A STUDY OF THE INFLUENCES OF PIPE ON VALVE CONTROL HYDRAULIC SYSTEM

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ABSTRACT

The accurate mathematical model of valve control hydraulic system with long pipeline is constructed through theoretical analysis. The influences of long pipeline on valve control hydraulic system are investigated. A series of conclusions were obtained, which are important to the design and analysis of valve control hydraulic system.

INTRODUCTION

Large-sized construction machinery usually has tens of actuators. All of them get power from a central hydraulic source. Some are far away from the hydraulic source. The long pipeline between actuator and hydraulic source is essential sometimes. It causes many problems to electro-hydraulic system. This paper studies the influences of long pipeline on valve control system and comes to some simply and valuable conclusions.

TRANSFER FUNCTION OF VALVE CONTROL SYSTEM

In order to analyze the characteristics of valve control system with long pipeline, The transfer function of valve control system must be established. Fig.1 shows the principle of valve control system with long pipeline

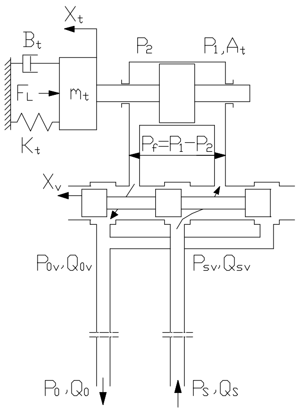

Fig.1 The principle of valve control system

(1) Pipe Dynamic Characteristics Equation[2][4]

$$\begin{cases} P_1(s) = P_2(s)ch\Gamma(s) + Z_C(s)Q_2(s)sh\Gamma(s) \\ Q_1(s) = Q_2(s)ch\Gamma(s) + \dfrac{1}{Z_C(s)}P_2(s)sh\Gamma(s) \end{cases}$$

Assume that the hydraulic source supply constant pressure oil, the return pressure is zero and the length of in-line and return line is equal, then we obtain

$$P_{sv}(s)ch\Gamma(s) + Z_C(s)Q_{sv}(s)sh\Gamma(s) = 0 \quad (1)$$

$$P_{0v}(s)ch\Gamma(s) - Z_C(s)Q_{0v}(s)sh\Gamma(s) = 0 \quad (2)$$

where $\Gamma(s)$ —propagation operator

$Z_c(s)$ characteristic impedance

(2) Four-way Slide valve Dynamic Equation

If orifice area of slide valve is matching and symmetric, then the flow-pressure equation is

$$Q_L = C_d A_1\sqrt{\frac{P_{sv} - P_f - P_{0v}}{r}} - C_d A_2\sqrt{\frac{P_{sv} + P_f - P_{0v}}{r}} \quad (3)$$

$$Q_{sv} = Q_{0v} = C_d A_1\sqrt{\frac{P_{sv} - P_f - P_{0v}}{r}} + C_d A_2\sqrt{\frac{P_{sv} + P_f - P_{0v}}{r}} \quad (4)$$

where

$$A_1 = \begin{cases} A_{10} + W\cdot X_V , & X_V \ge -\dfrac{A_{10}}{W} \\ 0 , & X_V \le -\dfrac{A_{10}}{W} \end{cases}$$

$$A_2 = \begin{cases} A_{20} - W\cdot X_V , & X_V \le \dfrac{A_{20}}{W} \\ 0 , & X_V \ge \dfrac{A_{20}}{W} \end{cases}$$

A_1 is the orifice area of $P \to A$ or $B \to T$, A_2 is the orifice area of $P \to B$ or $A \to T$, A_{10} and A_{20} are the orifice area of operating point, W is the area gradient, X_v is the relative motion of spool to operating point. C_d is the flow coefficient. The Laplace transforms of Eq. (3) and Eq. (4) are as follows

$$Q_L(s) = K_Q X_v(s) - K_C P_f(s) + K_S P_{sv}(s) + K_0 P_{0v}(s) \quad (5)$$

$$Q_{sv}(s) = K_{QS} X_v(s) - K_{CS} P_f(s) + K_{SS} P_{sv}(s) + K_{0S} P_{0v}(s) \quad (6)$$

