

DESIGN AND RESEARCH ON SCR SYSTEM CONTROL MODEL BASED ON SIMULINK

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Abstract: As a core aftertreatment technology for diesel engine exhaust, selective catalytic reduction (SCR) systems have attracted extensive research attention from domestic automotive manufacturers. Based on a self-developed urea dosing pump, this paper establishes the operating workflow of the SCR system and selects the Freescale MC9S12XS128 microcontroller as the core hardware of the aftertreatment control unit (ACU). A SCR system control model is constructed via MATLAB/Simulink, with executable C codes automatically generated from the established model to shorten development cycles and reduce overall system development costs. A four-cylinder in-line diesel engine is configured for the bench test, and multiple ESC and WHTC cycle experiments are carried out on the AVL GEM30 automated exhaust emission test bench. Experimental results verify that the proposed development framework combining Simulink-based modeling, modular control strategies and automatic C-code generation is feasible, efficient and reliable. The developed SCR system delivers superior control performance and remarkable NO_x reduction capability in practical engineering applications.

Keywords: Diesel engine; Exhaust emission; SCR; Control strategies; RTW; NO_x

1 INTRODUCTION

Owing to outstanding advantages including high power output and low specific fuel consumption, diesel engines are widely equipped on medium- and heavy-duty passenger and freight vehicles. Nevertheless, increasingly stringent emission legislations and global energy shortages impose strict restrictions on the further development of diesel engines. Against the backdrop of soaring vehicle population and worsening atmospheric pollution, diesel engines must be equipped with exhaust aftertreatment devices to satisfy China's National Stage IV and above emission standards. Among prevailing exhaust purification technologies, selective catalytic reduction (SCR) is recognized as one of the most effective technical solutions. Apart from efficient NO_x abatement, SCR also alleviates the difficulty of in-cylinder emission control and improves engine fuel economy by 2%–3%, which facilitates its widespread industrial application [1-3]. Major domestic engine manufacturers such as Weichai, Yuchai and Xichai have independently developed customized SCR aftertreatment systems matching diesel engines with varied raw NO_x emission levels [4-5]. Focusing on a self-developed urea dosing pump, this paper elaborates the formulation of SCR control strategies. On the MATLAB/Simulink platform, sub-models for reducing agent dosing calculation, driving motor operation and dosing pump status diagnosis are established with consideration of engine emission characteristics, ammonia storage properties and catalytic conversion efficiency of SCR catalysts. Standardized, robust and high-efficiency C codes are automatically generated from the simulation model, which significantly improves software development efficiency and program reliability of the ACU controller.

2 OVERALL SCHEME OF THE SCR SYSTEM

The SCR system consists of key components including SCR catalytic muffler, urea tank, precision dosing pump, aftertreatment control unit (ACU), urea injection nozzle, multi-type sensors and urea delivery pipelines. Serving as the system core, the ACU undertakes three primary functions: dosing pump regulation, CAN-based communication with engine ECU and on-board fault diagnosis. The Freescale MC9S12XS128 single-chip microcomputer is adopted as the core controller of ACU. The dosing pump is composed of stepping motor, diaphragm pump, urea heating assembly, temperature and pressure transducers; the rotating speed of the stepping motor directly determines the volumetric urea injection quantity.

In practical operation, the ACU collects multi-channel sensor signals including urea temperature and pressure inside the dosing pump, inlet/outlet exhaust temperature of the SCR catalyst and real-time liquid level of the urea tank. Via CAN bus communication with engine ECU, the ACU acquires real-time engine operating parameters (rotational speed, engine load) and NO_x concentrations upstream and downstream of the catalyst to calculate the theoretical target urea injection rate. Corresponding stepping motor speed is regulated according to calculated urea dosage; the urea heating circuit is activated or deactivated based on measured urea fluid temperature. Subsequently, the compressed air solenoid valve is energized to mix atomized urea solution with compressed air inside the mixing chamber, and the mixed fluid is sprayed into exhaust pipes via the injection nozzle to trigger selective catalytic reduction between urea decomposition products and exhaust NO_x inside the catalytic muffler. The overall structural layout of the SCR system is illustrated in Figure 1.

