Parameter optimization analysis of fuel injection system for high pressure common rail diesel engine

Wang Xuejun¹, a*, Xu Fangjian², b, Wang Yiran³, c

¹Shandong Huayu Institute of Technology, Dezhou, Shandong, China
²Shandong Huayu Institute of Technology, Dezhou, Shandong, China
³Shandong University of Science and Technology college of Materials Science and Engineering Qingdao, Shandong, China

a e-mail: 937976681@qq.com, b e-mail: 932105635@qq.com, e-mail: 1497024723@qq.com
*Corresponding author’s e-mail: kyc@sdhygxy.com

Abstract: The cleaning and energy-saving environmentally friendly diesel engine, with the high pressure common rail fuel injection system, is the main driving force in the transportation sector. Being the core and key technology, the high pressure common rail fuel injection system is the inevitable developing trend of the future fuel injection system. The parameter optimization design of the high pressure common rail fuel injection system is of great practical significance to improve the operation stability of common rail system. By upgrading the fuel control precision and optimizing the overall performance of the engine, the purpose of energy saving and emission reduction can be finally achieved.

1. Development advantages of high pressure common rail diesel engines

The high pressure common rail fuel system was put into practical application since the end of the 1990s. As the third generation of the electronic control technology of the diesel fuel system, it has been widely used. The high pressure oil supply pump driven by the engine pressurizes the fuel into the common rail, and the high pressure fuel is injected into the corresponding cylinder through the oil atomizer, which is controlled independently by the computer. So far, the fuel pressure of common rail can be maintained between 130 and 160MPa[1].

Compared with the traditional diesel engines, the common rail diesel engines have the following advantages:

1.1. Good adaptation.
It realizes single or multiple control of fuel injection system, supercharging system and discharge system. The fuel injection pressure can be adjusted flexibly, and the fuel injection parameters can be controlled precisely to make the diesel engine run well. When the outside temperature is low, the Electronic Control Unit (ECD) can control the air intake heater to heat up the air intake of the diesel engine. It can also enhance the starting capacity in the cold weather, as well as the running performance.
1.2. Higher reliability.
As the operating state parameters of diesel engine collected in real-time can make it possible to detect the operating obstacles of diesel engine, it is convenient for timely treatment. In addition, the fault code indication makes maintenance more convenient and has good maintainability.

1.3. The best operation mode.
The best operation mode refers to the free choice of diesel engine operation mode according to different user requirements, i.e., the economic operation mode, low emission operation mode and low load operation mode, so as to ensure the engine running in the best condition.

1.4. Comprehensive fault detecting.
Fault detecting can online examine the load of each cylinder, so as to ensure the uniform distribution of the load of each cylinder and to prevent the overload of diesel engine. It can alarm in advance and start the emergency treatment program before the fault occurs. Electronically controlled diesel engine has good protection function: during the operation process, when the key parameters appear for a period of time (usually in a few seconds or so), it will automatically reduce the torque and speed, and light the alarm lamp; when the issue goes badly wrong, the stop light will be automatically stopped and lit if the shutdown protection function is pre-set. [2]

2. Optimization requirements of fuel injection system for common rail diesel engines
According to the fuel injection system requirements of common rail diesel engines, the selection and parameter optimization of fuel injection system become the key work in the process of design, improvement and performance development of diesel engines. The fuel injection system shall meet the following requirements [3]:

2.1. Have sufficient working ability
The fuel system must meet the structural and operating parameters required by the diesel engine, including the number of cylinders, allowable power per cylinder, maximum allowable speed, maximum injection pressure.

2.2. High injection pressure
In the full speed range of the diesel engine, under low speed and low load conditions, the injection pressure should be increased as far as possible, so that the injection pressure is independent of the speed and load, and can be controlled flexibly.

2.3. Accurate measurement and control of fuel injection amount.
In particular, the minimum steady injection amount should be small and under control.

2.4. Good spray characteristics.
The transmittance, spray cone angle, spray particle size and distribution of the oil beam should be appropriate, and the oil beam should well-matched the shape of the combustion chamber and the airflow in the combustion chamber.

3. Optimization analysis of common rail diesel fuel injection system
In order to achieve all-round flexible control of diesel engine under different working conditions and achieve the desired optimal performance in all aspects, it is not enough to ensure good mechanical performance and hardware conditions of ECU module. The most important thing is to rely on the control strategy and control algorithm of hardware electronic control injection system of diesel engine. In the research and development of high pressure common rail electronic control fuel injection system, improving the system efficiency is the key control strategy research and design. The ideal control strategy can ensure the stability and reliability of the system. Firstly, the position sensors of water
temperature, crankshaft, throttle position, ambient temperature and cam are installed on the diesel engine to monitor the state parameters of the diesel engine in real time, and transmit them to the ECU module to judge the working conditions, so as to complete the nonlinear programming. Under the same working conditions, the common rail pressure, injection quantity, injection timing and injection rate can be accurately controlled\cite{4}.

