Yun-de SHEN*, Jing-yi ZHANG, Su-jie ZHOU, Lei WANG, Dong-ji XUAN

Motorcycle Engine Controller Design and Matlab/ Simulink Simulation

Abstract: In order to meet the requirements of environmental protection, energy-saving when people using motorcycle, the main propose of this article is to design a motorcycle engine controller based on the comprehensive control method of fuzzy control and PID control to control output speed and current air-fuel ratio(AFR) of motorcycle engine precisely under transient conditions. Then establishing the mathematical model of the motorcycle engine assembly based on Matlab/Simulink according to building fuel evaporation and dynamic oil film sub model, intake dynamic characteristic sub model, power output sub model and idle speed throttle control sub model. Finally combined with the control method of this paper, the simulation analysis is carried out to verify the feasibility of the scheme.

Keywords: Air-fuel ratio; control; Matlab/ Simulink; Motorcycle engine modeling; PID control.

1 Introduction

In recent years, environmental pollution and energy crisis is still generally concerned of all sectors of the community. Therefore, the future development trends of motorcycles also focus on low pollution emissions, energy-saving and more advanced technology. Accurate air-fuel ratio control is the key control technology for modem motorcycle engine and air-fuel ratio control technique based on model which is researched hotspot at home and abroad currently [1,2]. Air-fuel ratio has a very direct influence on the dynamic performance, fuel economy performance and emission performance of the engine, especially for the emission of tail gas [3].

This paper is organized as follows. Firstly, establishing four mathematical sub models of the motorcycle engine, then according to the correlation between them, the model assembly of the engine is obtained. Secondly, proposing an air-fuel ratio control strategy based on the comprehensive control method of fuzzy control and PID control under transient conditions. Concrete, Fuzzy control is adopted when there is big

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difference between the measurement result and the target quantity; on the contrary, classical PID control is priority. Making the fluctuation of the air fuel ratio is within the scope of design by using a precise control of the throttle opening and the input volume of cylinder fuel. Consequently, ensuring the engine speed and reducing the pollutant emission. Finally, it is combined with the control method of fuzzy control - PID control. The simulation analysis of motorcycle engine which obtains air-fuel ratio changes in the three cases include non-controller, PID controller and fuzzy control and PID control is carried out. And verifying the feasibility of the scheme through compare and analyses the simulation result of the three cases mentioned above.

2 The establishment of engine model

It's important to establish the mathematical model of the motorcycle engine, so as to simulate and control the input and the output quantity changes, such as air intake and air output, fuel injection mass and power output speed, etc. Laying the foundations for air/fuel ratio of motorcycle engine. Firstly, establishing four mathematical sub models of the motorcycle engine, including fuel evaporation and dynamic oil film sub model, intake dynamic characteristic sub model, dynamic output sub model and idle throttle control sub model. Then the four models are connected by the parameter association between them to generate the model assembly of the engine.

2.1 Fuel evaporation and dynamic oil film sub model

The fuel sprayed from the injector enters the cylinder in two ways: one part is to adhere to the inlet or the inlet valve wall, so a portion of the oil film is formed. This layer of oil film continues to evaporate and enters the cylinder with the air. While the other part of the fuel is directly gasified into fuel vapor to enters the cylinder. The differential equation of the sub model can be expressed as:

$$\dot{m}_{fv} = (1-X)\dot{m}_{fi} \tag{1}$$

$$\ddot{m}_{ff} = (1/\tau)(-\dot{m}_{ff}) + X\dot{m}_{fi} \tag{2}$$

$$\dot{m}_{f} = \dot{m}_{fv} + \dot{m}_{ff} \tag{3}$$

Where x is the distribution coefficient of fuel, τ is the time constant of oil film, $\dot{m}_{fv}$ is fuel mass flow sprayed from the injector, $\dot{m}_{f}$ is the fuel mass flow in the cylinder, $\dot{m}_{fi}$ is the evaporation capacity of deposited oil film and $\ddot{m}_{ff}$ is the mass change rate of oil film.

There is a dynamic balance in the formation and evaporation of oil film: if the fuel injection quantity, the engine speed or the cylinder temperature changes, it will interfere with the balance of fuel oil film to affect the quality of the fuel in the cylinder.

And when the engine is under acceleration and deceleration transient condition, the balance of oil film will be broken. The volume of fuel injected into the cylinder and the volume of oil emitted by the fuel injectors are no longer equal. So air-fuel ratio (AFR) of motorcycle engine will be impacted by the dynamic characteristics of oil film.

