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多次喷射模式下共轨系统喷油量波动预测与补偿

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摘要：为了解决多次喷射模式下喷油量的精确控制问题，进行了基于波动量的预测，实现了有效的喷油补偿。首先，分析了喷油器的动态特性，并基于AMESim仿真软件建立了共轨系统喷油器仿真模型；然后，通过仿真数据分析多次喷射模式下喷油量波动的影响因素，确定了喷油压力、预喷脉宽、主喷和预喷之间的时间间隔等为主要特征参数，提出基于LM—BP模型的喷油波动量预测方法；同时，基于喷油波动量的预测结果设计喷油量补偿控制器。结果表明，基于波动量的预测可以提高喷射精度，验证了所提策略的有效性。

关键词：共轨系统喷油器；喷油器建模；波动量预测；喷油补偿；多次喷射
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Fuel Injection Quantity Fluctuation Prediction and Compensation for Multiple Injections of Common Rail System

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Abstract： To solve the inaccurate injection quantity problem in multiple injections，in this paper，a simulation model of the electro injector is developed in the AMESim environment through dynamics analysis of injector，and the parameter matching and rationality verification of the model are also conducted. In addition，the influencing factors of fuel injection fluctuation are investigated. The results show that the change of injection pressure，pre-injection pulse width，the dwell time between the main and the pilot injection pulse can affect fuel fluctuation. Moreover，a fuel compensation control strategy based on self-learning system is constructed by using a certain sample of stimulation data to compensate for the deviation of multiple injection quantity. A self-learning system is realized by using the genetic algorithm（GA）and neural network，which can effectively improve injection control.

Key words： common rail system injector； injectors modelling； fluctuation prediction； injection quantity compensation；multiple injections

1 Introduction

With the consistently increasing demands on vehicle fuel economy and emissions worldwide，high engine control precision is becoming increasingly imperative for improving engine combustion fuel efficiency. As one of the key technologies，the high pressure common rail injection system has been applied to obtain significant reductions in engine noise and emissions with a higher injection pressure and multiple injections by good mixing of oil and gas. However，due to the constant opening and closing of the high-pressure pump and injectors，the injection pressure fluctuates greatly， which affects the accuracy of fuel injection directly[1]. The wave propagation phenomena arising in the system， subsequent to an injection event，leads to the mix ratio change，insufficient combustion，and engine performance degradation.

Present researches aim at further investigating multiple injection characteristics. For example， Henein proposed that the injection pressure fluctuation was caused by the end of the previous injection，which affected the opening and closing of the injector needle valve，and then the fuel injection

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quantity[2]. Andrea studied the relationship between pressure fluctuation and fuel injection, which showed when a single injection was completed, the injection pressure would drop rapidly and fluctuate in a form of attenuation oscillation. Then the cyclic fuel injection quantity would change differently as the follow-up injection happened on different frequency range[3]. By an integrated numerical-experimental approach, reference [4] found that the multi-injection fuel quantity fluctuation was caused by synthetic cyclical factors of needle opening, closure delays, and injection pressure due to the impulse of water hammer. However, researches of fuel injection quantity control were mostly based on the closed-loop control according to the speed or air-fuel ratio. Li proposed an injection quantity control scheme of high pressure common rail system based on traction demand[5], obtained the correlation between injection quantity and torque according to the vehicle dynamics, and calibrated the corresponding injection quantity under different working conditions. Xu[6] considered the real-time state parameter of diesel engine, used closed loop control to ensure the consistency of fuel injection quantity in each cylinder cycle through engine speed, and used other information such as actual intake pressure, environmental parameters, and coolant temperature to correct the fuel injection quantity of the system. However, there is little research on the multiple injection quantity fluctuation control. In reference [7], a parametric study was performed to identify the best geometrical configurations of the injector-supplying pipe so as to minimize injection oscillations. The other solution was to calibrate the modified MAP under different working conditions by experiments, then correct the fuel quantity by looking up tables and interpolating[8]. This strategy not only requires a large number of calibration experiments to draw the MAP table, but also has a poor portability with different engine models, which was not suitable for the forward development of engine combustion control.

