Research of the regulating value based on iterative learning control of Proportion-Integral-Derivative type

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Abstract. A proportional regulating valve is a hydraulic control valve that allows the output of the output oil parameter (pressure) to vary proportionally to the input electrical signal parameter (current or voltage). Due to the non-linearity of the regulating valve system and the problem of poor response characteristics, this paper studies the performance optimization problem of the system. In order to make the system work steadily, by adding iterative learning controller of Proportion-Integral-Derivative type, the system hydraulic pressure increases with the number of iterations gradually approaching the actual pressure required by the load. The simulation results show that the digital regulating valve based on Proportion-Integral-Derivative control law iterative learning control has fast response speed, high control precision and stable operation. So it can be used as an effective solution to achieve high-performance digital regulating valve.

1. Introduction
The regulating valve is an important pressure control element that must be used in a hydraulic drive system. The output torque of the hydraulic system actuator is achieved by changing the hydraulic system pressure through a proportional regulating valve. In the direct digital control system composed of the regulating valve, the opening of the valve port is directly changed by the stepping motor through the transmission device. By controlling the digital regulating valve, the purpose of controlling the whole system can be adjusted automatically. For the traditional hydraulic system, the control method generally adopts the conventional Proportion-Integral-Derivative control. The three parameters (Proportion, Integral, and Derivative) of the Proportion-Integral-Derivative controller have great influence on the control effect. In the industrial process control, the three parameters are set by the corresponding method, but the three Parameter is difficult to achieve the desired effect. Moreover, since the control object is constantly changing, these three parameters in the conventional Proportion-Integral-Derivative control once determined cannot automatically adjust with the changes in working conditions. So the digital regulating valve of the conventional Proportion-Integral-Derivative control can also be further improved in response to speed, control accuracy, etc.

Iterative learning control is suitable for control systems with repetitive operations over a finite time interval. This kind of control method runs multiple times and adjusts the learned signal with tracking error to achieve a complete tracking of the desired trajectory output by the system. The initial value problem of Iterative learning control is one of the basic problems of iterative learning system. When...
designing an iterative learning system, for the convergence of the system, it is often required that the initial value of the iteration at the beginning of each iteration is consistent with the expected initial value\(^2\). In reference [3], a Proportion-Derivative type learning law is proposed. This learning law can ensure that the limit trajectory tends to zero along the time axis under a fixed initial state. In literature [4], it takes into account the case of zero-mean initial error and proposes a learning algorithm with an average operator. In reference [5], it introduces an initial correction, and the proposed learning algorithm achieves full tracking from a pre-specified moment; the value of the initial correction is finite, thus overcoming the defect of initial pulse action. In references [6]-[9], it introduced the simulation model of the regulating valve. In references [10]-[14], it described the application of the regulating valve.

In this paper, a digital regulating valve based on Proportion-Integral-Derivative control law and iterative learning control is proposed for the shortcomings of the conventional digital control valve. The method is based on the previous experiment Information to obtain a control input capable of generating a desired output track.

2. The principle of proportional regulating value

As shown in figure 1, the pressure signal of the controller that collected by the sensor, compared with the set pressure signal. If when the system pressure value is bigger than the set pressure value, the controller calculates the size of the digital regulating valve core opening, and driven core movement by the stepper motor so that the core opens a certain degree of opening. The system oil pressure drops to the set pressure after the oil flows through the digital regulating valve.

![Figure 1. Block diagram of digital control system](image1)

2.1. Dynamic mathematical model of regulating value

Figure 2 shows the structure of the regulating valve block diagram. By establishing the mathematical model of each unit, the overall mathematical model of the regulating valve can be obtained by further integration.

![Figure 2. Block diagram of regulating valve structure](image2)
And then use a switching amplifier to form the power level of the electronic components for proportional solenoid control, the main role of which is pulse width modulation.

2.1.1. Mathematical model of proportional electromagnet and pilot valve body. As the model of power amplifier and proportional electromagnet is simple, so in the simplified analysis and calculation, it can be regarded as a proportional link and obtained between the control signal and the electromagnet thrust:

\[ \Delta F_{em} = \frac{K_e K_f}{R} \Delta u_i - K_m \Delta y \]  \hspace{1cm} (1)

If the influence of the pilot spool and baffle and the influence of the hydraulic and disturbances on these components is taken into account, the force balance equation of the pilot valve can be established:

\[ F_{em} - \sum p_i A_i - F_{j_x} - F_{j_y} = m \ddot{y} + D_y \dot{y} + K_y (y_{st} + y) \] \hspace{1cm} (2)

