The Composite Control Method for Piston Stop Position of the GDI Engine

Honghui Mu, Xuejun Li, Jun Tang

***Abstract*—**The instantaneous reverse starting technique can restart engine quietly and quickly, the crucial problem of this technique is the piston stop position. In this paper, the piston stop position is converted to the electric throttle control technique, the dynamical model of electric throttle is designed, and the composite controller is proposed to control the throttle opening, then the amount of air inflow cylinder is crucial for the piston stop position. The feed-forward nonlinear compensation controller is designed to compensate the friction force and spring torque, then the electric throttle system is described as nonlinear SISO system. The feedback controller is an adaptive fuzzy sliding-mode controller which is based on equivalent control and switching control, and combined with fuzzy logic and sliding mode control, that not only retain the rapidity and robustness of sliding mode control, but also reduce the buffeting. The simulation results show that the composite controller can enable the throttle opening track the input quickly and accurately.

***Keywords*—**piston stop position, throttle control, adaptive, sliding-mode control.

I. INTRODUCTION

IDLING start-stop (ISS) technology and gasoline direct injection (GDI) engine are both have great development potential. Idling start-stop technology is one of key techniques which can save energy and reduce emissions effectively by shutting down engine automatically when the vehicle idle. Matsuura’s research [1] show that when the vehicle stops for more than 7 seconds, idle stop system can save fuel consumption. Another research [2][3] also indicated that start-stop system can reduce the combined fuel observably. The motor start-stop technology is achieved with the help of high-performance engine at present, which is increase production cost of vehicle, meanwhile, the motor frequent start can caused the wear of starting system and maintenance costs are increased. Fuel injection and ignition parameters in cylinder are high-flexible controlled by GDI engine, it is also injecting fuel by ECU control system when engine under idle state, and igniting it to drive the crankshaft rotate, so the engine can restart without the electric motor working. Recently, there are two methods are used to restart engine directly in idle stop system: forward starting and instantaneous reverse starting. The instantaneous reverse starting technique restart by injecting fuel directly into compression stroke cylinder while the engine is stopped, then igniting it to generate force to push the piston down so that the crankshaft inverse, the piston of expansion stroke cylinder is drive upward by crankshaft, then injecting and igniting at appropriate time, the crankshaft is turned and the engine restart. The critical point of the second restart method is the piston of compression stroke stops in $60^{\circ} \sim 80^{\circ}$ CA before top dead center (BTDC), then small amount fuel is injected into a cylinder of compression stroke, then igniting the fuel to restart engine quickly and reliably. There are more researches about ISS technique, the DTC motor drive system is built to control the engine restart in literature [4], and the piston stop position is adjusted by the space vector pulse width modulation though control the opening of throttle. In [5], the automatic stop system is designed, compressing air of engine itself is used to control the piston stop position for the IRDSS system, and building the engine experimental platform. Literature [6] introduced the angular position of the throttle valve by using the DC servo motor. A PID, a STE-PID and MRAS with a SM adaptation mechanism are used to controlling the piston stop position. The nonlinear proportional-integral derivative controller is studied in [7] for the pneumatic positioning system, fuzzy logic technique was used to determine the appropriate rate.

In this paper, we take a 4G15GDI electronic throttle as the research object and establish model, the feed forward-feedback control strategy is designed, the feed-forward controller is designed to compensate the friction nonlinearity and the system parameters changed, then the electronic throttle is described as SISO nonlinear system. The feedback controller is an adaptive fuzzy sliding-mode controller, which can follow a class of nonlinear processes accuracy and stability. Simulation results show that compound control method has good control precision of the time-delay system, which can control the electric throttle opening track the target in real time.

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II. THE DESCRIPTION FOR IDLE STOP CONTROL SYSTEM

The critical technology of ISS is the piston stop position of the GDI engine after shutting down. The crankshaft flywheel under the effect of inertia is still rotate, but the kinetic energy of the crankshaft is consumed through drag torque of the cylinder residual gases and friction torque gradually. The crankshaft does retarded motion and the piston is stop completely at last. The figure 1 is the rate of compression piston stop position from the bench experiment, it shows that the piston stop position of compression are distribute regularly [8]: it is stopping on $80°$CA BTDC is probability about 50%, and stopping on the $70°$CA BTDC is probability about 30%. The probability of $40° \sim 60°$CA and $110° \sim 140°$CA are about 4%. So the piston position of compression stroke is stopping on $60°$CA ～ $80°$CA BTDC is the condition that ensure the compression stroke cylinder has enough air for fist combustion to restart engine, it can ensure the expansion stroke cylinder has more air volume, which can make the second combustion generate enough burning energy to make sure the crankshaft rotate forward and the engine starting quickly and reliably.

