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Compound Control of Sliding-Model Variable Structure and Fractional Order $PI^{\lambda}D^{\mu}$ for Automatic Clutch of Vehicle AMT

Yingchun Long[1,2,a] and Lifu Li[1,b]

[1]*School of Mechanical and Automotive Engineering South China University of Technology, Guangzhou 510640, China*
[2]*School of Physics and Mechanical & Electrical Engineering, Shaoguan University, Shaoguan 512005, China*

[1]*sgulyc@139.com*, [2]*pmlfli@scut.edu.cn*

Abstract

A compound control method of sliding-model variable structure and fractional order $PI^{\lambda}D^{\mu}$(SMC-FOPID) is proposed based on such factors as strong nonlinearity, time-varying parameters, disturbance, time delay, as well as the rapidity of a working clutch system in the process of automated manual transmission (AMT) clutch control. The self-tuning of the composite weight coefficient is realized by the fuzzy inference algorithm with single input and output. The coordinated control of the SMC-FOPID is realized through the real-time adjustment of the composite weight coefficient. The control performances of proportional-integral-derivative (PID), fractional order $PI^{\lambda}D^{\mu}$ (FOPID), sliding-model variable structure control (SMC), and SMC-FOPID were compared based on the performance index integral of time multiplied by absolute value of error (ITAE) to study the position tracking of an AMT clutch in the working process. The simulation result showed that the SMC-FOPID control method had higher synthetic control performance compared with the PID, FOPID, and SMC control methods. The feasibility and superiority of the position tracking of an AMT clutch with an SMC-FOPID controller were verified.

Keywords: *Sliding-model variable structure, Fractional order $PI^{\lambda}D^{\mu}$, Compound control, AMT, Clutch*

1. Introduction

The automatic control of an automated manual transmission (AMT) clutch requires the solution to and the tracking of the rule of the clutch engagement through reasonable control by the clutch actuator [1, 2].

The control method of the sliding-mode variable structure of the clutch was presented in the literature [1–6]. The control characteristics of the clutch were improved by the robustness of the control method against system disturbance and parameter changes. The dynamic sliding-mode control [7, 8] and fuzzy sliding-mode control [9] were proposed to mitigate the chattering phenomenon that occurs in traditional sliding-mode controllers and to improve system robustness. However, the actual system has the inevitable problems of spatial lag and time delay because of the switching device. As a result, the sliding-mode motion does not exactly occur on the ideal switching plane and easily causes the severe chattering of the system [10].

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The jitter in the torque transmission in the clutch engagement process usually occurs in the clutch system, resulting in impact attributed to vehicle gear shifting and the increase of the sliding friction of clutch.

The fuzzy proportional-integral-derivative (PID) control method of the clutch was proposed in the literature [11–13]. This method can effectively overcome the uncertainties of the clutch system and the effect of time-varying parameters while avoiding the chattering caused by sliding mode control. However, the three-dimensional fuzzy PID controller can degrade the dynamic performance of the system [14].

The compound control method (SMC-FOPID) of SMC and FOPID was proposed based on the consideration of the strong nonlinearity, time-varying parameters, disturbance, time delay, and other factors in automatic clutch control, as well as the rapidity of the working clutch system. The rapidity and robustness of the position tracking of AMT clutch were ensured with the SMC. The high-frequency chattering near the origin of the sliding-mode plane was controlled by the FOPID. The position tracking characterized by non-overshooting and zero static error was finally achieved. A fuzzy inference mechanism with both single input and output was designed to self-tune the composite weighting factor in real-time to realize the coordinated control of SMC and FOPID.

2. Mathematical Modeling of the Clutch System

2.1. Clutch structure and transmission relationship

The schematic diagram for the automatic clutch system studied in this article is shown in Figure 1. The system is composed of a drive system (DC motor, reduction gear mechanism, and lever mechanism) and clutch (diaphragm spring, pressure plate, clutch plate, and flywheel).

