Postprint of Research on Fuzzy Adaptive Fractional-Order PIλ-Based Servo Control Strategy

Authors: Shan Yayun, Pang Kewang, Liu Xuyu

Date: 2019-03-05T00:00:00+00:00

Abstract

This paper proposes a servo controller based on fuzzy adaptive fractional-order PIλ, which builds upon the conventional PI controller by integrating the widely applied fuzzy control theory with the rapidly developing fractional-order control theory. A simulation model is constructed in Simulink to verify its control performance. The simulation results demonstrate that the proposed servo controller exhibits superior performance. For high-precision servo systems, the fuzzy adaptive fractional-order PIλ controller can satisfy their stringent requirements for control performance, thus possessing certain feasibility.

Full Text

Abstract

This paper proposes a novel servo controller design based on fuzzy adaptive fractional-order PIλ control, built upon the foundation of traditional PI control combined with widely applied fuzzy control theory and rapidly developing fractional-order control theory. A simulation model was constructed in Simulink to verify its control performance. Simulation results demonstrate that the servo controller designed in this paper exhibits superior performance. For high-precision servo systems, the fuzzy adaptive fractional-order PIλ controller can meet stringent control performance requirements and represents a feasible solution.

Keywords: Traditional PI control, servo system, fuzzy adaptive fractional PIλ control, Simulink

1 Introduction

With technological advancement and continuous industrial development, servo control systems in various CNC applications face increasingly demanding requirements. Servo systems based on traditional PI control strategies can no longer satisfy these performance demands. For instance, in high-speed traverse applications for warp knitting machines, position control requirements are extremely stringent, as position deviations cause pattern distortion and degrade product quality [1].

AC servo control systems are not completely linear, with internal parameters continuously changing and loads that are not constant. Moreover, the system model is not entirely integer-order. The combined influence of these factors results in significant variations in dynamic performance. Traditional PI regulators exhibit poor adaptive capability and cannot achieve desired control performance in high-precision, high-reliability applications. Fuzzy adaptive PI controllers represent typical integer-order controllers that similarly struggle to achieve ideal control performance for fractional-order models.

To address these issues, this paper integrates widely cited fuzzy adaptive control with rapidly developing fractional-order control theory and the most widely applied classical PI control to design a novel fuzzy adaptive fractional-order PIλ AC servo controller [2-6]. Finally, a simulation model was built in Simulink to verify its control effectiveness, with experiments confirming its superior control performance.

2 Permanent Magnet Synchronous Motor Vector Model

Vector control is a high-performance AC motor control technology that achieves better torque control through coordinate transformation, which includes Clark and Park transformations [7]. After coordinate transformation, the permanent magnet synchronous motor voltage equations in the dq coordinate system are:

$$u_d = R_s i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \tag{1}$$

$$u_q = R_s i_q + \frac{d\psi_q}{dt} + \omega_r \psi_d \tag{2}$$

$$\psi_d = L_d i_d + \psi_f \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

where u_d and u_q are the dq-axis components of the stator voltage vector; i_d and i_q are the dq-axis components of the stator current vector; ψ_d and ψ_q are the dq-axis components of the stator flux linkage; L_d and L_q are the synchronous inductances of the dq axes; R_s is the stator winding resistance per phase; ω_r is the electrical rotor angle; and ψ_f is the rotor flux linkage.

The torque and motion equations are:

$$T_e = p_n(\psi_d i_q - \psi_q i_d) \tag{5}$$

$$T_e - T_L = J\frac{d\omega}{dt} + B\omega \tag{6}$$

where p_n is the number of motor pole pairs; T_L is the load torque; B is the viscous friction coefficient; and J is the moment of inertia.

From the rotor reference frame, the three-phase stator currents after coordinate transformation are ultimately equivalent to two components: torque current i_q and excitation current i_d. Vector control has various implementation methods. This paper adopts $i_d = 0$ control, which enables the motor to output smooth and maximum torque. The resulting motor torque equation becomes $T_e = p_n\psi_f i_q$. From this equation, p_n and ψ_f are internal parameters of the permanent magnet synchronous motor with fixed values. To obtain constant torque output, only i_q needs to be controlled as a constant value.

3 Fuzzy Adaptive Fractional-Order PIλ Controller

3.1 Fractional-Order Calculus Theory

Fractional-order calculus is an ancient yet novel research topic—ancient because its definition has long existed, yet novel because its application history is very brief, having only recently gained attention. The most important characteristic that distinguishes fractional-order from integer-order calculus is that its calculus operators are not fixed integer orders but can be fractional, or more broadly, arbitrary orders.

The most frequently encountered definitions are Grünwald-Letnikov and Riemann-Liouville. The operator ${}_aD t^\alpha$ describes fractional-order differentiation and integration, where a and t are the lower and upper limits of variable values during calculus operations, and α is the operator order.

