PID–PFC control of continuous rotary electro-hydraulic servo motor applied to flight simulator

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Abstract: Due to the uncertainties caused by high non-linearity, friction, leakage and other external factors existing in the flight simulator with continuous rotary electro-hydraulic servo motor and the traditional control strategies discontenting with the high-performance requirements, the mathematical model of continuous rotary electro-hydraulic position servo system is established and the compound control theory combining proportional-integral-derivative (PID) and the predictive function control (PFC) method is proposed. In order to enable the servo system to estimate the influence of uncertainties and correct it by repeating online optimisation continuously, PID–PFC compound controller basing on the structure of internal model control is designed and then applied to continuous rotary electro-hydraulic servo system. The simulation results show that compared with the traditional control strategy, PID–PFC compound control can effectively inhibit the interferences of the electro-hydraulic servo system, and greatly improve the response speed and tracking performances and expanding the system frequency band width. The accurate control of motor's position can be realised by applying PID–PFC compound control, which can make the servo system has stronger robustness.

1 Introduction

The flight simulator can simulate the actual flight posture of the aircraft on the ground and reproduce its dynamic characteristics. As the direct driving equipment of aircraft, continuous rotary electro-hydraulic servo motor should also have perfect low-speed performance, high precision and frequency response, wide speed range. If the motor speed is less than a certain value, the pulsation phenomenon will appear, which affects low-speed performance of servo system seriously [1–4]. The accurate mathematic model of electro-hydraulic servo system is difficult to be built because of oil source pulsation, friction and leakage, strong non-linearity and uncertainties caused by external interference. The approximate system model is used to design controller basing on the traditional control method, but the neglected uncertainties will lead to the instability of control system [5–7]. As the reference [8] approved that quantitative feedback theory (QFT) control made the tracking performance and steady-state error satisfy the requests of electro-hydraulic servo system in the low-frequency stage, but the accuracy and frequency response are relatively low, and the frequency band is just 10 Hz. Jin et al. [9] proposed the variable speed reaching law sliding mode control theory, which greatly accelerated the system response speed and enhanced the ability of system overcoming perturbation and external disturbance. Karimi et al. [10] designed a controller using the fuzzy algorithm, which was applied to electric-hydraulic actuator and made the dynamic response enhanced. Further some control methods usually combing with PID algorithm were adopted to deal with complicated and uncertain system because proportional-integral-derivative (PID) algorithm has advantages of simple algorithm structure and operation, steady-state error closing to zero as well. Such as in the reference [11], the self-tuning fuzzy PID control strategy was applied to the identification model to ensure the better dynamic and more steady-state performance of the system. Shao et al. [12] proposed the fractional PID control strategy based on repetitive control compensation, which greatly improved the anti-parameters perturbation ability and tracking accuracy of the system.

Therefore PID–PFC compound control (predictive functional control) is proposed in this paper, which is a discrete algorithm, and it has unique and obvious advantage in solving the problem of multivariate constrained optimisation. It is not necessary to establish an accurate mathematic model, only through repetitive online computing to optimise performance indexes, with the advantages of less calculation and real-time tracking. ‘Moving horizon optimisation’ is the core of PFC, which is composed of rolling optimisation, model predictive and feedback correction. Rolling optimisation means that the limited time domain optimisation is adopted to remedy the uncertainties timely by using the actual feedback information and repeating optimisation on-line. According to the amount of information about input and output of the past time and system future input, the next multi-step system output is predicted, which reflects the future trend of control system in process of model predictive. The last one is feedback correction, by applying the system future errors as feedback to correct the system real-time output, which makes the predictive ability more accurate [13–18]. This paper, when the electro-hydraulic servo system suffers from the influences of friction and leakage, the tracking accuracy of the sine signal and low-speed performance are analysed under the control of traditional PID, PFC and PID–PFC, respectively. By the simulation and comparison, PID–PFC compound control method combining the strength of PID and algorithm structure of PFC theory is more feasible to approach the actual system, and makes the servo systems have more higher tracking accuracy, frequency band, as well as stronger robustness.

2 Establishment of mathematical model

Given the influences of non-linear factors such as arbitrary external torques (friction and uncertainties) and leakage, the transfer function block diagram of electro-hydraulic servo system of continuous rotary motor is shown in Fig. 1 [19, 20].

