

Fuzzy Sliding-mode Control of the Electronic Throttle System

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Abstract -Electronic throttle is a DC-motor-driven valve that regulates air inflow into the vehicle's combustion system in modern automobiles. Electronic throttle system has the nonlinear dynamical characteristics, and it is difficult to be controlled with the satisfactory performance by the traditional PID control strategy. A fuzzy sliding-mode control method is proposed for the electronic throttle in this paper. At first, based on the dynamical model of the electronic throttle, sliding-mode controller is designed. The sliding-mode controller is composed of the equivalent control term and the switching control term. The fuzzy logic system is adopted to determine the gain of the switching control term. Therefore, the chattering of the controller is weakened. Finally, a computer simulation is performed, and simulation results verify that the proposed control method has the satisfactory control performance.

Index Terms - Electronic throttle; Fuzzy sliding-mode control; Fuzzy logic system.

I. INTRODUCTION

The electronic throttle is essentially a DC-motor-driven valve, which can regulate the air inflow into the vehicle's combustion system [1-3]. Its control system positions the throttle valve according to the reference opening angle which is provided by the engine control unit. In recent years, the electronic throttle is increasingly being used in modern automobiles in order to improve the vehicle drivability, fuel economy, and emissions.

There exist the strong nonlinear characteristic and parameter uncertainty in the electronic throttle. Due to the presence of the strong nonlinear characteristic and parameter uncertainty in the electronic throttle, it is difficult to obtain the satisfactory control performance by using the traditional PID control method. Sliding-mode control is an effective robust control method to deal with the strong nonlinear characteristic and parameter uncertainty of the controlled plant. For this advantage, sliding-mode control has been widely used in the practical applications [4-5].

There are also some works that introduce sliding-mode control to control the electronic throttle. In [6], a cascade control structure of the electronic throttle is presented and discussed, which is composed of an inner current sliding-mode controller, an intermediate velocity sliding-mode controller, and an outer position digital linear controller. In [7], the nonlinear hysteretic characteristic of the electronic throttle is described and the sliding-mode control method is proposed to

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control the electronic throttle. [8-9] designed an observer-based sliding-mode controller based on an identified model for a drive-by-wire throttle control system. In [10], a neural network-based sliding mode controller for an electronic throttle is proposed, in which a static neural network is used as an estimator of the state-dependent uncertainties in the system. In [11], the control of an electronic throttle valve based on second-order sliding-mode concepts is presented, and the twisting algorithm is chosen as the control law.

In this paper, a fuzzy sliding-mode control method of the electronic throttle is designed. At first, a mathematical model of the electronic throttle is built. Based on the dynamical model of the electronic throttle, sliding-mode controller is designed. In order to alleviate the chattering of sliding-mode control, fuzzy logic system is adopted to determine the gain of the switching control term in the sliding-mode control. The proposed fuzzy sliding-mode control of the electronic throttle can control the throttle valve with the satisfactory performance. Finally, a computer simulation is performed, and simulation results verify the effectiveness of the proposed control method.

II. NONLINEAR MODEL OF THE ELECTRONIC THROTTLE

There are some symbols in this section. At first, definitions of these symbols are described as follows:

- θ_r Set point of the valve plate angle
 $\theta(t)$ Actual angle of the valve plate
 θ_0 Static angle of the valve plate
 $\omega(t)$ Angle speed of the valve plate
 $i_a(t)$ Armature current
 R_a Armature resistance
 $U_a(t)$ Input voltage of the motor
 $U_b(t)$ Electromotive force
 U_{bat} Supply voltage
 $D(t)$ Duty cycle of the bipolar chopper
 $T_e(t)$ Electromagnetism torque
 $T_s(t)$ Return spring torque
 $T_f(t)$ Friction torque
 K_t Torque constant

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| K_b | Electromotive force constant |
| K_s | Elastic coefficient |
| K_m | Torque compensation coefficient |
| K_d | Sliding friction coefficient |
| K_k | Coulomb friction coefficient |

J Moment of inertia

G_r Gear ratio

The schematic of a typical electronic throttle control system is shown in Fig. 1.

