

Robust Output-feedback Control for Piloted Electro-hydraulic Proportional Pressure-reducing Valve

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Abstract. The paper aims at piloted electro-hydraulic proportional pressure-reducing valve characteristics of uncertain parameters, immeasurable states and effect of load flow, designed an observer including load flow and it's feedback controller ,achieve robust output-feedback control to the output pressure .Based on linear matrix inequalities, theoretical analysis showed that the system was stable and had robust H-infinity performance , given the method to obtain the observer gain L and controller gain K. By simulating a certain proportional pressure reducing valve, verified the validity of the algorithm, eliminated the influence of load flow to output pressure and ensured it following the set pressure quickly.

Introduction

The excitation system for track subgrade dynamic response test is used for simulating the comprehensive influence of the static load and dynamic load on the subgrade when train running at high speeds, the main unit of test system include dual stage servo hydraulic cylinders and hydraulic vibration system [1-2]. The system supplies constant pressure for static cavity of dual stage servo hydraulic cylinder by using piloted electro-hydraulic proportional pressure reducing valve, used to simulate the static force of train, at the same time the static cavity also be effected by alternating excitation force from dynamic cavity. How to make the static cavity loaded force kept constant, depending on the precise control of the pilot electro-hydraulic proportional pressure reducing valve.

In practical application, usually use open-loop control for electro-hydraulic proportional pressure reducing valve pressure control, because the system parameters are uncertainty and nonlinear, by using conventional control algorithms based on precise mathematical model, the output pressure is difficult to achieve the requirements of fast tracking performance, accuracy and robustness [3-4].

System description

The piloted electro-hydraulic proportional pressure reducing valve mainly include the amplifier, the proportional electromagnet, pilot poppet valve and three way slide valve [5].

Pilot level modeling. The response frequency of the proportional electromagnet controller is far higher than the proportional pressure reducing valve [6] , and Pilot poppet valve is little quality, small stroke and large elastic stiffness , therefore, obtained for the pilot stage simplified model:

$$P_2 = K_t U_g / A_x \quad (1)$$

Master valve equation [7-8]. The most important operating point of Pressure reducing valve is the origin (QL=P1= Y=0), if the system is stable in this operating point, it is stable at other operating points. So, the flow equation of master valve:

$$\frac{V_2}{E} \frac{dP_1}{dt} = C_d \omega \sqrt{P / \rho} Y + A_1 \frac{dY}{dt} - Q_L \quad (2)$$

The force balance equation of master spool:

$$A_2 K_t U_g / A_x - P_1 A_1 = M \frac{d^2 Y}{dt} + (B + A_1^2 R_2) \frac{dY}{dt} + K_{Y0} Y \quad (3)$$

Where, R_2 is the liquid resistance of fixed damper orifice, $N \cdot S/m^5$; Q_L is the load flow, m^3/S ; E is the elastic modulus of oil, N/m^2 ; P is the supply pressure, Pa; P_1 is the output pressure, Pa; P_{1S} is the left cavity pressure of master valve, Pa; A_1 is the effective area of the master spool left end, m^2 ; V_2 is the effective volume connecting master valve outlet and load orifice, m^3 ; C_d master valve port flow coefficient; ω is the area coefficient; ρ is the oil density, K_g/m^3 ; M is the master spool quality, K_g ; K_{Y0} is the reset spring stiffness coefficient, N/m ; B is the viscous damping coefficient, $N \cdot s/m$; Y is the master spool displacement, m .