where

$$K_Q = \frac{\partial Q_L}{\partial X_v}$$

$$= \begin{cases} \frac{C_d W}{\sqrt{r}} (\sqrt{P_{sv} - P_f - P_{0v}} + \sqrt{P_{sv} + P_f - P_{0v}}) , & A_{10} \cdot A_{20} \neq 0 \\ \frac{C_d W}{\sqrt{r}} (\sqrt{P_{sv} - | P_f | - P_{0v}}) & , A_{10} \cdot A_{20} = 0 \end{cases}$$

$$K_C = \frac{\partial Q_L}{\partial P_f}$$

$$= \begin{cases} \frac{C_d}{2\sqrt{r}} (\frac{A_{10}}{\sqrt{P_{sv} - P_f - P_{0v}}} + \frac{A_{20}}{\sqrt{P_{sv} + P_f - P_{0v}}}) , & A_{10} \cdot A_{20} \neq 0 \\ \frac{C_d}{2\sqrt{r}} (\frac{A_{10} + A_{20}}{\sqrt{P_{sv} - | P_f | - P_{0v}}}) & , A_{10} \cdot A_{20} = 0 \end{cases}$$

$$K_{CS} = -\frac{\partial Q_S}{\partial P_f}$$

$$= \begin{cases} \frac{C_d}{2\sqrt{r}} (\frac{A_{10}}{\sqrt{P_{sv} - P_f - P_{0v}}} - \frac{A_{20}}{\sqrt{P_{sv} + P_f - P_{0v}}}) & , \quad A_{10} \cdot A_{20} \neq 0 \\ \frac{C_d}{2\sqrt{r}} \frac{A_{10}}{\sqrt{P_{sv} - | P_f | - P_{0v}}} & , \quad A_{10} \geq 0 \text{çò} A_{20} = 0 \\ -\frac{C_d}{2\sqrt{r}} \frac{A_{20}}{\sqrt{P_{sv} - | P_f | - P_{0v}}} & , \quad A_{20} \geq 0 \text{çò} A_{10} = 0 \end{cases}$$

$$K_{QS} = \frac{\partial Q_S}{\partial X_v}$$

$$= \begin{cases} \frac{C_d W}{\sqrt{r}} (\sqrt{P_{sv} - P_f - P_{0v}} - \sqrt{P_{sv} + P_f - P_{0v}}) & \text{£¬} \; A_{10} \cdot A_{20} \neq 0 \\ \frac{C_d W}{\sqrt{r}} \sqrt{P_{sv} - | P_f | - P_{0v}} & \text{£¬} \; A_{10} \geq 0 \text{çò} A_{20} = 0 \\ -\frac{C_d W}{\sqrt{r}} \sqrt{P_{sv} - | P_f | - P_{0v}} & , \quad A_{20} \geq 0 \text{çò} A_{10} = 0 \end{cases}$$

$$K_S = \frac{\partial Q_L}{\partial P_S} = K_{CS} \quad , \quad K_0 = \frac{\partial Q_L}{\partial P_0} = -K_{CS}$$

$$K_{SS} = \frac{\partial Q_S}{\partial P_S} = K_C \quad , \quad K_{0S} = \frac{\partial Q_S}{\partial P_0} = -K_C$$

(3) The Continuity Equation and Force Balance Equation of Cylinder

$$Q_L = A_t \frac{dX_t}{dt} + \frac{V_t}{4E_y} \cdot \frac{dP_f}{dt} + C_{sl} \cdot P_f$$

$$(Continuity \quad Equation) \quad (7)$$

$$A_t P_f = m_t \frac{d^2 X_t}{dt^2} + B_t \frac{dX_t}{dt} + K_t X_t + F_L$$

$$(Force \quad Balance \quad Equation) \quad (8)$$

where A_t and X_t are the area and motion of hydraulic cylinder piston respectively, E_Y is the equivalent volume elastic modulus, V_t is the general volume of hydraulic cylinder, C_{sl} is the general leakage coefficient. Eqs. (1), (2), (5), (6) together with the Laplace transforms of Eq. (7) and Eq. (8) composed a set equations, from which we can obtain the transfer function of system as follows

$$G(s) = \frac{\dot{X}_t}{X_v}$$

$$= \frac{K_v + 2K_{vp} G_1(s)}{(\frac{s^2}{w_h^2} + \frac{2x_h}{w_h} s + 1) + 2G_1(s) K_C (\frac{s^2}{w_h^2} + \frac{2x_h^{'}}{w_h} s + 1)} \qquad (9)$$

