

In-Cycle Real-Time Prediction Technology of NOx Emission of Diesel Engines Based on Cylinder Pressure

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ABSTRACT

This paper was targeted on achieving in-cycle real-time prediction of NOx emission of diesel engines in both steady-state and transient processes based on cylinder pressure. Specifically, input parameters of the NOx emission model were determined, an offline empirical model of NOx emission was built based on steady-state test data, and in-cycle real-time prediction of NOx emission was achieved in the in-cylinder combustion analysis tool.

Based on the mechanism of NOx formation, combustion state parameters in strong correlation with NOx emission were extracted from cylinder pressure, rate of cylinder pressure, rate of heat release, accumulated heat release and burned zone temperature. Quantitative correlations between combustion state parameters and NOx emission were calculated based on steady-state test data and the inputs of the empirical model of NOx emission were determined. The quadratic polynomial model from combustion state parameters to NOx emission was built based on steady-state test data. The combustion state parameters and quadratic polynomial model functions were added in the in-cylinder combustion analysis tool, which was developed based on MPC5644A MCU. NOx emission measured from test data and predicted from in-cylinder combustion analysis tool were compared under both steady-state and transient processes, and the accuracy of in-cycle real-time prediction of NOx emission was verified. Under steady-state operating conditions: except for one bad condition, relative errors of the other 15 conditions were all less than 10% ; average relative error of the 16 conditions was 6.8%. Under transient operating conditions, the prediction accuracy of NOx emission was slightly worse.

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INTRODUCTION

Relying on the combustion closed-loop feedback control technology platform, the in-cylinder combustion process can be controlled and improved and thus the emission closed-loop control can be achieved through real-time prediction of emissions. Consequently the technology of real-time prediction of emissions has great potential in terms of reducing emissions and improving economic efficiency in diesel engines. Rich information on combustion process is contained in cylinder pressure signal, from which combustion state parameters in strong correlation with emissions can be obtained. Thus the empirical emission model based on combustion state parameters can be established and implemented online to achieve real-time prediction of emissions.

Jean Arrègle from Universidad Politecnica de Valencia built an empirical model of NOx emission in a 4-cylinder diesel engine [1]. Adiabatic flame temperature was predicted by cylinder pressure and intake air oxygen concentration, and rate of heat release was calculated by cylinder pressure. The empirical model of NOx emission was built based on the two variables

along with engine speed, and the parameters in the model were calibrated by test data. But they didn't apply this model to real-time prediction.

B. Winkler-Ebner from Johannes Kepler University Linz developed a virtual sensor of NOx emission [2], the sensor was an empirical quadratic polynomial model, essentially. The inputs of the model came from physical sensor signals of the diesel engine and test bench. The virtual sensor of NOx emission realized real-time prediction, but its inputs relied on all kinds of physical sensor signals, thus the performance of the virtual sensor was not that stable considering that the physical sensors might age with running time increasing.

Yue-Yun Wang from General Motors Company developed a neural network model of NOx emission [3]. The inputs of the model included injection pressure, EGR, phase of 50% accumulated heat release, the average temperature of burned zone, etc. The neural network model's functional form isn't amenable to online coding, so it isn't proper for real-time prediction.

The cylinder pressure signal itself contains rich information on combustion process in diesel engines, and based on it, we can obtain other signals, such as rate of cylinder pressure, rate of heat release, accumulated heat release and combustion temperature. These signals can also reveal the characteristics of the combustion process in diesel engines. We can analyze the combustion process and extract NOx emission related combustion state parameters from all these signals. When we determine the input parameters, we can build the NOx emission model with a proper mathematical method. The model's functional form is amenable to online coding, and the real-time prediction of NOx can be realized. In this paper, we will write the codes into MPC5644A MCU and realize in-cycle real-time prediction of NOx emission.

TEST EQUIPMENT AND METHODS

Test Equipment

The research is carried out on a 4.75L four-cylinder high pressure common rail diesel engine. The specific engine parameters are shown in Table 1.