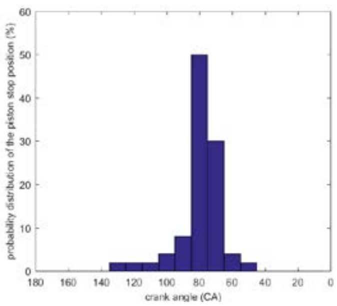

Fig. 1 stop position distribution

The stop position of the piston is controlled by lots of physical variables: gas resistance, mechanical resistance, the consumption of engine accessories and external device. The gas resistance torque depend on the amount of gas in cylinder, which is related to the throttle opening angle, the larger opening, the more air flows into cylinder. The mechanical resistance torque is come from the friction between piston and cylinder wall, which is not controllable. When the engine shutting down, the crankshaft and accessories rotation speed low, so the drive loss power can be ignored.

After engine shutting down, the power unit doesn't supply energy for engine control system, the piston is drive by inertial kinetic energy to do reciprocating motion until the energy is consumed. The more air flows into cylinder, the more inertial kinetic energy loss by gas motion, so the control problem of ISS is tracking the throttle opening. The test bench experiment shows that different engine has different throttle opening angle when piston stops in the desired position, which can compensate though the water temperature and rotation velocity [9].

III. Electronic Throttle Model

The structure of electronic throttle is shown in Figure 2, the 4G15GDI engines is selected as throttle system, which composed of a DC motor, a return spring, a position sensor, a set of reduction gears and a throttle valve. The motor is DC servo motor with 12V voltage, the throttle valve is driven by the motor through a set of reduction gears, the throttle angle is opened through overcome the resistance that come from a reset spring. The throttle percentage, which is the necessary position feedback signals are detected by the throttle position sensor, then the detected signals are converted to the electrical signals to import the closed-loop control system, the control system through compared the target opening and the actual opening to adjust control strategy.

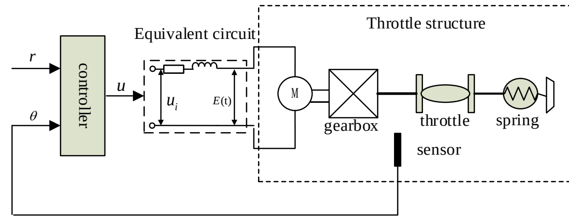

Fig. 2 the structure diagram of electronic throttle

A. Electric Analysis

Electrical throttle is driven by DC motor though a set of reduction gears to control the opening of valve block, the DC servo motor is controlled by armature, the equivalent circuit of DC servo motor is shown in left of Figure 2, the u_i is input voltage, ω_m is motor angular velocity (rad/s), i is armature current, L is armature inductance, R is armature resistance.

The equation of armature circuit of DC motor is given as blow:

$$\begin{aligned} u_i &= L\frac{di}{dt} + Ri + E(t) \\ E(t) &= k_e \omega_m (t) \end{aligned} \tag{1}$$

The back electromotive force $E(t)$ is related to motor angular velocity ω_m , k_e is electromotive force constant of motor.

B. Mechanical Analysis

For the electronic throttle body as figure 2, the throttle valve is rotate under the motor drive force, the reset spring force and frictional force. There are many torques acted upon the throttle: the return spring torque T_{rs} , the viscous friction torque T_{vf} , the coulomb friction torque T_{cf} , the motor output torque T_m and so on, so the electronic throttle has the nonlinear characteristics.

In order to ensure the stability of the throttle, the return spring is introduced to provide resilience for throttle, the throttle is pulled back to closed state from any opening. The reset spring torque is related to the opening of throttle valve and the throttle balance position opening θ_0 :

$$T_{rs} = -(k_s(\theta - \theta_0) + \mathrm{D}\,\mathrm{sgn}(\theta - \theta_0)) \tag{2}$$

k_s is the spring torque constant ($N \cdot m / rad$), D is the spring torque compensation coefficient.

The complex frictions acted upon the throttle system when it working, the frictional resistance torque is:

$$T_{vc} = T_{vf} + T_{cf} \tag{3}$$

T_{vf} is viscous frictional resistance torque, which is directly proportional to throttle rotate speed ω , the direction of T_{vf} is opposite to the rotation direction, so $T_{vf}=-k_v\omega$, k_v is coefficient of viscous friction ($V\cdot s/rad$). T_{fc} is coulomb friction, which is relate to the motion direction of plate, $T_{cf}=-k_f\,\mathrm{sgn}(\omega)$, k_f is coefficient of coulomb friction ($N\cdot m$). The direction of the above torques is negative, which are the drag force for the throttle.

