Research on Dynamic Characteristics of Constant Power Control of Plunger Pump Variable Regulator

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Abstract. This article takes K3VDT63 variable plunger pump original regulator as the research object, establishes its dynamic motion equation, uses matlab simulation software to establish its simulation model on the basis of this equation, and the dynamic characteristics of the simulation model under different physical parameters Experiment, and get the dynamic response curve and result of variable regulator constant power control under the influence of various factors.

1. Introduction
The variable regulator is a very important component in the hydraulic system of the variable plunger pump. It can adjust the displacement of the variable pump according to the load, so that the output flow of the pump matches the load, so as to ensure that the power of the variable pump is maintained within a certain range. Inside, protect the engine to prevent the engine from stalling due to overload. The working characteristics of the power regulator have a direct impact on the safety, stability and reliability of the hydraulic pump and the complete construction machinery. This article first analyzes the structure and working principle of the K3VDT63 plunger pump power control variable regulator. On this basis, the spool motion equation of the variable regulator is established. The dynamic characteristics of the constant power control are simulated and the data is analyzed. Come to a conclusion.

2. Structural composition and working principle of variable regulator
The K3VDT63 variable plunger pump produced by Japan’s Kawasaki Company is widely used in the hydraulic system of excavators. The K3VDT63 variable plunger pump is composed of main pump, pilot pump, pump 1 regulator, pump 2 regulator and rotary Moment control solenoid valve and other components, its variable control principle is shown in Figure 1. The main pump is composed of a swash plate type double-pump tandem plunger pump, which is used to supply oil to each actuator; the pilot pump is a gear pump, which provides pilot control pressure for negative flow control; the main pump regulator controls the main pump according to relevant command signals. Pump displacement, where the torque control solenoid valve is located on the pump 2 regulator. The variable modes of K3V series variable piston pump include constant power control, negative flow control, and power conversion control. The above-mentioned control methods are realized by two main pump regulators [1]. This article mainly studies its constant power control.
K3VDT63 variable regulator is mainly composed of load plunger 1, power spring 2, power setting plunger 3, machine-hydraulic proportional reversing valve 4, feedback connecting rod 5, servo plunger 6, pilot spring 7 and pilot plunger 8. The simplified diagram is shown in Figure 2.

The constant power control is completed by the load plunger 1. The $A_1$ and $A_2$ ring oil chambers of the load plunger are respectively connected to the outlets of the main pumps 1 and 2. As the outlet pressure of the main pump increases, the pressure on the ring surface of $A_1$ and $A_2$ also gradually increases. When the sum of the pressure $P_1 + P_2$ on the ring surface of the load plunger $A_1$ and $A_2$ is greater than the set pressure of the power plunger 3, the load plunger overcomes the force of the power spring to push and change the spool to the right to make the reversing valve in the left position, and the pressure oil connected to the reversing valve enters the large end of the servo plunger. Because the size of the servo plunger is different in area, the pressure difference will cause the servo plunger to move to the right. The servo plunger drives the swash plate angle of the plunger pump to decrease, so that the plunger pump changes to a small displacement, and the output flow of the hydraulic pump also decreases. While the displacement is reduced, the servo plunger drives the feedback link to rotate counterclockwise at the same time, the feedback link drives the reversing valve to move to the left until the reversing valve closes, the servo plunger large cavity oil inlet channel is closed, and the adjustment is complete. The plug pump stops the variable.

When the working load of the plunger pump decreases, the spring force of the power spring pushes the load plunger to move to the left, and at the same time drives the reversing valve core to move to the left, the reversing valve works in the right position, the large end of the servo plunger is connected.
to the oil tank, and the pressure is reduced, the servo plunger moves to the left, which drives the tilt angle of the swash plate of the plunger pump to increase, which increases the displacement of the plunger pump and speeds up the work speed. The servo plunger drives the feedback link to rotate clockwise at the same time, and the feedback link drives the reversing valve to move to the right to close the reversing valve. After the adjustment is completed, the plunger pump stops the variable.

So no matter how the load pressure $P_1$ and $P_2$ of the main pump change, the output power of the main pump can be kept constant. Through constant power control, the light-load high-speed and heavy-load low speed of the actuator can be realized, which can ensure that the plunger pump makes full use of the engine output power and prevent the engine from overloading[2~5].

3. The dynamic motion equation of the variable regulator of the axial piston pump

Since the variable process of the K3V63 plunger pump is a direct feedback process of displacement, the variable regulator directly realizes the displacement feedback of the servo plunger to the valve stem through the feedback shift fork. In order to analyze the control effect of the adaptive variable regulator, it is necessary to analyze its dynamic motion characteristics.