In this paper, in order to design a control strategy to improve the precision of fuel injection quantity during multiple injections, an injector simulation model was built. Then, a series of simulation tests were given to find the factors affecting the injection quantity fluctuation. The BP neuron network based on the injection pressure, pilot injection, dwell time between pilot and main injection was used to pre-rectify the main injection quantity.

2 Injector model

The high pressure common rail injection system (see Fig. 1) is composed mainly of a low pressure circuit, a high pressure pump (HPP), a common rail, 4 electro injectors, an electronic control unit (ECU), various sensors, and a fuel metering valve (FMV)[9].

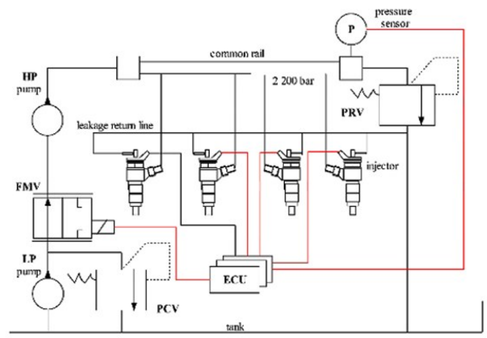


Fig.1　Structural diagram of high pressure common rail injection system

When the system works, the high pressure pump pumps fuel from the low pressure circuit into the chamber and increases fuel pressure by the reciprocating motion of pistons. A high pressure fuel is obtained and delivered to the common rail which is used to store fuel and accumulate pressure. The fuel injection strategy is given by the ECU from collecting vehicle status and working condition information. At last, the electro valve controls the opening and closing of the injectors, and the fuel is sprayed directly into the cylinders[10]. In the multiple injections process, the water hammer effect caused by the closure of needle valve by previous injection will inevitably lead to the deviation in the calculation of the next injection quantity.

Because the main body of the research is fuel injection, only the simulation model of the solenoid valve injector is built and the injection pressure is given a fixed value. The electro injector is shown in Fig. 2, which consists of the solenoid valve, the armature, the needle valve, the control chamber, the oil chamber, and the pressure chamber. It can be seen as being connected by a series of chambers, valves, and holes[11].

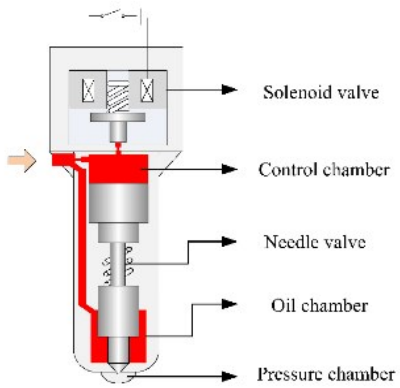


Fig.2 Structure of fuel injector

In the high pressure common rail injection system, the fuel that comes from the common rail will be divided into two branches, one entering the injector oil chamber and the other, the control chamber. When the solenoid valve coil is energized, the armature moves upward due to the electromagnetic force and the ball valve opens. Then, the fuel in the chamber leaks because of the opening of the drain hole located above the control chamber, which will cause the pressure in the control chamber above the piston to rapidly drop. The sum of the hydraulic pressure above the control piston and the spring pressure is less than the compression force of the needle valve, the needle valve will be lifted, and the fuel in the oil chamber is injected into the combustion chamber from the injection hole. When the solenoid valve coil current is disconnected, due to the spring force and the fuel pressure, the control piston acts on the ball valve, the drain hole was closed, the control chamber is gradually filled with fuel, and the higher fuel pressure presses the needle valve against the seat. The fuel passage to the fuel injection hole is closed and no fuel is injected. During the operation of the injector, it is the ongoing movement of these valves and chambers that causes fluctuations and instability of the fuel injection.

Taking a 4-cylinder diesel engine as an example, the electro injector model was built in AMESim, a multi-disciplinary complex system modeling and simulation platform, to reflect the complex dynamic characteristics of the fuel injection process. It is necessary to consider not only dynamic analysis above but also the physical structure and working principle of the system. The high precision AMESim injector model is shown in Fig. 3.