Thus the open-loop transfer function can be obtained as

$$G(s) = \frac{K_{0}o_{0}s}{s^2 + 2(o_{0}s + o_{0}o_{0}s ^2) + (o_{0}s + 4o_{0}o_{0}o_{0}s + o_{0})s } \times \frac{1}{1 + 2(o_{0}s + o_{0}s) + (o_{0}s + K/K_{0}s) }$$

(1)
where $\theta(s)$ is the input signal (rad); $\theta(s)$, the output signal (rad); $K_{a}$, non-load flow gain of servo valve (m³/(s·A)); $\omega_{o}$, the equivalent undamped natural frequency of electro-hydraulic servo valve (rad/s); $\xi_{o}$, the equivalent damping coefficient (dimensionless); $K_{n}$, the main controller transfer function (dimensionless); $K_{c}$, the whole pressure-flow coefficient; $K_{c} = K_{c} - C_{c}T_{l}(s)$, arbitrary external torque (Nm). $D_{m}$, the displacement of motor (m³/rad); $C_{m}$, the total leakage coefficient of the hydraulic motor (m³/(s·Pa)); $K_{p}$, the flow-pressure coefficient of servo valve (m³/(s·Pa)); $V_{i}$, total volume including the hydraulic motor, servo-valve chamber and the connected pipeline (m³); $\beta_{p}$, effective volume elastic modulus of the oil (Pa). $K_{a}$ the servo amplifier gain (A/V); $K_{t}$, The open-loop gain of the system, $K = (K_{a}K_{c}K_{o}/D_{m})$. $\omega_{o}$, undamped hydraulic natural frequency of electro-hydraulic servo motor (rad/s); $\xi_{o}$, hydraulic damping ratio (Dimensionless).

As the reference [21] demonstrated the total leakage coefficient $C_{m}$ of the hydraulic motor is obtained by simulation and a simplified function is adopted to describe $T_{l}(s)$ of electro-hydraulic position servo system, the expression is as follows.

$$T_{l} = 60 + 6\sin(4\pi t)$$

(2)

So it is assumed that (1) is regarded as the mathematical model of the actual servo system.

3 PID–PFC algorithm design

3.1 PFC parameters design

3.1.1 The selection of basis function: The control action can be expressed as a linear combination of several known basis functions $f_{o}(n = 1, \ldots, N)$.

$$u(k + i) = \sum_{i=1}^{N} \mu_{i} f_{o}(i) \quad i = 1, \ldots, p - 1$$

(3)

where $k$ is the moment of $k$; $f_{o}(i)$, the value of basis function at the time $t = iT_{s}$ ($T_{s}$, the sampling period); $p$, the prediction length of optimisation; $\mu_{i}$, the linear combination coefficient.

The expression of basis function is determined by the properties of control system and requests of reference trajectory. There are principles about selecting the basis function, if the change rate of set value is less than or equal to a certain threshold $\gamma$ in predictive horizon, the step function will be selected. Otherwise two basic functions can be selected, that is step function and slope function, respectively. Since continuous rotary motor electro-hydraulic servo system is high-frequency response system, generally $p$ is equal to 5. The system sampling frequency is $T_{s} = 0.001$ and working frequency is 0.001–15 Hz, so selecting the step function as a basis function [22], that is, $f_{o}(i) = 1$.

3.1.2 Prediction model: In order to simplify algorithm, regarding the nominal model of continuous rotary electro-hydraulic servo motor as the prediction model, the discrete state equation is

$$\begin{align*}
\dot{x}(k) &= Ax(k - 1) + Bu(k - 1) \\
y(k) &= Cx(k), \quad k = 1, 2, \ldots
\end{align*}$$

(4)

Meanwhile

$$\begin{align*}
y(k + 1) &= Cx(k + 1) = CAx(k) + CBu(k) \\
y(k + 2) &= Cx(k + 2) = CAx(k) + CABu(k) + CBu(k + 1)
\end{align*}$$

(5)

where $x(k)$ is the state vector of the model and $A, B, C$, the coefficient matrices of state equation.

