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Simulation on Pressure Control of Common Rail Line in High Pressure Fuel Injection System

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Abstract. To improving the controlled effect of common rail pressure of high pressure common rail system, dynamic simulation for common rail pressure control is studied. The demand of common rail pressure control and simulating mechanism for PID control is briefly analyzed, calculating model of common rail pressure is presented with mixing way of hydraulic pressure model and flux boundary, by AMESim. hydraulic simulation software, dynamic simulation module for common rail pressure control is constructed, the control effect of control parameter, control duration and variable target are compared respectively, its result showed that the model can meet controlled demand of common rail pressure and reflect controlled effect of different parameter.

Keywords: simulation, common rail pressure, PID control , diesel engine

1. Introduction

High pressure common rail fuel injection can flexibly control injection parameter, and effectively decrease diesel engine emission and become main means for electronic control technology in diesel engine. Common rail pressure is directly affect injection pressure, injection quantity and injection speed, accurate control of injection pressure can improve injection character and power performance in diesel engine. Common rail pressure is controlled by PID closed-loop regulation, it is necessary to determine suitable coefficient of PID, fast speed, precision and stability of regulating process is fulfilled. In current, regulation of pressure PID adjusting coefficient is adopted experience and collection method, there are technology report about this aspect research, [1] is present that PID control factor in experimental bench affected common rail pressure control effect, test data under different control parameter is compared. [2] is analyzed that common rail pressure wave affected fuel injection quantity, some remedying measurement is provided to modify control parameter for common rail pressure, all this research is made in experimental bench, its disadvantage is required high technology and less precision, therefore in order to acquire good PID control quickly, by means of computer simulation, it is overcome some shortages of experience method, large number of labor power and cost is saved, but in the condition of MATLAB/SIMULINK, pressure PID regulating model is found, as hydraulic fluid factor is simplified, control effect is far lower than real result. In this paper, considering the requirement of PID control and flow rate and hydraulic pressure relation. Dynamic state control model of common rail pressure is built, effect of pressure control affected by control parameter is studied, some direction is provided for real common rail pressure control.

2. PID Control for Common Rail Pressure

Fuel injection system with high pressure common rail is made up of high pressure pump, common rail, high pressure fuel line and electronic controlled injector, it is un-linearity hydraulic pressure system of pumping fuel, stable pressure and injection fuel independence, common rail line can absorb pressure wave

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resulted from supplying fuel and injection fuel, and ensure injector to inject fuel under the stable pressure. Electronic controlled unit (ECU) determined TDC position of piston and send signal to control common rail pressure and injector injection according to pulse signal of diesel rotational speed, control for common rail pressure is performed by closed-loop consisted by pressure control valve (PCV), pressure sensor and electronic control unit, as shown in figure 1. Based on target pressure determined by common rail pressure MAP, electronic controlled injector is controlled in the different profile of diesel engine, aperture of electronic valve is controlled by pulse width modulate with PID method to regulate common rail pressure, in order to made common rail pressure access to target, target value is varied with diesel engine profile. According to different objective, in the same objective control value, requirement of common rail pressure is controlled to objective pressure quickly.

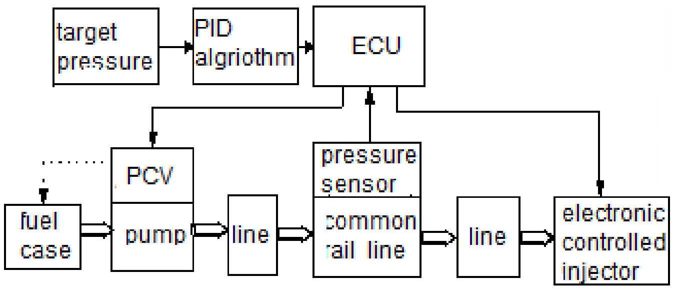

Fig. 1. (a) Closed-loop controlled system of common rail pressure

Theoretical design PID regulator is based on mathematical model of controlled target, transmission function is converted by math transformation, so accurate PID model is made. In the common rail system, pressure wave is closely related with supply fuel quantity, injection fuel quantity, pressure control is involved in parts of high pressure pump, common rail, high pressure fuel line, so it is difficult to obtain precision transmission function, therefore hydraulic mode of high pressure pump, common rail, high pressure fuel line are built to replace its transmission function. It can provide precision response for PID control and electronic controlled injector.