Although the fuel evaporation and dynamic oil film sub model is presented in the form of linearity on the surface, the fuel evaporation and dynamic oil film sub model is a nonlinear dynamic model actually because of the two nonlinear parameters and X it contains. Hendricks Elbert, a professor at the Technical University of Denmark proposed that in the case of fully preheating of the engine, the two parameter model τ and X can be expressed as [4-6]:

$$\tau(p_i,n) = 1.35\ (0.672n + 1.68)(p_i - 0.825)^2 + (0.06n + 0.15) + 0.56 \quad (4)$$

$$X = -0.277p_i - 0.055n + 0.68 \quad (5)$$

Where is absolute pressure of intake manifold and is the speed of engine.

According to the equations mentioned above, fuel evaporation and dynamic oil film sub model showed in Figure 1 can be established based on MATLAB/Simulink.

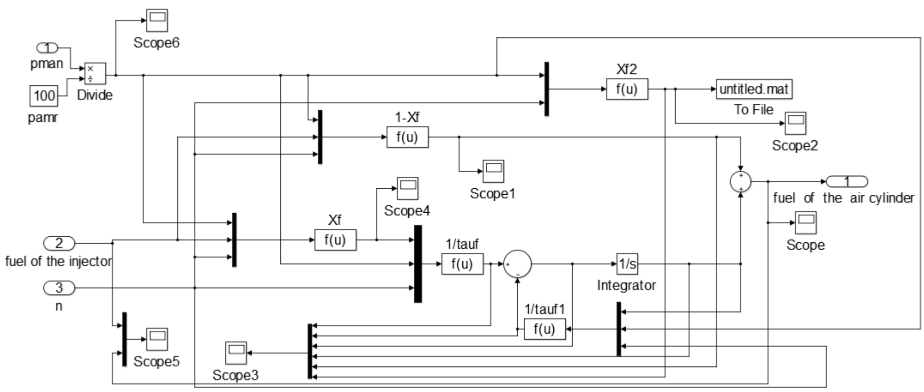

Figure 1. Fuel evaporation and dynamic oil film sub model

2.2 Intake dynamic characteristic sub model

The intake dynamic characteristic sub model is derived from the mass conservation equation. The following equations can be obtained according to the structure of the engine:

$$\dot{m}_a = \dot{m}_{at} - \dot{m}_{ap} \quad (6)$$

Where $\dot{m}_a$ is the air quality change rate of air intake pipe, $\dot{m}_{ap}$ is air mass flow at the intake valve and $\dot{m}_{at}$ is air mass flow at the throttle.

The air mass flow at the intake valve can be written as:

$$\dot{m}_{ap} = \frac{nV_d \eta_{vol}^{man}}{120RT_{man}} P_{man} \tag{7}$$

Where ς_{vol}^{man} is referred to as volumetric efficiency based on manifold conditions respectively. It mainly depend on engine speed n ,intake pressure P_{man} and intake temperature T_{man} . V_d is the displacement volume of the engine and R is the specific gas constant. And according to the ideal gas state equation, the air quality change rate of air intake pipe can be derived as:

$$\dot{m}_a = \frac{\dot{P}_{man} V}{RT_{man}} \tag{8}$$

$$\dot{P}_{man} = -\frac{nV_d \eta_{vol}}{120V} P_{man} + \frac{RT_{man}}{V} \dot{m}_{at}(\alpha, p_{man}) \tag{9}$$

The air mass flow at the throttle can be calculated in accordance with the compressible flow of the nozzle:

$$\dot{m}_{at} = C_1 \frac{\pi}{4} D^2 \frac{P_{man}\sqrt{2K/(K-1)}}{\sqrt{RT_{amb}}} \beta_1(\alpha)\beta_2(P_{man}) + \dot{m}_{at0} \tag{10}$$

$$\beta_1(\alpha) = \begin{matrix} 0 & 0 \le \alpha \le \alpha_0 \\ 1-\cos(\alpha) & \alpha_0 \le \alpha \le 90^\circ \end{matrix} \tag{11}$$

$$\beta_2(P_{man}) = \begin{cases} \sqrt{P_r^{\frac{2}{x}} - p_r^{\frac{K+1}{x}}} & P_r \ge (\frac{2}{K+1})^{\frac{K}{K-1}} \\ \sqrt{(\frac{x-1}{2x} - \frac{2}{x+1})^{\frac{K+1}{K-1}}} & P_r < (\frac{2}{K+1})^{\frac{K}{K-1}} \end{cases} \tag{12}$$

Where $\dot{m}_{at0}$ is the minimum air flow at throttle, D is throttle plate diameter and $\dot{m}_{at}$ is air mass flow at the throttle, T_{amb} is the atmospheric temperature, K is the specific heat of air, R is the specific gas constant, C_1 is the gas flow coefficient of throttle, P_{amb} is the barometric pressure, α is the opening of throttle and where

$$P_r = \frac{P_{man}}{P_{amb}} \tag{13}$$

According to the equations mentioned above, fuel evaporation and dynamic oil film sub model showed in Figure 2 can be established based on MATLAB/Simulink.