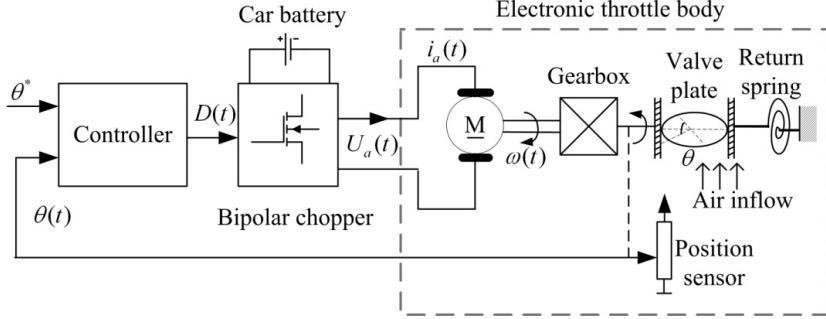


Fig. 1 Electronic throttle control system

There are a controller, a bipolar chopper and electronic throttle body (ETB) in Fig. 1. ETB consists of a DC drive powered by the bipolar chopper, a gearbox, a valve plate, a return spring and a position sensor. When the valve plate angle is regulated, the air inflow into the vehicle's combustion system can also be regulated. The control objective of the electronic throttle is to control the valve plate angle tracking its set point with the satisfactory performance.

According to the motion theory of the motor, the motion equation of the electronic throttle system is

$$G_r T_e(t) - T_s(t) - T_f(t) = G_r^2 J \frac{d\omega(t)}{dt} \quad (1)$$

In the motor armature circuit, the relation between current $i_a(t)$ is

$$i_a(t) = \frac{U_{bat} \times D(t) - K_b \times G_r \times \omega(t)}{R_a} \quad (2)$$

The electromagnetism torque of DC motor $T_e(t)$ is

$$T_e(t) = K_t i_a(t) \quad (3)$$

By substituting (2) into (3), we get

$$T_e(t) = K_t \frac{U_{bat} \times D(t) - K_b \times G_r \times \omega(t)}{R_a} \quad (4)$$

The expression of the return spring torque $T_s(t)$ is^[12]:

$$T_s(t) = K_s (\theta(t) - \theta_0) + K_m \operatorname{sgn}(\theta(t) - \theta_0) \quad (5)$$

The expression of friction torque $T_f(t)$ is^[13]:

$$T_f(t) = K_d \omega(t) + K_k \operatorname{sgn}(\omega(t)) \quad (6)$$

By substituting (4), (5) and (6) into (1), we get

$$\begin{aligned} \frac{d\omega(t)}{dt} &= -\frac{K_s}{G_r^2 \times J} \times (\theta(t) - \theta_0) - \left(\frac{K_b \times K_t}{JR_a} + \frac{K_d}{J^2 \times J} \right) \omega(t) \\ &\quad + \frac{K_t \times U_{bat} \times D(t)}{G_r \times J \times R_a} \\ &\quad + \frac{-K_m \operatorname{sgn}(\theta(t) - \theta_0) - K_k \operatorname{sgn}(\omega(t))}{G_r^2 \times J} \end{aligned} \quad (7)$$

Defining state variables $x_1(t) = \theta(t) - \theta_0$, $x_2(t) = \omega(t)$, input variable $u(t) = D(t)$, and the output variable $y(t) = \theta(t)$, we can obtain the state-space model of the electronic throttle system:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \frac{K_t \times U_{bat}}{G_r \times J \times R_a} u(t) - \frac{K_s}{G_r^2 \times J} x_1(t) \\ \quad - \left(\frac{K_b \times K_t}{JR_a} + \frac{K_d}{G_r^2 \times J} \right) x_2(t) \\ \quad + \frac{-K_m \operatorname{sgn}(x_1(t)) - K_k \operatorname{sgn}(x_2(t))}{G_r^2 \times J} \end{cases} \quad (8)$$