3. Calculation Model

Structure of injection pump and fuel injector is complex in high pressure common rail system. These are most precise and complex parts in diesel engine, fuel is flowed in injection pump and injector, and passed different diameter line and effective section, and finally compressed and injected. Considered relative factors of fuel supply and injection process and character of pressure and injection fuel independent, some supposition is made. Firstly, fuel flow is treated as one dimension fixed coefficient. Secondly, regardless of fuel temperature varied with time, high pressure common rail system is simplified to boundary of high pressure pump, common rail, high pressure fuel line, boundary of high pressure pump, common rail is volume flow, flow rate is input to high pressure pump and flow rate is output to injector, common rail line is simulated based on multiple branch line, so flow boundary model of high pressure pump and injector is built, it is really reflected input and output of common rail line, and formed simulation system of pressure control in common rail system.

3.1. Fluid Equations

Fuel flow in high pressure common rail system is treated as one dimension fixed coefficient

3.1.1 High Pressure Fuel Line

Fuel is run in high pressure fuel line to meet fluid compressible equation：

$$\Delta P = E\,\Delta V/V \tag{1}$$

Where, E is fuel volume elasticity, $\Delta V/V$ is fuel volume variety rate, ΔP is fuel pressure increased quantity.

Fluid continuous equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0 \tag{2}$$

Momentum equation

$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} = -F + \frac{4}{3}\mu \frac{\partial^2 u}{\partial x^2}$$

(3)

Where, u is fuel flow speed, ρ is fuel density, P is pressure, μ is fuel dynamic density, t is time, F is resultant force of controlled fluid flow resistance.

3.1.2 Common Rail Line

In common rail system, channel between common rail line and injector is adopted "T" connector to simplify as one input and two outputs[3], flow equation is followed.

$$\frac{V_{CR}}{\alpha^2\rho}\frac{dP}{dt} = u_1A_1 - u_2A_2 - u_3A_3 \quad (4)$$

Where, V_{CR} is volume of common rail line, P is somewhere pressure of common rail, α is sound speed, u_1 is input flow speed, u_2, u_3 is output flow speed respective, A is flow section area.

Input boundary of common rail line is volume flow rate supplied by three plunges, setting parameter of plunge pump and percent of pulse width mediation of pressure control valve to control input flow rate, volume flow rate is varied with distance of plunge pump and other factors of line; the boundary of output is pressure parameter. Fluid continuous equation of common rail line is followed

$$\frac{V_{CR}}{\alpha^2\rho}\frac{dP_{CR}}{dt} = \sum u_{in}A_{in} - \sum u_{out}A_{out} \quad (5)$$

Where, P_{CR} is pressure of common rail line, u_{in} is input flow speed, u_{out} is output flow speed.

3.2. Boundary Condition

3.2.1 High Pressure Pump

Three plunges pump of BOSCH company is supplied fuel in interval of 120 degree in one cycle of cam rotation, three cylinders is arranged in uniform distribution , supply fuel quantity is varied with cam degree change, variety relation of corresponding volume quantity is followed.

$$V_1 = \frac{V_{\max}}{3}(1-\sin(\varphi)) \quad (6)$$

$$V_2 = \frac{V_{\max}}{3}(1-\sin(\varphi+120)) \quad (7)$$

$$V_3 = \frac{V_{\max}}{3}(1-\sin(\varphi-120)) \quad (8)$$

$$V_{\max} = A_p\frac{dh}{dt} \quad (9)$$

Where, φ is rotational degree of cam, V_{max} is max supply fuel quantity of plunge, h is plunge displacement, A_p is plunge section area.

