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# Modeling and Simulation of an EPPR Valve Coupled with a Spool Valve

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**Key Words** : Flow Control, Hydraulic Excavator, Mathematical Modeling, IMV, Spool Valve

**Abstract**: EPPR (Electro-hydraulic Proportional Pressure Reducing) valves are pressure control valves. In this study, an independent metering valve (IMV), which is a combination of a spool valve opened and closed with the help of an EPPR valve, was discussed. The overall performance of the valve (IMV) was obtained by the respective modeling and simulation of the system. The valve investigated in this study is to be used for independent metering of hydraulic excavator actuator e.g. boom, arm, bucket etc. To design the model, continuity equations and force balance equations were used. The set of differential equations were then simulated in Simulink using ODE45 option in the configuration toolbox. The valve has to be able to control the flow rate going in and out of the cylinder separately, which is why the particular configuration was needed and selected.

## Nomenclature

$A_{cur}$ : Curtain/flow area at the EPPR inlet ($P_s$)
$A_{cur}^{'}$ : Curtain/flow area at the EPPR outlet ($P_t$)
$A_S$ : Cross-sectional area of the main main spool at the left side (figure 1)
$A_0$ : Area of entrance into the hole chamber ‘h’
$A_p$ : Area of EPPR pin
$C_f$ : Friction coefficient
$C_d$ : Discharge coefficient of flow
$F_f$ : Flow force on the EPPR spool
$F_f{'}$ : Flow force on the main spool
$F_{sol}$ : EPPR solenoid magnetic force
$k_s$ : Main spool spring constant
$k_1$ : EPPR spool spring
$k_2$ : EPPR solenoid spring
$L_0$ : Length of hole chamber ‘h’ when $x_s = 0$
$M_s$ : Mass of the main spool
$m_s$ : Mass of the EPPR spool
$P_s$ : Pressure at the EPPR valve inlet
$P_t$ : Return pressure
$P_A$ : EPPR valve control pressure
$P_h$ : Pressure forcing EPPR valve pin towards left
$x_s$ : Spool displacement of EPPR valve
$X_S$ : Spool displacement of the main spool valve
$X_{S0}$ : Pre-compression in the main valve spring
$V_{A0}$ : Part of chamber A volume in EPPR valve
$V_{AS}$ : Part of chamber A volume in spool valve
$\rho, \beta$ : Oil density and bulk modulus respectively

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## 1. Introduction

The goal of this study was to determine and evaluate the characteristics of a flow control valve which was developed for, but not limited to, use in independent metering systems and so was called IMV. The said goal was achieved through mathematical modeling of the valve and simulation of the mathematical model using simulink.

In this study, an IMV valve was defined as a combination of EPPR and spool valve. The EPPR valve, a pressure control valve used in this study, is a reducing valve which has a hole inside the spool and a pin is inserted in that hole as shown in figure 1. Due to the presence of pin, we call it pin-type EPPR valve[1].

The need for this study stems from the importance of evaluating different design options based on different parameters of the flow control valve. A study conducted by Janus et. al determined modeling of pressure reducing valves but it did not include its application[2] in a spool valve. In the past, other similar studies were conducted to model valves used in hydraulic power transmission systems[3-7]. Research work on EPPR valve flow force was done by yun et. al[8]. All these studies were aimed at predicting and validating the response characteristics of the valves. The IMV valve used in this study was to be used as a flow control valve for use in the independent metering hydraulic circuit of excavator.

The spool valve is one stage and contains a spring which limits the opening of the valve. The balance between the EPPR control pressure and the spring force determines the flow area and thus the flow rate of the main spool.

## 2. Working Principle

The construction of the flow control valve is shown in figure 1.

As can be seen from the figure below, the IMV valve consists of two main parts i.e. the EPPR valve and the main spool valve. The EPPR valve takes the input pressure of 50 bars, a solenoid magnetic force from corresponding to a voltage between 0V to 10V and provides an output in the form of a control pressure or a reduced pressure.

When the solenoid is activated, the EPPR spool is pushed to the left by solenoid plunger, allowing the fluid at the EPPR inlet to enter the hole inside the EPPR spool at the tip of the pin. The build-up of pressure around and inside the EPPR spool will push the spool against the solenoid force acting as a feedback mechanism.

The output from the EPPR valve, i.e. the control pressure, pushes the main spool against a spring. The main spool position controls the flow area and thus the output flow rate from the main inlet of the spool valve to the exit of the main exit of the spool valve.