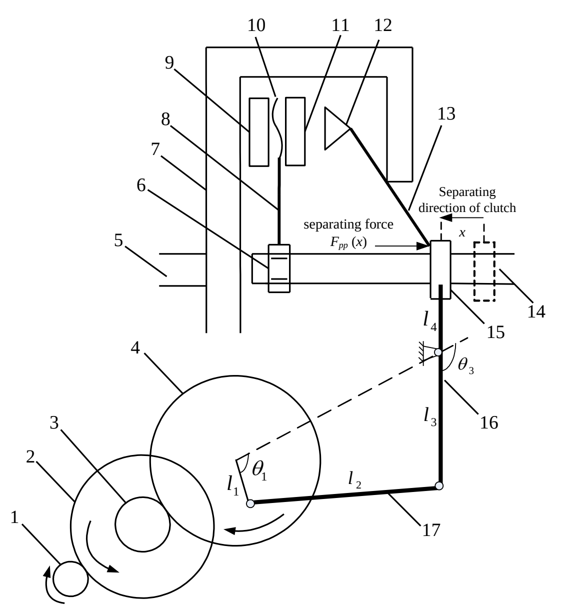

Figure 1. Schematic diagram of AMT clutch system

1. Output shaft gear of motor 2. First large reduction gear 3. Second small reduction gear 4. Second large reduction gear 5. Crankshaft 6. Drive plate hub 7. Flywheel 8. Clutch plate 9. Friction pad on the pressure plate side 10. Cushion spring 11. Friction pad on the flywheel side 12. Pressure plate 13. Diaphragm spring 14. Main shaft 15. Release bearing 16. Release lever 17. Push rod

As shown in Figure 1, when the DC motor rotates clockwise, the reduction gear mechanism and lever mechanism are driven to cause the right shift of the release bearing. Clutch engagement is realized through the diaphragm spring and pressure plate. When the DC motor rotates counter-clockwise, clutch separation is realized.

The relationship between the displacement x of the clutch release bearing and rotation angle of DC motor in Figure 1 is expressed as

$$x = f(\theta_m) \approx l_4 \frac{\theta_m}{i_1 i_2 i_3} \tag{1}$$

where θ_m – angular displacement of DC motor

i_1 , i_2 – reduction ratio of first to second reduction gear mechanisms

$i_3 = \dfrac{\dot{\theta}_1}{\dot{\theta}_3}$ – reduction ratio of the second reduction gear to the clutch fork determined by a lever mechanism composed of a push rod and release lever. θ_3 can be obtained using the kinematic constraint equation determined by the lever mechanism.

$$\theta_3 = 2\mathrm{atan}\left(\frac{-B \pm \sqrt{B^2 + A^2 - C^2}}{A + C}\right)$$

where $A = 2l_3(l_4 - l_1\cos\theta_1)$, $B = 2l_1 l_3 \sin\theta_1$, $C = l_2^2 - l_1^2 - l_3^2 - l_4^2 + 2l_1 l_2 \cos\theta_1$

l_1 ~ l_4 – the size of a lever mechanism shown in Figure 1

2.2. Relationship between the separating force of clutch and the displacement of release bearing

The force exerted by the diaphragm spring on the release bearing in the moving process is translated into the load of the clutch drive motor with strong nonlinearity. This force is the separating force F_{pp} (x) of the clutch. The relationship between the force and displacement x of the release bearing is determined through the experiment, as shown in Figure 2.

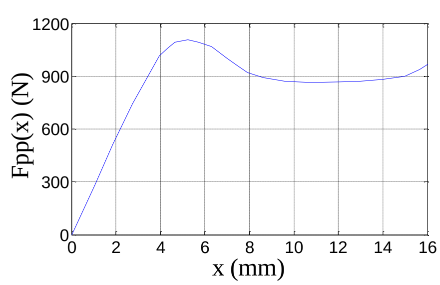

Figure 2. Separation characteristics curve of clutch

The expression fitted by the fourth-degree polynomial is as follows:

$$F_{pp}(x) = -0.0586x^4 + 3.7309x^3 - 71.2159x^2 + 494.795x + 1.235 \tag{2}$$

2.3. Model of clutch system

The dynamic equation of the motor can be obtained based on the torque equation and voltage equation of the DC motor.

$$\frac{d^3\theta_m}{dt^3} + \frac{1}{T_a}\frac{d^2\theta_m}{dt^2} + \frac{1}{T_aT_m}\frac{d\theta_m}{dt} = \frac{1}{T_aT_mc_m}u - \frac{1}{J_{eq}}\frac{dT_L}{dt} - \frac{1}{T_aJ_{eq}}T_L \tag{3}$$

where $J_{eq} = J + \frac{1}{i_1^{\,2}}J_{t1} + \frac{1}{i_1^{\,2}i_2^{\,2}}J_{t2} + \frac{1}{i_1^{\,2}i_2^{\,2}i_3^{\,2}}m_bl_4^{\,2}$