3.2.2 Fuel Injector

Flow rate equation of injection out port is followed.

$$Q = K_{OP}C_dAt\sqrt{\frac{2\Delta P}{\rho}} \quad (10)$$

Where, K_{op} is on-off coefficient, K_{op} =0, only when uninjection time, K_{op} =1, only when injection duration from injection advance angle, C_d is flow coefficient, A is flowing section area, t is injection duration, ΔP is pressure difference of hydraulic, ρ is fuel density.

3.2.3 PID Control

Pressure regulating valve is controlled by pulse width mediation (PWM), PWM signal is determined based on increased PID algorithm， PID algorithm is followed.

$$e(k) = r(k) - y(k) \tag{11}$$

$$\Delta u(k) = k_p[e(k) - e(k-1)] + k_i e(k) + k_d[e(k-1) - e(k-2)] \tag{12}$$

$$u(k) = u(k-1) + \Delta u(k) \tag{13}$$

Where, $r(k)$ is given presssure target, $y(k)$ is real measurement pressure, $u(k\text{-}1)$ is PWM output quantity in the time of k-1, $\Delta u(k)$ is PWM output increaed quantity in the time of k, $e(k)$, $e(k\text{-}1)$, $e(k\text{-}2)$ is common rail pressure error in the time of k, k-1, k-2 recpective, K_p、K_i、K_d is proportional, integral, differential coefficient repsectively.

4. Simulation Model

Research object is selected as four cylinders diesel engine, model of injector and injection pump is built by general hydraulic software AMEsim, using basic element of pipeline, throttle, volume, piston, spring, electromagnet, according to realtionship by means of hydraulic ,mechanic and special connection, injector and high pressure pump mode is found, concentrate volume is used in every common rail, common rail line mode is made by multiply branches pipe,so it can decreased calculation error caused from math approximation and calculation simplification, feedback is formed with pressure sensor, PID mode is made by propotation,integral and differential coefficient element, pressure model is shown in figure 2 by software AMEsim.