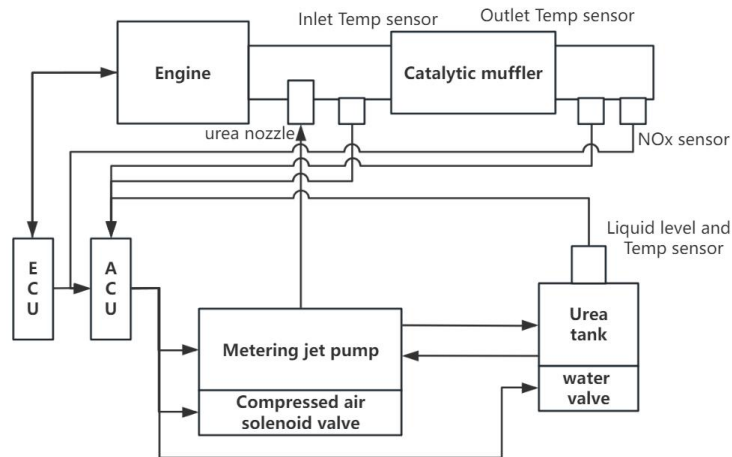


Figure 1 Overall Layout of the SCR System

3 DESIGN OF SCR SYSTEM CONTROL MODEL

Modular modeling methodology is adopted for SCR control model construction on Simulink. Compared with conventional hand-coded programming, model-based automatic C-code generation features superior efficiency, clear logical framework, visualized programming and convenient secondary transplantation.

3.1 Development of Bottom Hardware Driver Modules

Bottom driver modules act as the hardware-software interface for ACU embedded software. In this work, S-Function in Simulink is employed to encapsulate underlying driver programs into reusable graphical modules. This encapsulation strategy provides multiple merits including visual parameter configuration, convenient modular debugging and transplantation, as well as seamless integration between control algorithms and underlying drivers during automatic code generation.

Driver development is initiated by sorting out required hardware resources in accordance with overall SCR operational logic, followed by component selection of MCU, sensors and actuators. The finalized driver modules cover MCU initialization, analog input, digital input/output, input capture, CAN communication, stepping motor drive and compressed-air solenoid valve drive (Figure 2).

MCU initialization module: Configures phase-locked loop and external crystal oscillator to set the MCU bus frequency at 32 MHz with no extra input/output terminals required.

Analog input module: Completes initialization of AD converter and real-time acquisition of multi-channel analog signals, involving urea tank liquid level & temperature, pump internal urea temperature & pressure, and upstream/downstream catalyst exhaust temperature.

Digital input/output module: Controls malfunction indicator lamp and compressed-air electromagnetic relay.

Stepping motor drive module: Adjusts motor rotational speed dynamically to match target urea injection volume.

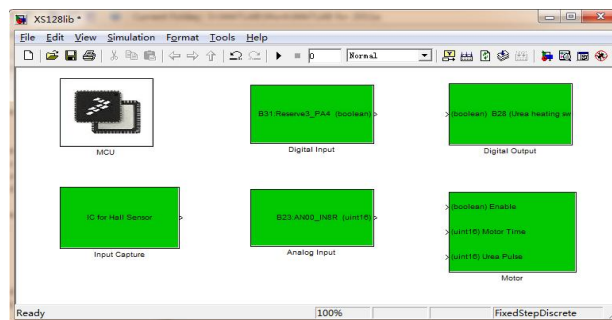


Figure 2 Underlying Driver Modules

3.2 State Management Strategy of the SCR System

The state management module governs system operating modes and realizes orderly state transition of the entire SCR device. Six core operating states are defined: initialization, standby preparation, non-pressure regulation, closed-loop pressure control, pressure relief and post-shutdown purging, with detailed state transition rules displayed in Figure 3.

Initialization & Standby: The system enters the initialization phase after power-on to complete peripheral configuration and CAN communication self-check. If critical faults are detected, the system remains locked in standby mode; otherwise, it switches to non-pressure regulation.

Non-pressure regulation: The controller judges whether engine speed exceeds 600 r/min and monitors catalyst inlet/outlet temperature and urea solution temperature. The urea heating system is activated once urea is frozen; the system transfers to pressure control after fluid temperature returns to the normal operating range.