$$T_L = i_1i_2i_3[F_{pp}(x) - k_m\dot{x}]l_4$$

$$T_a = \frac{L}{R_a}$$

$$T_m = \frac{J_{eq}R_a}{c_m^{\,2}}$$

where c_m – motor constant

T_a – electrical time constant of DC motor

T_m – electromechanical time constant of DC motor

u – Voltage of DC motor

T_L – Equivalent load torque of DC motor output shaft

J_{eq} – Equivalent to the moment of inertia of DC motor rotor

R_a – Total resistance of the armature circuit of DC motor

L – Inductance of the armature circuit of DC motor

J – Moments of inertia of DC motor rotor and output shaft gear

J_{t1} – Moment of inertia of first reduction gear

J_{t2} – Equivalent moments of inertia of second reduction gear and lever mechanism

k_m – Damping coefficient of diaphragm spring

m_b – Mass of release bearing

Formula (1) is substituted into Formula (3) to obtain the dynamic equation for the relationship among the displacement of clutch release bearing, motor control voltage, and load torque of release bearing is obtained as follows:

$$\dddot{x} = -\frac{1}{T_a}\ddot{x} - \frac{1}{T_aT_m}\dot{x} + \frac{1}{T_aT_mc_m}\frac{l_4}{i_1i_2i_3}u - \frac{1}{J_{eq}}\frac{l_4}{i_1i_2i_3}\frac{dT_L}{dt} - \frac{1}{T_aJ_{eq}}\frac{l_4}{i_1i_2i_3}T_L \tag{4}$$

The definitions of the clutch system state variable X, control input vector U, and external load vector W are given by

$$X = [x, \dot{x}, \ddot{x}]^T = [x_1, x_2, x_3]^T$$

$$U = [u]$$

$$W = [\frac{dT_L}{dt}, T_L]^T$$

The state equation of the system can be expressed as follows:

$$\dot{X} = AX + BU + DW \tag{5}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{1}{T_a T_m} & -\frac{1}{T_a} \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & \frac{1}{T_a T_m c_m}\frac{l_4}{i_1 i_2 k_l} \end{bmatrix}^T, \quad D = \begin{bmatrix} 0 & 0 & -\frac{1}{J_{eq}}\frac{l_4}{i_1 i_2 k_l} \\ 0 & 0 & -\frac{1}{T_a J_{eq}}\frac{l_4}{i_1 i_2 k_l} \end{bmatrix}^T$$

3. Design of Controller

The essence of a clutch control system is the position servo system. The curve of the target position of the system is determined according to the intention of the driver, working state of engine, ride comfort, and other factors by the transmission control unit (TCU) [15]. The servo system has to realize the position control of the clutch and overcome the effects of a series of factors, such as the nonlinearity of the clutch system, time delay, external disturbance, and parameter perturbation. The scheme of compound control of SMC-FOPID is thus proposed in this article. The rapid tracking of the clutch position and robustness was realized by the SMC. The FOPID determined the accuracy of control and overcame the chattering problem in sliding-mode control. The structure of the compound control system is shown in Figure 3, where α is the composite weight coefficient.

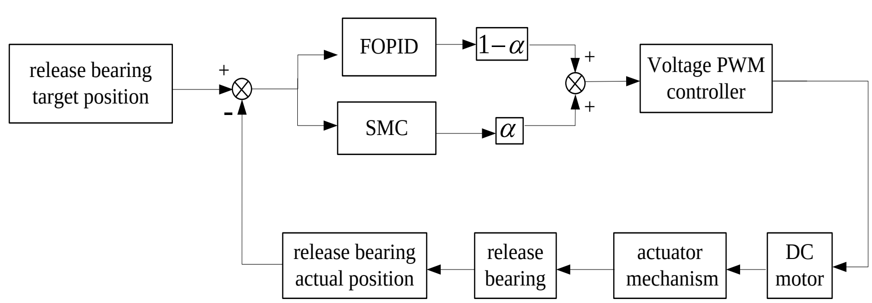

Figure 3. Structural diagram of the compound control system

3.1. Controller of sliding-mode variable structure

The design of the controller of the sliding-mode variable structure includes the selection of the switching hyperplane and control law design. A reasonable switching hyperplane can guarantee that the system will achieve the switching hyperplane rapidly and steadily in the non-sliding mode region. The control law design aims to obtain the control input that generates the sliding mode near the switching plane. As a result, the state quantity X of the system can track the predetermined trajectory r in real-time.

The switching function is set in this article as

$$s = CE = c_1 e_1 + c_2 e_2 + e_3 \tag{6}$$

where $E = [e_1, \ e_2, \ e_3]^T$ is the tracking error vector of the system. $e_1, \ e_2, \ e_3$ is defined as follows:

$$e_1 = e = r - x$$
$$e_2 = \dot{e} = \dot{r} - \dot{x}$$
$$e_3 = \ddot{e} = \ddot{r} - \ddot{x}$$

Constant coefficient vector $C = [c_1, \ c_2, 1]$ is the gain coefficient of the switching plane, which can be determined by the pole placement method.