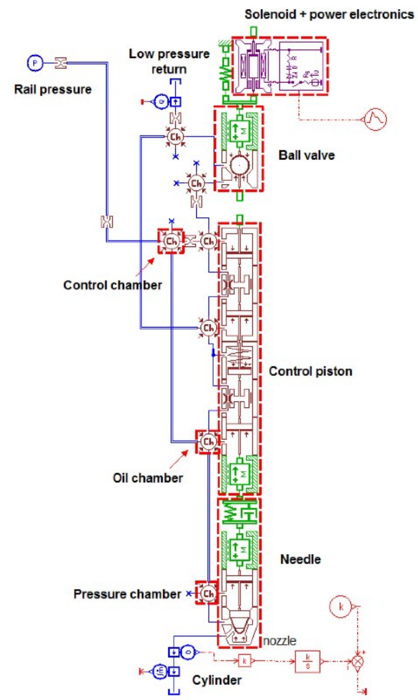
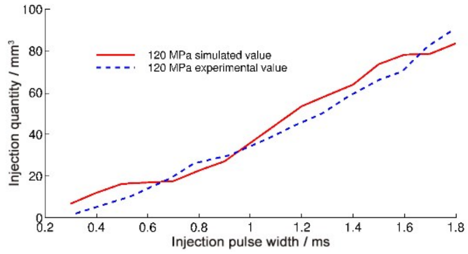
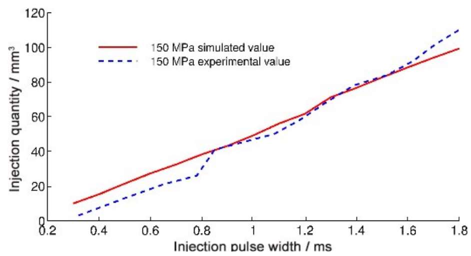


Fig.3 AMESim model of injector

Next, the fuel injection characteristic verification test of the injector simulation model is conducted. The injection pulse width was changed under different injection pressure conditions of 120 MPa and 150 MPa, and the simulated value of injection quantity was compared with experimental value. As shown in Fig. 4, the data of the two groups were basically identical. As shown in Fig. 5, a multiple injections mode can be obtained that the pulse width of 2 ms single injection is divided into several injections, i. e. , the pre-injection pulse width is 0. 2 ms, the main injection pulse width is 1. 5 ms, and the post-injection pulse width is 0. 3 ms. Above all, the injector model established is reliable.

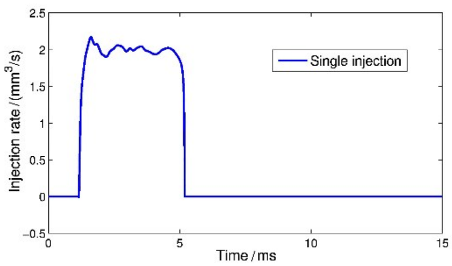


a Injection pressure of 120 MPa

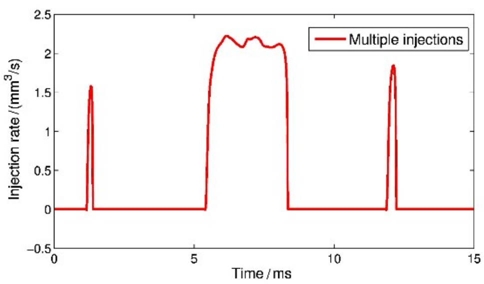


b Injection pressure of 150 MPa

Fig.4 Comparison of fuel injection quantity of simulated and experimental values



a Single injection

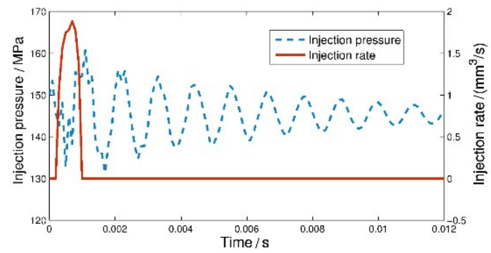


b Multiple injections

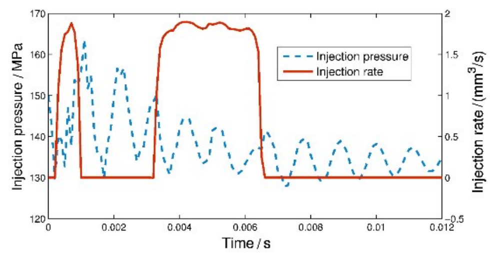
Fig.5 Realization of single injection and multiple injections