Closed-loop pressure control: This mode contains five sub-states: priming filling, pressure build-up, air venting, pipeline fault detection and quantitative urea metering. During priming filling, the stepping motor starts and the backflow solenoid opens to fully fill pipelines and pump cavities with urea. The backflow valve closes once internal pressure reaches the preset threshold to initiate pressure build-up. If target pressure cannot be achieved, residual air inside pipelines is eliminated by cyclic backflow opening for a maximum of five attempts; persistent pressure failure is diagnosed as pump mechanical fault after repeated venting. After stable pressure establishment, blockage inspection for delivery pipelines and injection nozzles is performed, and the system proceeds to precise urea dosing control under fault-free conditions.

Pressure relief: The system switches to pressure relief mode and opens the backflow valve at a constant motor rotating speed to release internal pipeline pressure once malfunctions emerge during pressure regulation and fault diagnosis.

Post-shutdown purging: Four sequential sub-processes (delayed waiting, pipeline urea emptying, pressure compensation and shutdown standby) are executed before power-off to thoroughly drain residual urea from pumps and pipelines and prevent urea crystallization and pipeline blockage [6-8].

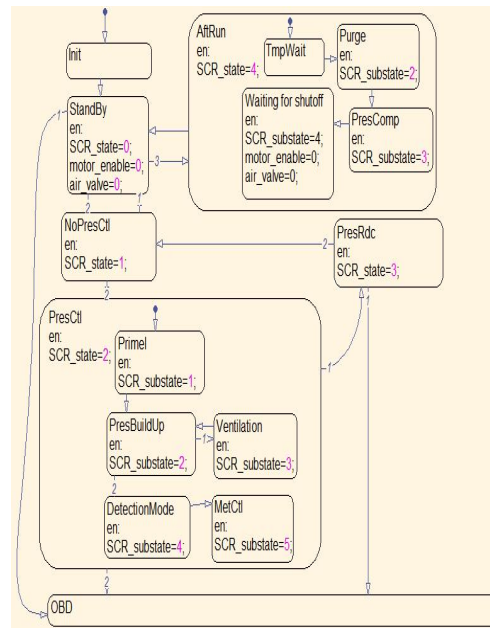


Figure 3 State Management Control Strategy of SCR System

3.3 Calculation Model for Urea Injection Quantity

Urea dosing precision dominates NO_x catalytic conversion efficiency: insufficient urea supply results in incomplete NO_x elimination, whereas excessive urea injection triggers ammonia slip and secondary atmospheric pollution. Therefore, a hybrid open-loop plus closed-loop control framework is proposed for urea dosage calculation. The final urea injection rate is determined by three coupling terms: baseline theoretical urea dosage, feedforward correction coefficient and closed-loop feedback correction coefficient, as expressed in Eq.(1):

$$Adblue_{final} = Urea_{base} * K_{pre_corr} * K_{feedback_corr} \quad (1)$$

Where: $Adblue_{final}$ = final actual urea injection rate; $Urea_{base}$ = baseline theoretical urea consumption calculated from engine raw emission data; K_{pre_corr} = feedforward correction coefficient accounting for steady-state condition, transient temperature fluctuation and catalyst ammonia storage variation; $K_{feedback_corr}$ = real-time closed-loop feedback correction coefficient based on downstream NO_x sensor feedback.

3.3.1 Baseline urea injection calculation model

As the core of SCR control algorithm, baseline urea consumption is calculated following the logic illustrated in Figure 4. Real-time engine speed and load signals are imported to query three pre-calibrated MAP tables: target NO_x conversion efficiency, raw NO_x exhaust concentration and exhaust mass flow rate under corresponding operating conditions. Theoretically required urea amount is calculated based on target NO_x conversion rate, raw NO_x concentration and exhaust mass flow. The average temperature of upstream and downstream catalyst is calculated to characterize catalyst bed temperature, and baseline urea dosage is further amended via catalyst reaction rate MAP indexed by bed temperature and exhaust space velocity to acquire the finalized baseline injection volume.