When the solenoid is deactivated, the already established pressure in chamber A, pushes EPPR spool to left allowing the chamber A to connect to the tank port, thereby, reducing the pressure at the main spool left side. As the pressure to the left of main spool drops, the main spool is moved leftward by the spring

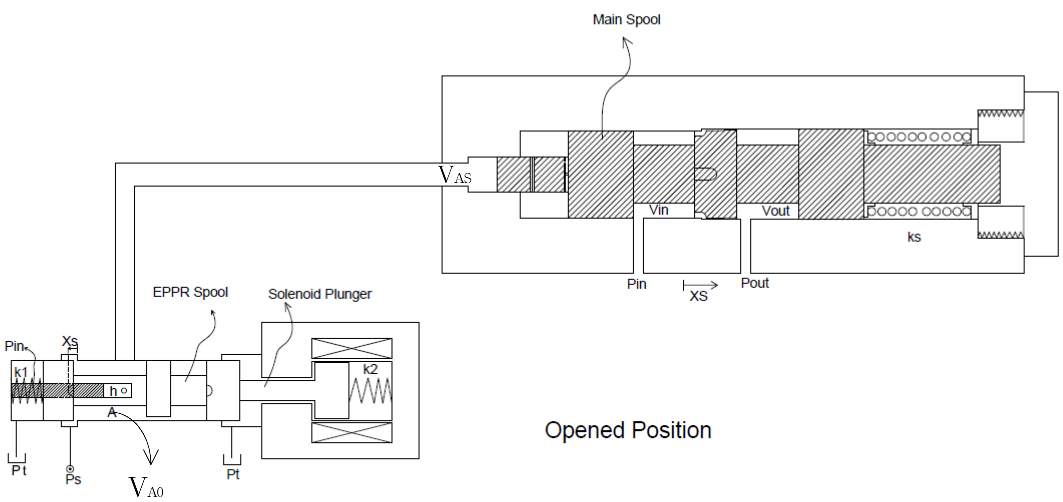


Fig. 1 Schematic of the IMV

force, hence closing the flow area between the two ports of main spool valve.

## 3. Mathematical Modeling

The mathematical modeling consists of applying the continuity equations[9] to the control volumes, $V_A$ and $V_h$ and applying the force-balance equations to the two moving masses which include the EPPR valve spool and the main spool.

### 3.1 Continuity Equations

The entire IMV valve can be divided into two main control volumes.

The continuity equation applied to the chamber A is given by:

$$A_{cur} C_d \sqrt{\frac{2(P_s - P_A)}{\rho}} = A'_{cur} C_d \sqrt{\frac{2(P_A - P_t)}{\rho}} + \left(\frac{V_{A0} + A_S X_S + V_{AS}}{\beta}\right)\frac{dP_A}{dt} + A_S \dot{X}_s \qquad (1)$$

The left hand side of equation (1) is the flow going into the control volume. The right hand side accounts for outflow, the rise in pressure as well as a reduction in the control volume. The curtain areas are a function of the spool position determined by the geometry of the valve.

The continuity equation applied to the chamber “h” is given by equation (2):

$$A_0 C_d \sqrt{\frac{2(P_A - P_h)}{\rho}} = \frac{A_p (L_0 - x_s)}{\beta}\frac{dP_h}{dt} - A_p \dot{x}_s \qquad (2)$$

### 3.2 Force-Balance Equations

Just like the control volumes there are two moving parts, the EPPR spool and the main spool.

Force balance equation applied to the EPPR spool is given by equation (3)

$$m_s \ddot{x}_s + C_f \dot{x}_s + (k_1 + k_2) x_s + F_f = F_{sol} - A_p P_A \qquad (3)$$

Force balance applied to the main spool is given as follow:

$$P_A A_S - k_S (X_S + X_{S0}) - C_f \dot{X}_S + F_f' = M_S \ddot{X}_S \qquad (4)$$

The above four equations constitute the mathematical model of the IMV valve. Certain assumptions were made while performing the solution of the above model as followed in the next section

### 3.3 Assumptions

Hydraulic fluid HLP-45 was used as a working fluid, the pressure in the return line was considered negligible, temperature variation was not accounted for due to its insignificance during standard testing, the escape angle of the flow out of each spool was considered close to 90 degrees, flow across each spool edge was considered as the orifice flow, pressure variation within different points of each control volume was considered negligible.