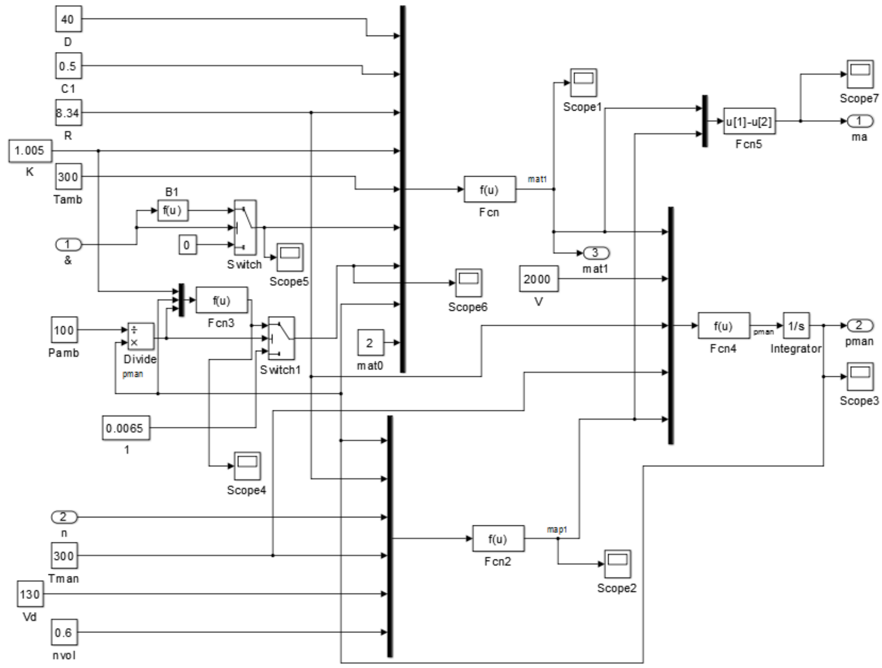

Figure 2. Intake dynamic characteristic sub model

2.3 Power output sub model

The main parameters associated with the engine power output sub model are the fuel mass flow in the cylinder of fuel evaporation, dynamic oil film sub model and air mass flow in the cylinder of intake dynamic characteristic sub model and there are some other parameters of the engine such as: ignition timing, engine speed and so on, in order to calculate the change rate of the output power and speed of the engine.

When air and fuel vapor enter the cylinder, they will be ignited by a spark plug, then burn severely and release energy driving the piston motion to rotate the crankshaft to produce the torque. Basing on the law of conservation of energy, external output torque of the engine is equal to the value that the running torque of crankshaft minus the friction resistance moment, pumping resistance moment and load torque, it's equation is given as follows [7-11]:

$$\dot{n} = -(P_f + P_P + P_h)/(I \quad n) + H_u \eta_i \dot{m}_f (t - \tau_d)/(I \quad n) \tag{14}$$

$$P_f + P_h + P_P = n(a_0 + a_1 n + a_2 n^2) + n(a_3 + a_4 n) P_{man} \tag{15}$$

$$\eta_i = \eta_m(n) \eta_{\dot{p}} (P_{man}) \eta_{i\lambda}(\lambda) \eta_{i\theta}(\theta, n, P_{man}) \tag{16}$$

Where a_i is the parameters of engine state. $\eta_m(n)$, $\eta_p(P_{man})$, $\eta_{i\lambda}(\lambda)$, $\eta_{i\theta}(\theta, n, P_{man})$ are the combustion efficiency coefficients related to the usage status of the engine. P_f is friction power and P_h is output power. H_u is the calorific value of fuel. θ is the ignition timing. τ_d is total time delay. P_p is pumping power. I is the moment of inertia of engine moving parts. η_i is the heat efficiency obtained of the engine and λ is excess air ratio.