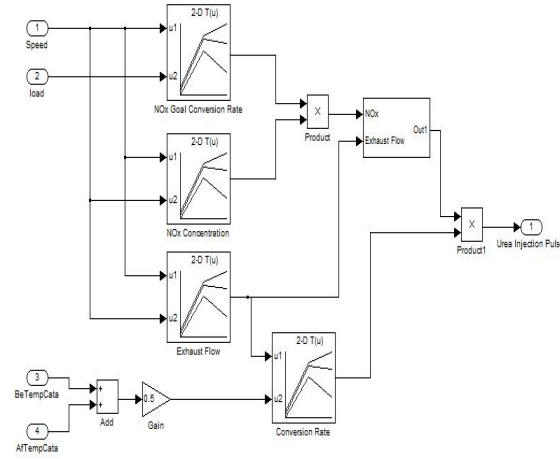


Figure 4 Calculation Model of Base Urea Dosing Quantity

3.3.2 Feedforward correction of urea dosage

Actual catalytic efficiency is restricted by catalyst space velocity and bed temperature, which necessitates feedforward compensation for baseline urea dosage. Steady-state correction factors are obtained from pre-calibrated MAPs corresponding to space velocity and catalyst temperature. In transient engine operating conditions, catalyst bed temperature lags behind exhaust gas temperature, leading to either ammonia over-spray or inadequate NO_x reduction. Despite inherent feedback adjustment capability, closed-loop control suffers from evident response delay. Accordingly, real-time engine load variation monitoring is integrated into feedforward correction to compensate transient calculation errors and shorten the regulation period of closed-loop feedback (Figure 5).

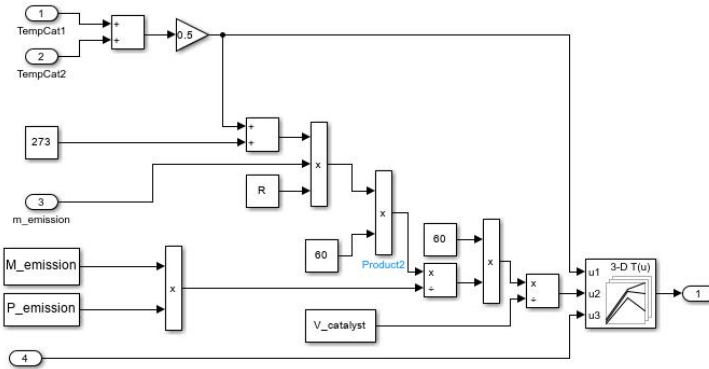


Figure 5 Urea Dosage Correction Model

3.3.3 Closed-loop feedback regulation

To eliminate residual dosing deviation originating from inaccurate open-loop calculation under drastic transient conditions, downstream NO_x sensor signals are sampled to compute actual catalytic efficiency and realize closed-loop urea trimming. Actual NO_x conversion efficiency is defined in Eq.(2):

$$k_{real} = \frac{NO_{x_B} - NO_{x_A}}{NO_{x_B}} \quad (2)$$

Where: k_{real} = measured NO_x conversion efficiency; NO_{x_B} = NO_x concentration upstream of SCR catalyst; NO_{x_A} = NO_x concentration downstream of SCR catalyst.

A calibrated target NO_x emission MAP is predefined to balance NO_x reduction performance and ammonia slip risk. Urea injection is suspended when measured post-catalyst NO_x concentration is lower than the calibrated threshold; otherwise, closed-loop correction coefficient is calculated via Eq.(3) for dosage trimming:

$$C_{feedback} = \frac{k_{real}}{K_e} \quad (3)$$

Where: $C_{feedback}$ = closed-loop correction coefficient; K_e = calibrated target NO_x conversion efficiency.

The structural diagram of closed-loop feedback module is given in Figure 6.