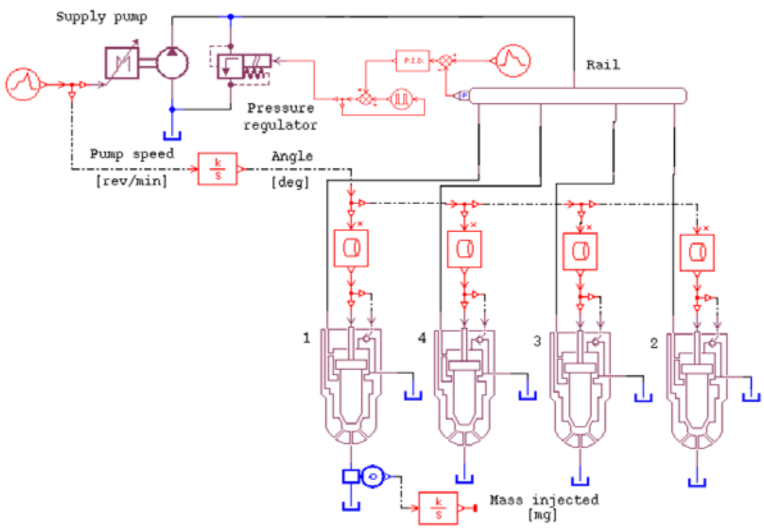

Fig. 2. Simulation mode of closed-loop control for common rail pressure

In order to verify precision of simulation model, calculation and experimental result is compared, YN4100 diesel engine is used as experimental engine. Its technology specification is shown in table 1, parts parameter of Bosch company is shown in table 2. In the condition of 1000r/min of cam speed, fuel injection quantity 40 mg /stroke ,pressure control and pressure un-control method is applied in this mode verification, pressure target is set as 100MPa, pressure variety is shown in figure 3 by different methods. In figure 3, common rail pressure is decreased with injection process when pressure un-control method is applied, and finally common rail pressure is no stable to 100MPa, on the other side, common rail pressure is in fluctuate state in injection process when pressure control method is applied, and finally common rail pressure is stable to 100MPa, all this result is showed that pressure control model is effective. When pressure target is set as 80,120MPa respectively and PWM is 1.0 ms, propotation,integral, differential coefficient is 0.05, 0.9, 0 respectively, effect of common rail pressure is shown in figure 4. In the condition of 80MPa common rail pressure, real measurement curve is existed to simulation one, variety trend of both curves is consistent, with pressure increase from 80MPa to 120MPa, variety trend of real measurement curve is consistent best, it showed that simulation mode is basically reasonable.

Table 1. Basic parameter of YN4100QBdiesel engine

Parameter name	value
Engine brand	YN4100QB
Type	water cool, four strok
Cylinder diameter and stroke (mm)	100×105
Displacement (L)	3.29
Compress ratio	17.5：1
Rated power /rotation speed (kW/r/min)	73.5/3200

Table 2. Parts parameter of Bosch common rail system

Parameter name	value
High pressure pump	flow rate0.1cm^{3}output pressure 135MPa
Common rail volume	23ml
Orifice diameter	6X0.16

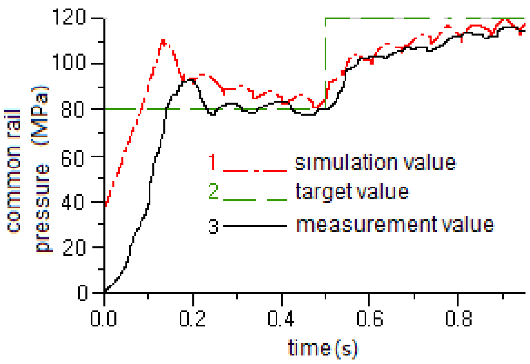

Fig. 3. Control comparison of common rail pressure;

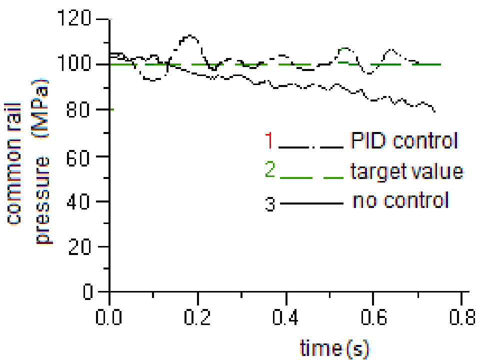

Fig. 4. Control effect of common rail pressure

5. Simulation Analysis

Increased PID algorithm is used in closed –loop control, sampling period, PID coefficient determined effect of common rail pressure, requirement of different control target to PID coefficient is different.

5.1. Control Period

All tables should be numbered with Arabic numerals. Headings should be placed above tables, left justified. Leave one line space between the heading and the table. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which authors may find useful.

Injection fuel quantity and injection frequency is determined by load and rotation speed of diesel engine. In the high pressure common rail system, Injection fuel quantity and injection frequencies determined change of common rail pressure, in order to make common rail pressure maintain stable extent, control method of pressure regulating once after every cylinder injection is adopted, control period of 42ms, 13.6ms and 9.3ms correspond to engine idle speed, max torque speed and max speed is used in model, target pressure is 80MPa, 120MPa and 135MPa respectively, comparison of control effect is shown in figure 4 in different control period. From figure 4, in the condition of control period 42ms, common rail pressure 80MPa, common rail pressure fluctuated little, but pressure increased to 120MPa, since injection frequency is enlarged, common rail pressure fluctuated seriously. in the condition of control period 13.6ms, common rail pressure 80, 120MPa, common rail pressure waved little too, when control period decreased to 9.3ms, common rail pressure 80MPa, common rail pressure wave is obviously little. But with control period decrease, it is not helpful to make PCV act frequently, and affect PCV reliability. Control period of 13.6ms correspond to engine max torque speed is suitable so that it is made common rail pressure stable.