The gear of the throttle system play an important role in transmit torque, and gear transmission can be equivalent as rigid transmission，the transmission relationship of gear is:

$$\frac{T_g}{T_m}=\frac{\omega_m}{\omega}=\frac{\theta_m}{\theta}=N \tag{4}$$

T_g is gear output torque, θ is throttle rotation angle (rad), N is the gear ratio of reduction gear, T_m is motor load torque .

The driving torque of motor is directly proportional to armature current, according to the principle of dynamics, the mechanical rotation equation of motor is:

$$\begin{aligned} &J_m\frac{d\omega_m}{dt}=k_m i-T_i-T_m \\ &T_i=M_m\omega_m \end{aligned} \tag{5}$$

T_i is motor viscous friction torque, which is relevant for motor rotation velocity ω_m , k_m is motor torque constant, M_m is motor viscous friction torque constant, J_m is rotational inertia of motor shaft.

Based on the Newton's second law, the throttle plate dynamics is obtained as follows:

$$J_{th}\frac{d\omega}{dt}=T_g+T_{rs}+T_{vc}-T_L \tag{6}$$

J_{th} is the rotational inertia of throttle flap shaft, T_L is air flow load torque. Taking the equations (2)-(5) into (6), the throttle plate dynamics can be expressed by following formula:

$$\begin{aligned} J\frac{d\omega}{dt}=&Nk_m i-N^2M_m\omega-k_s(\theta-\theta_0)-\mathrm{D}\,\mathrm{sgn}(\theta-\theta_0)- \\ &k_v\omega-k_f\,\mathrm{sgn}(\omega)-\mathrm{T_L} \end{aligned} \tag{7}$$

where $J=J_{th}+N^2J_m$.

The relationship of throttle shaft rotate velocity ω and the throttle angle θ is:

$$\dot{\theta}=\omega \tag{8}$$

Because the electronic throttle is a low pass system, the value of inductance L is small, so the influence of inductance can be ignored. The formulas (1)-(8) are integrated, the mathematical model of electronic throttle is obtained:

$$J^{'}\dot{\omega}=u_i-b\omega-F(\theta,\omega,\mathrm{T_L}) \tag{9}$$

where $J^{'}=\dfrac{R(J_{th}+N^2J_m)}{Nk_m}$, $b=\dfrac{RNM_m}{k_m}+Nk_e$,

$$\begin{aligned} F(\theta,\omega,\mathrm{T_L})=&\frac{k_sR(\theta-\theta_0)}{Nk_m}+\frac{k_fR\,\mathrm{sgn}(\dot{\theta})}{Nk_m}+ \\ &\frac{\mathrm{D}\,R\,\mathrm{sgn}(\theta-\theta_0)}{Nk_m}+\frac{k_v\omega R}{Nk_m}+\frac{T_LR}{Nk_m} \end{aligned}$$

Considering the T_L and θ_0 are uncertain parameters, and k_v, k_c , k_s are changed with the different throttle opening, so $F(\theta,\omega,\mathrm{T_L})$ is unknown parameter, which is a bounded function, $|F(\theta,\omega,\mathrm{T_L})|\le\eta$ [10], η is unknown constant. Figure 3 is the equivalent structure diagram of electronic throttle.

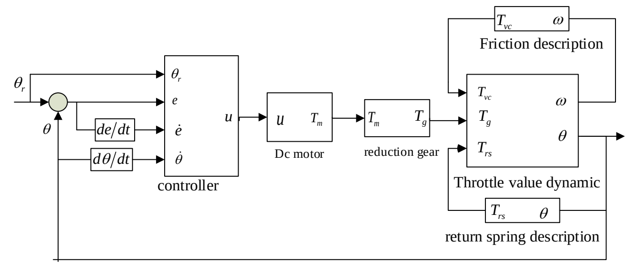

Fig. 3 the equivalent structure diagram of electronic throttle

The controlled aim of the electronic throttle system is as followed: the adjust time of dynamic process is less than 100 ms, and the step response non-overshoot. The dynamic tracking error less than 7, the static tracking error is less than 1.

IV. Feed Forward-Feedback Control Strategy Design

The goal of the electronic control system is the throttle valve can follow the target opening accurately, however, the nonlinear characteristics and time-varying are caused by the friction and a backlash, which influence the dynamic performance of the electric throttle. So the traditional single linear feedback is difficult to meet the requirements of control precision and response characteristics. A composite control method is design to compensate the error which caused by friction and backlash of mechanical.

The composite control stagey structure is shown in figure 4. A feed -forward control usually eliminate spring and friction error through collected and reported data, grasp the rules, predicted trends, taken precautions and so on. In this paper, a feed-forward nonlinear compensation controller is introduced to compensate the reset spring torque and the friction force. The desired opening as input, suitable voltage signal as output which can accelerate the speed of follow the target opening. The feedback controller is adaptive fuzzy sliding mode controller, which not only resolve the nonlinear of system, but also can eliminate the vibration in the sliding mode control.