Table 1. Engine parameters

Item	Parameter
Cylinder bore/Stroke	110×125mm
Compression ratio	17.5
Max. power/Speed	120kw/2400r/min
Max. Torque/Speed	610N·m/1300~1500r/min
Rail pressure	60~160MPa
Pilot injection timing	20~5(°) BTDC
Pilot injection quantity	2~5mg
Main injection timing	15~0(°) BTDC
Main injection quantity	8~100mg

Mass-produced Pressure Sensor Glow Plug (PSG) is installed for each cylinder of the engine [4]. The PSG is a resistance type pressure sensor, and its parameter is shown in Table 2. NOx emission is measured by MEXA 7100DEGR exhaust analyzer.

Table 2. Pressure Sensor parameters

Item	Parameter
Test range	0 MPa~21 MPa
Temperature range	-40°C ~140°C
Max. Pressure	23 MPa
Power supply	3.3V
Signal type	Linear voltage
Accuracy	2%

Cylinder pressure signal is acquired through the in-cylinder Combustion Analysis Tool (iCAT). The iCAT is independently developed based on MPC5644A MCU by our group at Tsinghua University, and its main function is shown in Figure 1.

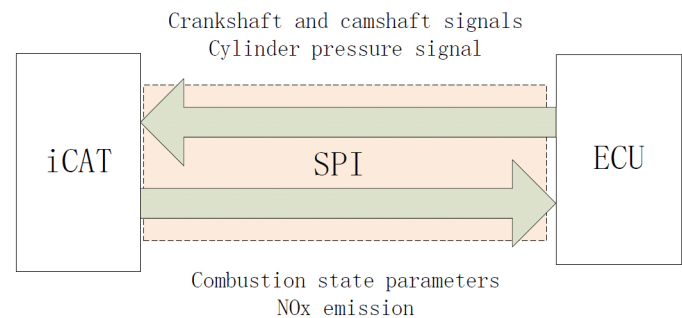


Figure 1. Function diagram of iCAT

iCAT and engine ECU make intercommunication through SPI. The existing main function of iCAT is acquiring crankshaft, camshaft and cylinder pressure signals from engine ECU through SPI, calculating part of combustion state parameters and sending them to engine ECU through SPI. In this paper, we will also write function expressions of more combustion state parameters and the NOx emission model into iCAT, so that iCAT can calculate in-cycle NOx emission as soon as combustion state parameters are obtained. After this, the predicted NOx emission can be sent to engine ECU through SPI.

Test Methods

In this paper, we carry out three tests. The first test is carried out for analyzing the correlations between combustion state parameters and NOx emission. When engine speed and brake torque are fixed, NOx emission will decrease linearly with main injection timing retard, and this phenomenon is good for analyzing the correlations. So the first test includes 3 steady-state operating conditions, and its main control parameters are shown in Table 3.

Table 3. Main control parameters of the first test

Condition number	Speed/ r/min	Torque/ N·m	Main injection timing / (°)BTDC
1	1600	280	10, 8, 6, 4, 2, 0
2	1400	240	10, 8, 6, 4, 2, 0
3	1200	130	10, 8, 6, 4, 2, 0

The second test data are used to build the mathematical model of NOx emission. We set 11 different engine speeds from 1000r/min to 1800r/min. Under each engine speed, we plan to change the throttle position from 10% to 100%. In the process of the actual test, we avoid some seldom-used operating conditions. Finally, we get 72 steady-state operating conditions, shown in Figure 2.

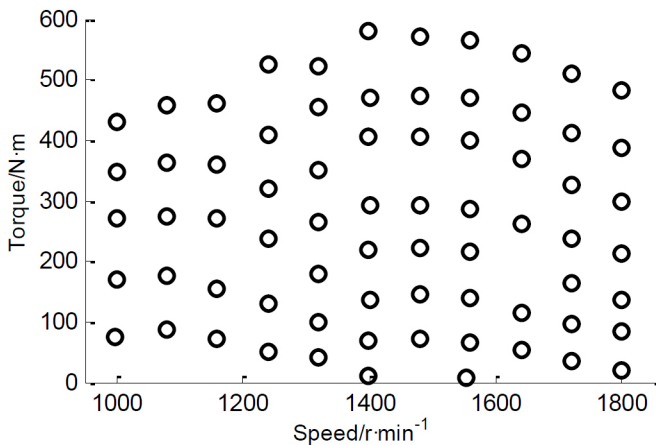


Figure 2. Operating conditions of the modeling test

The last test is carried out to validate the accuracy and practicability of the in-cycle real-time prediction of NOx emission respectively. It will include both steady-state and transient processes. In the final validation part of this paper, we will see detailed parameter diagram of the last test.