Model description. Set $x_x=Y$ as the main spool displacement, P_r desired output pressure of the proportional pressure reducing valve, P_1 is output pressure measurements. The state variables $x_1=x_x$, $x_2=\dot{x}_x$, $x_3=P_r - P_1$, $X=[x_1 \ x_2 \ x_3]^T$, by formula (2) and (3) to obtain the state equation of the system as follows:

$$\begin{cases} \dot{X}_1 = X_2 \\ \dot{X}_2 = -a_1 X_1 - a_2 X_2 + a_3 X_3 + bb U_g - P_{r1} + \Delta_1 X + \Delta_3 U_g + \Delta_4 P_r \\ \dot{X}_3 = -a_4 X_1 - a_5 X_2 + Q_{lk} + \Delta_2 X \end{cases} \quad (4)$$

Where, $a_1 = K_{Y0}/M$, $a_2 = (B + A_1^2 R_2)/M$, $a_3 = A_1/M$, $a_4 = C_d \omega \sqrt{P/\rho} E/V_2$, $a_5 = A_1 E/V_2$, $bb = A_2 K_t / (A_x M)$, $P_{r1} = a_3 P_r$, $Q_{lk} = Q_L E/V_2$, above parameter is the basic parameter. $\Delta_1 = [-da_1 \ -da_2 \ da_3]$, $\Delta_2 = [-da_4 \ -da_5 \ 0]$, $\Delta_3 = d_{bb}$, $\Delta_4 = da_3$, is the uncertainty part, and bounded, $|da_i| \leq D_{aj}$, $|d_{bb}| \leq D_{bb}$, $i=1 \sim 5$, D_{aj} and D_{bb} are known positive.

Robust output feedback controller design

Set the $\zeta_1 = x_1 - Q_{lk}/a_4$, $\zeta_2 = x_2$, $\zeta_3 = x_3$, $\zeta = [\zeta_1 \ \zeta_2 \ \zeta_3]^T$, formula (4) can be transformed into:

$$\begin{cases} \dot{\zeta} = A\zeta + B(U_g - S_5) + D_1(S_1 + S_3 + S_4) + D_2 S_2 \\ y = C\zeta \end{cases} \quad (5)$$

Where, $A = [0 \ 1 \ 0; -a_1 \ -a_2 \ a_3; -a_4 \ -a_5 \ 0]$, $B = [0 \ bb \ 0]^T$, $D_1 = [0 \ 1 \ 0]^T$, $D_2 = [0 \ 0 \ 1]^T$, $C = [0 \ 0 \ 1]^T$, $S_1 = \Delta_1 \zeta - da_1 Q_{lk}/a_4$, $S_2 = \Delta_2 \zeta - da_4 Q_{lk}/a_4$, $S_3 = \Delta_3 U_g$, $S_4 = -da_3 P_r$, $S_5 = (P_{r1} + a_1 Q_{lk}/a_4)/bb$.

The system state variables only system output x_3 can be measured, therefore, need to construct the full-order observer was used to estimate all state variables.

$$\dot{\delta} = A\delta + B(U_g - S_5) + D_1 S_3 + L(y - C\delta) \quad (6)$$

Where, δ is the estimated value of ζ , $L \in \mathbb{R}^{3 \times 1}$ is the observer gain. Estimates error is set as $\varepsilon = \zeta - \delta$, dynamic error equations are as follows:

$$\dot{\varepsilon} = A_{11}\varepsilon - LC\varepsilon + D_1(\Delta_1 \delta + \theta_1) + D_2(\Delta_2 \delta + \theta_2) \quad (7)$$

Where, $A_{11} = A + D_1 \Delta_1 + D_2 \Delta_2$, $\theta_1 = S_4 - da_1 Q_{lk}/a_4$, $\theta_2 = -da_4 Q_{lk}/a_4$.

Based on the full order observer (6), get the robust output feedback controller:

$$U_g = K\delta + S_5 \quad (8)$$

The observer can be simplified as:

$$\dot{\delta} = (A + B_1 K)\delta + B_2 \theta_3 + LC\varepsilon \quad (9)$$

Where, $B_1 = [0 \ bb + d_{bb} \ 0]^T$, $B_2 = [0 \ d_{bb} \ 0]^T$, $\theta_3 = S_5$, $K \in \mathbb{R}^{1 \times 3}$ is the gain of the feedback controller.