3 Analysis of fuel injection fluctuation characteristics

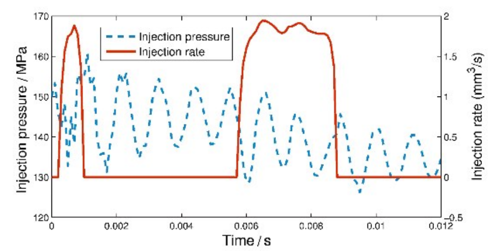
Take two injections as an example, the injection characteristics are studied and analyzed based on the model of electro injector built above. When the engine working condition remains unchanged and the internal pressure of common rail remains stable, the injector is set up for small pulse to inject (injection pulse width is 0.4 ms). The pressure fluctuation after injection is shown in Fig. 6 a. It can be seen that at the beginning of the injection, the injection pressure drops rapidly due to the high pressure fuel discharge, and at the end of the injection, the injection pressure has a regular attenuation oscillation fluctuation.



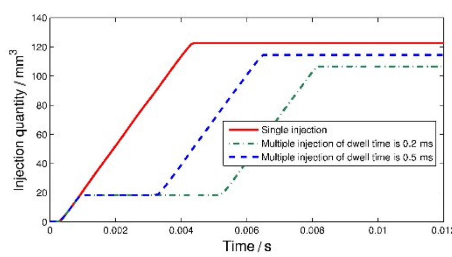
a An injection pulse width of 0.4 ms



b An injection interval of 2 ms



c At an injection interval of 5 ms



d Injection quantity deviation

Fig. 6 Analysis of multiple injections characteristics

When the second injection occurs in the same working cycle of the injector, the injection pressure fluctuation is shown in Fig. 6 b and c, in which the injection intervals are 2 ms and 5 ms respectively. Because of the short injection interval, the injection pressure controller cannot replenish the pressure in time and then the subsequent injection occurs on the lower average injection pressure. The injection quantity is determined by the injection pressure and the injection pulse width. Therefore, the injection quantity in this cycle has a certain deviation, as shown in Fig. 6d. It can also be seen that the deviation of multiple injection quantity occurring in different frequency bands is also different.

As shown in Fig. 6b, when the second injection occurs in the same working cycle of the injector, the injection pressure is lower because of the short injection interval. The injection quantity is determined by the injection pressure and the injection pulse width. Therefore, the injection quantity in this cycle has a certain deviation, as shown in Fig. 6c. It can also be seen that the deviation of multiple injection quantity occurring in different frequency bands is also different.

In the injector model system, the single injection test with a pulse width of 1.7 ms is conducted under the condition that the engine speed is unchanged, the injection pressure is 100 MPa, and the corresponding single injection quantity is 82.4 mm^3. Keeping the working conditions unchanged, the single injection is divided into two stages, i.e., the pre-injection pulse width is 0.2 ms and main injection pulse width is 1.5 ms, the dwell time is changed in the range of 2-8 ms with a step of 0.1 ms. The multiple injection quantity at each time interval point is recorded and reduced with the corresponding target injection quantity (single injection pulse width of 1.7ms). Combined with the data, the fuel injection fluctuation curve is shown in Fig. 7. It can be seen that with increasing dwell time between the pilot and the main injection, the injection quantity fluctuates periodically and the fluctuation range attenuates gradually.

Keeping the initial injection pressure at 100 MPa, the main injection pulse width at 1.5 ms, and the dwell time varying in the range of 2-8 ms, the fuel injection fluctuation tests were carried outconducted under the conditions ofat a pre-injection pulse width at of 0.2 ms, 0.3 ms, and 0.4 ms respectively. The simulation results are shown in

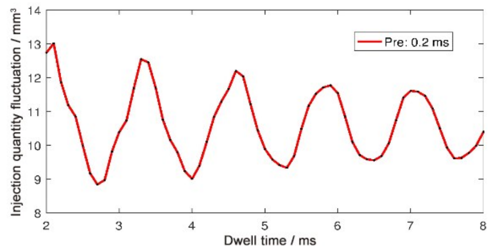


Fig. 7 Injection fluctuation at a pilot injection pulse width of 0.2 ms

Fig. 8, in which the longitudinal axis represents the fluctuation value., The target fuel injection quantity (82.4 mm^3, 88.1 mm^3 and 93.8 mm^3 corresponding to injection pulse width areof 1.7 ms, 1.8 ms, and 1.9 ms) reduces the actual fuel injection quantity. It can be seen the fluctuation range increases with the increase of pre-injection pulse width.