3.1. Working condition judgment.
According to the change of working conditions, the control strategy can be switched reasonably. The diesel engine can be divided into several different working conditions, such as starting, idling, transient and steady state. The stateflow module in Simulink can establish various state machines to design and develop logic diagrams in control and management. In fact, stateflow can be regarded as a state flow diagram design tool, which can design some states and transition conditions between States, and then put it into Simulink simulation. Condition judgment can be regarded as a state machine with five state systems, which can be used to identify 0 and 1 switch value between the states of diesel engine.

3.2. Fuel injection control.
In order to achieve the ideal control effect under different working conditions, it is necessary to monitor some state parameters of diesel engine in real time, such as speed, coolant temperature, environmental parameters, load and accelerator pedal position. According to the data information, the fuel control unit obtains the target value of each cylinder in a cycle.

3.3. Common rail pressure control.
The rail pressure target value is calculated by using the data information monitored by the sensor, and then the rail pressure measurement value is calculated according to the data information monitored by the sensor. The deviation of the valve is calculated by combining the determined target injection quantity, and the power on current of the electromagnetic throttle valve at the oil inlet of the high-pressure oil pump, the opening time and time of the PCV valve and th.

3.4. Fuel injection timing control.
According to the real-time state parameters of diesel engine, combined with the target injection quantity signal of diesel engine, the accurate injection starting point under different working conditions is calculated.

3.5. Injection rate control.
The correct injection law depends on the working conditions. In order to achieve multiple injections, injection rate control is the most important.
   The task is to accurately calculate the coordinated distribution of each injection quantity and the total fuel quantity in the whole injection process.

3.6. The actuator mainly includes the injector and the high pressure common rail unit.
According to the status information of the diesel engine in different working conditions, it controls the engine and obtains the ideal output characteristics. The number of working plunger are obtained.

4. Injection quantity control of common rail diesel engine
The analysis of the fuel injection system belongs to the time pressure control, for each cylinder of diesel engine, the injection quantity is the most basic parameter affecting its work. Therefore, under different operating conditions, each injection can achieve the best control effect, and realize the self-adaptive adjustment of demand and fuel injection, that is, on-demand injection. The injection quantity is determined by the current rail pressure and pulse time. When the rail pressure is constant, the injection quantity varies linearly with the injection pulse width. The steps of ECU to determine the
injection quantity are as follows: firstly, the target injection quantity of each injection is calculated based on the state parameters of diesel engine speed, cooling water temperature and intake pressure monitored by each sensor; Then, according to the target value, the pulse duration of the injector solenoid is energized. Therefore, the working conditions of diesel engine are different, and the selection of control mode is also different[5].

4.1. Fuel injection quantity control in starting state

The starting process of diesel engine is very short, whether it can start quickly is also an important index to measure the performance of diesel engine, and there are many fast and changeable parameters in the starting process, which affect the reliability of operation. Therefore, starting state control is also a difficult and key link in the necessary diesel engine control.

The starting of diesel engine can be divided into three stages according to the change of speed: dragging period, starting period and warm-up period. When starting, the influence of diesel engine speed and cooling water temperature is mainly considered. When the speed is low, the fuel demand is large. When the speed is high, the fuel injection quantity slowly drops to the idle fuel injection quantity; ECU uses the temperature of cooling water to determine whether it is a cold engine state or a hot engine state. When the engine is cold, it is necessary to increase the fuel quantity, accelerate the fuel evaporation and atomization, and improve the starting performance; When heating the engine, try to avoid black smoke and reduce the fuel injection properly. Therefore, we can flexibly control the injection quantity under different working conditions to obtain the best starting effect.

The control process of fuel injection quantity under starting condition is as follows: at the initial stage of starting, the diesel engine is driven by the starter, at this time, the speed and injection pressure are small, the fuel atomization is not ideal, and the gas mixing degree is not high. At the same time, the speed is not equal to the starting speed, and the rail pressure is lower than the starting pressure, so there is no fuel injection. The diesel engine is driven by an electric motor until the speed and rail pressure meet the starting conditions. In order to ensure the normal starting of diesel engine, the injection pulse width is set to a fixed value according to the speed and cooling water temperature, and the injection is carried out according to the set injection pulse width; When approaching the idle speed, slowly shorten the injection pulse width to the idle value. When the speed is equal to the target value at idle speed, enter the idle state.

4.2. Fuel injection quantity control after starting

The injection quantity after starting is mainly obtained by checking map. The ECU module feeds back the expected speed and load information of the diesel engine to the diesel engine, obtains its basic value by querying the map of fuel injection quantity, and then corrects it through the cooling water temperature. In addition, in order to stabilize the speed of diesel engine, it is necessary to carry out closed-loop control. The deviation between the actual value and the expected value is used to correct the injection quantity, so as to reduce the wide range of speed changes and make the diesel engine transition smoothly between various working conditions.