According to the equations mentioned above, fuel evaporation and dynamic oil film sub model showed in Figure 3 can be established based on MATLAB/Simulink.

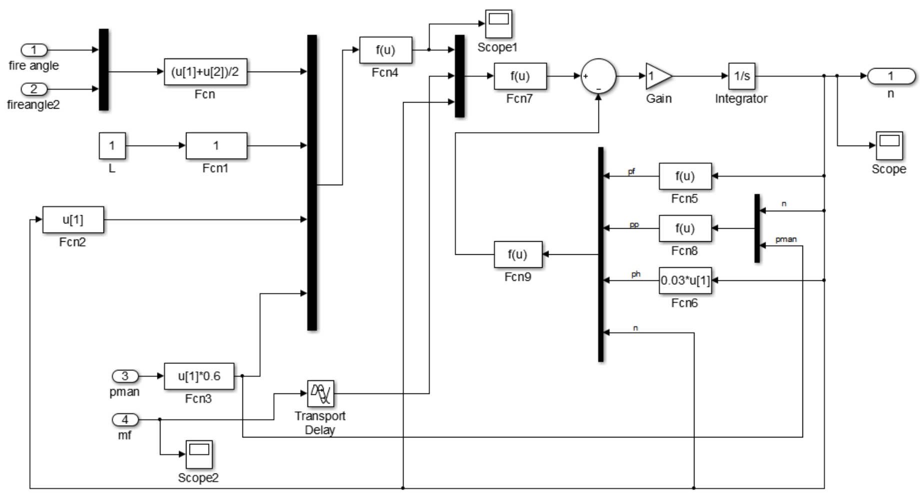

Figure 3. Power output sub model

2.4 D. Idle speed throttle control sub model

The size of the throttle opening is realized by controlling the rotation angle of permanent magnet brushless DC wheel motor and the error value of the target and the current opening can be obtained by using the encoder-error detector. At the same time, an error signal is produced and be converted to a load power

by using an encoder gain and a power amplifier to control the rotation angle of permanent magnet brushless DC wheel motor. The equation is as follows:

$$\theta_e(t) = \theta_i(t) - \theta_o(t) \tag{17}$$

$$e(t) = K_s \theta_e(t) \tag{18}$$

$$e_a(t) = K_A e(t) \tag{19}$$

$$L_a \frac{di_a(t)}{dt} + R_a i_a(t) = e_a(t) - e_b(t) \tag{20}$$

$$e_b(t) = K_b \omega_M(t) \tag{21}$$

$$T_M(t) = K_T i_a(t) \tag{22}$$

$$J \frac{d\omega_M(t)}{dt} + B\omega_M(t) = T_M(t) \tag{23}$$

According to the equations mentioned above, fuel evaporation and dynamic oil film sub model showed in Figure 4 can be established based on MATLAB/Simulink.

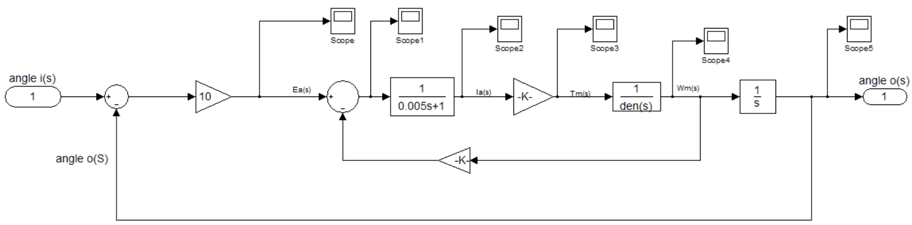

Figure 4. Idle speed throttle control sub model

2.5 The model of the motorcycle engine assembly

The most important characteristic of this mean value engine model is that the fuel evaporation and dynamic oil film sub model and the inlet dynamic characteristic sub model are studied separately and their effects can be analyzed accurately. Meanwhile, the effects of dynamic characteristics are showed in the power output sub model.

The model of the motorcycle engine assembly is illustrated in Figure 5, it is established by connecting the four sub models according to the correlation of their parameters.

3 The design of air-fuel ratio controller for motorcycle engine

In this article, a motorcycle engine controller based on the comprehensive control method of fuzzy control and PID control is designed. When air enters the cylinder, the fuel injection has a time delay and there are a process of the formation and evaporation of oil film to make the value of air-fuel ratio larger during the prophase. If using PID control at this time, it may cause an phenomena of integral saturat and it can even cause system instability. While fuzzy control can be a better solution to the problem that air-fuel ratio may be too large during the prophase. Using the classic PID control during the anaphase to control air -fuel ratio more precisely, stably.