![Block diagram of system transfer function](image)

The output of prediction model $y(k)$ in (3) is composed of prediction model free output $y(k)$ and the model function output $y_{f}(k)$ in the single input and single output system.

$$y(k) = y(k) + y_{f}(k)$$

(6)

$y_{f}(k + j)$ can be expressed as

$$y_{f}(k + j) = \sum_{n=1}^{N} \mu_{n} f_{o}(j), \quad j = 1, \ldots, P$$

(7)

where $j$ is the predicted steps number, $g_{f}(j)$ is the responding output of the $f_{o}(j)$, it can be calculated offline ahead of time.

By using the mathematical derivation, $y(k + j)$ and $y_{f}(k + j)$ can be obtained at the time of $k + j (j = 1, \ldots, p)$, as follows:

$$\begin{align*}
y(k + j) &= CAx(k) \\
y(k + j) &= C \sum_{i=0}^{j-1} A^{-i-1}Bu(k + i)
\end{align*}$$

(8)

The state equation of the nominal model for continuous rotary motor electro-hydraulic position servo system can be expressed as

$$\begin{align*}
x_{1} &= 0 \\
x_{2} &= \frac{1}{\omega_{h}} \\
x_{3} &= -k_{a}\omega_{h}^{2}/2 - \omega_{h}^{2}/2 \\
x_{4} &= k_{a}\omega_{h}^{2}/2
\end{align*}$$

(9)

where $x_{1}, x_{2}, x_{3}$ represent the displacement, speed and acceleration of the actuator, respectively. $\omega_{h}, \xi_{h}$ represent the natural frequency and damping ratio of the hydraulic system. $k_{a}$ is the systemic magnification coefficient. For continuous rotary electro-hydraulic servo motor, $y(k)$ is $\theta(k)$, which is angular displacement output of continuous rotary motor single-channel closed-loop system.

3.1.3 Feedback revise: Generally, the future error can be taken as

$$e(k + j) = y(k) - y_{m}(k)$$

(10)

where $y(k)$ is the actual output of $k$ moment and $y_{m}(k)$ is the predictive output of $k$ moment.

3.1.4 Rolling optimisation: Reference trajectory is selected as follows:

$$y_{r}(k + i) = r(k + i) - \alpha'(r(k) - y(k)); \quad 0 \leq i \leq P$$

(11)

where $y_{r}$ is the reference trajectory, $r$ is the set value, $\alpha = c^{-T_{s}}/T_{s}$, $T_{s}$, the reference time constant is 0.01; $y$, the actual system output.

Optimisation indicator is the quadratic performance index, as the following equation shows

$$J = \sum_{i=1}^{P} (y_{r}(k + i) - y(k))^2$$

(12)
where \( y_p(k+j) \), the predictive actual system output; \( y_m(k+j) \), the predictive output of model at the \( k+j \) moment; \( e(k+j) \), the future error.

Through (11)

\[
J = \sum_{j=1}^{p} [y_p(k+j) - y_m(k+j)]^2 = \sum_{j=1}^{p} [\mu^T g_f - (k+j)]^2
\]  

(13)

where \( \mu = [\mu_1, \mu_2, \ldots, \mu_l]^T \);

\[
g_f = [g_f(1), g_f(2), \ldots, g_f(P)]^T;
\]

\[
d(k+j) = r(k+j) - \alpha_{ef}(r(k) - y(k)) - CA^r(x(k) - e(k) + j)
\]

Minimising the performance indicator, that is

\[
\frac{\partial J}{\partial \mu} = 2(G_fG_f^T \mu - G_fd') = 0
\]  

(14)

where

\[
G_f = \begin{bmatrix}
g_{f1}(1) & g_{f1}(2) & \ldots & g_{f1}(P) \\
g_{f2}(1) & g_{f2}(2) & \ldots & g_{f2}(P) \\
\vdots & \vdots & \ddots & \vdots \\
g_{fp}(1) & g_{fp}(2) & \ldots & g_{fp}(P)
\end{bmatrix}
\]

\[
d = d(k+1), d(k+2), \ldots, d(k+P)
\]

Therefore

\[
\mu = (G_fG_f^T)^{-1}G_fd'
\]

Since \( G_f \) is known, \( (G_fG_f^T)^{-1}G_f \) can be calculated in advance. The control effect \( u \) can be obtained only by the matrix vector multiplication during optimisation calculation. Compared with other prediction control, the on-line calculation of PFC is greatly reduced, so it is possible to apply it to the real-time control of the fast and high-frequency response system such as the continuous rotary motor system as [23] described.