In the formula, the \( F_{em} \) is an electromagnet thrust at an electric current; \( \sum p_i A_i \) is the algebraic sum of the fluid pressure on the corresponding area of the moving element; \( F_{j_x} \) is the hydraulic force at the pilot valve port; \( F_{j_y} \) is the Coulomb hydraulic force on the pilot spool; \( m \) is the mass of the pilot-level moving parts; \( D_y \) is the damping factor; \( K_y \) is the equivalent spring stiffness; \( y \) is the opening of the pilot valve port; \( y_{st} \) is the preload of the spring. Usually, \( F_{j_x} \) and \( F_{j_y} \) can be ignored, and the upper form is further simplified:

\[ \Delta F_{em} = F_{em} - \sum (\Delta p_i A_i) = (m s^2 + D_y s + K_y) \Delta y \] \hspace{1cm} (3)

The Laplace transformation of the above formula can be obtained:

\[ G_i(s) = \frac{\Delta y}{\Delta F} = \frac{1}{m s^2 + D_y s + K_y} \] \hspace{1cm} (4)

\( G_i(s) \) conversion of the pilot-level moving parts and displacements That \( \zeta_y \) is the relative damping coefficient of the pilot level, \( w_y \) is the natural frequency of the pilot level. Then \( G_i(s) \) can be rewritten as:

\[ G_i(s) = \frac{\frac{K_y}{s^2 + 2 \zeta_y s + 1}}{w_y^2 + 2 \zeta_y \omega + 1} \] \hspace{1cm} (5)

2.1.2. Mathematical model of pilot-operated fluid resistance network.
Figure 3 shows the pilot-operated fluid resistance bridge network analysis diagram. According to the working principle of the pilot liquid resistance bridge, the relation of $\Delta Q_{R1}$, $\Delta Q_{R1}'$, and $\Delta Q_x$ can be obtained:

$$\Delta Q_x = \Delta Q_{R1} + \Delta Q_{R1}'$$

(6)

$$\Delta Q_x = -K_{yp} \Delta y + K_{qy} (\Delta p_s - \Delta p_y) = G_y \Delta p_s'$$

(7)

In the formula, $K_{yp}$ is the pilot-operated valve orifice flow gain; $K_{qy}$ is the pilot-operated valve port flow pressure coefficient; $G_y$ is the equivalent liquid guide for series $R_x$, $R_y$, $R_g$. When the opening of the pilot-operated valve is $y$, and the gain is $\Delta y$. When the valve is closed, and the pressure increment $\Delta p_s' > 0$, $\Delta Q_x$ are reduced, and

$$\Delta Q_{R1} = G_y (\Delta p_s' - \Delta p_y)$$

(8)

$$\Delta Q_{R1} = G_y (\Delta p_s' - \Delta p_y) = sA_x \Delta x - \frac{V_s \Delta p_s}{E_s}$$

(9)

$x$ is the main valve displacement; $\Delta x$ is the main valve spring preload. It can get the following a formula by the above several formula:

$$\Delta p_s = \frac{C_s \Delta p_s + A_s \Delta x}{G_y} + C_y K_{yp} \Delta y$$

(10)

2.1.3. Mathematical model of main valve control chamber.
Figure 4. Schematic diagram of main valve control chamber

Figure 4 shows the schematic diagram of main valve control chamber of the pilot-operated fluid bridge. The hydrodynamic parameters are the output variables of the main valve, and the flow balance equation for controlling the liquid power, the pressure chamber and the control chamber is:

\[
\begin{aligned}
A_1 p_1 - A_x p_x &= m \dot{x} + ksc(x + x_0) + F_{jx} \\
Q_x &= Q_x - Q_{x1} = A_x \dot{x} - \frac{V_x \dot{p}_x}{E} \\
Q_1 - A_4 \dot{x} - \frac{V_1 \dot{p}_1}{E} &= Q_v = Q_L + \frac{V_2 \dot{p}_2}{E}
\end{aligned}
\]

The steady-state hydraulic power increment of the main valve is decomposed into \(K_{s1} \Delta x\) and \(K_{ps} \Delta p_1\), and the Laplace transformation of the above expressions is carried out and simplified:

\[
(A_1 - K_{ps}) \Delta p_1 - A_4 p_x = (K_{s1} + K_{ps})(\frac{x^2}{w^2} + 1) \Delta x
\]