The exponential approach law is given by

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks \qquad (\varepsilon > 0, \ k > 0) \tag{7}$$

where the constant approach term $-\varepsilon \operatorname{sgn}(s)$ can ensure that any position in the system space can reach the switching plane in finite time. The exponential approach term $-ks$ can shorten the approach time.

The following can be obtained by Formulas (4), (6), and (7):

$$\begin{aligned}\dot{s} &= c_1 \dot{e}_1 + c_2 \dot{e}_2 + \dot{e}_3 = c_1 e_2 + c_2 e_3 + (\dddot{r} - \dddot{x}_3) \\ &= c_1 e_2 + c_2 e_3 + \dddot{r} + \frac{1}{T_a}\ddot{x} + \frac{1}{T_a T_m}\dot{x} - \frac{1}{T_a T_m c_m}\frac{l_4}{i_1 i_2 i_3}u + \frac{1}{J_{eq}}\frac{l_4}{i_1 i_2 i_3}\frac{dT_L}{dt} + \frac{1}{T_a J_{eq}}\frac{l_4}{i_1 i_2 i_3}T_L \\ &= -\varepsilon \operatorname{sgn}(s) - ks\end{aligned}$$

The control voltage of sliding mode is given by

$$\begin{aligned}u &= T_a T_m c_m \frac{i_1 i_2 i_3}{l_4}\left(c_1 e_2 + c_2 e_3 + \dddot{r} + \frac{1}{T_a}\ddot{x} + + \frac{1}{T_a T_m}\dot{x} + \varepsilon \operatorname{sgn}(s) + ks\right) \\ &\quad + T_a T_m c_m \left(\frac{1}{J_{eq}}\frac{dT_L}{dt} + \frac{1}{T_a J_{eq}}T_L\right)\end{aligned} \tag{8}$$

3.2. FOPID controller

Strictly speaking, the actual system is of fractional order. Control effect can be improved using the fractional order controller [16]. Compared with the integer order calculus, fractional calculus is genetic and is characterized by infinite dimensionality and nonlinearity. This feature endows the system rich dynamic characteristics and better robustness [17]. Therefore, the FOPID [18, 19] controller is introduced in this article to reduce the chattering of system output caused by $\varepsilon\text{sgn}(s)$ in the sliding-mode controller.

The transfer function of the FOPID controller has the following form:

$$G_c(s) = K_p + K_I s^{-\lambda} + K_D s^{\mu} \tag{9}$$

A feasible parameter tuning method for engineering purposes has not yet been formulated [20]. The parameters are optimized with the integral of time multiplied by absolute value of error (ITAE) performance index as the fitness evaluation function.

Laplace operator s^{γ} of the FOPID controller was fitted by the Oustaloup recursive approximation [21], which realizes the approximation to the finite high-order integer of fractional calculus.

Suppose that the frequency band of filtering in the fitting is $(\omega_b \sim \omega_h)$. $\omega_b\omega_h = 1$ is chosen to construct the transfer function of the filter

$$s^{v} = K\prod_{j=-n}^{n}\frac{s+\omega_j'}{s+\omega_j} \tag{10}$$

The pole-zero and gain of the filter are given by

$$\omega_j = \omega_b\left(\frac{\omega_h}{\omega_b}\right)^{\frac{j+N+0.5(1+\gamma)}{2N+1}}, \quad \omega_j' = \omega_b\left(\frac{\omega_h}{\omega_b}\right)^{\frac{j+N+0.5(1-\gamma)}{2N+1}}, \quad K = \left(\frac{\omega_h}{\omega_b}\right)^{-\frac{\gamma}{2}}\prod_{j=-N}^{N}\frac{\omega_j}{\omega_j'}$$

where γ is the order of the fractional calculus, $\gamma > 0$ is the differential operation, $\gamma < 0$ is the integral operation, and $2N+1$ is the order of a high-order system.

Based on the fractional order parameters and the fitted high-order integer order system, the simulation model constructed using MATLAB/Simulink is shown in Figure 4.