## 4. Simulation Results and Discussion

The mathematical model was solved using Matlab simulink to determine how the flow rate and the displacement of moving parts of the valve respond to

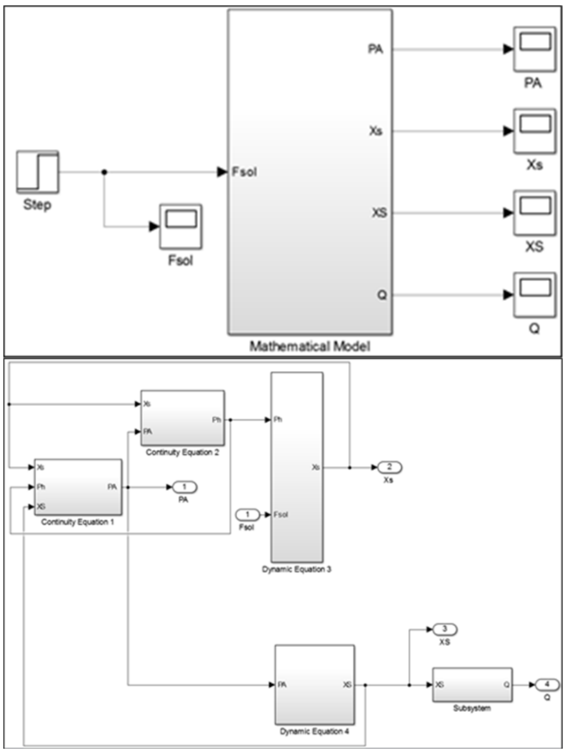


Fig. 2 Simulink Model of the Valve

different conditions under certain design parameters. The simulink model is given by figure 2.

### 4.1 Control Pressure

If the input solenoid actuation force is varied, the control pressure responds linearly as evident from the below figures:

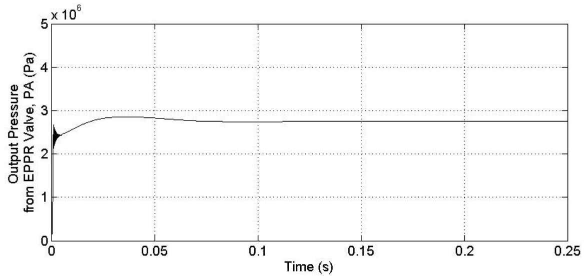


Fig. 3 When Fsol=10 N

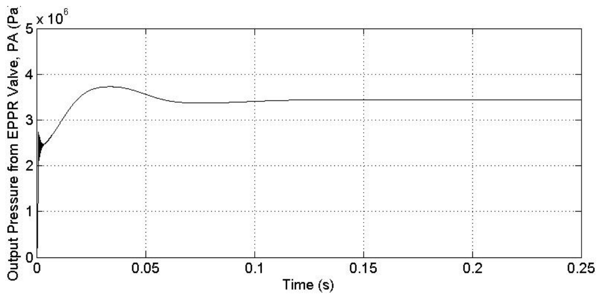


Fig. 4 When Fsol=12.5 N

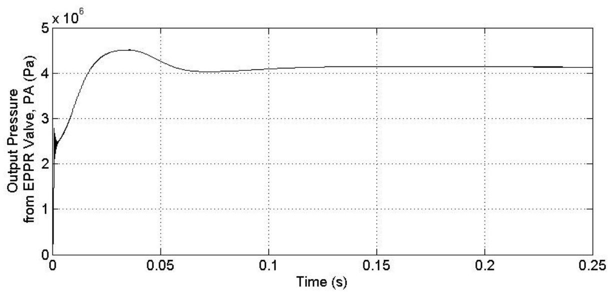


Fig. 5 When Fsol=15 N

As can be seen, the response is very quick, this is because the mass of the EPPR spool is 32 grams. If this value is reduced, the response can be even more quicker but it will create more challenges related to the stability and the safety of the EPPR

For 10N, the steady state value of the control pressure is 28 bars, for 12.5N, the value is 35 bars, and for 15N, the value is 42 bars, which indicates and confirms the proportional nature of the EPPR valve, which is the reason for choosing the valve in this work.

### 4.2 Main Spool displacement

As the control pressure increases, the force on the main spool drives the main valve spool to the right side against the spring, $k_s$. The displacement of the spool is important because it gives rise to the main flow through the valve. The spool displacement would increase or decrease the flow area between the inlet and outlet of the main spool valve.

Fig. 6, 7 and 8 show the main spool displacement under different values of EPPR solenoid force.