3.2 PID parameters design

As the first step adjustment, PID controller calculates the deviation between the reference trace \( r(k+i) \) and the output of predictive model \( y_p(k+j) \).

\[
ed(k+i) = r(k+i) - y_p(k+i)
\]  

(15)

The control variable of PID control is as follows:

\[
u(k') = K_p e(k') + 1/K_i \int_0^{k'} e(k)d(k) + K_d \frac{d(e(k))}{d(k)}
\]  

(16)

where \( K_p \) is the proportional coefficient, \( K_i \) is the integration time constant, and \( K_d \), the differential time constant.

When establishing the mathematic model of servo system in the Simulink module, the three coefficients can be adjusted to make the model output closing to the reference trajectory. The coefficients are \( K_p = 1.22, K_i = 2.2, K_d = 0 \) in continuous rotary electro-hydraulic servo motor, respectively.

Above of all, according to the principle of internal model control structure [24], PID–PFC block diagram is shown in Fig. 2.

3.3 Continuous rotary electro-hydraulic servo motor PFC controller

System actuator is continuous rotary electric-hydraulic servo motor whose arc discharge is \( 1.2 \times 10^{-3} \text{ m}^3/\text{rad} \), and the oil source pressure is 12 MPa. The total effective volume of motor, servo valve and connecting tubes \( V_r = 1.078 \times 10^{-2} \text{ m}^3 \), and the load inertia \( J_f = 42.97 \text{ kg.m}^2 \). The volume elastic modulus of oil \( \mu_k = 6.9 \times 10^5 \text{ N/m}^2 \). The natural frequency of the hydraulic servo system \( \omega_n = 92.63 \text{ rad/s} \), and \( \zeta_h = 0.1 \). The type of electric-hydraulic servo valve is FF106-100. The no-load flow of servo valve is \( Q_s = 1.2599 \times 10^{-3} \text{ m}^3/\text{s} \), and the flow gain is \( K_{oc} = 0.0315 \text{ m}^2/\text{s}\text{A} \). The saturation value of servo amplifier control voltage is \( \pm 10 \text{V} \), so its gain is \( K_a = 0.004 \text{ A/V} \). Based on the above system parameters, the open-loop transfer function of servo system can be described as (see (17)) . If the dynamic characteristic of servo valve is ignored, the system open-loop transfer function can be simplified as follows

\[
G_k(s) = \frac{0.105}{s((s/282.75)^2 + 2 \times (0.6/282.75)s + 1)((s/92.63)^2 + 2 \times (0.2/92.63)s + 1)}
\]  

(17)

Consequently, because it is not necessary to establish an accurate model for electro-hydraulic servo system when applying PFC algorithm, the simplified (17) can be adopted. Then the coefficient matrix of controlled model's state equation is described as follows by discretisation

\[
A = \begin{bmatrix}
1 & 9.9858 \times 10^{-3} & 4.935 \times 10^{-7} \\
0 & 0.995765 & 9.803 \times 10^{-4} \\
0 & -8.4117 & 0.95944
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
1.487 \times 10^{-7} \\
4.446 \times 10^{-4} \\
0.88318
\end{bmatrix}
\]

\[
C = [1 \ 0 \ 0]
\]

The three parameters \( k_v, o_{th}, \zeta_h \) can be adjusted in the 20% range of their own given value, so the coefficient matrix can be chosen [25–27] by calculating (8).

\[
A_v = \begin{bmatrix}
1 & 9.986 \times 10^{-3} & 4.923 \times 10^{-7} \\
0 & 0.995776 & 9.767 \times 10^{-4} \\
0 & -25 & 0.95235
\end{bmatrix}
\]
Therefore

\[ \mathbf{B}_0 = \begin{bmatrix} 1.514 \times 10^{-7} \\ 4.524 \times 10^{-1} \\ 0.89754 \end{bmatrix} \]

\[ \mathbf{C}_0 = [1 \quad 0 \quad 0] \]

Therefore

\[ \mathbf{G}_{f_{10}} = [g_{f_{10}(1)} \ g_{f_{10}(2)} \ g_{f_{10}(3)} \ g_{f_{10}(4)} \ g_{f_{10}(5)}] \]