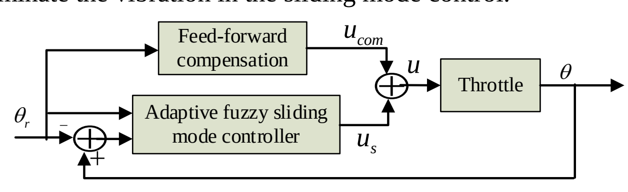

Fig. 4 the composite control system structure

In figure 4, θ_r is desired opening which is derived from the bench test and the value is decided by the piston stop position. The input of throttle is normalized voltage u_i , the output is actual opening of electric throttle θ , which is controlled by measured voltage, when the real-time detection of opening error is not meeting the requirement, the composite controller can compensate it effectively.

A. Feed-Forward Nonlinear Compensation Control

The electric throttle is affected by uncertain factors: the spring force, friction force, temperature excursion, unknown disturbance and unfounded model at the same time, and characteristic parameters k_v, k_f and k_s are changed with the different throttle opening. So the feed-forward controller is designed to compensate the reset spring torque and coulomb friction [11].

$$u_{com} = k'_s(\theta - \theta_0) + \mathrm{D}'\mathrm{sgn}(\theta - \theta_0) + k_f'\,\mathrm{sgn}(\dot{\theta}) + k_v'\dot{\theta} \quad (10)$$

in the formula, u_{com} is compensation control quantity of feed-forward, $k_s' = \frac{k_s R}{Nk_m}$, $\mathrm{D}' = \frac{\mathrm{D}R}{Nk_m}$, $k_f' = \frac{k_f R}{Nk_m}$, $k_v' = \frac{k_v R}{Nk_m}$, let $u_i = u_{com} + u_s$, the formula (9) can rewrite:

$$J'\ddot{\theta} = u_s - b\dot{\theta} - \frac{T_L R}{Nk_m} \quad (11)$$

u_s is the output of adaptive fuzzy sliding-mode controller, let $f(\theta,t) = -\frac{b}{J'}\frac{d\theta}{dt}$, $g = \frac{1}{J'}$, $d(t) = \frac{T_L R}{Nk_m} + d$, the electronic throttle is described as SISO nonlinear system:

$$\ddot{\theta} = f(\theta,t) + gu_s(t) + d(t) \quad (12)$$

Model parameter is changed with the electric throttle working, disturbance d is introduced to replace model error and unbuilt model dynamics.

B. Adaptive Fuzzy Sliding-mode Controller Design

The electronic throttle is a nonlinear system including a non-linear spring, a viscous friction, intake disturbance and backlash strike and son on, so the controller is designed by using the adaptive sliding mode control based on fuzzy logic. This control method can solve control accuracy and stability, and compensate the spring force and friction force effectively. The structure of adaptive fuzzy sliding mode control system is shown in figure 5:

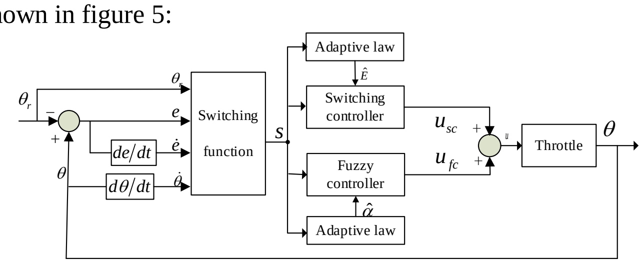

Fig. 5 the structure of adaptive fuzzy sliding-mode controller

The desired angle of sliding mode controller output is θ_r, and the tangential angle at the point cut P of the reference path is $\theta(t)$, then the output direction angle which is controlled by sliding control is tracking the trajectory tangential angle, and the central position deviation d tending to zero. The electric throttle angle trick the given trajectory smoothly, angle tracking error $e(t) = \theta(t) - \theta_r(t)$. The state variables of the electronic throttle system are defined: $x_1 = e = \theta - \theta_r$, $x_2 = \dot{x}_1 = \dot{\theta} - \dot{\theta}_r$.

(1) Sliding surface design

In order to improve the dynamic performance and robustness of control system, the integration sliding surface is designed:

$$s(t) = \dot{\theta}(t) - \int_0^t [\ddot{\theta}_d(t) - k_1\dot{e}(t) - k_2 e(t)]dt \quad (13)$$

k_1 and k_2 are non-zero positive constant.