CALCULATION OF COMBUSTION PROCESS CURVES

Rate of Heat Release

According to first law of thermodynamics, discrete rate of heat release can be deduced from acquired cylinder pressure and volume, as shown in [Formula 1](#) [5].

$$R_{hr_i} = \left[\frac{\gamma}{\gamma-1} \cdot p_i \cdot (V_i - V_{i-1}) + \frac{1}{\gamma-1} \cdot V_i \cdot (p_i - p_{i-1}) - Q_{w_i} \right] / (\theta_i - \theta_{i-1}) \quad (1)$$

In this formula, R_{hr} is rate of heat release; γ is adiabatic index of gas mixture; p and V are cylinder pressure and volume respectively; θ is crank angle; Q_w is heat loss caused by cylinder wall heat dissipation; i and $i-1$ are serial number of acquired cylinder pressure.

γ and Q_w are not fixed values, and they can be calculated by mathematical model. Considering that this research aims to realize real-time prediction of NOx emission, complex mathematical model calculation is not proper. So we simplify γ as a fixed value 1.37 according to engineering experience [5], and ignore the heat loss of cylinder wall.

Accumulated Heat Release

Accumulated heat release Q_{hr} is the total heat release at certain crank angle, as shown in [Formula 2](#).

$$Q_{hr_i} = Q_{hr_{i-1}} + R_{hr_{i-1}} (\theta_i - \theta_{i-1}) \quad (2)$$

Combustion Temperature

Combustion temperature has important effect on formation of high temperature NO. According to ideal gas state equation, we can calculate the average temperature in the cylinder, which is irrelevant with formation of high temperature NO. Therefore it's necessary to build a two zone combustion model, dividing combustion zone into burned zone and unburned zone, and the former is where high temperature NO is formed. The two zone combustion model satisfies the following assumptions [6]:

1. The mixed gas in the cylinder is ideal gas, and its temperature and pressure is homogeneous;
2. The mixed gas in the burned and unburned zone is ideal gas, and their temperature and pressure are homogeneous;
3. Gaseous mass can be transferred between the two zones, while heat can't;
4. Ignore radiation heat and gas leakage;
5. NOx emission is formed in the burned zone.
6. The mole number of mixed gas in the whole cylinder doesn't change in the combustion progress.

Based on the assumptions above, burned zone temperature can be calculated in [Formula 3](#) [6].

$$T_{bz_i} = \frac{n_g T_{g_i} - (n_g - n_{bz_i}) T_{uz_i}}{n_{bz_i}} \quad (3)$$

In this formula, n_g and T_g are mole number and average temperature of mixed gas in the whole cylinder respectively; n_{bz} and T_{bz} are mole number and average temperature of burned zone gas respectively; T_{uz} is average temperature of unburned zone gas.

Burned zone gas consists of two parts: burned fuel and the air consumed by it. According to the literature [6], mole number of burned zone gas can be calculated as shown in [Formula 4](#).

$$n_{bz_i} = \frac{Q_{hr_i}}{Q_{LHV} \cdot M_f} \cdot \left(1 + \frac{M_f \cdot \lambda_{bz} \cdot \alpha_s}{M_a} \right) \quad (4)$$

In this formula, Q_{LHV} is low heating value of the fuel; M_f and M_a are the relative molecular mass of fuel and air respectively; λ_{bz} is excess air ratio of burned zone; α_s is chemical reaction stoichiometric ratio of air and fuel.

Result Demonstration

Take operating condition of 270N·m/1600r/min as an example, the mole number and average temperature in the whole cylinder, unburned zone and burned zone are demonstrated respectively in [Figure 3 \(a\)](#) and [\(b\)](#).