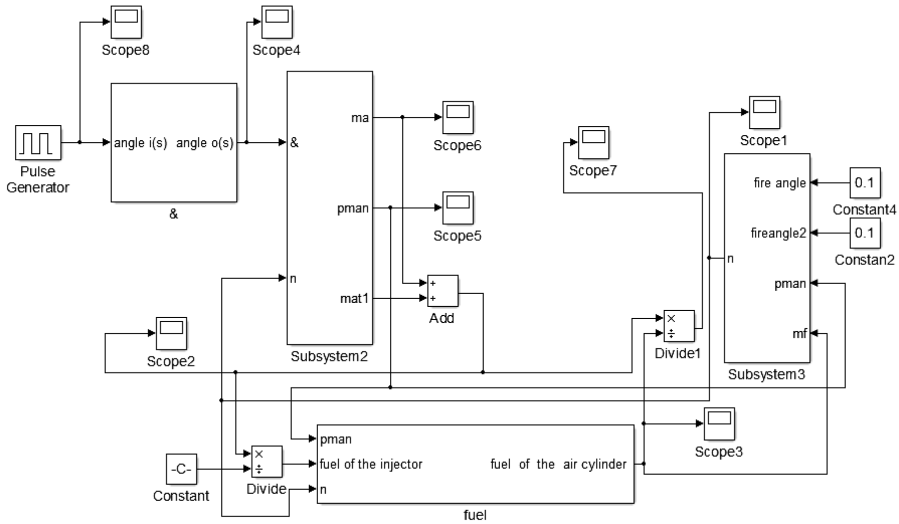

Figure 5. The model of the motorcycle engine assembly

3.1 Fuzzy control for air fuel ratio

3.1.1 Overview

Up to now, there is no clear definition of fuzzy control. It is universally acknowledged that fuzzy control is a kind of computer digital control technique, which is based on fuzzy set theory, fuzzy language variable and fuzzy logic reasoning. Compared with the traditional control method, the fuzzy control has the following prominent features:

1. It has strong robustness, when the parameters of the controlled objects are changed, it can still control the object smoothly.
2. It is applicable for all kinds of nonlinear, time-varying and delay system.
3. The control effect to the system is well without strict requirement of equipment, moreover it pay well in economy.

When we design the fuzzy controller, we don't have to set up the exact mathematical model of the controlled object. This feature makes fuzzy control very special compared to the general control.

3.1.1.1 Basic principle of fuzzy control

The basic structure of the fuzzy control system is shown in Figure 6.

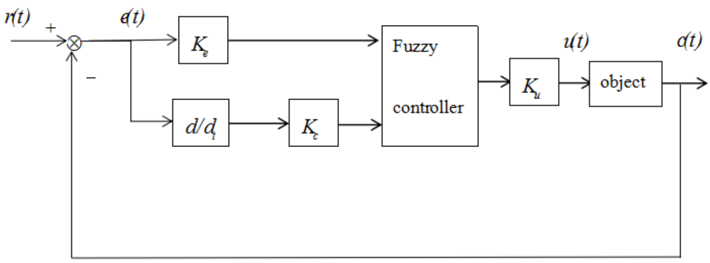

Figure 6. Block diagram of fuzzy control

3.1.1.2 Design of fuzzy controller

Fuzzy sets and domain must be defined according to the basic principle of fuzzy control [1]. In this paper, E and EC are respectively error and error rate. U is regarded as the control variable. For the output variables seven fuzzy subsets have been used (PB,PM,PS,ZE,NS,NM,NB), in order to smooth the control action. And set corresponding to the domain between [-6,6]. Choosing trigonometric function which is the most common and of a high resolution as a membership function of input variables. For control variable, simple Gauss function is used. The specific parameters of membership functions are shown in Figure 7 and 8. Besides, basing on the principle of Fuzzy-PID parameter setting, the fuzzy control rule table is established in Table 1.

By doing the work mentioned above, the establishment of the fuzzy inference system is completed. Finally, based on Matlab/simulink, establishing the fuzzy control system for air-fuel ratio of motorcycle engine shown in Figure 9 is established. Because the domain is [-6,6] and the actual amount is between [-0.5,0.5], so it is easily to determine the magnification K_E, K_{EC}=2, K_U=0.2(K_E=12, K_{EC}=2,K_U=0.2).