(1) The Grünwald-Letnikov fractional-order calculus definition:

$${}_aD t^\alpha f(t) = \lim_{h\to 0}\frac{1}{h^\alpha}\sum_{j=0}^{(t-a)/h}(-1)^j\binom{\alpha}{j}f(t-jh) = \lim_{h\to 0}\frac{1}{h^\alpha}\sum_{j=0}^{(t-a)/h}\frac{\Gamma(\alpha+1)}{\Gamma(j+1)\Gamma(\alpha-j+1)}f(t-jh)$$

(2) The Riemann-Liouville fractional-order calculus definition:

$${}_aD t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)}\frac{d^m}{dt^m}\int_a^t\frac{f(\tau)}{(t-\tau)^{\alpha-m+1}}d\tau$$

where $m-1 < \alpha < m$, $m \in \mathbb{N}$.

3.2 Traditional PID Controller

The differential equation for PID control is:

$$u(t) = K_p e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}$$

where $e(t)$ is the deviation between the system setpoint and feedback value, K_p is the proportional coefficient, T_i is the integral time constant, and T_d is the derivative time constant.

The PID controller consists of three components: proportional, integral, and derivative. The proportional component reduces deviation but exhibits steady-state error. The integral component eliminates steady-state error but reduces system stability and dynamic response speed. The derivative component acts ahead of the deviation, improving dynamic performance and reducing overshoot.

3.3 Fractional-Order PIλD Controller

The differential equation for the fractional-order PIλD controller is:

$$u(t) = K_p e(t) + K_i D_t^{-\lambda} e(t) + K_d D_t^{\mu} e(t)$$

where $\lambda > 0$ and $\mu > 0$ are arbitrary real numbers representing the integral and derivative orders of the fractional-order controller, respectively; K_p, K_i, and K_d are the proportional, integral, and derivative coefficients. After Laplace transformation, the transfer function becomes:

$$G_c(s) = K_p + K_i s^{-\lambda} + K_d s^{\mu}$$

Compared with traditional PID, the fractional-order PIλD controller adds two adjustable parameters λ and μ, expanding the parameter tuning range and broadening its application fields. The controller becomes more flexible, but this also introduces parameter tuning difficulties.

3.4 Digital Implementation of Fractional-Order Calculus

Fractional-order systems are undoubtedly complex and cannot be simply described with finite dimensions. Their complexity determines that integer-order control methods cannot be directly applied. Mathematicians have developed alternative approaches by approximating fractional-order systems through finite differential equations. This paper employs the Oustaloup approximation method, which belongs to indirect approximation methods.

The Oustaloup approximation transfer function form is:

$$H(s) = \prod_{k=-N}^{N} \frac{1 + s/\omega'_k}{1 + s/\omega_k}$$

Within a given frequency band $[\omega_A, \omega_B]$, we substitute s^α with $C_0 \frac{1+s/\omega_b}{1+s/\omega_h}$, where $(\omega_b \omega_h)^{1/2} = \omega_\mu$, $\omega_b < \omega_A$, $\omega_h > \omega_B$, and $C_0 = \omega_b/\omega_\mu = \omega_\mu/\omega_h$. This allows the transfer function to undergo Laplace transformation.

3.5 Design of Fuzzy Adaptive Fractional-Order PIλ Controller

The fuzzy adaptive fractional-order PIλ controller is shown in [Figure 1: see original paper].

The design approach introduces a fuzzy inference module into the fractional-order PIλ control loop. Through fuzzy control rules, the current values of each parameter are periodically inferred and transmitted to the fractional-order PIλ controller in real-time, enabling online parameter tuning. The fuzzy inference module uses deviation e and its change rate ec as input variables, and ΔK_p, ΔK_i, and λ as output variables.

All variables share the same fuzzy subset: {Positive Big, Positive Medium, Positive Small, Zero, Negative Small, Negative Medium, Negative Big}, denoted as {PB, PM, PS, ZO, NS, NM, NB}. The domain for input variables e and ec is [-3, 3]; the domain for output variables ΔK_p and ΔK_i is [-3, 3]; and the domain for output variable λ is [0, 1]. Input variables e and ec use Gaussian membership functions, while output variables ΔK_p, ΔK_i, and λ use symmetric triangular membership functions, as shown in [Figure 2: see original paper].

After determining the membership functions, fuzzy control rules are established. These rules consist of conditional statements, most frequently using if-then format. This study employs such statements to create 49 fuzzy rules, compiled into tables shown in through :

```
if (e is NB) and (ec is NB) then (kp is PB)(ki is NB)($\lambda$ is PS)
```

The Matlab/Simulink model of the fuzzy adaptive fractional-order PIλ controller is shown in [Figure 3: see original paper]. The fuzzy controller uses Mamdani inference and centroid defuzzification. The fuzzy controller periodically outputs inferred values ΔK_p, ΔK_i, and λ. ΔK_p and ΔK_i are added to preset parameter values K_p and K_i, respectively. λ is set as a global variable, and an S-Function module is introduced in the model. During simulation, the S-function is repeatedly called with code instructions to modify variable λ, enabling periodic modification of the order and thus online tuning of fractional-order PIλ controller parameters K_p, K_i, and λ.

4 System Simulation

Based on the established permanent magnet synchronous motor vector control model, an AC servo control simulation system using the fuzzy adaptive fractional-order PIλ controller was built in Matlab/Simulink, as shown in [Figure 4: see original paper].