Changing the injection pressure to 150 MPa, keeping the main injection pulse width of 1.5 ms unchanged and repeating the test above, as shown in Fig. 9, the contrast curve of injection quantity fluctuation is obtained when the pre-injection pulse width is 0.2 ms, 0.3 ms, and 0.4 ms, respectively. It can be seen that the fuel fluctuation is affected by the injection pressure.

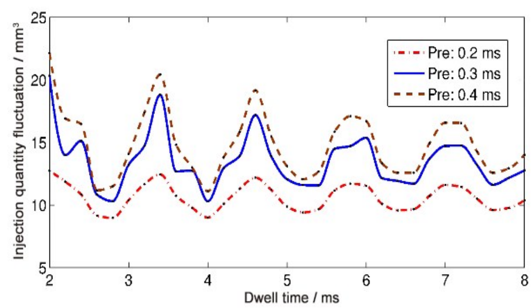


Fig. 8 Injection fluctuation of different pilot injection pulse widths at a rail pressure of 100 MPa

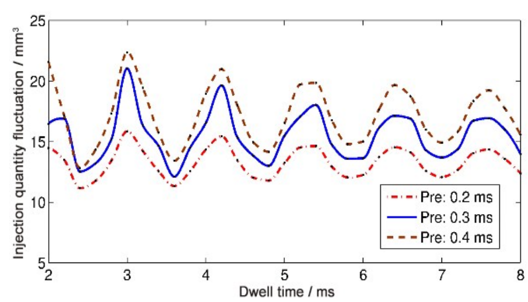


Fig. 9 Injection fluctuation of different pilot injection pulse widths at a rail pressure of 150 MPa

4 Injection quantity compensation control

To solve the problem of injection quantity fluctuation during consecutive injections and improve engine performance, the corresponding fuel correction control strategy of multiple injections should be designed and implemented. However, the fluctuation of fuel injection is related to the engine operating conditions and it is difficult to describe the complicated injection process with a precise physical mechanism. So asTherefore, to realize the accurate control of injection in multiple injections, the self-learning method can be used to identified the influence law model of injection quantity fluctuation and then the injection compensation value willcan be obtained.

Considering the system′s characteristics of non-linear characteristics ity and labeled data of the system, the self-learning system can be designed by using BP neural network. The overall control strategy of the fuel injection control algorithm is designed as shown in Fig. 10. From the analysis of fuel injection fluctuation, three influencing factors (dwell time, pre injection pulse width, and injection pressure) should be input into the trained BP neural network and theto obtain the fuel injection compensation value Δq. Finally, the value of corrected main injection pulse width can be acquired through correction MAP, which is shown in Fig. 11.

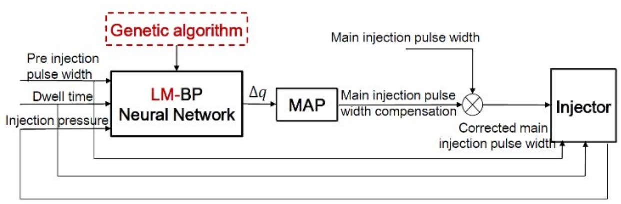


Fig.10　Control strategy of the fuel injection control algorithm

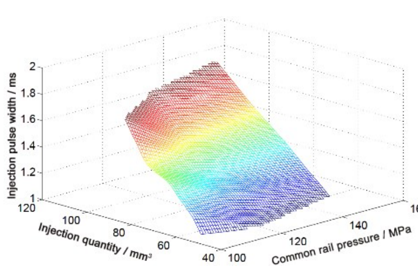


Fig.11　Main injection pulse width calculation MAP

4.1 Prediction of injection quantity fluctuation

The fluctuation of fuel injection is related to the engine operating condition and it is difficult to describe the complicated injection process with a precise physical mechanism. Therefore, to realize the accurate control of injection in multiple injections, the self-learning method can be used to identified the influence model of injection quantity fluctuation and to obtain the injection compensation value. Considering the system nonlinearity and labeled data, the self-learning system can be designed by using BP neural network. From the analysis of fuel injection fluctuation, three influencing factors (dwell time, pre-injection pulse width, and injection pressure) should be input into the trained BP neural network to obtain the fuel injection compensation value.

