Simulation and Analysis on Flow Rate of Electro-Hydraulic Proportional Control Piston Pump

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ABSTRACT

In this paper, the flow rate model of an electro-hydraulic proportional variable piston pump is set up through mathematical modeling, and the simulation analysis is carried out through the MATLAB. The result provides some reference for the study of the electro-hydraulic proportional variable piston pump.

KEYWORDS

Electro-Hydraulic Proportional; Piston Pump; Flow Rate; Simulation

INTRODUCTION

The composition of the electro-hydraulic proportional control piston pump is shown in Fig. 1. It consists of ten parts, they are variable piston pump 1, control plunger 2, differential pressure control valve 3, throttle orifice 4, flow control valve 5, throttle orifice 6, electro hydraulic proportional flow valve 7, safety valve 8, electro-hydraulic proportional relief valve 9 and swash plate 10.

MATHEMATICAL MODELING

Output flow equation of the electro-hydraulic proportional control piston pump:

\[ Q_p (s) = -K_p n x_c (s) \]  \hspace{1cm} (1)

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In the formula, $K_p$—Ratio coefficient of output flow of variable pump; $n$—the revolution of the variable pumper/min; $x_c$—Displacement of plunger, m; $Q_p$—output flow of variable pump, m$^3$/s;

Figure 1. The composition of the electro-hydraulic proportional control piston pump, 1-variable piston pump; 2-control plunger; 3-differential pressure control valve; 4-throttle orifice; 5-flow control valve; 6-throttle orifice; 7-electro hydraulic proportional flow valve; 8-safety valve; 9-electro-hydraulic proportional relief valve; 10-swash plate.

According to the kinematics equation, the force balance equation of the electro hydraulic proportional flow valve 7 can be obtained

$$K_i - 0.5W_i x_i (P - P_i) - L_i C_i \sqrt{2 \rho (P - P_i)} \frac{dx_i}{dt} = M_i \frac{d^2 x_i}{dt^2} + f_i \frac{dx_i}{dt} + k_i x_i$$

(2)

The formula (2) is linearized and Laplace transformation, we can obtain,

$$K_i(s) - g_i(P(s) - P_i(s)) = (M_i s^2 + (f_i + g_i)s + (k_i + k_i)) x_i(s)$$

(3)

In the formula, $K$—Electromagnetic force coefficient of electromagnet, N/A; $i_1$—The size of the electromagnetic force of the electromagnet, A; $W_7$—The area gradient of the valve 7, m$^2$; $x_7$—Displacement of valve core of valve 7, m; $M_7$—The quality of the spool, Kg; $L_7$—Distance between the inlet and outlet of valve 7, m; $k_7$—Stiffness of spring, N/m; $f_7$—The viscosity coefficient of the movement of the spool, $\frac{\mu l_i}{\delta}$; $\mu$—Dynamic viscosity coefficient of oil, Kg/(m$\cdot$s); $A_7$—Contact area between valve core and valve sleeve, m$^2$; $g_1=0.57 W_7 x_7 0$; $g_2= L_7 C_7 W_7 \sqrt{2 \rho (P_0 - P_{i0})}$; $k_c=0.57 W_7 (P_0 - P_{i0})$; $d_7$—Diameter of a round hole of valve 7, m.
The flow through flow valve 7 is,

\[ Q_7 = C_d W_7 x_7 \sqrt{\frac{2}{\rho}} (P - P_7) \]  \hspace{1cm} (4)

The formula (4) is linearized and Laplace transformation, we can obtain,

\[ Q_7(s) = K_{q7} x_7(s) + K_{p7} (P(s) - P_7(s)) \]  \hspace{1cm} (5)

In the formula,

\[ K_{q7} = C_d W_7 \sqrt{\frac{2}{\rho} \left( P_0 - P_{70} \right)} \]

is the valve port flow gain of valve 7;

\[ K_{p7} = C_d W_7 \frac{1}{\sqrt{2 \rho \left( P_0 - P_{70} \right) \rho}} \]

is the valve port pressure gain of valve 7.

From formula (3) and (5), we can obtain

\[ Q_7(s) = K_{q7} \frac{K_i - g_1(P(s) - P_7(s))}{M x^2 + (f_1 + g_2) s + (k_1 + k_2)} + K_{p7}(P(s) - P_7(s)) \]  \hspace{1cm} (6)

According to the continuity equation of flow, the output flow of the pump is satisfied

\[ Q_p = \frac{V}{E} \frac{dP}{dt} + \lambda_v P + Q_5 + A_5 \frac{dx_5}{dt} + Q_7 \]  \hspace{1cm} (7)

In the formula, \( V \) — Volume of high pressure cavity of variable pump, \( m^3 \); \( E \) — Elastic modulus of hydraulic oil, \( Pa \); \( P \) — Output pressure of variable pump, \( Pa \); \( \lambda_v \) — Leakage coefficient in a variable pump; \( Q_5 \) — the flow through valve 5, \( m^3/s \); \( A_5 \) — End area of valve 5 valve core, \( m^2 \); \( x_5 \) — Displacement of valve 5 valve core, \( m \); \( Q_7 \) — Inflow of load flow, \( m^3/s \).