Table 1. Rule table for Fuzzy control

U / EC / E	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PM	ZO	ZO
NM	PB	PB	PB	PB	PM	ZO	ZO
NS	PM	PM	PM	PM	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NM	NS	NM	NM
PM	ZO	ZO	NM	NB	NB	NB	NB
PB	ZO	ZO	NM	NB	NB	NB	NB

NB: Negative Big ; NM: Negative Medium; NS: Negative small; ZE: Zero; PB: Positive Big ; PM: Positive Medium ; PS: Positive Small

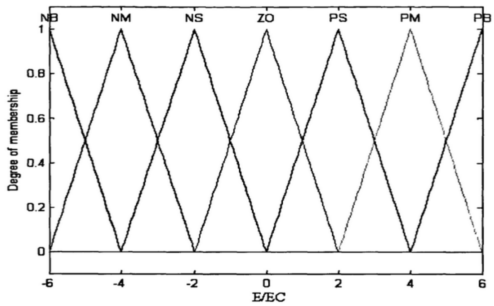

Figure 7. Membership functions of E and EC

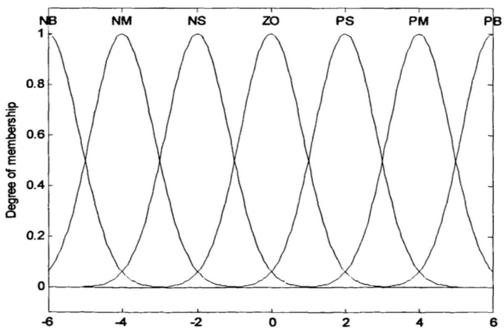

Figure 8. Membership functions of control variables

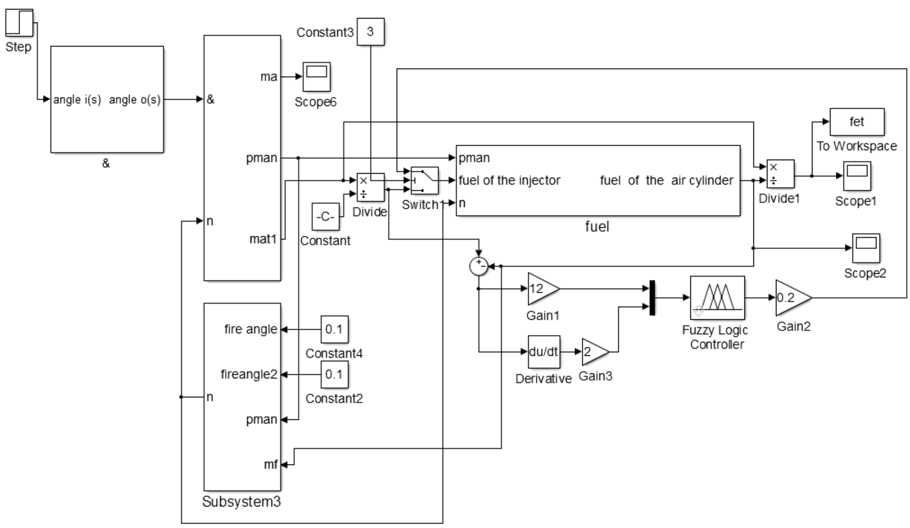

Figure 9. Fuzzy control system for air-fuel ratio of motorcycle engine

3.2 Classic PID control for air fuel ratio

3.2.1 A method of PID control design

The basic principle of PID control is relatively simple, it is mainly consists of three elements, including proportional element P, integral element I and differential element D. The controlling rule can be described as $G(s) = K_P + \frac{K_I}{s} + K_D s$. The method of PID control design is usually divided into the following steps:

3.2.1.1 Determine the proportional gain

In order to avoid the influence on the KP parameters due to integral terms and differential terms, it's better to remove the integral terms and differential terms in PID controller first to make the controller become a pure proportional control system. Then set the input value to 60% of the maximum value which is allowed of the system and increase the proportion gain gradually until there is an obvious oscillation of the system. And then reduce the proportional gain gradually until the system oscillation completely disappeared. Record the proportion of gain at this time, while setting the proportion gain of PID to 60% of the current value.

3.2.1.2 Determine the integral time constant

After determining the proportion gain, it's better to give a initial value of first, then to reduce this value gradually until there is an obvious oscillation of the system. And then reduce the proportional gain gradually until the system oscillation completely disappeared. Record the integral time constant at this time, while setting the integral time constant of PID to 150% of the current value.