4.2 GA optimized LM-BP neural network

The analysis above indicates that there are three important influencing factors including the dwell time, the pre-injection pulse width, and the injection pressure which leads to the fluctuation of injection quantity. A series of labeled fluctuation data can be obtained from the simulation tests. In this case, the supervised learning method in machine learning can be used to effectively identify the fluctuation value with less data. Due to the nonlinear characteristics of fuel injection fluctuation, ANN can be used to learn the fluctuation model.

In order to improve the convergence rate, the second-order convergence algorithm is used to design the BP neural network in this paper, which has a more fast convergence rate. Aimed at the problem of the fuel injection fluctuation compensation algorithm, the objective function is selected as follows:

$$E(\omega)=\frac{1}{2}\sum_{i=1}^{p} pY_i - Y_i^{*} p^2=\frac{1}{2}\sum_{i=1}^{p} e_i^2(\omega) \quad (1)$$

where: p is the number of fuel injection samples; Y_i is the actual value of fuel injection fluctuation (output of neural network); Y_i^{*} is the expected value of fuel injection fluctuation (expected output); e_i is the learning bias of fuel injection fluctuation.

The updated formula of the weight threshold is as follows:

$$\omega^{k+1}=\omega^{k}+\Delta\omega \quad (2)$$

where: ω^k is the vector consisting of weights and thresholds in the kth iteration; $\omega^{k+1}$is the updated vector; $\Delta\omega$ is the vector correction value. The weight and threshold updating formula is written as follows:

$$\Delta\omega=\left[\boldsymbol{J}^{\mathrm{T}}(\omega)\boldsymbol{J}(\omega)+\mu\boldsymbol{I}\right]^{-1}\boldsymbol{J}^{\mathrm{T}}(\omega)e(\omega) \quad (3)$$

where: μ is learning rate; $\boldsymbol{I}$ is unit matrix, $e(\omega)$ is the learning bias of fuel injection fluctuation.

In this paper, the GA is used to optimize the initial weights and thresholds to avoid the LM-BP neural network falling into local minimum. The operational flowchart is shown in Fig. 12.

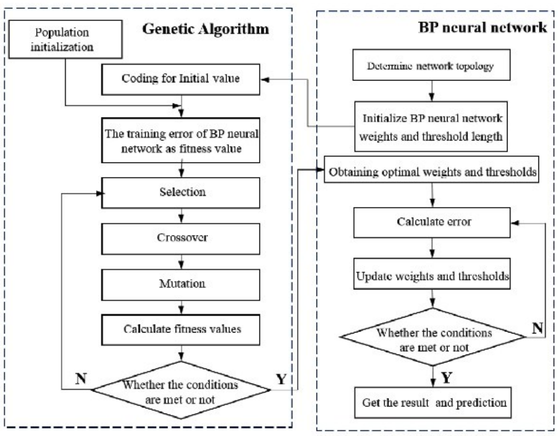


Fig.12　Flow chart of optimizing BP neural network by GA

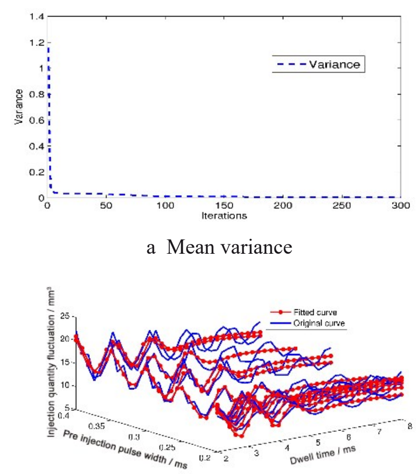
Firstly, determine the network topology. Then, optimize the initial weights and thresholds by GA algorithm. Finally, predict with the network after updating the weights and thresholds. The specific operation of BP algorithm is shown in the preceding section. In this genetic algorithm, the size of population is set to n, that is to say, there are n individuals. The weights and thresholds of each individual are randomly initialized and marked as X_i, then the initial population $P_X=\{X_1, X_2, ..., X_n\}$ is created. In this paper, code individual with real numbers. The absolute deviation value of LM-BP neural network in training progress is defined as fitness function, whose formula is shown in Eq. (4). As the fitness value decreases, the probability of being selected for the next generation increases.

$$F=k\sum_{p=1}^{p}\left|e_i\right|=k\sum_{p=1}^{p}\left|Y_i-Y_i^*\right| \quad (4)$$

The optimal weights and thresholds of the network are not obtained until achieving the requirements of the necessary optimal individual, Then the sample data are trained by using the GA optimized LM-BP neural network.