$$y(t) = x_1(t) + \theta_0 \quad (9)$$

Then, letting

$$\begin{aligned} \mu_0 &= \frac{K_t \times U_{bat}}{j \times J \times R_a} \\ \mu_1 &= \frac{K_s}{j^2 \times J}, \\ \mu_2 &= \left(\frac{K_b \times K_t}{JR_a} + \frac{K_d}{J^2 \times J} \right) \\ F(x_1, x_2, t) &= \frac{-K_m \operatorname{sgn}(x_1(t)) - K_k \operatorname{sgn}(x_2(t))}{j^2 \times J} \end{aligned}$$

Considering the external disturbance, Eq. (8-9) are rewritten as

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \mu_0 u(t) - \mu_1 x_1(t) - \mu_2 x_2(t) \\ \quad + F(x_1, x_2, t) + d(t) \end{cases} \quad (10)$$

where $d(t)$ is the external disturbance, and satisfy the following condition:

$$|d(t)| \leq D \quad (11)$$

where D is an constant, which represents the maximum value of the external disturbance.

III. DESIGN OF THE FUZZY SLIDING-MODE CONTROL

A. Sliding-mode Controller of the Electronic Throttle

Defining the tracking error as

$$e(t) = x_1(t) - x_r \quad (12)$$

The sliding surface is

$$s(t) = ce(t) + \dot{e}(t) \quad (13)$$

where c is a positive constant.

The Lyapunov function is selected as

$$V(t) = \frac{1}{2} s^2(t) \quad (14)$$

It can be noted that this function is positive definite.

The derivative of the Lyapunov function is

$$\dot{V}(t) = s(t)\dot{s}(t) \quad (15)$$

The derivative of the sliding surface $s(t)$ is

$$\begin{aligned} \dot{s}(t) &= c\dot{e}(t) + \ddot{e}(t) \\ &= c(\dot{x}_1 - \dot{x}_r) + (\dot{x}_2 - \ddot{x}_r) \\ &= cx_2 - c\dot{x}_r + \mu_0 u(t) \\ &\quad - \mu_1 x_1(t) - \mu_2 x_2(t) + F(x_1, x_2, t) + d(t) - \ddot{x}_r \end{aligned} \quad (16)$$

The sliding-mode control signal $u(t)$ is designed as

$$u(t) = u_{eq} + u_{sw} \quad (17)$$

$$u_{eq} = \frac{1}{\mu_0} [-cx_2(t) + c\dot{x}_r + \mu_1 x_1(t) + \mu_2 x_2(t) - F(x_1, x_2, t) + \ddot{x}_r] \quad (18)$$

$$u_{sw} = \frac{1}{\mu_0} [-K \operatorname{sgn}(s)] \quad (19)$$

where u_{eq} is the equivalent control term, and u_{sw} is the switching control term.

In Eq. (19), K is switching gain, which is satisfied the following condition

$$K \geq D \geq d(t) \quad (20)$$

By substituting (17-19) into (16), we get

$$\dot{s}(t) = -K \operatorname{sgn}(s) + d \quad (21)$$

By substituting (21) into (15), we get

$$\begin{aligned} \dot{V}(t) &= s(t)\dot{s}(t) \\ &= s[-K \operatorname{sgn}(s) + d] \\ &= -K|s| + d \times s \end{aligned} \quad (22)$$

According to Eq. (20), we know

$$\dot{V}(t) = -K|s| + d \times s \leq 0 \quad (23)$$

From Eq. (23), we know if we choose the controller shown in Eq. (17-19), the closed-loop system is asymptotically stable.

B. Fuzzy Sliding-mode Controller of the Electronic Throttle

A pure sliding-mode control of the electronic throttle shown in Eq. (17-19) suffers from the chattering disadvantage. Chattering is the high-frequency oscillations of the controller output. It is highly undesirable because it may excite unmodeled high-frequency plant dynamics. In order to eliminate the chattering of the sliding-mode control, fuzzy logic system is utilized to adjust the gain K in the switching control term.

