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Gasoline Engine Fuel Pump Pressure Nonlinear Function Fuzzy Control

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Abstract

In order to improve the accuracy of electronic fuel injection (EFI) engine fuel pump pressure, according to the characteristics of pump directly driven by motor, a nonlinear mathematical model is built for the fuel supply system of EFI engine pressure control. And then, the nonlinear-function-optimized flow signal is introduced to adjust the parameters of nonlinear function. With the PI control algorithm, the precise tracking control of injection pressure is achieved. The simulation and experiment results show that, it can indirectly realize from the speed control to pressure control.

Keywords: *EFI gasoline engine, fuel pump, nonlinear, fuzzy control*

1. Introduction

The parameters and loads of EFI gasoline engine fuel injection system change with the changing of engine speed and load, electric fuel pump which is directly controlled by the pump control unit has become a major method of the engine oil pump control [1]. Through the acquisition of car running real-time information, the system can change the engine gasoline pump speed to meet the requirements of the engine. This method, with lower emissions and higher fuel economy, can improve the car dynamics, and it has been widely used in luxury car [2].

In order to prevent the high fuel consumption caused by higher system oil pressure, or low oil pressure caused car power shortages, gasoline engine electric fuel pump has four functions [3]. It not only meets the requirement for variable speed operation at normal engine operating time, but also meets the requirements of the pre operation without starting the engine, the engine is driven by starter and engine flameout even when the ignition switch is still in the on position. The pump can automatically stop to protect the EFI system. But because of the nonlinear of hydraulic system and the fuel injection process, the air flow and the load signal in the engine management system are time-varying and uncertainty [4], which greatly increased the difficulty of precise control of the engine fuel pump. At present, the neural network method [5-7], grey prediction control method [8] and adaptive control [9] are generally adopted at home and abroad to solve the problem.

But the response time of those methods is too long, and convergence speed is too slow. Furthermore, those methods are generally used to control the injector solenoid valve injection speed. There is few methods to direct control the oil pump pressure, which will cause the fuel pipe pressure reflex and great influence on the amount of fuel injection [10-11]. This paper uses quadratic function based on the nonlinear optimization method to measure the difference between the actual measured pressure and the control unit output signal. Then, combination of fuzzy control with PI control algorithm to control the engine fuel pump motor speed, and thus control pump output pressure. This allows the injection pressure control to become a closed-loop control, and the engine electronic control unit can accurately track the actual injection pressure command pressure.

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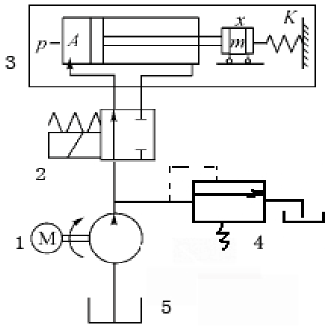
2. Gasoline Supply System Modeling

The EFI gasoline engine gasoline supply system as shown in Figure 1, then builds the dynamics model of the system. The oil pump (1) speed is controlled by electronic control unit. When adjust the pump speed, the fuel pressure through tank (5) to the electromagnetic valve (2) injected into the cylinder (3) is adjusted. 4 for return pipe of the system. The fuel injection process, injection pressure and speed of response was related to engine operating conditions, so the fuel injection system changes caused by cylinder compression pressure changing is added in the Figure 1. Use spring-mass subsystem with the variable stiffness to simulate the actual injection pressure of the cylinder [12].



1- pump, 2-injector, 3-cylinder, 4-oil return valve, 5-tank

Figure 1. Schematic Diagram of EFI

Ignoring the pressure of hydraulic oil return chamber, to the hydraulic cylinder, there is [13]:

$$pA = m\ddot{x} + Kx + F_t \quad (1)$$

Where p is the fuel injection pressure; A is piston action area; m is the simulated load quality; x is simulated load displacement; K is the stiffness of spring; F_t is the internal resistance of fuel system. Ignoring the leakage, the flow continuity equation in cylinder is:

$$qv_1 = A\dot{x} + \frac{Ax + V_2}{E}\dot{p} + C_t p \quad (2)$$

Where qv_1 is the flow into the cylinder; V_2 is the initial volume of the cylinder; E is elastic modulus of the fuel; C_t is the cylinder internal leakage coefficient.