4.3　Prediction effect

Taking the dwell time between main and pre-injection, the pre-injection pulse width, injection pressure as the network input, an the fuel injection quantity fluctuation value as the network output, the number of input layer neurons is 3 and the number of output layer neurons is 1. According to the trial-and-error method, the number of hidden layer neurons can be selected as 25 for the design of the fuel injection fluctuation compensation algorithm network. If only LM-BP is used for the algorithm, it can easily lead to a local optimum solution without the optimization of the GA. Integrate the collected data into three parameter input training samples and put into the designed network, the simulation results are shown in Fig. 13. From Fig. 13a, it is seen that when the number of convergence is 50, the deviation has basically converged, but the data fitted and prediction effects are poor. As shown in Fig. 13b and Fig. 14, the error is greater than 2.



a　Mean variance

b　Data fitting

Fig. 13　Training of LM-BP neural network with three-parameter input

Put the training samples into the GA-LM-BP fuel injection fluctuation compensation algorithm network, the fitting of data training is shown in Fig. 15. From Fig. 15a, it can be seen that the fitness

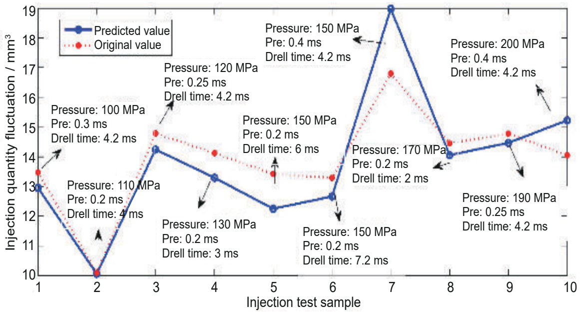
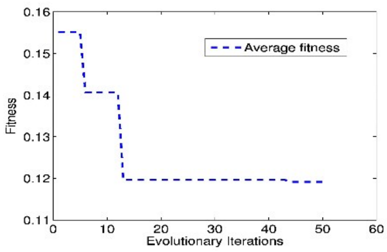
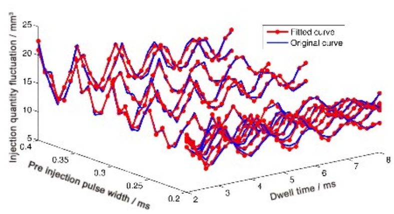


Fig.14 Prediction of LM-BP neural network with three-parameter input

value has basically converged after the 13th genetic iteration. Fig. 15b shows that the data fitted degree is high and the fitting error is less than 0.5. The prediction of test data is shown in Fig. 16, from which it is observed that the predicted value is approximately consistent with the original data value, and the prediction error is less than 1.



a Mean variance



b Data fitting

Fig. 15 Training of GA-LM-BP neural network with three-parameter input

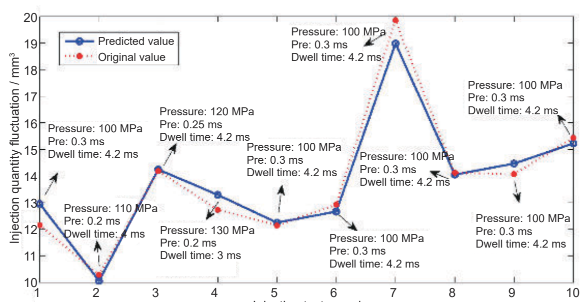
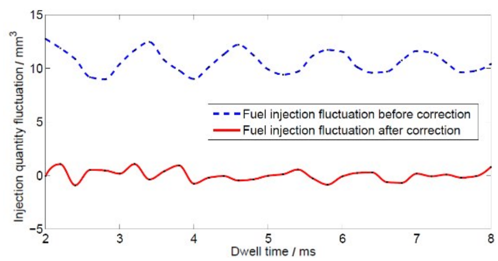