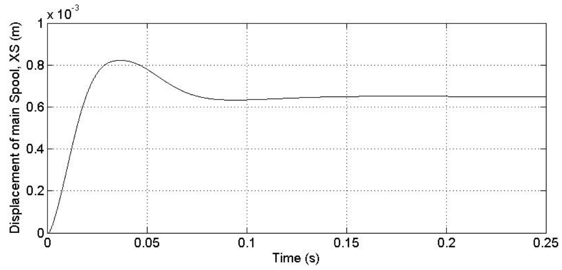


Fig. 6 When Fsol=10 N

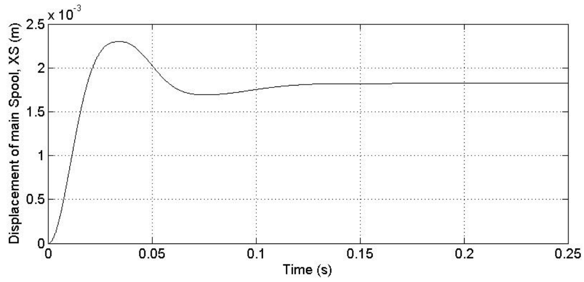


Fig. 7 When Fsol=12.5 N

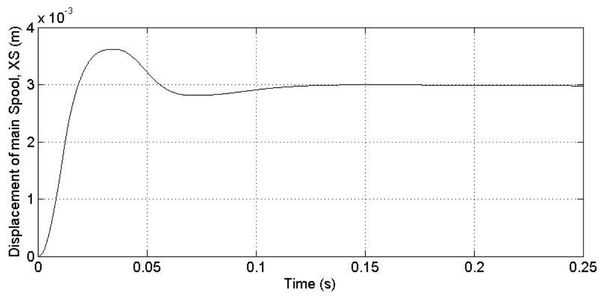


Fig. 8 When Fsol=15 N

As can be seen the valve is stable under the given conditions. The response time of the valve can be reduced by decreasing the size of the spool. The change in displacement gives rise to a a change in flow rate as will be discussed in the next section.

The main spring precompression was kept at 4mm, which if reduced would lead to an unstable behaviour, which is why it is very important to consider other ways of how to reduce the pre-compression for improved response and reduced deadband. This can be a topic for future study in which the model developed in this study can be used.

### 4.3 Output Flow rate

Flow rate is the main output of the valve under study. Figures 9 to 11, show the output flow rate in response to the change in input solenoid actuation force.

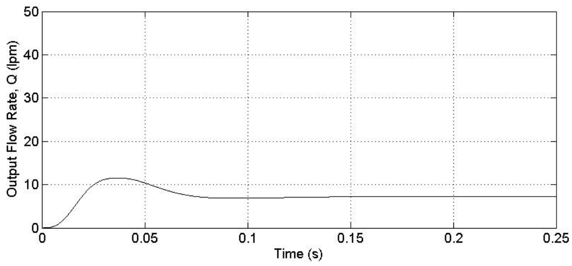


Fig. 9 When Fsol=10 N

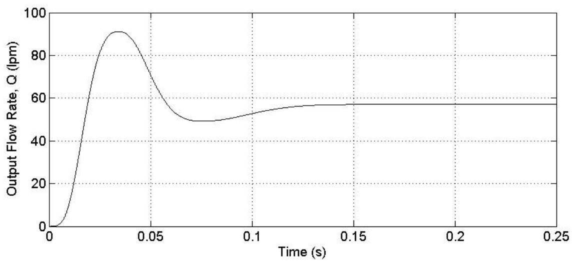


Fig. 10 When Fsol=12.5 N

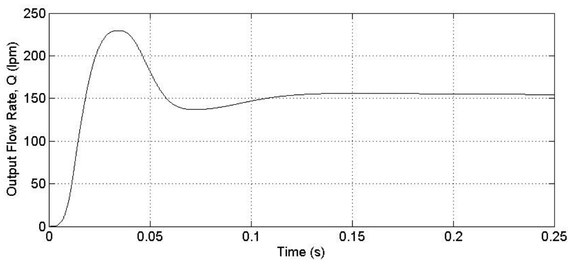


Fig. 11 When Fsol=12.5 N

The output flow rate follows the same trend as that of the displacement response as is clear from the above graphs.

The reason of using the solenoid force as the actuation force was because the solenoid actuator is proportional to the current and the relation between the solenoid current signal and the solenoid force was found through experiment. The developed EPPR's solenoid result can be seen from figure 12.

As can be seen the input signal gives rise to a force which is proportional to the input signal which is why it is called the proportional pressure reducing valve.

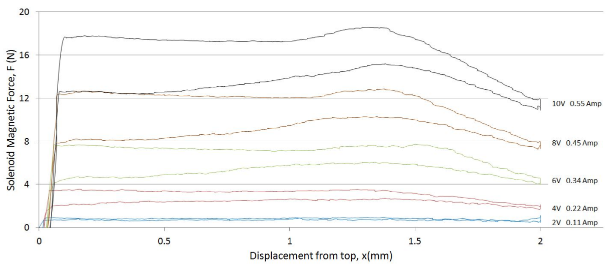


Fig. 12 Experimental results of EPPR solenoid

## 5. Conclusion

A matlab tool, Simulink, was used to simulate the mathematical model which was developed after applying the continuity equation and force balance equation. The model was run under different operational and geometric conditions.

The output flow rate for 15N solenoid force crossed 150 lpm. It highly depends on the main spool diameter and pressure conditions as well as EPPR pressure.

The response of IMV depends heavily on the construction of the spool valve as well as the output of the EPPR valve and the pressure at the inlet.

## Acknowledgement

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