3.2.1.3 Determine the integral time constant

The method to Determine the integral time constant is the same as the method of determining Ti, and set the integral time constant to 30% of the current value, which is recorded when there is no oscillation in system.

Finally, fine tune the data based on the simulation curve.

3.2.2 The establishment of PID controller

PID controller is shown in Figure 10. In this paper, step signal is selected as input signal to ensure that the state of the entire system is stable, and set the time of initial value is within a high range.

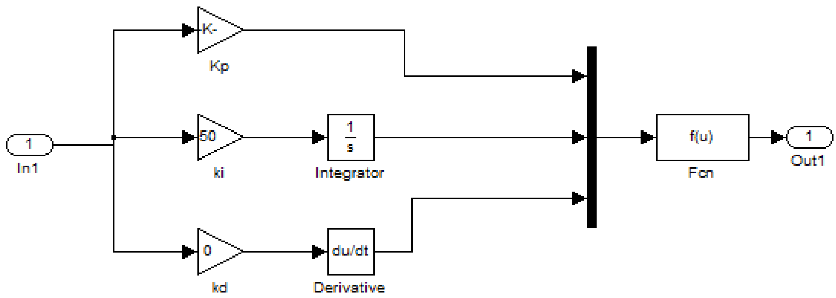

Figure 10. PID controller

3.3 A design of fuzzy -PID controller

The value of air-fuel ratio is large during the prophase, while in anaphase it becomes smaller. So as mentioned above it's reasonable to use the method combining fuzzy control and PID control, as shown in Figure 11. In this paper, a difference comparison between the target air-fuel ratio and the actual air-fuel ratio is carried out. And a threshold is set to make a judgement to choose fuzzy control or PID control.

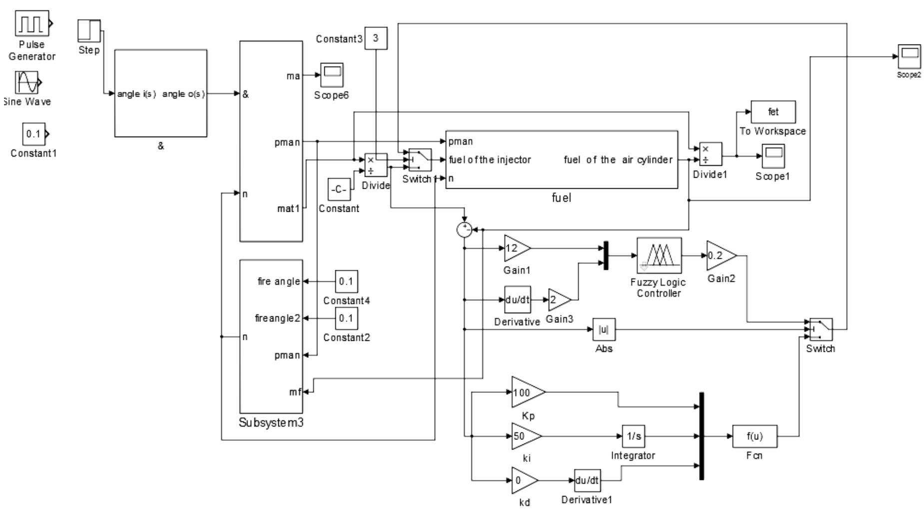

Figure 11. Fuzzy-PID controller

4 The results and analysis of simulation

Figure 12 shows a change curve of the air fuel-ratio without control, we can see the fluctuant of the curve ranges between 14-17.5, so it's far beyond the scope of what we want to control and it has a long transition time.