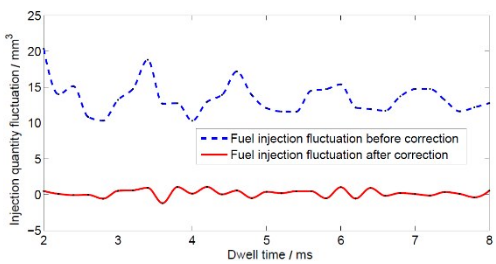
Fig. 16 Prediction of GA-LM-BP neural network with three-parameter input

4.4 Compensation control results

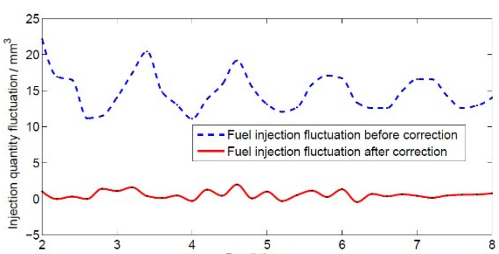
The GA-LM-BP neural network is used to design the compensation algorithm for fuel injection fluctuation, and the validity of the algorithm is verified in the injector model. When the injection pressure is set to 100 MPa (training data), the correction effect curves of injection quantity corresponding to the pre-injection pulse width of 0.2 ms, 0.3 ms, and 0.4 ms are obtained as shown in Fig. 17. It can be seen that the multiple injections quantity inaccuracy problem can be effectively controlled, with a control error of less than 1. As shown in Fig. 18, when the injection pressure is set to 150MPa (test data), the injection quantity control of 0.2 ms, 0.3 ms, and 0.4 ms pre-injection pulse width can be effectively controlled, with a control error of less than 1.5. Therefore, it is concluded that the fuel injection control strategy can effectively reduce the fluctuation of fuel quantity in multiple injections.



a 0.2 ms pilot injection pulse width

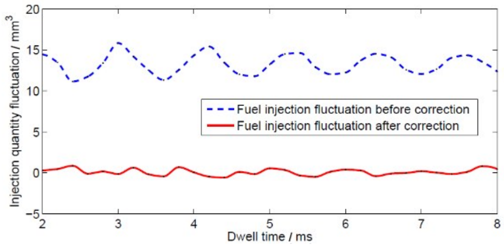


b 0.3 ms pilot injection pulse width

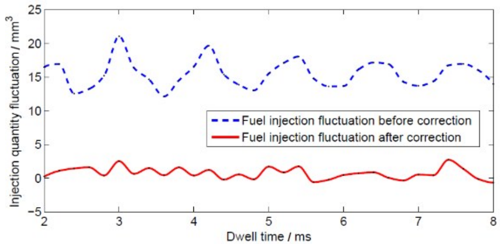


c 0.4 ms pilot injection pulse width

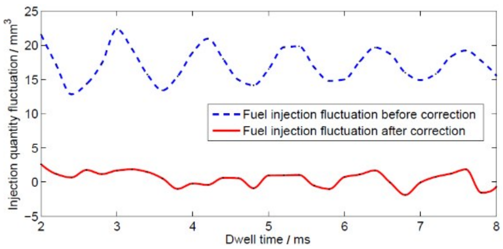
Fig. 17 Correction of injection fluctuation under injection pressure of 100 MPa



a 0.2 ms pilot injection pulse width



b 0.3 ms pilot injection pulse width



c 0.4 ms pilot injection pulse width

Fig.18 Correction of injection fluctuation at an injection pressure of 150 MPa

5 Conclusions

Focusing on the fuel injection fluctuation in the multiple injections of high pressure common rail system, this paper presents a fuel correction strategy based on the GAs and neural network to make the fuel quantity accurate. First, a simulation model of the electro injector on AMESim environment is built through analysis of working principle and dynamics. Then, the dynamic characteristics of multiple injections are simulated and the results show that the injection pressure, pre-injection pulse width, dwell time between the main and pilot injection pulse are the main influencing factors for fuel injection fluctuation. The BP neural network is used to design the fuel injection compensation, and the GA is applied to optimize the neural network for which it is easy to fall into local optimal solution. Of course, there are still some works needing to be conducted in the future, such as making improvement in the fuel injection control algorithm.

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