Theorem 1 for the augmented system (7), (9) and given positive α , β_1 and appropriate positive definite diagonal matrix λ_1 , if exists symmetric positive real matrix $W \in \mathbb{R}^{3 \times 3}$ and $V \in \mathbb{R}^{3 \times 3}$, real matrix $E \in \mathbb{R}^{3 \times 1}$ and $F \in \mathbb{R}^{1 \times 3}$, positive real numbers R_{11} and R_{12} , which makes the follows linear matrix inequality has a solution, so $u(t) = FV^{-1} \delta(t) + S_5$ is the optimal H-infinity robust control law of this closed loop system composed of $u(t)$ and the augmented system (7), (9), also make the closed loop system bounded.

$$\min_{W, E, R_{11}} R_{11}$$

$$s.t. \begin{bmatrix} \Psi_1 & WD_1 & WD_2 \\ D_1^T W & -\frac{R_{11}}{2} & 0 \\ D_2^T W & 0 & -\frac{R_{11}}{2} \end{bmatrix} \leq 0 \quad (10)$$

$$\min_{V, F, R_{11}, N} \text{Trace}(N)$$

$$s.t. \quad (i) \begin{bmatrix} \Psi_2 & B_2 & V\Delta_{11}^T & V\Delta_{22}^T \\ B_2^T & -R_{12} & 0 & 0 \\ \Delta_{11}V & 0 & -R_{11}^{-1} & 0 \\ \Delta_{22}V & 0 & 0 & -R_{11}^{-1} \end{bmatrix} \leq 0 \quad (11)$$

$$(ii) \begin{bmatrix} -N & F^T \\ F & -I \end{bmatrix}$$

Where, $\Delta_{11} = [D_{a1} \ D_{a2} \ D_{a3}]$, $\Delta_{22} = [D_{a4} \ D_{a5} \ 0]$, $\Psi_1 = A_{11}^T W + WA_{11} - EC - C^T E + \alpha W + \lambda_1$, $\Psi_2 = VA^T + AV + B_1 F + F^T B_1^T + \alpha V + LCC^T L^T / \beta_1$.

By the calculated real symmetric positive matrices W and V , real matrix E and F , we can get the observer gain $L = W^{-1}E$ and controller gain $K = FV^{-1}$.

Proof: select Lyapunov function $Z(\varepsilon, \delta) = Z(\varepsilon) + Z(\delta) = \varepsilon^T W \varepsilon + \delta^T Q \delta$, where Q is a symmetric positive definite matrix.

The time derivative of estimation error:

$$\dot{Z}(\varepsilon) = \dot{\varepsilon}^T W \varepsilon + \varepsilon^T W \dot{\varepsilon} = \varepsilon^T \left(A_{11}^T W + WA_{11} - (LC)^T W - WLC \right) \varepsilon + 2\varepsilon^T WD_1(\Delta_1 \delta + \theta_1) + 2\varepsilon^T WD_2(\Delta_2 \delta + \theta_2) \quad (12)$$

By the correlation lemma shows that the existence of any positive scalar R_{11} , satisfies the following inequalities:

$$2\varepsilon^T WD_1(\Delta_1 \delta + \theta_1) \leq 2R_{11}^{-1} \varepsilon^T WD_1 D_1^T W \varepsilon + R_{11} \delta^T \Delta_{11}^T \Delta_{11} \delta + R_{11} \theta_1^2 \quad (13)$$

$$2\varepsilon^T WD_2(\Delta_2 \delta + \theta_2) \leq 2R_{11}^{-1} \varepsilon^T WD_2 D_2^T W \varepsilon + R_{11} \delta^T \Delta_{22}^T \Delta_{22} \delta + R_{11} \theta_2^2 \quad (14)$$

Set $E = WL$, feeding the formula (13), (14) into (12), by linear inequality (10), fined that:

$$\dot{Z}(\varepsilon) \leq -\alpha Z(\varepsilon) - \varepsilon^T \lambda_1 \varepsilon + R_{11} \theta_\varepsilon \quad (15)$$

In the formula, $\theta_\varepsilon = \delta^T \Delta_{11}^T \Delta_{11} \delta + \delta^T \Delta_{22}^T \Delta_{22} \delta + \theta_1^2 + \theta_2^2$ is disturbance quantity caused by parameter uncertainty part, select the smallest positive real number R_{11} , we can ensure that the disturbance to observer caused by parameter uncertainty part, is reduced to a minimum, so that the observer can accurately estimate the system state.