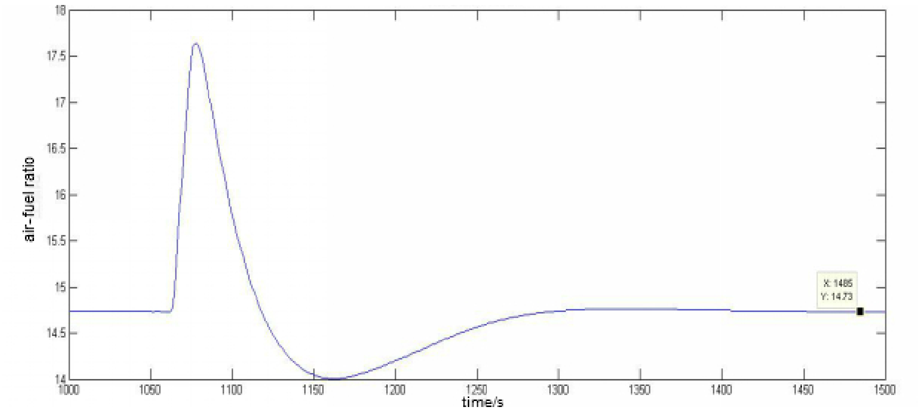

Figure 12. Change curve of the air fuel-ratio without control

Figure 13 shows a change curve of the air-fuel ratio under the control of PID controller. As shown in Figure 13, the fluctuant of the curve ranges between 14.8888-14.6605, besides, the maximum overshoot and the final steady-state value were 0.2188 and 14.673 respectively. There a difference of 0.03 between the target air-fuel ratio 14.67 and the current air-fuel ratio in case of the control of a PID controller. This means the steady state error is relatively small under this condition.

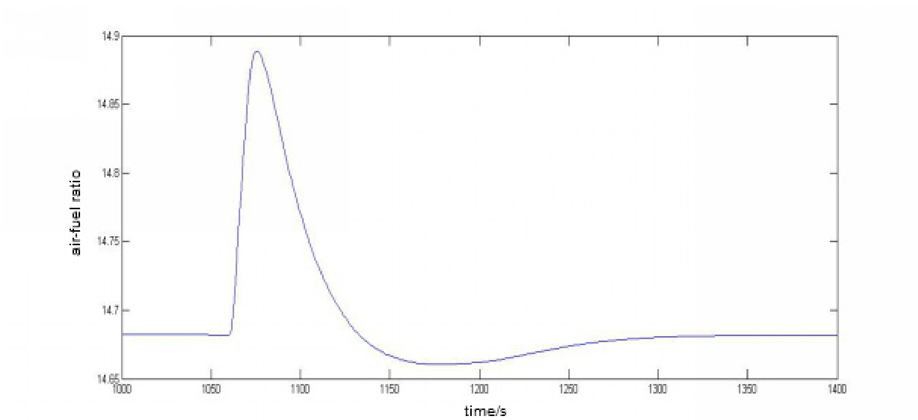

Figure 13. Change curve of the air fuel-ratio under the control of PID controller

Figure 14 shows the change curve of the air-fuel ratio with the control of Fuzzy-PID controller, and he maximum overshoot and the final steady-state value were 14.677 and 14.669 respectively. It can be seen that this kind of control method has the best control effect of air-fuel ratio.

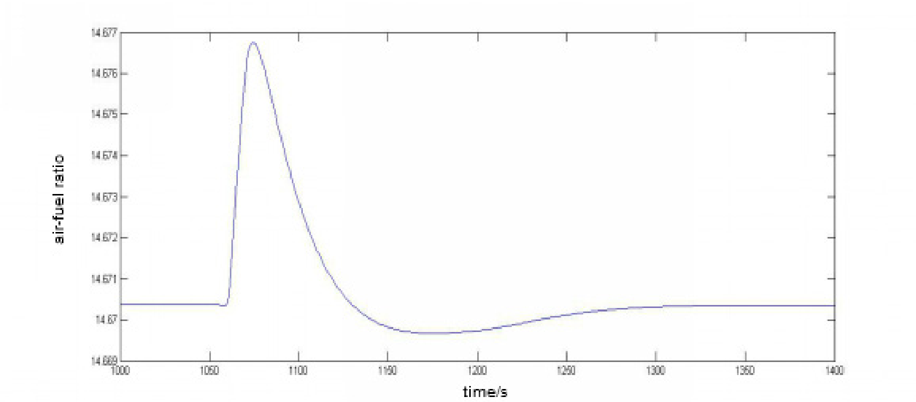

Figure 14. Change curve of the air fuel-ratio with the control of Fuzzy-PID controller

5 Conclusion

Air-fuel ratio has a very direct influence on the dynamic performance, fuel economy performance and emission performance of the engine, especially for the emission of tail gas. This paper propose an control strategy of air-fuel ratio for motorcycle engine based on the comprehensive method of fuzzy control and PID control.

In this paper, we establish four mathematical sub models and the model assembly of the motorcycle engine. Using Fuzzy-PID comprehensive controller under transient conditions and making the fluctuation of the air fuel ratio is within the scope of design by using a precise control of the throttle opening and the input volume of cylinder fuel. The simulation analysis of motorcycle engine which obtains air-fuel ratio changes in the three cases include non-controller, PID controller and fuzzy control and PID control is carried out. And verifying the feasibility of the scheme through compare and analyze the simulation result of the three cases mentioned above.

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