And the pump outlet flow equation is:

$$qv = V_t n(u)\eta \quad (3)$$

Where qv is the oil pump outlet flow; η is the overall efficiency of the pump; V_t is pump for gasoline engine; n is engine fuel pump speed; u is the engine control unit input signal.

According to the flow conservation principle, the flow continuity equation of the pump outlet is:

$$qv = qv_1 + \frac{V_1}{E}\dot{p}_s \quad (4)$$

Where p_s is the pump outlet pressure; qv_1 is the volume between pump and injector. Define state variables of the system to:

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

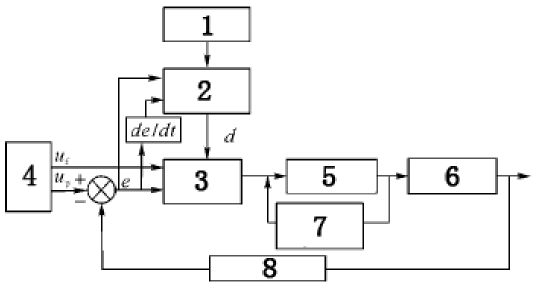
By equation (1) and (2), it can get the system state equation:

$$\left.\begin{aligned} &\dot{x}_1 = x_2 \\ &\dot{x}_2 = -\frac{K}{m}x_1 + \frac{A}{m}x_3 - \frac{F_t}{m} \\ &\dot{x}_3 = Eh(x_1)[qv_1 - Ax_2 - C_t x_3] \end{aligned}\right\} \quad (5)$$

Where $h(x_1) = 1/(Ax_1 + V_1)$. As the formula (5) shows, this system is a nonlinear system. But when the car is running, the engine speed signal and the car load signal is changing with the time, so E, C_t and K is not only uncertainty, but boundary.

3. Research Method

As shown in Figure 2, a nonlinear optimal controller is composed of an optimal controller and a fuzzy controller, and optimal controller is composed of flow optimization function and PI controller, the parameters of optimal controller is adjusted by fuzzy controller in real time [14].



1-rules base, 2-fuzzy controller, 3-optimal controller, 4-PLC signal,
5-server motor, 6- hydraulic system, 7-speed sensor, 8-pressure sensor

Figure 2. Block Diagram of the Controller

3.1. Introduction of Nonlinear Functions

As it can be seen from Figure 2, the controller uses the master and slave computer structure and layout. The slave computer is the design of the controller, for receiving analog signals. And the master computer use PLC to control. According to the working characteristics of fuel injection system, pre control, starting control, speed control and automatic shutdown protection control should be processed by the pump speed control unit. At present, there are 3 ways to the commonly velocity and pressure switching control, that is [15] time switch, pressure switch and position switch 3 ways. Defining the optimization function $f(\Delta p)$, whose range is (-1, 1), by using pressure error $\Delta p = p_{\mathrm{m}} - p_{\mathrm{f}}$, the pressure switch function is:

$$f(\Delta p) = \frac{\Delta p}{|\Delta p| + \dfrac{d}{c + (\Delta p)^2}} \quad (6)$$

Multiply optimization function and the PLC flow signal, there will obtain a new flow signal: $u_{f1} = f(\Delta p)u_f$, where u_{f1} is the new flow signal. In Formula (6), p_f is a feedback pressure for real system; p_m is the system set pressure, c and d are the adjustment parameters. In Formula (6), $\frac{d}{c+(\Delta p)^2}$ is positive. While c=1, d=1, the function curve was shown in Figure 3.