2.1.4. Mathematical model of inlet chamber of main valve.

Figure 5. Flow balance of inlet chamber of main valve

The flow balance equation of the inlet valve can be analyzed by figure 5:

\[
\Delta Q_i = \Delta Q_{p} - \Delta Q_{a} = \Delta Q_{m1} + \Delta Q_{x} + A_s \Delta x + \frac{V_i \Delta p_1}{E_c}
\]
\[ \Delta Q_i = K_{q_i} \Delta x + K_{q_p} \Delta p_i \]

\[ \Delta p_i = \frac{1}{G_i + K_{q_p}} \left[ \Delta Q_p - \Delta Q_e + G_i \Delta p_v - (K_{q_p} + A_s) \Delta x \right] \]

\[ \Delta p_i = \frac{s}{w_s + 1} \]

The simplified transfer function block diagram of the indirect detection regulating valve obtained from the above links is shown in figure 6.

**Figure 6.** Transfer function chart of indirect detection regulating valve

2.2. **Model simulation of regulating valve**

The parameters of the transfer function of the proportional regulating valve are shown in table 1:

**Table 1.** Parameters of transfer function of proportional regulating valve

| Parameter name | Meaning                                             | Size         | Parameter name | Meaning                                             | Size         |
|----------------|-----------------------------------------------------|--------------|----------------|-----------------------------------------------------|--------------|
| \( R_p + r_p \) | Electromagnetic coil and power amplifier internal resistance | 24 \( \Omega \) | \( K_{p_p} + K_s \) | Main valve equivalent spring stiffness               | 12000 N/m    |
| \( K_v \)      | Voltage amplification factor                         | 3.5          | \( K_{q_p} \)   | Pilot valve port flow pressure coefficient           | 504.6 \( \text{cm}^3/\text{MPa} \cdot \text{s} \) |
| \( K_g \)      | Current negative feedback coefficient                | 6 V/A        | \( G_i \)       | Fixed liquid resistance guide                        | 200.6 \( \text{cm}^3/\text{MPa} \cdot \text{s} \) |
| \( K_{sy} \)    | Armature assembly equivalent spring stiffness         | 2921 N/m     | \( A_s \)       | Main surface area of the main spool                 | 804 mm\(^2\) |
| \( m \)        | Armature component mass                              | 0.012 kg     | \( K_{q_c} \)   | Main valve flow gain                                | 754.2 \( \text{cm}^3/\text{s} \) |
| \( \omega_n \)  | Lead-level natural frequency                         | 493 Hz       | \( M \)         | Main spool mass                                     | 0.071 kg     |
| \( K_i \)      | Electromagnet current force gain                     | 6 N/A        | \( K_{q_b} \)   | Main valve flow pressure coefficient                | 29.4 \( \text{cm}^3/\text{MPa} \cdot \text{s} \) |
| \( K_e \)      | Coefficient of back electromotive force of coil      | 0.0494 Vs    | \( E \)         | Effective elastic modulus of oil                    | 700 MPa      |
| $K_p$ | Pressure gain of pilot valve port | 47.4 MPa/cm | $V_l$ | Valve front pipe volume | 2540 cm$^3$ |
|------|----------------------------------|-------------|------|------------------------|------------|
| $a_o$ | The area of the pilot port | 2.54 mm$^2$ | $K_p$ | Coefficient of steady hydrodynamic pressure | 571 mm$^2$ |
| $A_l$ | Surface area of main valve | 804 mm$^2$ | $\alpha_l$ | Main valve area ratio | 1 |

Set the relevant parameters, according to the model simulink simulation environment simulation shown in figure 7:

![Figure 7. Transfer function chart of indirect detection regulating valve](image1)

![Figure 8. Step response curve](image2)

The simulation of figure 7 above shows the step response of the proportional relief valve signal input and the interference input, as shown in figure 8. By reducing the stiffness of the spring, the gain of the signal input becomes larger, the gain of the flow interference is reduced, and the traffic interference is effectively suppressed.

### 3. Iterative learning control principle

Conventional Proportion-Integral-Derivative controller is the proportion of the given value and the actual return value of the deviation, integral, differential operation, multiplied by the corresponding coefficient superposition to form the control. Its three parameters, namely scale factor, integral coefficient and differential coefficient, are important parameters that influence the control effect.

The idea of iterative learning control is to improve the control quality by repeatedly applying the information obtained from previous experiments to obtain inputs that can produce desired output.
trajectories. Iterative learning control can deal with dynamic systems with very high uncertainty in a very simple way. It is adaptable and easy to implement. More importantly, it does not depend on the exact mathematical model of the dynamic system. It is an algorithm that generates the optimized input signal iteratively and makes the output of the system approach the ideal value as close as possible.