If sliding-mode control is in perfect condition, then $s(t) = \dot{s}(t) = 0$, so

$$\dot{s}(t) = \ddot{e}(t) + k_1\dot{e}(t) + k_2 e(t) = 0 \quad (14)$$

though determined the value of k_1 and k_2, the tracking error $e(t)$ will approach zero gradually [12]. It presumed $d(t)$ is a known volume, then the control rate function is given:

$$u^*(t) = g^{-1}(-\eta s_\Delta(t) - f(\theta,t) - d(t) + \ddot{\theta}_d - k_1\dot{e} - k_2 e) \quad (15)$$

where, $s_\Delta(t) = s(t) - \delta sat(s(t)/\delta)$, η is positive constant, δ is boundary layer thickness, $s_\Delta(t)$ is algebraic distance of boundary layer and state, which has two states:

① if $|s_\Delta(t)| = |s(t)| - \delta$, if $|s(t)| \le \delta$, $s_\Delta(t) = \dot{s}_\Delta(t) = 0$, taking the equations (12) and (15) into (14), the mathematical relationship is:

$$\dot{s}(t) + \eta s_\Delta(t) = 0 \quad (16)$$

② if $|s(t)| > \delta$ and $t \to \infty$, $s_\Delta(t) \to 0$, then $s(t) \to 0$, so in the neighborhood of $e(t) \to 0$, the neighborhood size is relate to the value of δ [13].

(2) Fuzzy logic design

Because of $d(t)$ is an unknown disturbance, $u^*(t)$ is difficult to realize, so using fuzzy system approximation method to approximate the ideal controlled rate $u^*(t)$. $s(t)$ and $\dot{s}(t)$ are selected as inputs of fuzzy system. The fuzzy system are constitute by IF-THEN shape:

$R^{(j)}$: IF x_1 is F_1^j and x_2 is F_2^j THEN y is G^j $(j = 1,2,\cdots L \cdots l)$

$[x_1, x_2]^{\mathrm{T}} \in U$ and $y \in R$ are inputs and output of fuzzy logic system, F_1^j, F_2^j and G^j are fuzzy set, l is the number of fuzzy rules.

Singleton fuzzifier, product inference engine and center average defuzzizer are used in fuzzy logic system, then the output of fuzzy system is:

$$y(x) = \frac{\sum_{j=1}^{l}\alpha_j \prod_{i=1}^{2}\mu_{F_i^j}(x_i)}{\sum_{j=1}^{l}\prod_{i=1}^{2}\mu_{F_i^j}(x_i)} \quad (17)$$

$$\alpha_j = \arg\max_{y\in R}\mu_{G^j}(y)$$

The $\alpha_j \in \boldsymbol{\alpha}$ is maximum center of $\mu_{G^j}(y)$, $\mu_{F_i^j}(x_i)$ is subordinating degree function of fuzzy set F_i^j. The output of fuzzy logic system is approximated can be expressed by following formula:

$$u_{fr}(s,\boldsymbol{\alpha}) = \boldsymbol{\alpha}^{\mathrm{T}}\boldsymbol{\xi} \tag{18}$$

where, $\boldsymbol{\alpha} = [\alpha_1, \alpha_2 \cdots, \alpha_{\mathrm{m}}]^{\mathrm{T}}$, which value is adjusted by adaptive law:

$$\dot{\alpha} = \beta s_{\Delta}(\mathrm{t})\xi(\mathrm{x}) \tag{19}$$

β is positive constant, $\boldsymbol{\xi} = [\xi_1, \xi_2, \cdots, \xi_{\mathrm{m}}]^{\mathrm{T}}$ as fuzzy basis vector, ξ_i is be defined as $\xi_i = \frac{w_i}{\sum_{i=1}^{m} w_i}$, and $w_i = \prod_{i=1}^{2} \mu_{F_i^j}(x_i)$.

According to the fuzzy approximation theory, an optimal fuzzy system $u_{fr}(\mathrm{s}, \boldsymbol{\alpha}^*)$ is exist to approximate $u^*(\mathrm{t})$.

$$u^*(\mathrm{t}) = u_{fr}(\mathrm{s}, \boldsymbol{\alpha}^*) + \varepsilon = \boldsymbol{\alpha}^* \boldsymbol{\xi}^{\mathrm{T}} + \varepsilon \tag{20}$$

ε is approximate error, and $|\varepsilon| < \mathrm{E}$. Using fuzzy system u_{fr} approximate $u^*(\mathrm{t})$, then $u_{fr}(\mathrm{s}, \hat{\boldsymbol{\alpha}}) = \boldsymbol{\alpha}\boldsymbol{\xi}^{\mathrm{T}}$, $\hat{\boldsymbol{\alpha}}$ is the estimated value of $\boldsymbol{\alpha}^*$.