In the fuzzy logic system, the input variables are s and \dot{s} , and the output variable is K_{fuzzy} . Each input fuzzy variable is quantized into five qualitative fuzzy sets:

- PB—Positive Big
- PS—Positive Small
- ZE—Zero
- NS—Negative Small; and
- NB—Negative Big

Output fuzzy variable is quantized into four qualitative fuzzy sets:

- ZE—Zero
- PS—Positive Small
- PM—Positive Medium
- PB—Positive Big

For simplicity, triangular-type membership functions are chosen for the above-stated fuzzy variables. Fuzzy rules are designed in an attempt to satisfy. The resulting fuzzy rule base is shown as follows:

Rule1: If s is PB and \dot{s} is PB, then K_{fuzzy} is PB.

Rule2: If s is PB and \dot{s} is PM, then K_{fuzzy} is PM.

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Rule20: If s is NB and \dot{s} is NB, then K_{fuzzy} is PB.

Therefore, the final fuzzy sliding-mode controller of the electronic throttle is

$$\begin{aligned} u_{FS}(t) &= \frac{1}{\mu_0} [-cx_2(t) + c\dot{x}_r + \mu_1 x_1(t) + \mu_2 x_2(t) - F(x_1, x_2, t) + \ddot{x}_r] \\ &\quad + \frac{1}{\mu_0} [-K_{fuzzy} \operatorname{sgn}(s)] \end{aligned} \quad (24)$$

IV. SIMULATION

In this section, we perform simulation experiment to confirm the effectiveness of the proposed fuzzy sliding-mode controller. Simulation results are shown in Fig. 2 and Fig. 3.

The curve of the set point of the plate angle is shown in Fig. 2. During 0 to 200 second, the set point of the plate angle is 50 degrees. When time is 200 seconds, the set point of the plate

angle is increased to 70 degrees. When time is 400 seconds, the set point of the plate angle is decreased from 70 to 30 degrees. The curve of the actual plate angle is shown in Fig. 3. From Fig. 2 and Fig. 3, we know the actual angle can track its set point with the satisfactory performance.