The time derivative of observer estimate variable:

$$\dot{Z}(\delta) = \dot{\delta}^T Q \delta + \delta^T Q \dot{\delta} = \delta^T \left((A + B_1 K)^T Q + Q(A + B_1 K) \right) \delta + 2\delta^T QLC\varepsilon + 2\delta^T QB_2 \theta_3 \quad (16)$$

There have any positive scalar R_{12} and β_1 , satisfy the following inequalities:

$$2\delta^T QLC\varepsilon \leq \beta_1^{-1} \delta^T QLCC^T L^T Q \delta + \beta_1 \varepsilon^T \varepsilon \quad (17)$$

$$2\delta^T QB_2 \theta_3 \leq R_{12}^{-1} \delta^T QB_2 B_2^T Q \delta + R_{12} \theta_3^2 \quad (18)$$

Set $V = Q^{-1}$, $F = KV$, by linear inequality (11), fined that:

$$\dot{Z}(\delta) \leq -\alpha Z(\delta) + \beta_1 \varepsilon^T \varepsilon - R_{11} \theta_\delta + R_{12} \theta_3^2 \quad (19)$$

Where $\theta_\delta = \delta^T \Delta_{11}^T \Delta_{11} \delta + \delta^T \Delta_{22}^T \Delta_{22} \delta$.

According to formula (15), (19), obtained the time derivative of system Lyapunov function is:

$$\dot{Z}(\varepsilon, \delta) = \dot{Z}(\varepsilon) + \dot{Z}(\delta) \leq -\alpha Z(\varepsilon, \delta) - \varepsilon^T (\lambda_1 - \beta_1) \varepsilon + R_{11}(\theta_1^2 + \theta_2^2) + R_{12} \theta_3^2 \quad (20)$$

From the inequality (20), we can found that, if choices appropriate parameters α , β_1 and λ_1 , estimation error ε and estimated value δ all converged to finite bounds determined by R_{11} and R_{12} , so that the closed-loop system composed of the controller (8) and the augmented system (7), (9), are bounded, and has a robust H-infinity performance. In addition, minimize R_{11} , select the appropriate R_{12} , through the $\text{Trace}(\delta^T K^T K \delta)$, the amplitude of controller output is minimized, thus its magnitude

is limited in the range of the valve control input signal, and disturbance caused by the parameters uncertain part is inhibited to the narrow limits. Theorem 1 is proved.

Simulation examples

Through the simulation of a certain proportional pressure reducing valve as an example, to verify the effectiveness of the robust output feedback control method. The physical parameters of the proportional pressure reducing valve as follow: $K_t=7$; $K_{Y0}=1e^4$ N/m; $\omega=0.036$ m; $C_d=0.7$; $B=5$ NS/m; $R_2=4.07e^9$ NS/m⁵; $P=2.06e^7$ Pa; $A_X=3.14e^{-6}$ m²; $\rho=850$ kg/m³; $E=9e^8$ N/m²; $A_1=2.94e^{-4}$ m²; $A_2=2.94e^{-4}$ m²; $M=0.16$ Kg; $V_2=5e^{-3}$ m³.

The uncertain parameters are set to $da_1=300$, $da_2=50$, $da_3=1e^{-4}$, $da_4=2000$, $da_5=500$, $d_{bb}=175.7$, and the upper bound are $D_{a1}=500$, $D_{a2}=100$, $D_{a3}=1e^{-4}$, $D_{a4}=5000$, $D_{a5}=2000$, $D_{bb}=175.7$.

Set the proportional pressure reducing valve setting pressure is $P_r=1.2e^7$ Pa, the amplitude of load flow is $Q_L=1.67e^{-3}$ m³/s, we can get the system initial $\zeta(0)=[0 \ 0 \ P_r]^T$ and the observer initial $\delta(0)=[0 \ 0 \ P_r]^T$. According to theorem 1, given the simulation data are $\alpha=0.2$, $\beta_1=1e^5$ and $\lambda_1=\text{diag}([2e^2 \ 4e^1 \ 1.32e^9])$, by formula (10) and (11) we can get: $R_{11}=4.9e^{-11}$, $R_{12}=0.067$, $L=[-629.5; -1.2987e^{13}; 3.489e^{10}]$, $K=[-1.7039e^9 \ -1.2745e^5 \ 0.046597]$.