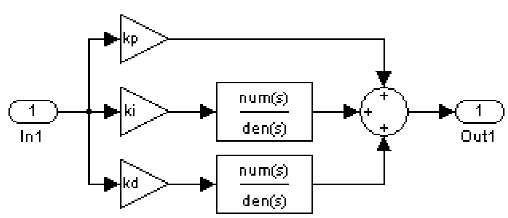

Figure 4. Simulation model of the fractional order PI$^{\lambda}$D$^{\mu}$

3.3. Composite weight coefficient

The adjustment of the composite weight coefficient is very important for the performance optimization of the controller. The conventional compound control often influences the control effect because of the improper selection of the switching point [22] .The weight coefficient was adjusted using the fuzzy inference algorithm in this article. When the position deviation of the system is large, the sliding mode controller serves the leading function, which guarantees the rapidity and robustness of system response. When the position deviation of the system is small, the FOPID control serves the leading function and executes the position control characterized by non-overshooting and no static error. The high-frequency chattering in the sliding-mode control system is eliminated near the switching plane.

The input is the absolute value of the position deviation of release bearing $|e|$ $(0 \le |e| \le 1)$. The output is the value of weight coefficient α $(0 \le \alpha \le 1)$. The fuzzy language variable corresponding to the input, and the output is B (large), M (medium), or S (small). The Gaussian function is adopted as the membership function. The fuzzy variable of weight coefficient is calculated using the gravity method. The fuzzy rule is defined as follows:

R1: If $|e|$ is B, then α is B;

R2: If $|e|$ is M, then α is M;

R3: If $|e|$ is S, then α is S;

4. Simulation and Analysis of Results

According to the system structure shown in Figure 3, the simulation model was established using MATLAB/ Simulink. The simulation parameters of the system are as follows:

The main parameters of the clutch system are $R_a = 0.347\Omega$, $L = 6\times10^4\text{H}$, $c_m = 0.026$, $i_1 = 59/9$, $i_2 = 63/11$, $l_1 = 30mm$, $l_2 = 173.4mm$, $l_3 = 145.36mm$, $l_4 = 87.82mm$, and $J_{eq} = 4.2\times10^4\text{Nms}^2$

$s = 50000e_1 + 2200e_2 + e_3$ is taken as the switching function of sliding-mode controller. The approach law is $\dot{s} = -300\text{sgn}(s) - 10s$.

The FOPID controller is $G_c(s) = 400 + 50s^{-0.853} + 2s^{0.756}$.The order of approximation transfer function of Laplace operator s^γ is $2N+1=5$, the sampling period is 1ms.

4.1. Comparative analysis of step signal of position

The automatic clutch control system is actually a position servo control system. Based on the unit step signal and five-time unit step signal of the positions of release bearing, the curves of position tracking of clutch were obtained using the PID, FOPID, SMC, and SMC-FOPID controllers, respectively, along with the change curves of ITAE value, as shown in Figures 5 and 6.

