MODELLING AND SIMULATION ANALYSIS OF SOLENOID VALVE FOR SPRING CONSTANT INFLUENCE TO DYNAMIC RESPONSE

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ABSTRACT

Hydraulic system is widely used in much application such as metal forming and press machine. The Solenoid valve is an important part of modern hydraulic systems. This paper presents a new approach of modeling and simulation of solenoid valve by using mathematical expressions for describing the spool displacement. The objective of this paper is to investigate spring constant influence to dynamic response characteristic of the spool displacement. The analysis method use modeling solenoid valve to describe physical model into mathematical models and simulation solenoid valve with the variable of spring constant and describe into dynamic response. Simulation results show that the spring constant was influence to the dynamic response. The spring constant more relevance were achieved using variable with K_1 = 6,000 N.m^{-1} and K_2=8,000 N.m^{-1}.

Keywords: modelling, simulation, solenoid valve, spring constant, response.

INTRODUCTION

Hydraulic system are widely used in many application such as metal forming and press machine, because of their vast driving ability and high dynamic response characteristic. The Solenoid valve is an important part of modern hydraulic systems. The press machine use solenoid valve to adjust stroke the actuator. Main function of solenoid valve is to direct and distribute flow from pump and tank to actuator. In position control applications where the accuracy of positioning the load is to be matched with the cost of achieving it, solenoid valve provide a much cheaper alternative than the costlier more accuracy servo valve. This is mainly due to reduced manufacturing tolerance and lesser control electronics required for solenoid valve.

Solenoid valve have integration of electronic and hydraulic component significantly increase the use hydraulic control in industrial machine (press machine). It used in a circuit powered by pressure compensated or load sensing pump. Current through the solenoid coil windings generates a magnetic potential difference across the air gap. This creates an attractive force between the armature and stator, which causes the armature to move and close the air gap thereby minimizing the reluctance in magnetic circuit. A pushpin connected to the centre of the armature acts directly on the spool, causing the displacement of the spool. The spool slides back and forth within the limit of maximum and minimum permissible spool displacement.

The invention of proportional valve has been filled the great gap between solenoid valve and servo valve. The proportional valve was used to control the flow direction and flow rate simultaneously. The valve model was used to predict the dynamic performance of the electro-hydraulic proportional system when the system works under different operating condition [1]. The Proportional solenoid valve has been successfully used in hydraulic system due to the benefits associated with higher accuracy compared to on/off solenoid valve, and the robustness and cost compared to servo valve [2].

The dynamic response of the on/off valve is investigated by using feedback of axial position of the spool of valve which is driven axially by gear pump. A fuzzy logic parameter self tuning PID controller is used to overcome the system nonlinearity and simulation result shows that the overshoot is decreased greatly than conventional PID controller [3].

The mathematical model can used analytical fault detection on single solenoid proportional valve. Total failure can readily be detected using the signals available on the valve electronic. The experiment validated analytical model is used as a reference model such that the solenoid actual current can be compared with the theoretical current. Since the valve hysteresis is considered, the model calculates maximum and minimum current value that correspondent to undamaged valve [4]. The Proportional valve can be analysis with electrical position feedback for its failure behaviour. The behaviour of the valve for square and ram reference signal was recorded and systematically analysis. It was shown that failures could be detected by monitoring the residual signal from the equipment under control or the residual signal from the sensor [5].The proportional valve can also controlled with close loop control system [6].

In the mechanism of solenoid valve, the axial force required to move the spool is a consequence of the necessary force to accelerate the spool and anything else that moves with it, to overcome friction and the force due to the flow through the valve. There is also the force necessary to overcome spring used to centre or return then spool valve. The inertial force is related to the effective moving mass that consist the mass of the valve moving part plus fluid containing in the valve chamber and drain port at the spool end. The dampening force is a consequence of the transient flow force related to flow

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acceleration and the viscous friction force caused by fluid adjacent to the valve moving part. The flow areas to the supply and return port of the spool valve proportional to the spool displacement. Then the flow rate of oil is across the spool valve and flow to actuator.

The objective of this paper is to investigate spring constant influence to dynamic response characteristic of the spool displacement. In first step this method use modelling solenoid valve to describe physical model into mathematical models, which free body diagram analysis and mathematical equation. In second step this method use simulation solenoid valve with the variable of spring constant and describe into dynamic response.

The mathematical modelling system can be used to represent physical systems into transfer function equations. Simulation can be used to effectively determine the best performance dynamic response spool displacement.