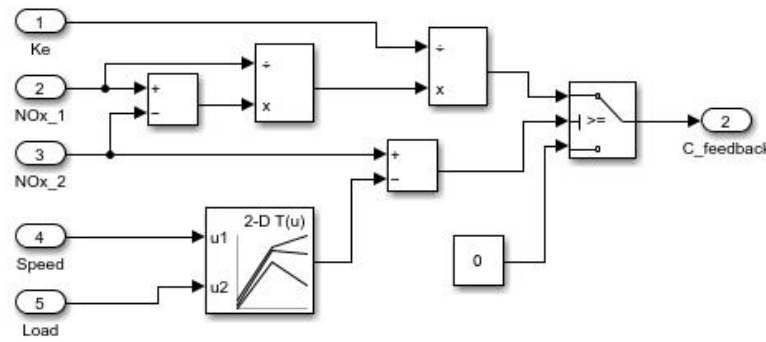


Figure 6 Closed-Loop Feedback Regulation Model

4 BENCH TEST AND RESULT ANALYSIS

4.1 Experimental Test Bench Configuration

A four-cylinder in-line turbocharged intercooled diesel engine is employed for bench validation, with core engine specifications listed in Table 1. The AVL GEM30 automated exhaust emission testing system is deployed to conduct standardized ESC and WHTC cyclic tests. The ACU controller receives engine speed and load parameters via CAN bus from engine ECU, while multi-channel physical sensors acquire temperature, pressure and NO_x concentration signals of the aftertreatment pipeline.

Table 1 Main Parameters of the Engine

Item	Specification
Cylinder layout	In-line four-cylinder
Intake type	Turbocharging with intercooler
Bore diameter	93 mm
Displacement	2.892 L
Idle speed	750 r/min
Rated power	110 kW
Rated rotational speed	2800 r/min
Peak torque	375 N·m
Speed at peak torque	2000 r/min

4.2 Test Result Discussion

Raw engine NO_x emissions and post-SCR NO_x emissions under ESC and WHTC cycles are contrasted in Figure 7. The original diesel engine without SCR aftertreatment presents excessively high NO_x concentration with drastic cyclic fluctuation and prominent emission peaks, failing to satisfy current statutory emission limits. After integration of the developed SCR control system, overall NO_x emission drops sharply with significantly suppressed fluctuation, realizing stable and timely NO_x abatement under both steady and transient working conditions without obvious overshoot or response lag.

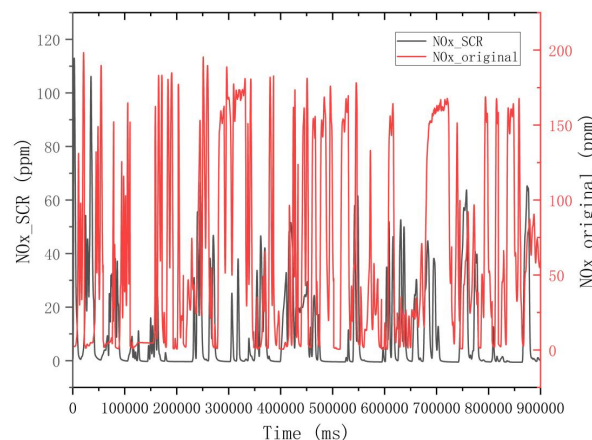


Figure 7 Test Results of NO_x Emission

Experimental results demonstrate that the proposed compound control strategy combining baseline calculation, feedforward pre-correction and closed-loop feedback accurately matches urea supply with instantaneous engine working conditions and optimizes SCR catalytic efficiency. During full-cycle experiments, the developed SCR system

realizes rapid startup, stable pipeline pressurization and precise urea metering, with no typical faults including abnormal pressure fluctuation, nozzle clogging and urea crystallization observed. Consistent NO_x purification effect is maintained across low/high speed and low/high load operating regions, and final tailpipe NO_x emissions fully comply with statutory emission limitations.

5 CONCLUSIONS

A complete modular SCR control framework is established on MATLAB/Simulink in this research, and a three-stage urea dosing calculation scheme (baseline calculation + feedforward correction + closed-loop trimming) is proposed to improve dosing accuracy. Bench verification draws the following conclusions:

- (1) A complete SCR system operating workflow is formulated, laying the structural foundation for subsequent control modeling.
- (2) Targeted underlying driver modules are developed matching the Freescale MC9S12XS128 ACU microcontroller to realize seamless connection between control software and system hardware.
- (3) Full-set SCR simulation models covering system state management and multi-stage urea dosing regulation are completed, and standard executable C codes are automatically generated via RTW toolbox.
- (4) Bench cyclic tests confirm stable system operation and outstanding NO_x reduction performance of the developed SCR controller.

The proposed model-based SCR development scheme achieves favorable NO_x purification performance and provides valuable references for high-precision urea dosing algorithm optimization in industrial SCR controller development.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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