The constant power control transfer flow of the working condition adaptive variable regulator is shown in Figure 3. The outlet pressure of the plunger pump controls the displacement of the load plunger. The displacement of the load plunger drives the linkage mechanism to move the proportional reversing valve. The outlet pressure flow of the plunger pump enters the large end of the servo plunger, which pushes the servo plunger to move and make it oblique. The disc inclination angle changes, changing the pump outlet flow.

![Fig.3 Axial piston pump variable regulator constant power control transfer flow diagram](image-url)

3.1. Proportional directional valve motion equation

When the displacement of the load plunger is $X_Z$, the proportional coefficient of displacement transmitted by the servo connecting rod is $k_s$.

$$k_s = \frac{X_{m}}{X} = \frac{l_1 l_3}{l_2}$$

(1)

Then the proportional directional valve is driven by the load plunger through the connecting rod to move the distance $X_{n1} = X_2 k_s$.

Suppose the displacement of the servo plunger is $X_s$, and the proportional coefficient of the displacement transmitted by the feedback link is $k_f$.

$$k_f = \frac{l_3 - l_1}{l_1}$$

(2)

The servo plunger drives the reversing valve to move a distance of $X_{n2} = X_s k_f$ through the feedback link, so the actual moving distance of the reversing valve is:

$$X_4 = X_{n1} - X_{n2} = X_2 k_s - X_s k_f$$

(3)
Laplace transform to (3) formula:

\[ \Delta PA = m_s S^2 X_s + B_s S X_s + k_s X_s \]  \hspace{1cm} (4)

Bringing (4) into (3) equation gives:

\[ X_s = \frac{\Delta PA}{\frac{S^2}{\omega_n^2} + \frac{2 \xi}{\omega_n} S + 1} - X_s k_s \]  \hspace{1cm} (5)

In the formula, \( \omega_n = \frac{k_s}{m_s} \) is the natural frequency of the load plunger, and \( \xi_s = \frac{B_s}{2 S k_s m_s} \) is the load plunger damping ratio.

3.2 Servo plunger motion equation

According to the linearized flow calculation formula of the spool valve:

\[ q_s = K_q X_o - K_q (p - p_o) \]  \hspace{1cm} (6)

In the formula, \( K_q \) is the valve port flow gain, \( K_q \) is the flow pressure coefficient, \( p \) is the pump outlet pressure, \( p_o \) is the servo plunger large end pressure.

Servo plunger flow continuity equation:

\[ q_s = A_s \dot{X}_s + C_p p_s + \frac{V}{4 \beta_s} \dot{p}_s \]  \hspace{1cm} (7)

In the formula, \( A_s \) is the acting area of the large end of the servo plunger, \( V \) is the effective volume of the large cavity of the servo plunger, \( \beta_s \) is the effective volume modulus of elasticity, and \( C_p \) is the total leakage coefficient of the servo plunger.

The force balance equation between the input force of the servo plunger and the load force:

\[ p_s A_s - p A_s = m_s \ddot{X}_s + B_s \dot{X}_s + F_s \]  \hspace{1cm} (8)

In the formula, \( A_s \) is the servo plunger small end acting area, \( m_s \) is the servo plunger mass, \( B_s \) is the servo plunger viscosity-resistance coefficient, \( F_s \) is the external force applied to the servo plunger.

Laplace transform to (6), (7), (8) formulas:

\[ Q_s = K_q X_s - K_q P_s \]  \hspace{1cm} (9)

\[ Q_s = A_s S X_s + C_p P_s + \frac{V}{4 \beta_s} S P_s \]  \hspace{1cm} (10)

\[ P_s A_s = m_s S^2 X_s + B_s S X_s \]  \hspace{1cm} (11)

Combine (9), (10) and (11) together, Because the viscous damping coefficient \( B_s \) is very small, the piston velocity \( \frac{K_s B_s A_s}{A_s} S X_s \) produced by the leakage amount \( \frac{K_s B_s A_s}{A_s} S X_s \) caused by the viscous friction force \( B_s S X_s \) is much smaller than the movement velocity of the piston \( SX_s \), which is \( \frac{K_s B_s A_s}{A_s} \ll 1 \), of where \( K_s = K_v + C_p \) is

\[ X_s = \frac{K_v A_s}{A_s} X_s \]

\[ \frac{S^2}{\omega_n^2} + \frac{2 \xi}{\omega_n} S + 1 \]  \hspace{1cm} (12)
3.3. Constant power control transfer function

Combine formulas (7) and (14) to establish a control block diagram of the system transfer function, as shown in Figure 4:

![Axial piston pump variable regulator power control transfer function diagram](image)

The resume of the power control transfer function establishes the theoretical basis for the subsequent simulation analysis of the dynamic characteristics of the constant power variable regulator of the plunger pump.

4. Dynamic Characteristic Simulation of Variable Regulator Constant Power Control

According to the transfer function, the dynamic model of the power control of the adaptive regulator is designed in Matlab using the Simulink visual simulation toolkit as shown in Figure 5 below. Set the current P to 15MPa, the step signal \( \Delta P \) to 2.5MPa, and the step signal start time to 0s.