SOLENOID VALVE MODELING

The solenoid valve is operated with given electric voltage to the coil. The basic formula for electric force is calculation in equation 1 [7].

$$f_e = 2\pi aN\beta\ i \tag{1}$$

Where f_e is electric force, a is coil radius, N is coil number, β is magnetic flux, *i* is electric current. The mechanical energy was resulted in equation 2.

$$e_m = 2\pi aN\beta\ v \tag{2}$$

Where e_m is mechanical energy and v is rotation speed.
The voltage law is calculation in equation 3.

$$L\frac{di}{dt} + Ri + (2N\beta la)\dot{\theta} = e_i(t) \tag{3}$$

The free body diagram of solenoid valve is shown on Figure-1.

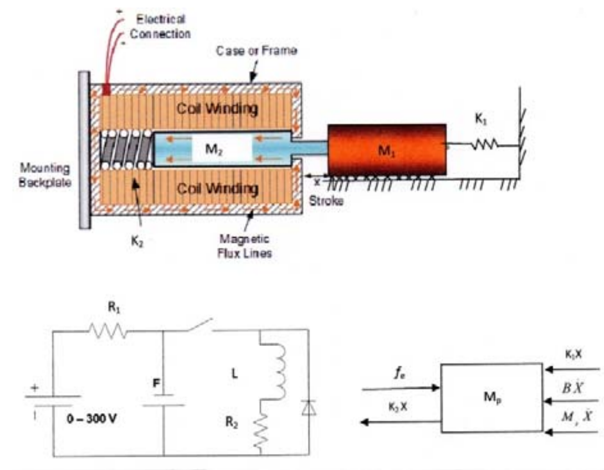

Figure-1. Free body diagram the solenoid valve spool mechanism.

From the solenoid circuit and based equation 3 can get equation 4.

$$L\frac{di}{dt} + (R_1 + R_2)i + (2N\beta la)\dot{\theta} = e_i(t) \tag{4}$$

$$L\frac{di}{dt} + (R_1 + R_2)i + \alpha\,\dot{\theta} = e_i(t) \tag{5}$$

State variable:

$$\dot{\theta} = \mathrm{v}$$

$$\frac{di}{dt} = \frac{1}{L}[-\alpha v - (R_1 + R_2)i + e_i(t)] \tag{6}$$

Where $\alpha = 2\pi aNB$

The spool displacement is influenced by spring force, plunger mass and spool mass, shown in equation 7.

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = f_e \tag{7}$$

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = 2\pi aNBi \tag{8}$$

$$(M_1 + M_2)\ddot{X} + B\dot{X} + (K_1 + K_2)X = \alpha i \tag{9}$$

State variable:

$$\dot{X} = v$$

$$\dot{v} = \frac{1}{M_1 + M_2}[-(K_1 + K_2)X - Bv + \alpha i \tag{10}$$

The Transfer function of equation 5 and 9:

$$(Ls + R_1 + R_2)I(s) + \alpha X(s) = E(s) \tag{11}$$

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$$[(M_1+M_2)s^2+Bs+(K_1+K_2)]X(s)=\alpha I(s) \quad (12)$$

The input output equation:

$$[(M_1+M_2)s^2+Bs+(K_1+K_2)]X(s)=\alpha[\frac{E(s)-\alpha X(s)}{Ls+R_1+R_2}] \quad (13)$$

$$(Ls+R_1+R_2)[(M_1+M_2)s^2+Bs+(K_1+K_2)]X(s)=\alpha E(s)-\alpha^2 X(s) \quad (14)$$

The results modelling are input output equation, which input is electric voltage (E) and the output is spool displacement (X). Input output is given by equation 15.

$$\frac{X(s)}{E(s)}=\frac{\alpha}{(Ls+R_1+R_2)[(M_1+M_2)s^2+Bs+(K_1+K_2)]-\alpha^2} \quad (15)$$

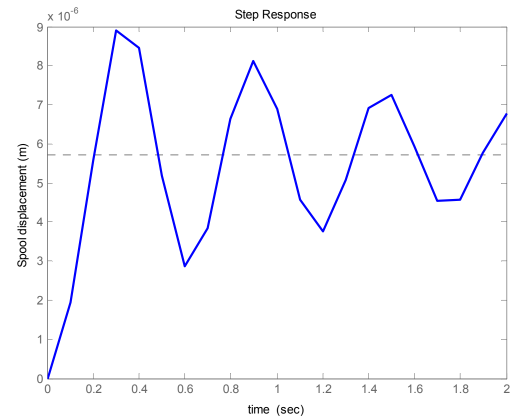
Where L is inductance, R_1 and R_2 is resistance, M_1 is plunger mass , M_2 is spool mass, *B* is friction coefficient, K_1 and K_2 is spring constant and $\alpha = 2\pi aNB$.