According to (7), that can be obtained

\[ g_{f_{10}(1)} = \mathbf{C}_0^\intercal \mathbf{B}_0 = 1.514 \times 10^{-7} \]

\[ g_{f_{10}(2)} = \mathbf{C}_0 \sum_{i=0}^{1} \mathbf{A}_i^\intercal \mathbf{B}_0 = 1.196 \times 10^{-6} \]

\[ g_{f_{10}(3)} = \mathbf{C}_0 \sum_{i=0}^{2} \mathbf{A}_i^\intercal \mathbf{B}_0 = 3.982 \times 10^{-6} \]

\[ g_{f_{10}(4)} = \mathbf{C}_0 \sum_{i=0}^{3} \mathbf{A}_i^\intercal \mathbf{B}_0 = 9.289 \times 10^{-6} \]

\[ g_{f_{10}(5)} = \mathbf{C}_0 \sum_{i=0}^{4} \mathbf{A}_i^\intercal \mathbf{B}_0 = 1.781 \times 10^{-5} \]

Thus, the linear coefficient of PID–PFC compound controller is as follows:

\[ \mu_{10} = (\mathbf{G}_{f_{10}} \mathbf{G}_{f_{10}}^\intercal)^{-1} \mathbf{G}_{f_{10}} \mathbf{d}_O = [359.8 \quad 2842.3 \quad 9463.2 \quad 22075.1 \quad 42325.2] \mathbf{d}_O \quad (19) \]

Eventually, through (2), PID–PFC control \( u \) can be obtained.

**4 Simulation research**

According to PID–PFC algorithm structure and mathematical model of electro-hydraulic servo system, the simulated model can be established in the Simulink module.

The simulating model input is sine signal whose amplitude is 0.5 and frequency is various, and the model output should satisfy the double-ten index that amplitude error is <10%, and phase error is <10°. The control effect of PID, PFC and PID–PFC compound control can be obtained by simulating [28]. The response curves of sine signal are shown as Figs. 3–11. Fig. 3 shows the simulated model response curves and Fig. 3b shows the local amplified drawing. Figs. 4–7 are the same as Fig. 3, besides curve 4 is the output of model response under PFC control, and curve 3 is the output of model response under PID control. Figs. 4–7 are the output of model response under PID–PFC compound control.
In Figs. 8–11, curve 1 is the sine input signal, curve 2 is the response under PFC control, and curve 3 is the response under PID–PFC control.

According to the figures, the simulation data is obtained in Tables 1–3. The figures and tables show that the effect of PID–PFC compound controller is the best both in amplitude and phase error for continuous rotary motor electro-hydraulic servo system.

It can be concluded that the control effect is weakened gradually from the changing trend of simulated model. The phase error of PID control is bigger and bigger and the amplitude is steadier with the frequency increasing, which do not meet the double-ten index. The phase error of PFC is smaller and steadier than PID. So the PID control has the worst control effect on phase error, but best effect on amplitude error, as well as PFC has better effect on phase error, but worse effect on amplitude error. So the analysis result of PID control illustrates that the tracking effect of PID is not suitable to control the phase error under the influence of the uncertainties and external interferences. Compared with the PID, the PFC has great advantage of controlling the phase error. Therefore PID–PFC compound control combining the strength of PID with PFC has better control effect no matter in amplitude or phase. The high-frequency band of PID–PFC compound control is up to 14 Hz, and the high-frequency band of PFC control is 13 Hz. Eventually, it can be concluded that PID–PFC compound control has a better tracking performance than PFC and PID control, which mainly reflects in expanding the range of frequency response and increasing the anti-interferences property, the response precision and systemic stability, enhancing the system robustness.
5 Conclusion

PID–PFC control strategy was proposed for continuous rotary motor electro hydraulic position servo system in this paper. Based on the non-linear factors including external friction and leakage, the mathematical model of servo system was established. By analysing the control effect of PID, PFC and PID–PFC by simulating in Simulink, PID–PFC controller combining advantages of PID and PFC can reduce the non-linear factors influence on system effectively. When the double-ten index is satisfied, the highest response frequency of continuous rotary motor electro hydraulic position servo system is 14 Hz, which confirms that PID–PFC control improves the system response speed and widens the response frequency band. So the validity and feasibility of the designed controller can also be proved by the comparative simulation.

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