![Variable regulator simulation model](image)

Simulink can set up modeling single-rate and multi-rate discrete systems and hybrid continuous discrete systems by controlling the execution speed of the block. For the convenience of research, the
sampling time of the step signal is set to 0.01, the start time of the step is set to 0.2, and the Simulink simulation time is set to 1s. The simulation results are shown in Figure 6.

It can be seen from Figure 6 that the displacement of the servo plunger starts to change at 0.2s and tends to a stable state at 0.285s. From the curve point of view, the control mechanism responds quickly after obtaining the control pressure signal, and it can be stable at about 0.085s, which meets the requirements of the rapidity of variable pump constant power control flow adjustment. In order to make the system have a faster response speed and better stability, reasonable matching of various parameters of the working condition adaptive regulator is very important. In order to study the influence of different parameters on the constant power control of the regulator, the following sets of comparative simulation experiments are done.

4.1 Constant power control transfer function

The stiffness of the external spring of the power control determines the proportional coefficient of the load pressure and the flow rate, and determines the flow rate change rate of the pump variable. Under the same load pressure, it determines the pump output flow rate. The measured stiffness of the outer spring for power control is 120N/m. In order to study the influence of the increase and decrease of the stiffness of the outer spring on the dynamic response, the stiffness is changed to 110N/m and 130N/m, respectively, and the servo plunger dynamics obtained by simulation. The response curve is shown in Figure 7, the dynamic response curve of the pump variable is shown in Figure 8, and the response data results are compared in Table 1.

![Fig.7 Dynamic response curve of new variable regulator servo plunger with different outer spring stiffness](image1)

![Fig.8 Dynamic response curve of flow change with different outer spring stiffness](image2)


Table 1: Comparison of dynamic response results of different outer spring stiffness

| Power control outer spring stiffness | Rise Time | Steady state displacement | Steady state flow |
|-------------------------------------|-----------|---------------------------|------------------|
| 110N/m                              | 0.273S    | 0.3201mm                  | 62.53L/min       |
| 120N/m                              | 0.262S    | 0.2716mm                  | 62.61L/min       |
| 130N/m                              | 0.266S    | 0.2335mm                  | 62.65L/min       |

It can be seen from Figure 7 and Table 1 that the stiffness of the power control outer spring decreases and the steady-state value of the servo plunger increases. As the stiffness becomes larger, the steady-state value of the servo plunger decreases. The response time of the servo plunger from the start of the step to the steady state is basically unchanged. This is because when the load pressure on the load plunger changes, the response speed is relatively fast compared to the response of the servo plunger, and the spring stiffness is within a certain range. When it changes, it has little effect on the response speed of the servo control system. It can also be seen from Figure 8 that when the load pressure changes $\Delta P$ the same, the increase in spring stiffness will reduce the change in flow rate, but it has little effect on the response speed of the control.

4.2. The influence of the proportional coefficient of the transmission displacement of the feedback fork on the dynamic response of the variable regulator

The displacement transfer proportional coefficient of the feedback fork determines the magnitude of the feedback gain, so its value will also affect the stability and response speed of the system. The initial displacement transfer proportional coefficient is 0.1101. In order to study the influence of the increase and decrease of the coefficient on the dynamic response, under the condition of the other parameters unchanged, the proportional coefficient is increased and decreased by 0.01 respectively, and set to 0.1001, 0.1101 and 0.1201, simulation. The results are shown in Figure 9 and Table 2.

Table 2: Comparison of the dynamic response results of the displacement transfer ratio coefficients of different feedback forks

| Scale factor | Rise Time | Steady state displacement |
|-------------|-----------|---------------------------|
| 0.1001      | 0.347s    | 0.3137mm                  |
| 0.1101      | 0.326s    | 0.2852mm                  |
| 0.1201      | 0.324s    | 0.2615mm                  |

It can be seen from Figure 9 and Table 2 that by increasing the proportional coefficient of the displacement transmission of the feedback fork, the rise time of the condition-adaptive regulator is basically unchanged, but the steady-state displacement value of the servo plunger changes, and the larger the proportional coefficient, the smaller the steady-state displacement value. Therefore, the change of the proportional coefficient of the feedback fork within a certain range will not have much impact on the response speed of the system.
5. Conclusion
The stiffness of the power control outer spring increases, and the steady-state displacement value of the servo plunger decreases. It basically has no effect on the steady-state response time of the servo plunger displacement. At the same time, the increase in spring stiffness will reduce the amount of change in flow, but has little effect on the response speed of the control.

The change of the displacement transfer ratio coefficient of the feedback fork within a certain range will only affect the steady-state displacement value of the servo plunger, and then change the pump outlet flow, but it will affect the dynamic response of the axial plunger pump variable regulator not big.

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