where

$$G_1(s) = \frac{Z_C sh(\Gamma(s))}{ch(\Gamma(s))}$$

$$w_h = \sqrt{\frac{4E_y A_t^2}{m_t V_t}}$$

$$x_h = \frac{(K_C + C_{sl})}{A_t} \sqrt{\frac{E_y m_t}{V_t}} + \frac{B_t}{4A_t} \sqrt{\frac{V_t}{E_y m_t}}$$

$$x_h^{'} = x_h - \frac{K_{CS}^2}{A_t K_C} \sqrt{\frac{E_y m_t}{V_t}}$$

$$K_v = \frac{K_Q}{A_t}$$

$$K_{vp} = \frac{K_Q K_C - K_{QS} K_{CS}}{A_t}$$

THEORETICAL ANALYSIS OF THE INFLUENCES OF PIPE ON VALVE CONTROL HYDRAULIC SYSTEM

When the influence of pipe is neglected

$P_{sv} = P_s$ =constant $\quad P_{0v} = P_0 = 0 \quad G_1(s) = 0$

The transfer function of system is

$$G^{'}(s) = \frac{\dot{X}_t}{X_v} = \frac{K_v}{\frac{s^2}{w_h^2} + \frac{2x_h}{w_h} s + 1}$$

The influences of pipe on system can be measured by the difference between $G(s)$ and $G^{'}(s)$.

While the difference in amplitude frequency and phase-frequency characteristic is expressed by

$$e_A(w) = \frac{\| G(jw) | - | G^{'}(jw) \|}{| G(jw) |}$$

and

$$e_j(w) = | j(G(jw)) - j(G^{'}(jw)) |$$

respectively, we can reach the following conclusion.

If $2(2K_C - \frac{K_{QS}}{K_Q} K_{CS}) | G_1(jw) | \leq E << 1$ then

$e_A(w) \leq E$ and $e_j(w) \leq E$

The certification is neglected here

If we define

$$e(w) = 2(2K_C - \frac{K_{QS}}{K_Q} K_{CS}) | G_1(jw) | ,$$

then $e(w)$ can be used to measure the influences of pipe on system approximately..

When slide valve is in different operating position, the influences of pipe to system are discussed as follows

(i) Zero position

When slide valve is in zero position, $K_C = K_{CS} = 0$, $e(w) = 0$. Pipe has a little influence on the dynamic characteristics of system. The actual value of K_c and K_{cs} aren't zero but very small. So, the influence of pipe to system is minimal under the condition

(2) Nonzero position

When slide valve is in nonzero position,

$$K_Q = K_{QS}\ ,K_C = K_{CS}\ ,e(w) = 2K_C\ |G_1(jw)|$$

It will be seen that if K_C is small enough, the influences of pipe on system can be neglected. According to the theory of fluid transmission lines, $|G_1(jw)|$ reaches maximal point at resonance frequency and fluctuates periodically as frequency ascends. Accordingly, $G(jw)$ fluctuates periodically relating to $G^{'}(jw)$. The fluctuation frequency is proportional to the length of pipe. The fluctuation amplitude descends as frequency ascends.

SIMULATION STUDY

It will be seen that the influences of pipe on hydraulic system are related to the steady-state point of slide valve. Slide valve is in zero position in position control system and in nonzero position in velocity control system. The following is the simulation study of them.

(1) Position Control System

The simulation parameters are as follows:

$w_h = 137.2$

s^{-1} $K_C = 4.2\times10^{-11}$ $K_{CS} = 3.2\times10^{-12}$

$K_Q = K_{QS} = 0.5$

$x_h = 0.5$ $x_h^{'} = 0.495$ $K_v = 250$

$K_{vp} = 9.7\times10^{-9}$

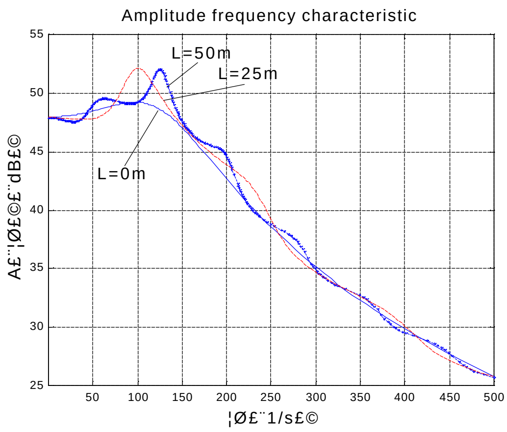

Fig.2 presents the frequency response characteristics of valve control hydraulic system under different pipe length. The simulation result shows:

the frequency response curve of system exists periodic fluctuation

the fluctuation frequency is proportional to the length of pipe.

the fluctuation amplitude reaches maximum near the natural frequency of system and is smaller in low-frequency and high-frequency stage

The frequency response is generally approximate to second-order system.