Substitute the observer gain L and controller gain K into formula (7), (9), and constitute a robust output feedback closed-loop system with the original system (5), using Mat lab to simulate the system when the load flow was 20Hz sine signal $Q_{L2}=Q_L(1-\cos(40*\pi*t))/2$, get the curve of observer output and system state response, shown in figure 1. We can see that the observer and the robust controller can not only adapt to the change of load flow, rapid estimate the observed state, but also can guarantee the system output pressure quickly reach the set pressure, and has very strong robustness to parameter perturbation.

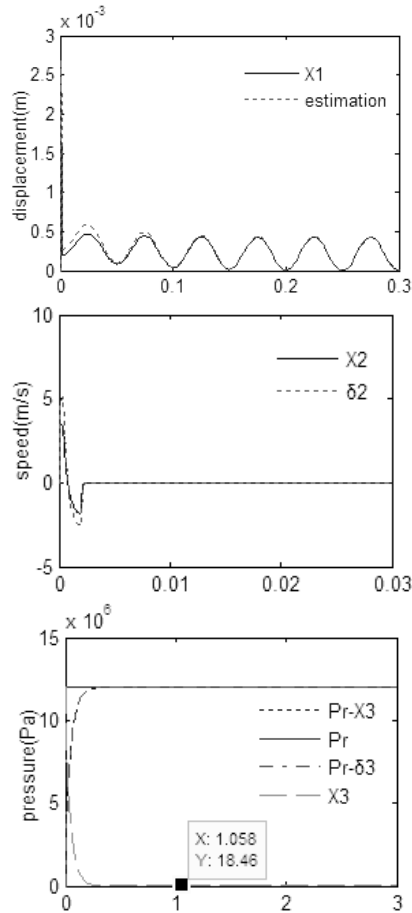


Fig1 the simulation curve of sine load flow

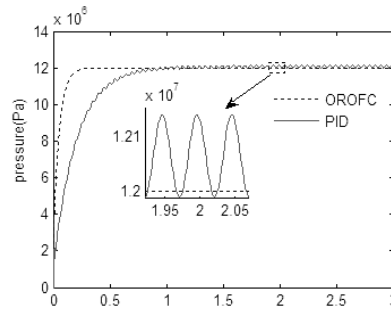


Fig 2 the output pressure of robust output feedback control and PID control

When the load flow was sine signals, we compared the simulation result of the proportional pressure reducing valve with robust output feedback control and PID control, simulation curve as shown in figure 2. We can see that the robust output feedback control has a good dynamic performance of fast response, non-overshoot, response curve smoothing and so on, and the static performance of convergence, and small steady-state error. When system load flow is above sine signal, robust output feedback control existed only 18.45Pa small pressure deviation between the output pressure and the set pressure, while the amplitude pressure deviation of PID control was up to 1.54×10^5 Pa. Therefore, in terms of proportional pressure reducing valve, the robust output feedback control has better dynamic and static performance comparing with the conventional feedback control.

Conclusion

Aim at the characteristics of proportional pressure reducing valve pressure control system with uncertain parameters, immeasurable states and effect of load flow, this paper proposed a robust output-feedback control algorithm based on state observer. Firstly, constructed an observer contain load flow, designed a robust output feedback controller to control the valve output pressure. Secondly, by using the linear matrix inequality, in theory, proposed the control method could guarantee the system stability and had robust H-infinity performance, and given the methods to obtain the observer gain L and controller gain K . Finally, through the simulation of a certain proportional pressure reducing valve, verified the validity of the control algorithm, compares with traditional feedback control, it could not only eliminate the influence of load flow to output pressure, but also made proportional pressure reducing valve having better dynamic and static performance.

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