(3) Switch control design

The switching control rate u_{sc} is used to compensate error ε between u_{fr} and $u^*(\mathrm{t})$, so the total control rate of fuzzy sliding mode control can be expressed by following formula:

$$u(t) = u_{fr} + u_{sc} \tag{21}$$

then the control rate function can be expressed :

$$\begin{aligned} u^*(t) &= g^{-1}(-\eta s_{\Delta}(t) - f(\theta,t) - d(t) + \ddot{\theta}_{\mathrm{d}} + \ddot{e}(t) - \dot{s}(t)) \\ &= g^{-1}(-\eta s_{\Delta}(t) - f(\theta,t) - d(t) + \ddot{\theta} - \dot{s}(t)) \\ &= g^{-1}(-\eta s_{\Delta}(t) + gu(t) - \dot{s}(t)) \end{aligned} \tag{22}$$

Taking the formula (21) into (22):

$$\begin{aligned} \dot{s}(t) &= g(u(t) - u^*(t)) - \eta s_{\Delta}(t) \\ &= g(u_{fr} + u_{sc} - u^*(t)) - \eta s_{\Delta}(t) \end{aligned} \tag{23}$$

Lyapunov function $V_1(t) = \frac{1}{2}s^2(t) + \frac{b}{2\eta}\tilde{\alpha}^{\mathrm{T}}\tilde{\alpha}$ is selected, then we have:

$$V_1(t) = \frac{1}{2}s^2(t) + \frac{g}{2\eta_1}\tilde{\alpha}^{\mathrm{T}}\tilde{\alpha} \tag{24}$$

where, $\tilde{\alpha} = \hat{\alpha} - \alpha^*$, $\hat{\alpha}$ is the estimated value of α^*, then $\tilde{u}_{fr} = \hat{u}_{fr} - u^* = \tilde{\boldsymbol{\alpha}}\boldsymbol{\xi}^{\mathrm{T}} - \varepsilon$, η_1 is positive real.

$$\begin{aligned} \dot{\mathrm{V}}_1(t) &= s(t)\dot{s}(t) + \frac{g}{\eta_1}\tilde{\alpha}^{\mathrm{T}}\dot{\tilde{\alpha}} \\ &= s(t)(\mathrm{g}(u_{fr} + u_{sc} - u^*(t)) - \eta s_{\Delta}(t)) + \frac{g}{\eta_1}\tilde{\alpha}^{\mathrm{T}}\dot{\tilde{\alpha}} \\ &= s(t)\,\mathrm{g}(\tilde{u}_{fr} + u_{sc}) - g\eta s_{\Delta}(t) + \frac{g}{\eta_1}\tilde{\alpha}^{\mathrm{T}}\dot{\tilde{\alpha}} \\ &= s(t)\,\mathrm{g}(\tilde{\alpha}^{\mathrm{T}}\xi - \varepsilon + u_{sc}) - g\eta s_{\Delta}(t) + \frac{g}{\eta_1}\tilde{\alpha}^{\mathrm{T}}\dot{\tilde{\alpha}} \\ &= g\tilde{\alpha}^{\mathrm{T}}(s(t)\xi + \frac{1}{\eta_1}\dot{\tilde{\alpha}}) + s(t)\,\mathrm{g}(u_{sc} - \varepsilon) - g\eta s_{\Delta}(t) \end{aligned} \tag{25}$$

In order to achieve $\dot{\mathrm{V}}_1 \le 0$, let $s_{\Delta}(t) \to 0$, the blow adaptive law and switch control are selected:

$$\begin{aligned} \dot{\tilde{\boldsymbol{\alpha}}} &= \dot{\hat{\boldsymbol{\alpha}}} = -\eta_1 s(t)\xi \\ u_{sc} &= -E(t)\,\mathrm{sgn}(s\ (t)) \end{aligned} \tag{26}$$

then

$$\begin{aligned} \dot{\mathrm{V}}_1(t) &= -E(t)b\ |s(t)| - \varepsilon s(t)b \\ &\le -E(t)b\,|s(t)| + |\varepsilon|\,|s(t)|\,b \\ &= -b\ |s(t)|(E(t) - \varepsilon) \le 0 \end{aligned} \tag{27}$$

$\dot{E}(t) = \eta_2 |s(t)|$ is the adaptive law of $E(t)$, if $\dot{\mathrm{V}}_1 \equiv 0$, $s(t) \equiv 0$, according to LaSalle invariant set theory, $t \to \infty$, $s \to 0$.