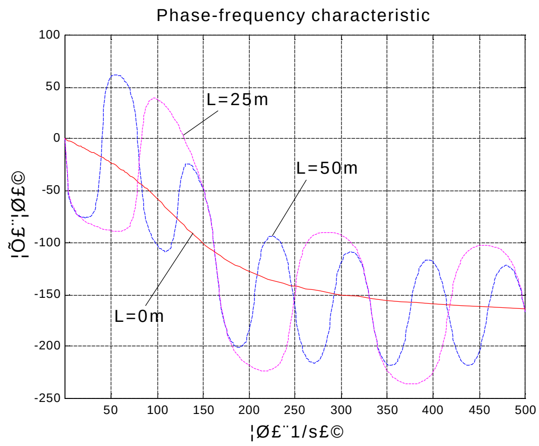

Fig.2 The frequency response characteristic of system when slide valve is in zero Position

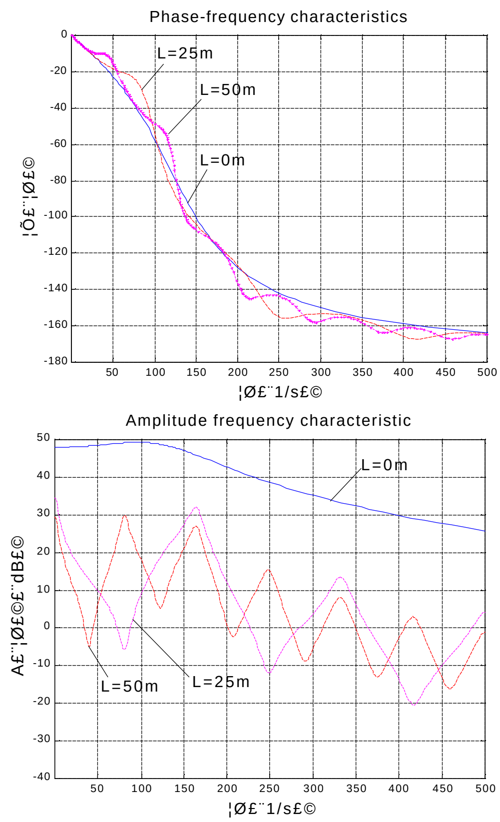

Fig.3 The frequency response characteristic of system when slide valve is in nonzero position

(2) Velocity Control System

The simulation parameters are as follows

$w_h = 137.2$

s^{-1} $K_C = 4.2\times10^{-11}$

$K_{CS} = 4.2\times10^{-12}$ $K_Q = K_{QS} = 0.5$

$x_h = 0.5$ $x_h^{'} = 0.495$ $K_v = 250$ $K_{vp} = 0$

Fig.3 presents the frequency response characteristics of valve control hydraulic system under different pipe length.

The simulation result shows:

the frequency response of system fluctuates periodically.

the fluctuation amplitude descends when the frequency ascends

the fluctuation frequency is proportional to the length of pipe.

If the length of pipe or the value of K_C isn't small enough, the system can't be considered as second-orde system.

CONCLUSION

This paper has presented an accurate mathematical model for valve control hydraulic system with long pipeline. On the basis of the analysis to it, some conclusions are reached.

1. The influences of pipe on system can be measured approximately with the frequency domain criterion

$$e(w) = 2(2K_C - \frac{K_{QS}}{K_Q}K_{CS})\,|G_1(jw)|$$

2. For given pipe parameters, K_c decides the influences of pipe on system in terms of ideal zero lap slide valve.
3. Pipe makes the frequency response of system fluctuating periodically. The fluctuation frequency is proportional to the length of pipe. The fluctuation amplitude is decided by valve coefficient, pipe elastic modulo and pipe inner diameter.
4. The influences of pipe are greater to velocity control system than to position control system.

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