The formula (7) is linearized and Laplace transformation, we can obtain,

\[ Q_p(s) - Q_5 - Q_7 - A_5 s x_5(s) = \left( \frac{V}{E} s + \lambda_v \right) P(s) \]  \hspace{1cm} (8)

The relationship between the output \( Q_p \) of the variable pump and the output pressure \( P \) of the variable pump can be obtained from the formula (8).

The relationship between the output flow \( Q_p \) of the variable pump and the piston displacement \( x_c(s) \) can be obtained from the formula (1).

The relationship between piston displacement \( x_c(s) \) and valve 5 outlet pressure \( P_5(s) \) is...
\[ x_c(s) = \frac{A_c}{M_c s^2 + f_c s + k_c} P_c(s) \] (9)

In the same way, force balance equation of valve 5 is

\[ A_5(P_0(s) - P_5(s)) - 0.57 W_{s5} x_{s5}(P(s) - P_5(s)) = \]

\[ (M_5 s^2 + (f_{5c} + L_5 C_o W_5 \sqrt{2 \rho (P_0 - P_{50})}) s + (k_{5c} + 0.57 (P_0 - P_{50})) x_{s5}(s) \] (10)

\[ Q_5(s) = K_{s5} x_{s5}(s) + K_{p5} (P(s) - P_5(s)) \] (11)

In the formula, \( K_{s5} = C_{s5} W_{s5} \frac{2}{\sqrt{\rho (P_0 - P_{50})}} \) is the valve port flow gain of valve 5

\( K_{p5} = C_{p5} W_{p5} \frac{1}{\sqrt{2 \rho (P_0 - P_{50})}} \) is the valve port pressure gain of valve 7.

Simultaneous formula (10) and formula (11), we can obtain

\[ Q_5(s) = K_{s5} \frac{A_5(P_0(s) - P_5(s)) - b_1(P(s) - P_5(s))}{M_5 s^2 + f_{2c} s + k_2c} + K_{p5} (P(s) - P_5(s)) \] (12)

In the formula, \( b_1 = 0.57 W_{s5} x_{s5}, f_{2c} = f_{2c} + L_5 C_o W_5 \sqrt{2 \rho (P_5 - P_{50})}, \)

\( k_{2c} = k_{2c} + 0.57 W_{s5} (P_0 - P_{50}) \)

According to the continuity equation of flow, the flow rate into the plunger chamber is

\[ Q_5(s) = A_c x_c(s) + \frac{V}{E} s P_5(s) + \lambda_c P_5(s) \] (13)

In the formula, \( V \)—the volume of the high pressure cavity of the plunger, m³

\( \lambda_c \)—Leakage coefficient of plunger;

From formula (12) and formula (13), we can get

\[ K_{s5} \frac{A_5(P_0(s) - P_5(s)) - (b_1 + b_2) (P(s) - P_5(s))}{M_5 s^2 + f_{2c} s + k_2c} + K_{p5} (P(s) - P_5(s)) \]

\[ = A_c x_c(s) + \frac{V}{E} s P_5(s) + \lambda_c P_5(s) \] (14)
From formula (11) to formula (24) we can obtain the relationship between input current \( i(s) \) and output flow \( Q(s) \) of plunger pump. In this way, the mathematical model of the flow of the electro-hydraulic proportional control axial variable displacement piston pump is obtained.

![Dynamic response curve](image)

**Figure 2. Dynamic response curve of outlet flow of electro-hydraulic proportional variable displacement piston pump.**

**SIMULATION AND ANALYSIS ON FLOW RATE**

The initial parameters of the system are as follows: \( \rho = 880 \text{kg/m}^3 \); \( K = 64.4 \); \( i = 500 \text{mA} \); \( \text{Cd} = 0.63 \); \( E = 2.01 \times 10^9 \text{ Pa} \); \( V = 3 \times 10^{-4} \text{ m}^3 \); \( L7 = 32 \text{mm} \); \( k7 = 16000 \text{N/m} \); \( M7 = 0.12 \text{kg} \); \( d7 = 20 \text{mm} \); \( f7 = 1.32 \); \( dc = 24 \text{mm} \); \( n = 1500 \text{r/min} \). The simulation analysis of the model is done by software MATLAB. The dynamic response curve of the outlet flow of the electro-hydraulic proportional variable piston pump is shown in Fig. 2. As shown in Fig. 2, the steady state flow value of the dynamic response of the plunger pump is 36L/min, the rise time is 5.2ms, the adjustment time is 32ms, and the overshoot is 23.8%.

**CONCLUSIONS**

A flow rate model of an electro-hydraulic proportional piston pump is given. The dynamic response characteristic curve of flow rate is obtained. The steady state flow value of the dynamic response of the plunger pump is 36L/min, the rise time is 5.2ms, the adjustment time is 32ms, and the overshoot is 23.8%. It provides a valuable reference for the deep research of electro-hydraulic proportional variable piston pump.
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