Then the total control law of adaptive fuzzy sliding-mode is:

$$u(t) = u_{fr} + u_{sc} = \hat{\alpha}^{\mathrm{T}}\xi - \hat{E}(t)\,\mathrm{sgn}(s(t)) \tag{28}$$

V. Simulation Analysis

The simulation model of the closed-loop system is shown as figure 6, the simulation model is constituted of controller and throttle model. The step signal and sine signal are selected as reference, the physical parameters of electronic throttle are shown in table 1 [14].

Table 1 engine model parameters

Parameter (symbol)	Values (unit)
Power voltage (u_i)	12V
Transmission ratio (N)	22.08
Initial throttle opening (θ_0)	0.116 rad
Electrical resistance (R)	2.8 Ω
Motor torque constant (k_m)	0.016 $N \cdot m / \mathrm{A}$
Motor electromotive force (k_e)	0.016 $\mathrm{V} \cdot s / rad$
Viscous friction coefficient (k_v)	0.1393 $N \cdot m \cdot s / rad$
Motor shaft rotational inertia (J_{th})	4.0×10^{-6} $\mathrm{kg \cdot m^2}$
Spring torque compensation coefficient （D）	0.00374
Motor viscous friction torque constant (M_m)	0.0088 $N \cdot m / rad$
Coulomb friction coefficient (k_f)	0.0048 $N \cdot m$
Spring torque constant (k_s)	0.0195 $N \cdot m / rad$

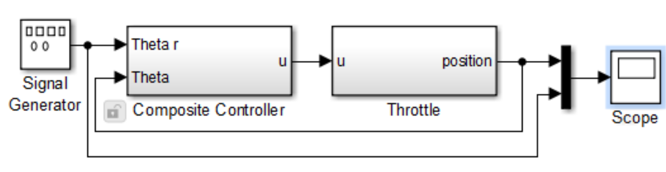

Fig. 6 closed-loop system simulation model

The input of fuzzy controller x_1 is s, x_2 is $\dot{s}$, the domain of x_1, x_2 is [-1 1], the state variables are described with seven kinds of fuzzy language, the fuzzy membership function are defined as following [15]:

$$\mu_{NB} = \exp[-((x_i + 0.897)/0.15)^2]$$
$$\mu_{NM} = \exp[-((x_i + 0.598)/0.15)^2]$$
$$\mu_{NS} = \exp[-((x_i + 0.3)/0.15)^2]$$
$$\mu_{ZO} = \exp[-(x_i/0.15)^2] \qquad (i = 1, 2)$$
$$\mu_{PS} = \exp[-((x_i - 0.3)/0.15)^2]$$
$$\mu_{PM} = \exp[-((x_i - 0.598)/0.15)^2]$$
$$\mu_{PB} = \exp[-((x_i - 0.897)/0.15)^2]$$

In order to verify the effectiveness of adaptive fuzzy sliding mode control, the electric throttle control system model is setup in the real-time environment Matlab/Simulink as shown in figure 7, the initial values of fuzzy sliding-mode control are: $k_1 = 5$, $k_2 = 12$, $\eta = 0.3$, $\delta = 0.2$, the parameters of controller $\eta_1 = 120$, $\eta_2 = 0.45$, the initial values of $\hat{\alpha} = 0.2$, $\hat{E} = 0.2$.

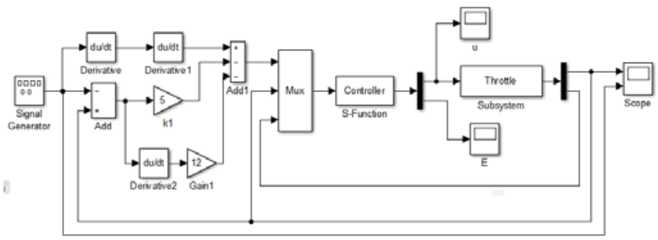

Fig. 7 the electric throttle control system model

The unit step signal is selected to be input, the response curve figure is showed in Figure 8. The unit step response rise time of sliding-mode control is 0.08 s, there is 20% overshoot and closed-loop regulating time is 0.18 s. The rise time of adaptive fuzzy sliding-mode controller is 0.05 s, 3% overshoot and 0.12 s closed-loop regulated time. It has the high tracking speed and small overshoot and small overshoot.

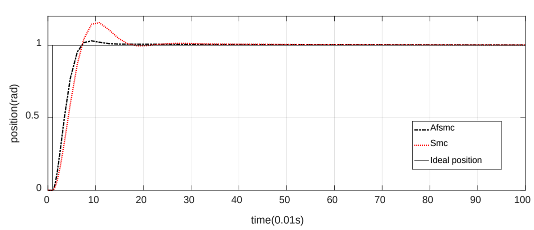

Fig. 8 step response curve

The sine signal is selected as input to emulate the capacity of electric throttle following the input. The amplitude of the sine wave is 0.2, the frequency is 5 Hz, the response of sliding-mode control is showed in figure 9. The delay of output following input is 3.8 ms, and it have a large vibration at speed tracking before 0.5 ms. The tracking feature not meeting the control requirements. The figure 10 shows that the angle tracking trajectory of Adaptive fuzzy sliding-mode controller control can track input orders quickly and accurately, there are no overshoot.