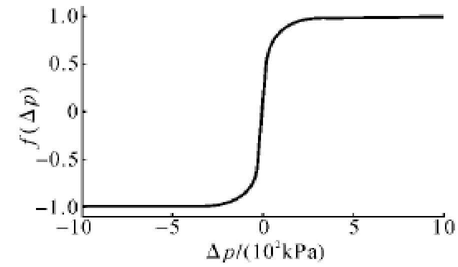
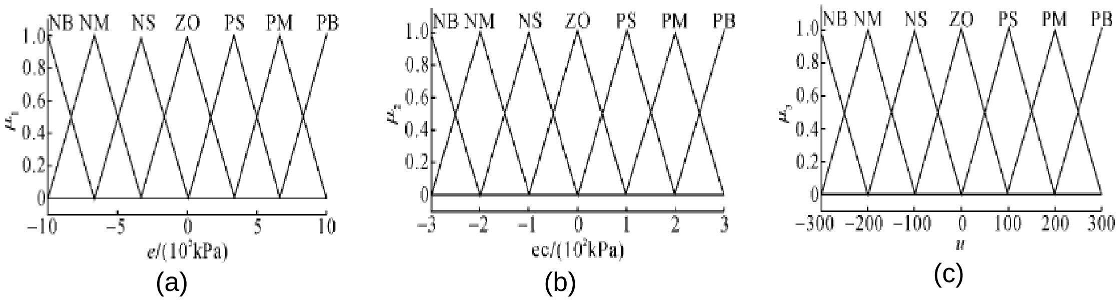


Figure 3. Optimization Function Curve where c=1 and d=1

The pump motor speed can be controlled by PI control algorithm. In the optimization function, the independent variable is the pressure difference. If the pressure difference is positive and the value is large, $f(\Delta p) \approx 1$. After multiplying the difference, PLC's flow command remained basically unchanged, which is the constant speed control of engine fuel pump motor speed; if the pressure difference decreases, $f(\Delta p)$ also decreases, the system enter into the automatic stop protection control stage. So the algorithm is simple, and it is adaptive to the variation of system pressure.

3.2. Design Fuzzy Controller

As shown in Figure 4, choose the triangular input and output form as the membership functions [16], in which, μ_1 is the membership function of error e, $e \in [-10,10]$; μ_2 is the membership function of error rate of change e_c, $e_c \in [-3,3]$; μ_3 is the membership function of output value u, $u \in$[-300,300].



(a) (b) (c)

Figure 4. Inputs and Outputs Membership Functions

The following Table 1 shows the detailed control rules. using ‘If $e = \mathrm{NB}$ and $e_c = \mathrm{NI}$, then $u = \mathrm{NM}$’ as the design rules, the maximum and minimum fuzzy as reasoning method, it was defuzzified by area center of gravity method.

Table 1. Fuzzy Control Rules

e	e_c NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	NS	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

4. Results and Discussion

4.1. Simulation Analysis

Take a car electronic fuel injection engine as the base, simulation modeling and control was processed on Matlab. The main controller parameter values are as follows:

$$K = \begin{cases} 1200x, & x \le 0.1; \\ 50000(x-0.1)+120, & x > 0.1。 \end{cases}$$

Fuel elastic modulus E=2000MPa; cylinder internal leakage coefficient $C_t = 2\times10^{-15}\,\mathrm{m}^3/(\mathrm{s}\cdot\mathrm{Pa})$; $c = 20$; integral coefficient $K_\mathrm{i} = 0.06$; scale coefficient $K_\mathrm{p} = 1.4$; initial value of parameter d is set to 300. The calculation process is adjusted by fuzzy control algorithm real time.