The simulation system consists of a position regulator, speed regulator, current regulator, Park inverse transformation module, SVPWM module [8], permanent magnet synchronous motor, parameter measurement module, Clark module, Park module, etc. The system employs three-loop control: position, speed, and current. The inner two loops use digital PI controllers, while the outermost position loop uses the designed fuzzy adaptive fractional-order PIλ controller as the position regulator.

The position setpoint θ^* is compared with the actual rotor position θ to obtain the deviation value, which serves as input to the fuzzy adaptive fractional-order PIλ controller. The controller outputs the speed setpoint ω^*, which is compared with the measured speed ω to obtain the deviation for the PI speed controller. After regulation, the torque current setpoint i_q^* is output. This vector control adopts maximum torque control, setting the excitation current setpoint $i_d^* = 0$. The measured three-phase currents i_a, i_b, and i_c undergo Clark and Park transformations to obtain the direct and quadrature axis current feedback values i_d and i_q, which are compared with the torque and excitation current setpoints. The deviations pass through current regulators and a current-source inverter to control the motor three-phase currents, completing servo motor position control.

The permanent magnet synchronous motor parameters are: stator winding resistance $R_s = 0.62\Omega$, d-axis inductance $L_d = 0.0085$ H, q-axis inductance $L_q = 0.0085$ H, rotor magnetic flux $\psi_f = 0.175$ Wb, moment of inertia $J = 0.008$ $\mathrm{kg \cdot m^2}$, pole pairs $p = 4$, and $B = 0$. The simulation uses ode3 solver with simulation time 0–10 s, comparing step response control effects between traditional PI and fuzzy adaptive fractional-order PIλ controllers.

The step response curves for servo system position control under both controllers are shown in [Figure 5: see original paper]. The dotted line represents the traditional PI controller response, while the solid line shows the fuzzy adaptive fractional-order PIλ controller response. Performance comparison data calculated from [Figure 5: see original paper] are listed in .

The comparison demonstrates that the AC servo control system based on the fuzzy adaptive fractional-order PIλ controller significantly reduces overshoot, provides faster response speed, and delivers better control performance. Its dynamic characteristics, steady-state performance, and robustness are far superior to the traditional PI-controlled AC servo system.

5 Conclusion

This paper aims to improve AC servo system control performance by designing a fuzzy adaptive fractional-order PIλ servo controller. The design concept introduces a fuzzy inference module into the fractional-order PIλ control loop, using fuzzy inference rules to obtain results that modify the fractional-order PIλ controller parameters in real-time. The additional adjustable parameter λ in the fractional-order PIλ controller expands the parameter tuning range, broadens its application fields, and increases flexibility.

Based on the established motor vector model, a position-speed-current three-loop simulation system was built in Simulink. Simulation experiments were conducted using both digital PI and fuzzy adaptive fractional-order PIλ controllers as position regulators. Results show that the fuzzy adaptive fractional-order PIλ controller produces smaller overshoot, faster response speed, and better control performance, with dynamic characteristics, steady-state performance, and robustness far exceeding traditional PI control. For high-precision servo systems, the fuzzy adaptive fractional-order PIλ controller-based servo system can meet stringent control requirements and represents a viable solution.

References

[1] Guo Junhua, Jiang Gaoming, Xia Fenglin. Research on electronic sway system of warp knitting machine based on servo control[J]. Knitting Industries, 2007(5): 14-16, 71.

[2] Dou Yanyan, Qian Lei, Feng Jinlong. Design and simulation of fuzzy PID control system based on Matlab[J]. Electronic Technology, 2015, 28(2): 119-112.

[3] Sun Shucheng, Lang Lang, Chen Mengyuan. Research on fuzzy adaptive PID controller in AC servo control system[J]. Journal of Changchun Institute of Technology (Natural Science Edition), 2012, 13(2): 39-42.

[4] Zhao Chunna, Li Yingshun, Lu Tao. Fractional-order System Analysis and Design[M]. Beijing: National Defense Industry Press, 2011: 42-48.

[5] Liu Jun, Qian Weixie. Research on the fuzzy PID speed control system of permanent magnet linear synchronous motor based on genetic algorithm[J]. Applied Mechanics and Materials, 2014, 2963(494).

[6] Wang Siming, Wang Huan. Design and simulation of fractional-order PID controller[J]. Modern Defence Technology, 2015, 43(6): 204-208.

[7] Qi Naiming, Song Zhiguo, Qin Changmao. Fractional-order PID parameter tuning based on optimal Oustaloup[J]. Control Engineering, 2012, 19(2): 283-285.

[8] Liu Xiaoli. Theoretical, simulation, experimental and applied research on vector control based on permanent magnet synchronous motor mathematical model[D]. Hefei: Hefei University of Technology, 2017: 19-22.

[9] Sui Jun, Wang Jing, Fan Jian, et al. Application and simulation of permanent magnet in PMSM system[J]. Ordnance Industry Automation, 2011, 30(3): 55-58.

[10] Liu Jinkun. Advanced PID Control MATLAB Simulation[M]. Beijing: Electronic Industry Press, 2004.

Note: Figure translations are in progress. See original paper for figures.