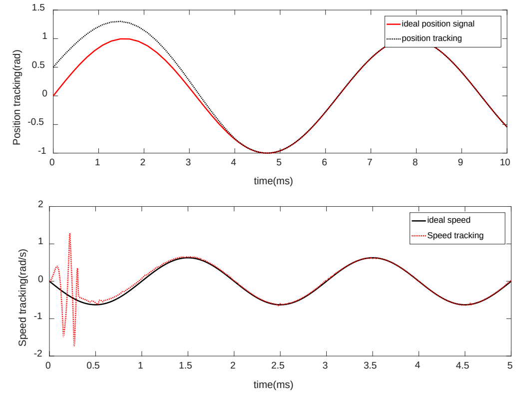

Fig. 9 the angle tracking trajectory and speed tracking trajectory of sliding-mode control

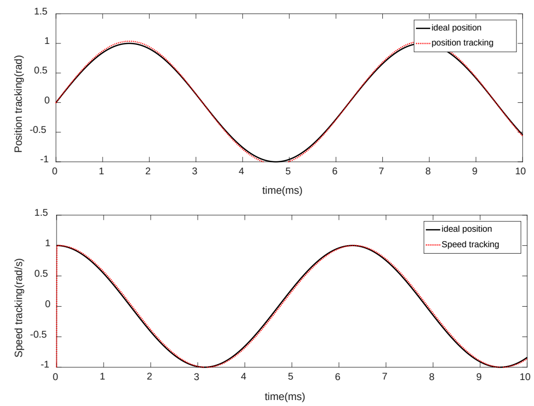

Fig. 10 the angle tracking trajectory and speed tracking trajectory of Adaptive fuzzy sliding-mode control

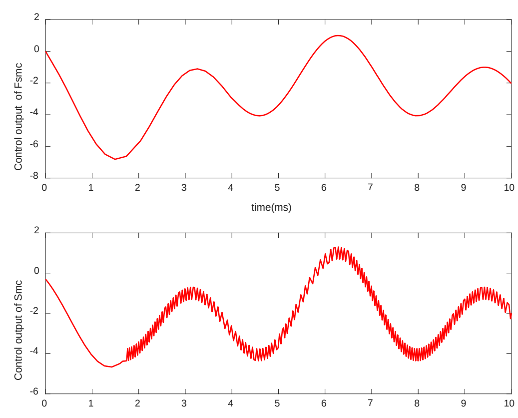

Fig. 11 dynamic control curve

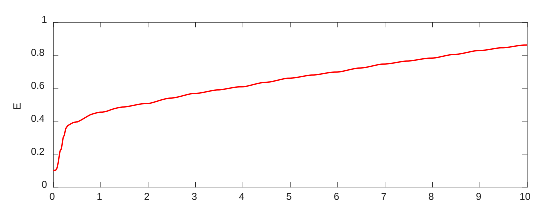

Fig. 12 the change of switching gain

The dynamic control curve is showed in Figure 11, it shows that dynamic control curve of adaptive fuzzy sliding-mode controller is smooth, which because of it can calculate output control in real time according of angular deviation and fuzzy theory, which ensure the precision of trajectory tracking. The chattering of sliding-mode controller dynamic control curve is obvious, which controlled variable is calculated by the equation (14), it is influenced by parameter perturbation and external disturbance. The figure 12 is the change of switching gain.

VI. CONCLUSION

In this paper, the relationship of the air inflow and the electric throttle opening is analyzed, then the piston stop position of GDI engine is converted to the electric throttle control problem. The model of electronic throttle is set up, and a feed forward-feedback composite controller is designed to control the opening of the electric throttle, the feed-forward controller is devised to compensate the friction nonlinearity and the system parameter change, then the electronic throttle is described as SISO nonlinear system. The feedback controller is adaptive fuzzy sliding-mode controller which is combine with fuzzy control, sliding mode control and self-adaptive control. Switching control and fuzzy control are adjusted by the $E(t)$ and $\theta(t)$ in real time. The simulation results show that the feed-forward nonlinear compensation controller and adaptive fuzzy sliding-mode controller enable the electric throttle to overcome the influence of non - linear characteristic, which are come from the reset spring and friction, and it control the throttle opening track order input quickly and accurately.

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