At the same time, in the case of rapid acceleration and deceleration of diesel engine, due to the change of exhaust parameters, the response of turbocharger will lag behind the solenoid valve of injector, the intake volume of cylinder can not reach the standard, and the injector can not immediately and accurately inject the required amount of fuel. If the target injection quantity is still obtained by directly checking the map map, it will inevitably lead to excessive injection quantity, combustion deterioration and smoke emission increase. Therefore, the maximum injection quantity must be obtained from the intake pressure and diesel engine speed to limit the target value. In addition, the influence of pressure in cylinder must be considered. Finally, the injection pulse width is calculated according to the maximum limit and the pressure difference between the common rail pressure and the cylinder pressure[6].
4.3. Speed PID closed loop control

After starting the diesel engine, it must ensure that the speed can run smoothly according to the expected speed. Therefore, the injection quantity is corrected by speed closed-loop control, that is, the error between the expected value of the sensor and the measured value is transmitted to the controller, and the injection quantity is corrected online, so as to change the injection quantity and maintain the stability of the system. At present, PID controller is widely used because of its simple structure and easy adjustment of parameters. For the control object with complex mathematical model and variable system parameters, the PID controller can be adjusted online according to the engineering experience to achieve the ideal control effect.

As the fuel injection system itself has the characteristics of nonlinear, variable parameters and time delay, PID parameters can only achieve the best control effect under specific conditions, and cannot meet the best control effect under all conditions. Therefore, a piecewise PID controller is adopted, as shown in equation (1).

$$y(t) = k_c \left[ X e(t) + y \frac{1}{T_i} \int e(t) dt + T_d \frac{de(t)}{dt} \right]$$  \hspace{1cm} (1)

Where $y(T)$ is the output signal of the controller; $e(T)$ is the controller deviation; $k_c$ ratio constant; $TT_i$ is the integral time constant; $TD$ is the differential time constant.

The piecewise PID control only needs to multiply a coefficient $X$, $y$ and $Z$ before the proportion, differential and integral of the traditional PID control. The coefficient varies with the error range $e(T)$. As shown in equation (2), it is the value distribution range of $X$, and the distribution of $Y$ and $Z$ are similar. 10. The final dimensions of $Y$ and $Z$ need to be adjusted online.

$$X = \begin{cases} A, |e(t)| < p \\ B, p \leq |e(t)| \leq q \\ C, |e(t)| < p \end{cases}$$  \hspace{1cm} (2)

According to the speed variation characteristics and equation (2) of diesel engine in actual working condition, the piecewise PI controller is selected; The value of $D$ is fixed. When the deviation is large, the response speed can be faster, and the value of $X$ needs to be larger, so as to avoid the phenomenon of integral limitation when the integral is saturated, and make $y = 0$; When the error approaches the stable region, $X$ and $y$ are smaller; When the speed is stable, the large fluctuation of the speed should
be prevented, so that the value of X is as small as possible and the value of Y is as large as possible.

4.4. Overspeed control
The overspeed state of diesel engine belongs to abnormal state. When the speed is the same as the rated speed, there will be a small fluctuation. The upward fluctuation will increase the speed. If the upper limit of fluctuation is higher than the rated speed, it will be in overspeed state, which is very dangerous. In case of over speed, oil reduction control must be carried out in time to prevent "flying". When the speed is lower than the rated value, restart the injection. If the speed is still rising, it means that the diesel engine is faulty and must be forced to stop maintenance.

In high pressure common rail fuel system, the precise control of common rail pressure has a great influence on fuel injection metering and atomization. If the common rail pressure control is not accurate or the following condition is poor, the common rail pressure fluctuates greatly, which affects the spray quality. Therefore, according to the changes of diesel engine working conditions and external factors, the research of common rail pressure intelligent control strategy can provide a reliable basis for improving the stability and accuracy of common rail pressure control.

5. Conclusion
In high pressure common rail fuel system, accurate control of common rail pressure has great influence on fuel injection metering and fuel injection atomization. If the common rail pressure control is not accurate or the following conditions are poor, the common rail pressure will fluctuate greatly, which will affect the spray atomization quality. So, according to the diesel engine working condition and the change of external factors, the study of common rail pressure intelligent control strategy can provide a reliable basis for improving the stability and accuracy of common rail pressure control.

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Reference:
[1] Chen LY (2016) Experimental study on random cylinder stop strategy of high pressure common rail diesel engine [J]. Internal combustion engine engineering,37 (5): 205-210
[2] Fang Y.Zhejiang University, (2017) Model based control strategy research and bench optimization of high pressure common rail diesel engine [D].
https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201701&filename=1017043889.nh&v=sh0b9YstAUqYWd2ET69vwNjplEzyWy0crZLA6KOUSdVmp%25md2FpljR4udLvufUW9tz.
[3] Xu JS, Wei L, Wu HB, (2018) Study on injection control strategy of high pressure common rail diesel engine [J]. Journal of agricultural machinery, (04): 294-300
[4] Wang J (2019) Matching of combustion system of electronically controlled diesel engine, China Machine Press, Beijing
[5] Xu JS, Wei L, Wu HB, (2016) Research on injection control strategy of high pressure common rail diesel engine [J].Journal of agricultural machinery, (04): 294-300.
[6] Han XM, Lin XD, Li DG, (2017) Research on transient fuel injection control strategy of light duty diesel engine during starting process [J]. Automotive Engineering, (01): 23-27.