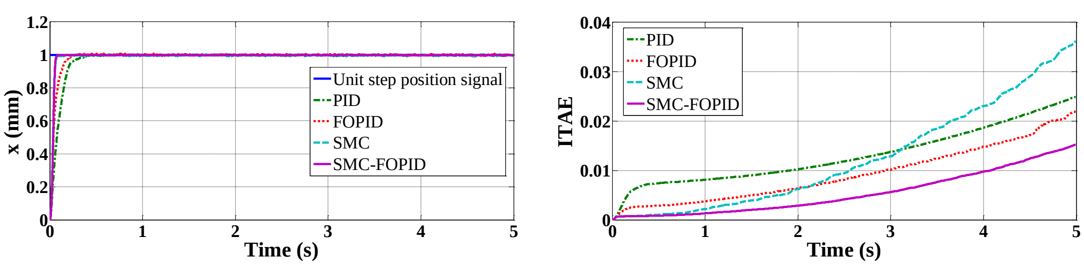

Figure 5. Unit step signal response of the position of release bearing

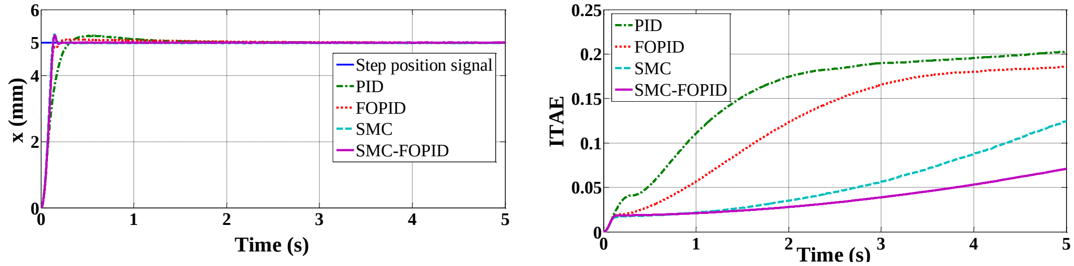

Figure 6. 5 Times unit step signal response of the position of release bearing

Figure 5 shows that no overshoot of the position of clutch was obtained by each control method under the tuned parameters. However, compared with the PID and FOPID control methods, the SMC and SMC-FOPID control methods have the capability for fast-position tracking. The rise time is about approximately 0.1 s. With increasing time, the ITAE value increases because pulse width modulation (PWM) is adopted in the control voltage of the DC motor in the simulation model, thus resulting in jitter in the actual position of the clutch. Compared with SMC control, the ITAEs by PID, FOPID, and SMC-FOPID control increase slowly, showing that the PID, FOPID, and SMC-FOPID control methods have good inhibitory effect on the position jitter during position tracking of the clutch, thus presenting good position stability.

Figure 6 shows that when the amplitude of the step signal of position increases, the actual release bearing displacement x of the clutch for each control method exhibits an overshot. However, a small difference exists in the overshoot amplitude. The ITAE value by SMC-FOPID changes slightly over time, which indicates that the SMC-FOPID control method has good position stability.

4.2. Comparative analysis of robustness in case of the change of load

The five-time unit step signal of the position is illustrated as an example. When the system is stable, an impact load is applied to the system with amplitude of 0.2 Nm during the period of 2.5 s to 3 s. The corresponding curves of position tracking and ITAE values are shown in Figure 7.

Figure 7 shows that the SMC-FOPID control method presents better performance, regardless of the amplitude of position change caused by load changes or ITAE values.

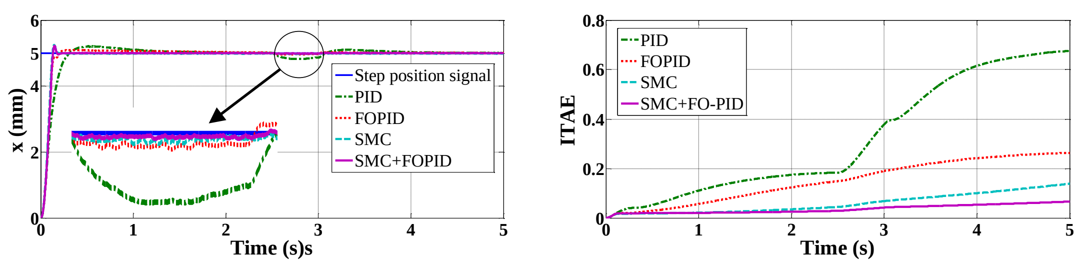

Figure 7. Position response of release bearing when the load interference signal is applied

4.3. Comparative analysis of robustness in case of the changes of the parameters of system structure

In Figure 8, the curves of position tracking and ITAE value are compared under SMC and SMC-PID control methods when the resistance of the drive motor of the clutch changes. The changes in resistance were selected as 1.2 times Ra and 1.4 times Ra.

The simulation result shows that the SMC-PID control method has a small overshoot for the same change in resistance. With increasing resistance, the change curves of ITAE value under the SMC-PID control method coincide fundamentally. The parameter Ra value has a slight influence on the ITAE value. The amplitude of the ITAE value becomes larger with increasing Ra. Therefore, the SMC-PID control method presents better robustness compared with SMC when the parameters of system structure change.

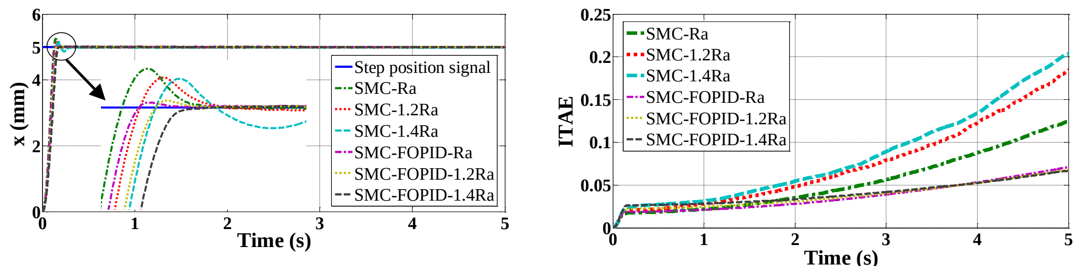

Figure 8. Position response of release bearing under the change of resistance parameter of motor

4.4. Comparative analysis of the position tracking when vehicle starting

The effect of parameter change on the position tracking of the clutch when the vehicle is in a state of slow or fast starting is discussed next.