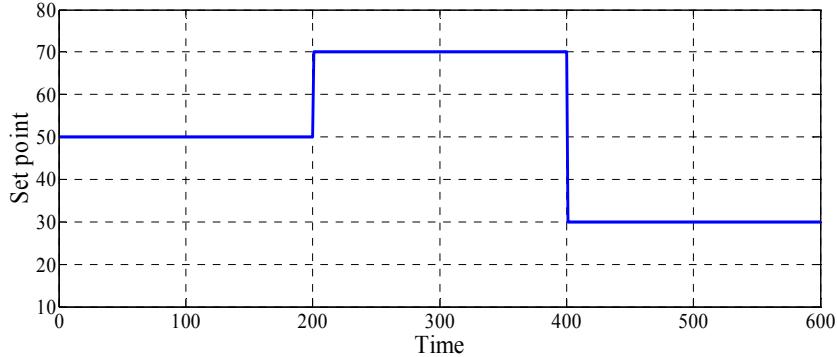


Fig. 2 Set point of the plate angle

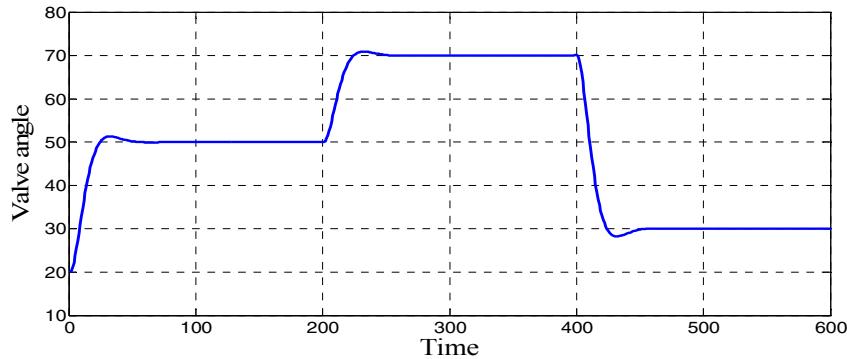


Fig. 3 Actual angle of the valve plate

V. CONCLUSIONS

In this paper, according to the dynamical characteristics of the electronic throttle, a fuzzy sliding-mode controller is developed for the electronic throttle. In order to alleviate the chattering, fuzzy logic system is adopted to adjust the gain of the switching term in the sliding-mode control. Computer simulation results confirm the effectiveness of the proposed control method.

REFERENCES

- [1] C H Wang, D Y Huang, A New intelligent fuzzy controller for nonlinear hysteretic electronic throttle in modern intelligent automobiles, *IEEE Transaction Industrial Electronics*, vol. 60, no. 6, pp. 2332-2345, 2013.
- [2] X F Yuan, Y N Wang, A Novel Electronic-Throttle-Valve Controller Based on Approximate Model Method, *IEEE Transaction on Industrial Electronics*, vol. 56, no. 3, pp. 883-890, 2009.
- [3] T Aono, T Kowatari, Throttle-control algorithm for improving engine response based on air-intake model and throttle-response model, *IEEE Transaction on Industrial Electronics*, vol. 53, no. 3, pp. 915-921, 2006.
- [4] X H Yu, O Kaynak, Sliding-Mode Control With Soft Computing: A Survey, *IEEE Transaction on Industrial Electronics*, vol. 56, no. 9, pp. 3275-3285, 2009.
- [5] Y Feng, X. H. Yu, F. L. Han, High-order terminal sliding-mode observer for parameter estimation of a permanent-magnet synchronous motor, *IEEE Transactions on Industrial Electronics*, vol. 60, no. 10, pp. 4272-4280, 2013.
- [6] C Rossi, A Tilli, A Tonielli, Robust Control of a Throttle Body for Drive by Wire Operation of Automotive Engines, *IEEE Transaction on Control Systems Technology*, vol. 8, no. 6, pp. 993-1002, 2000
- [7] Y Pan, U Ozguner, O H Dagci, Variable-structure control of electronic throttle valve, *IEEE Transaction on Industrial Electronics*, vol. 55, no. 11, pp. 3899-3907, 2008.
- [8] A Beghi, L Nardo, M Stevanato, Observer-based discrete-time sliding mode throttle control for drive-by-wire operation of a racing motorcycle engine, *IEEE Transaction on Control System and Technology*, vol. 14, no. 4, pp. 767-775, 2006.
- [9] K Nakano, U Sawut, K Higuchi, Y Okajima, Modelling and Observer-based Sliding-Mode Control of Electronic Throttle Systems, *ECTI Transaction on Electrical Eng., Electronics, and Communications*, vol. 4, no. 1, pp. 22-28, 2006.
- [10] M Baric', I Petrovic', N Peric', Neural network-based sliding mode control of electronic throttle, *Engineering Applications of Artificial Intelligence*, vol. 18, no. 3, pp. 951-961, 2005
- [11] M Reichhartinger, M Horn, Application of Higher Order Sliding-Mode Concepts to a Throttle Actuator for Gasoline Engines, *IEEE Transaction on Industrial Electronics*, vol. 56, no. 9, pp. 3322-3329, 2009.
- [12] D Kim, H Peng, S S Bai, J M Maguire, Control of Integrated Powertrain With Electronic Throttle and Automatic Transmission, *IEEE Transaction on Control Systems Technology*, vol. 15, no. 3, pp. 474-482, 2007.
- [13] Y F Hu, C Li, Y Li, H Y Guo, P Y Sun, H Chen, Observer-based Output Feedback Control of Electronic Throttles, *Acta Automatica Sinica*, vol. 37, no. 6, pp. 745-754, 2011