In this paper, the closed loop Proportion-Integral-Derivative type iterative learning control based on feedback is adopted. At the beginning of the study, the initial state of the system is $x_0(0)$, the task of learning control is to design $u_{k+1}(t)$ through the Proportion-Integral-Derivative type learning control law, reduce the $i+1$ times kinematic error by $e_{k+1}(t)$. Considering that the controlled object in this paper is a nonlinear time-varying system, its dynamic process is:

$$\begin{align*}
\dot{x}_i(t) &= A(t)x_i(t) + B(t)u_k(t) \\
y_k(t) &= C(t)x_i(t)
\end{align*}$$

(15)

Closed loop Proportion-Integral-Derivative type iterative learning control law. Among them $\Gamma$, $L$, $\Psi$ are the learning gain matrices.

$$u_{k+1}(t) = u_k(t) + (\Gamma \frac{d}{dt} + L + \Psi \int dt)e_{k+1}$$

(16)

Next, use the formula (15) and (16) to prove it, the motion error $e(t)$ gradually decreases during the iterative learning process.

$$\therefore \quad \dot{x}_i(t) = A(t)x_i(t) + B(t)u_k(t)$$

$$x(t) = Ce^{\int_0^t A(t)dt} + e^{\int_0^t A(t)dt} \left[ \int_0^t B(t)u(t)e^{-\int_0^t A(t)dt} d\tau \right]$$

$$x(t) = Ce^{\int_0^t A(t)dt} + \int_0^t e^{\int_0^t (\tau-	au')} \cdot B(\tau)u(\tau)d\tau$$

$$\phi(t, \tau) = e^{\int_0^t (\tau-	au')}$$

$$x_k(t) - x_{k+1}(t) = \int_0^t \phi(t, \tau)B(\tau)(u_k(\tau) - u_{k+1}(\tau))d\tau$$

(17)

$$\therefore \quad e_k(t) = y_d(t) - y_k(t) \quad e_{k+1}(t) = y_d(t) - y_{k+1}(t), \quad y_d(t) \text{ is the given value,}$$

$$\therefore \quad e_{k+1}(t) - e_k(t) = y_k(t) - y_{k+1}(t) = C(t)(x_k(t) - x_{k+1}(t))$$

$$= C(t)\int_0^t \phi(t, \tau)B(\tau)(u_k(\tau) - u_{k+1}(\tau))d\tau$$

(18)

Final: $\lim_{k \to \infty} |e_k(t)| = 0$

It can be seen from the above equation that the error is gradually reduced with the number of iterations using the Proportion-Integral-Derivative iterative learning control. In other words, the output trajectory $y_d(t)$ converges to the desired trajectory $y_{k+1}(t)$ after $N$ iterations in finite time. In figure 9, The output $u_{k+1}(t)$ of the closed-loop Proportion-Integral-Derivative iterative learning control law is related to the $(k+1)$-th error and the $k$-th output $u_k(t)$.
4. Simulation result analysis
In As shown in figure 10, for the control system of digital regulating valve simulation model, which includes sinusoidal signal input, iterative learning controller, proportional regulating valve model. The controller parameters are selected by debugging $\Gamma = 4$, $L = 2$, $\Psi = 0$. The number of iterations is set to 20 times, the given curve and the output response curve as shown in figure 11, the red curve is a given sine signal, the blue curve is the output response curve. It can be seen from the figure that when the number of iterations is 2, the error value is very small. As the number of iterations increases, the deviation of the output response curve from the given curve is gradually reduced. When the number of iterations is 3, the error is almost zero.
Figure 11. Response curve of iterative learning process

Figure 12 shows the graph of error rate-iteration times, clearly. When the number of iterations is 1, the error rate is the highest, which is 19.68%. When the number of iterations is 3, the error is close to zero.

Figure 12. Iteration error rate

5. Simulation result analysis
The development of iterative learning control theory and its application in engineering are mutually reinforcing. The iterative learning control can be applied to the controlled object with repetitive motion, and the control target can be improved by iterative correction, which has wide application prospect. In this paper, iterative learning control is introduced, and the Proportion-Integral-Derivative control law iterative learning controller is combined with digital regulating valve to control the hydraulic pressure of the regulating. It is found that the controller model is not sensitive to the accuracy of the model and the regulating valve model is not sensitive to the flow disturbance through the Matlab simulation. When given a pressure value and flow disturbance value, iterative learning controller of Proportion-Integral-Derivative type compared with the traditional Proportion-Integral-Derivative controller has the advantages of a small error, high precision, fast response and so on.

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