According to the literature [8], the target displacement curves of the release bearing for slow and the fast starting of the vehicle with constant engine rotating speed are shown in Figures 9 and 10. The fast separation process of the clutch occurs before 1 s, and clutch engagement occurs after 1s, and both comprise the starting process of a vehicle.

The simulation result shows that overshoot occurs when the rapid target position tracking of the clutch is realized by two control methods. With increasing motor resistance, the overshoot and ITAE values increase. However, the position overshoot and ITAE value are small relative to SMC by the SMC-FOPID control under the same resistance parameters.

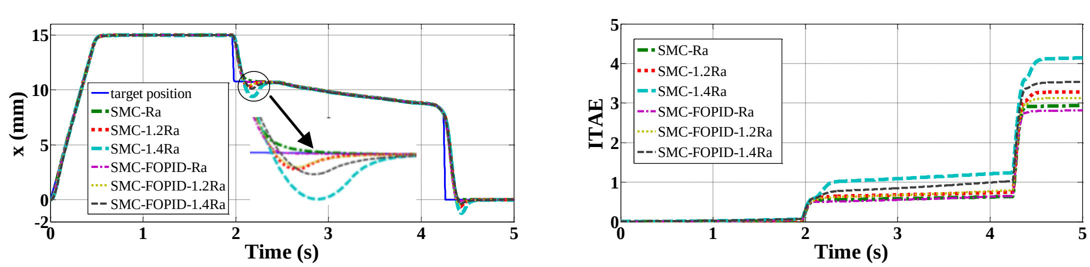

Figure 9. Position tracking of release bearing under the slow starting of vehicle

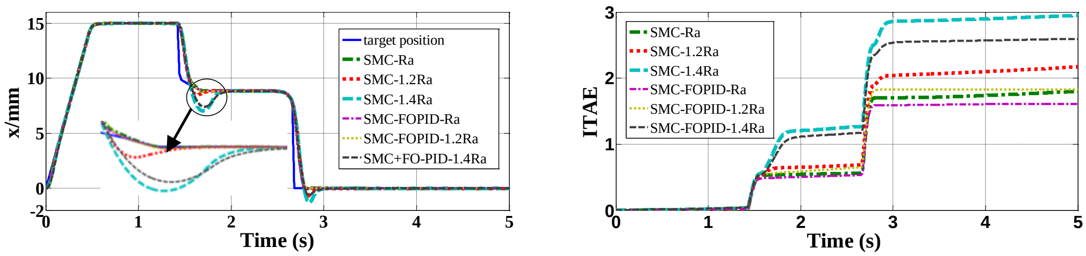

Figure 10. Position tracking of release bearing under the fast starting of vehicle

5. Conclusion

The compound control method of SMC-FOPID was studied in this article. The composite weight coefficient was self-tuned by the fuzzy controller. The position tracking control of the clutch control system was realized by the reasonable selection of parameters. The SMC-FOPID compound control method was found to have the characteristics of quick response, strong anti-interference capability, good stability, and strong robustness in the position tracking of clutch compared with the PID, FOPID, and SMC control methods. Moreover, SMC-FOPID was found to be insensitive to parameter changes.

References

[1] R. Prabel, D. Schindele, H. Aschemann and S. S. Butt, "Model-based control of an electro-pneumatic clutch using a sliding-mode approach", In: Proc. 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), Singapore, **(2012)** July, pp. 1195-1200.

[2] H. P. Zhao, F. Liu and J. W. Zhang, "Application of variable structure control method for an automatic Clutch", Transactions of the Chinese Society for Agricultural Machinery, vol. 33, no. 2, **(2002)**, pp. 24-27.

[3] F. Liu, Y.X. Li, J. W. Zhang and H. C. Huang, "Robust control for automated clutch of AMT vehicle", In: Proc. SAE 2002 World Congress on Transmission and Driveline Systems Symposium: 2002-01-0933, Detroit, Michigan, **(2002)** March, pp. 4-7.

[4] R. Knoblich, C. Gühmann and J. Beilharz, "Sliding mode position control for automotive dry clutch system: Nonlinear observer/sliding mode control design for an electro-hydraulic actuation system", In: Proc. 2012 IEEE 9th International Multi-Conference on Systems, Signals and Devices (SSD), Chemnitz, **(2012)**.

[5] J. Wang and L. J. Zheng, "Model parameter identification and sliding mode control of clutch disk test machine", In: Proc. 2010 International Conference on Computer, Mechatronics, Control and Electronic Engineering (CMCE), Changchun, China, **(2010)**, pp. 318-321.

