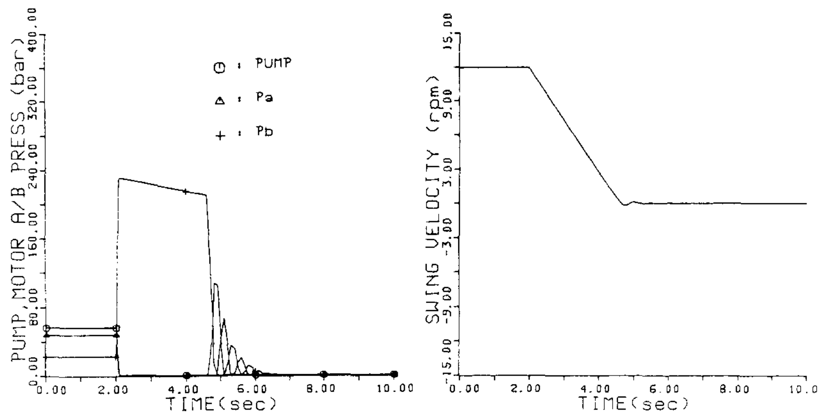
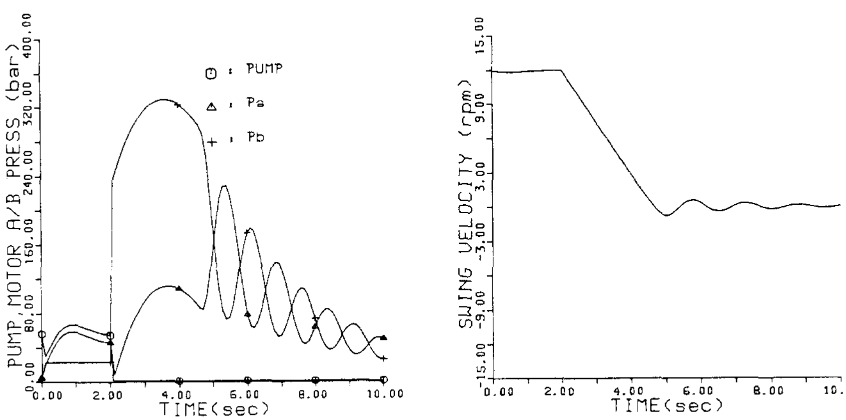


FIG. R3 (a) (b)



(a) (b)

FIG. R4

CONCLUSION

Using bond graphs description method, each element consisting of the selected hydraulic system was modelled and each bond graph was simply synthesized to construct full bond graphs of the total system. The obtained bond graphs and each node equation were entered into, solved through a software, ENPORT. The simulation result agrees well to the experimental data, despite of the simple procedure of modelling.

The bond graphs description method is efficient tool for the analysis and design of complicated hydraulic systems. The model used in this paper gives useful design information for the similar hydraulic driving systems.

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