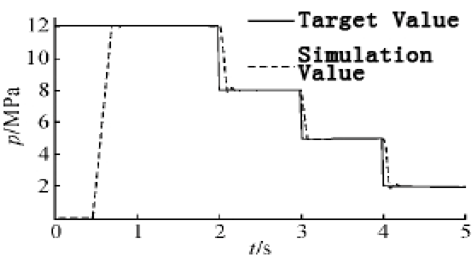


Figure 5. Tracking Injection Pressure

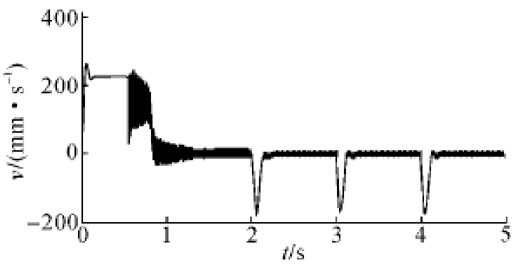


Figure 6. Velocity of Injection Cylinder by Simulation

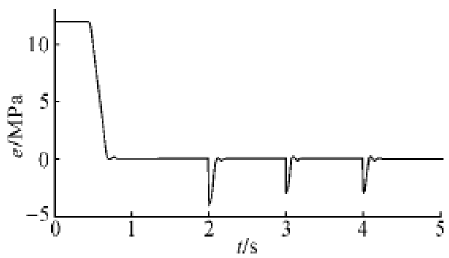


Figure 7. Tracking Error of Injection Pressure by Simulation

Figure 5 shows the system tracking conditions when the injection pressure is 12MPa. Figure 6, Figure 7, respectively shows engine speed and pump pressure tracking error signal.

These figures show that the steady-state error is small and almost no overshoot, and the system has high tracking accuracy. Considering the actual of a slight engine cylinder leaks, the piston has a slight speed when it is on the top dead point, which is consistent with the actual fuel engine cylinder combustion process.

4.2. Experiment Analysis

The installation of the controller was shown in Figure 8. The controller, replacing the original engine control unit, installed in a test bench of electronic controlled gasoline engine. The controller is the engine slave computer controller, and the master computer is controlled by PLC.

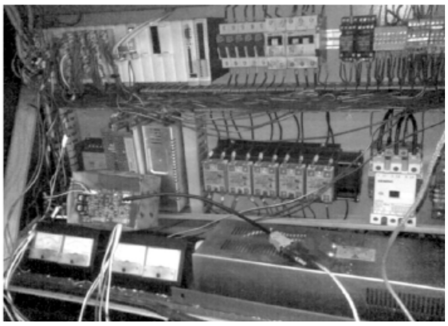


Figure 8. Experimental Installation

Figure 9, figure 10, respectively shows fuel injection pressure of the system and fuel injection pressure tracking error when the pressure is set to 10MPa. As it can be seen from the figures, the response of the system is fast, the pressure tracking is good, and the steady state error can be maintained within 0.1MPa.

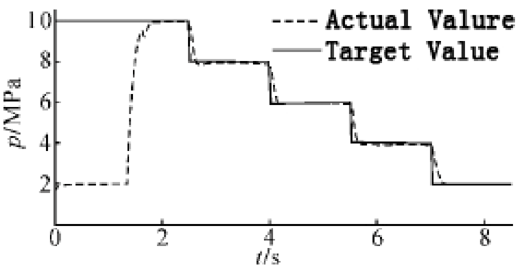


Figure 9. Tracking Error of Injection Pressure

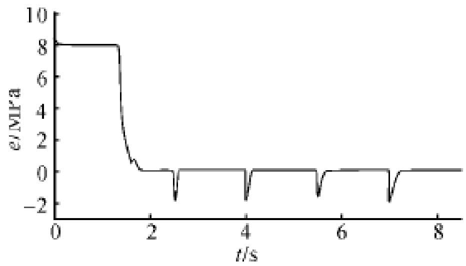


Figure 10. Injection Pressure

5. Conclusion

According to the mechanism of the engine, which fuel supply system is directly driven by fuel pump motor, this paper designed a nonlinear controller by introducing a nonlinear function. Combining a fuzzy control with PI control algorithm to optimize the injection quantity control signal, it can indirectly realize from the speed control to pressure control, so as to realize the adjusting part parameters real-time. Bench test also shows that, this control method can improve the response speed of the system, reduce the steady-state error. And it also can effectively control the fuel pump pressure with simplifying calculation and high utility.

But, at present, the control method has not yet reached high control precision. We plan to research high precision control method of fuel pump driven by motor in the days to come.

Acknowledgements

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