[6] X. Y. Song and Z. X. Sun, "Pressure-Based Clutch Control for Automotive Transmissions Using a Sliding-Mode Controller", Transactions on mechatronics, vol. 17, no. 3, **(2012)**, pp. 534-546.

[7] Y. S. Zhao, Z. F. Liu, W. T. Yang and L. G. Cai, "Dynamic sliding mode control for automatic clutch of AMT vehicle", Automotive Engineering, vol. 31, no. 6, **(2009)**, pp. 536-539.

[8] Y. -S. Zhao, Z. -F. Liu, L. -G. Cai, W. -T. Yang and J. Yang, "Study of control for the automated clutch of an automated manual transmission vehicle based on rapid control prototyping", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 224, no. 4, **(2010)**, pp. 475-487.

[9] Y. -S. Zhao, L. -P. Chen and Y. -Q. Zhang, "Enhanced fuzzy sliding mode controller for automated clutch of AMT vehicle", In: Proc. SAE 2006 World Congress on Transmission and Driveline Systems Symposium :2006-01-1488, Detroit, Michigan, USA, **(2006)**.

[10] J. Liu and X. Wang, "Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation" Tsinghua University Press, Beijing, **(2012)**.

[11] H. Tanaka and H. Wada, "Fuzzy Control of Clutch Engagement for Automated Manual Transmission", Vehicle System Dynamics, vol. 24, no. 4-5, **(1995)**, pp. 365-376.

[12] C. Dragos, S. Preitl, R. Precup, E. Petriu and M. Stinean, "Adaptive control solutions for the position control of electromagnetic actuated clutch systems", In: Proc. 2012 IEEE Intelligent Vehicles Symposium, (IV),

(2012), pp. 81-86.
[13] W. -Q. Ren, Y. -S. Zhao and Y. -Q. Zhang, "The Fuzzy-PID control strategy for automated membrane spring clutch", Journal of System Simulation, vol. 17, no. 2, **(2005)**, pp. 108-110.
[14] W. P. Fuzzy, "control and fuzzy systems", Research Studies Press, New York, **(1993)**.
[15] F. Vasca, L. Iannelli, A. Senatore and G. Reale, "Torque transmissibility assessment for automotive dry-clutch engagement" Transactions on mechatronics, vol. 16, no. 3, **(2011)**, pp. 564-573.
[16] Y. Q. Chen, I. Petras and D. Xue, "Fractional order control a-tutorial", In: Proc. American Control Conference, 2009 (ACC '09), St. Louis, MO, USA, **(2009)**, pp. 1397-1411.
[17] C. A. Monje, B. M. Vinagre, V. Feliu and Y. Q. Chen, "Tuning and auto-tuning of fractional order controllers for industry applications", Control Engineering Practice, vol. 16, no. 7, **(2008)**, pp. 798-812.
[18] I. Podlubny, "Fractional-order systems and $PI^{\lambda}D^{\mu}$ controller", IEEE Trans. Automatic Control, vol. 44, no. 1, **(1999)**, pp. 208-214.
[19] C. Yeroglu and N. Tan, "Note on fractional-order proportional–integral–differential controller design", IET Control Theory and Applications, vol. 5, no. 17, **(2011)**, pp. 1978-1989.
[20] D. Xue, C. Zhao and Y. Q. Chen, "Fractional order PID control of a DC-Motor with elastic shaft: a case study", In: Proc. American Control Conference, 2006 (ACC '06), Minneapolis, MN, USA, **(2009)**, pp. 1397-1411.
[21] A. Oustaloup, F. Levron, B. Mathieu and F. Nanot, "Frequency-band complex noninteger differentiator: characterization and synthesis", IEEE Transactions on Automatic Control, vol. 47, no. 1, **(2000)**, pp. 25-39.
[22] L. Li, H. Liu, Z. Luo and Y. Sun, "Study on improved Fuzzy-PID composite control arithmetics and its applications", Journal of Northeastern University (Natural Science), vol. 30, no. 2, **(2009)**, pp. 274-278.

Authors

Yingchun Long

He received his Master of Electronics and Communications Engineering (2005) from South China University of Technology. Now he is an associate professor of Physics and Mechanical & Electrical Engineering, Shaoguan University, China. His current research interests include Eelectromechanical systems Control and Artificial Intelligence.

Lifu Li

He received his Master of Mechanical Engineering and Automation and his Ph.D. of Precise Instruments & Machinery, both from Chongqing University, in 1991 and 1997, respectively. He is currently a Professor in School of Mechanical and Automotive Engineering South China University of Technology. His current research interests include Optoelectronic & Mechanical Engineering; industrial computed tomography measurement.