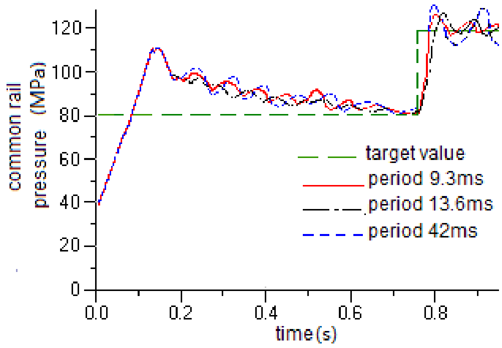

Fig. 5. Pressure control effect of in different control period ;

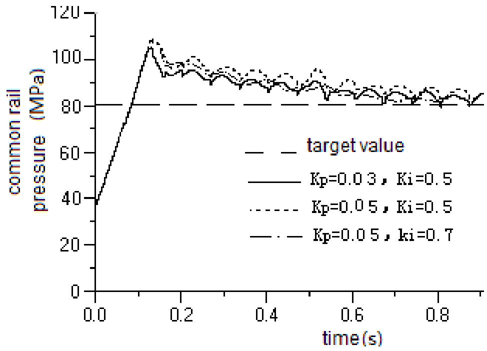

Fig. 6. Control effect of common rail pressure in different PI

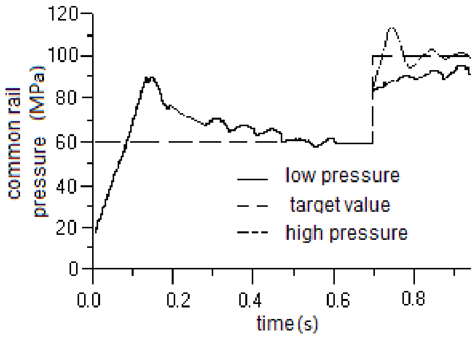

Fig. 7. Pressure control effect of different target

5.2. Control Parameter

Proportional, integral and differential coefficient in PID coefficient has different inflence on control effect, in this paper due to limited page, affection of propotation and integral coefficient is only studied, control effect of target pressure 80MPa result from different PID coefficient is shown infigure 6, when integral coefficient is fixed, control PWM quantity is increased with propotation coefficient enlarging, control steady time and pressure wave is more large, when integral coefficient is increased, control PWM quantity is increased with propotation coefficient enlarging, control steady time and pressure wave is decreased.

5.3. Control Target

When diesel engine is operated in different profile, target value of common rail pressure is varied, for example, target pressure in idle profile, formal profile is set as 60MPa, 100MPa respectively, control effect of common rail pressure in a same set of PID coefficient and is shown in figure 7. When proportion, integral and differential coefficient in PID coefficient is 0.03, 0.5, 0.1, its control effect for 60MPa common rail pressure is good, its tracking response for 100MPa common rail pressure is slow. When propotation,integral and differential coefficient in PID coefficient is 0.06, 0.7, 0.1, its control effect for 100MPa common rail pressure is good, therefore it should use different PID coefficient to different target pressure so that it can achieve good control effect.

6. Conclusion

Simulation calculation is made with flow rate boundary to replace complex element, by means of hydraulic pipe line method, simulation model of common rail line is made, closed-loop control for common rail pressure is studied, pressure model is made by software AMEsim. Effect of control pressure affected by control period, PID coefficient and different control target is analyzed, data showed that model can meet control requirement of common rail pressure and reflect control effect in different PID coefficient.

7. Acknowledgements

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