SOLENOID VALVE SIMULATION

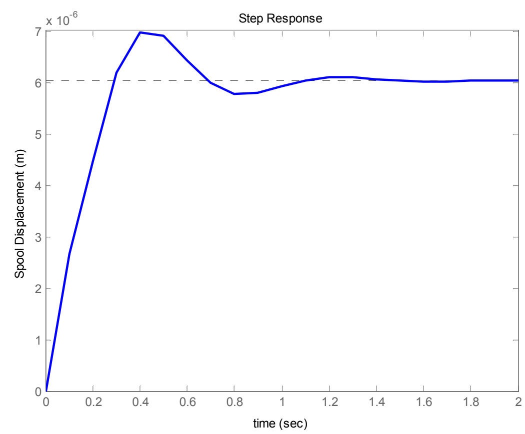
The Solenoid valve Simulation is used to effectively determine the best performance dynamic response of spool displacement. The calculation equation is used parameter the solenoid valve characteristic, which inductance (L) = 0.59 H, resistance (R_1) = 100 Ohm, resistance (R_2) = 50 Ohm, friction coefficient (B) = 1, 4 N.s/m, Flux magnetic (β) = 4 volt. s, Mass plunger (M_1) = 0.15 kg, mass plunger (M_2) = 0.3 kg, coil number (N) = 40, coil radius (*a*) = 0.05 m.
So can get input output equation:

$$\frac{X(s)}{E(s)}=\frac{15,07}{0,27s^3+66,6s^2+10.850s+269977.8}$$

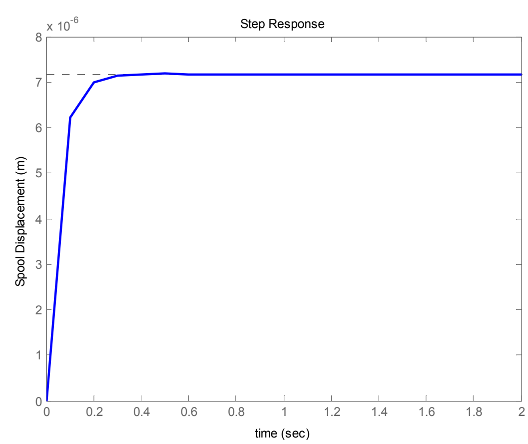
The solenoid valve model has been implemented in versatile software Matlab, which is widely used in control engineering around the world. The solenoid valve simulation using spring constant variable, which variable 1 with K_1 = 8,000 N.m^{-1} and K_2=12, 000 N.m^{-1}, variable 2 with K_1 = 7,000 N.m^{-1} and K_2=10,000 N.m^{-1} and variable 3 with K_1 = 6, 000 N.m^{-1} and K_2=8,000 N.m^{-1}



(a)



(b)



(c)

Figure-2. Step response graphic of spool displacement: (a) with K_1 = 8,000 N.m^{-1} and K_2=12,000 N.m^{-1} (b) with K_1 = 7, 000 N.m^{-1} and K_2=10, 000 N.m^{-1} (c) with K_1 = 6,000 N.m^{-1} and K_2=8, 000 N.m^{-1}.

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The Figure-2.a show step response with rise time 0.25 s, settling time more than 2 s and overshot 55%. The figure 2.b show step response with rise time 0.25 s, settling time 1 s and overshot 34%. The Figure-2.c show step response with rise time 0.1 s, settling time0.2 s and zero overshot.

The Simulation results show that the spring constant influence to dynamic response, with the step response were achieved the better using variable 3 with K_1 = 6,000 N.m^{-1} and K_2=8,000 N.m^{-1} (Figure-2.b), get overshoot and settling time less than variable 1 and 2 (Figures 2.a. and 2.b). So the spool displacement can flow the oil to actuator optimum.

CONCLUSIONS

The solenoid valve analysis is resulted dynamic modelling with mathematical model to describe physical model and the simulation show that the spring constant influence to dynamic response. The spring constant more relevance were achieved using variable with K_1 = 6,000 N.m^{-1} and K_2=8,000 N.m^{-1}.

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