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Urea-SCR Process Control for Diesel Engine Using Feedforward-Feedback Nonlinear Method ⋆⋆

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Abstract: Urea selective catalytic reduction (urea-SCR) process control is very important for exhaust gas aftertreatment in diesel engines. A control system tracking ammonia coverage ratio is designed to achieve high NO_x conversion efficiency and low ammonia slip for urea-SCR process in this paper. The control system consists of a nonlinear feedforward controller based on flatness and a PI feedback controller to deal with the uncertainties and disturbance. Furthermore, a tuning method of controller parameters is presented based on randomized algorithms. Finally, the simulation results are given to demonstrate the effectiveness of the proposed control scheme.

Keywords: urea-SCR, ammonia distribution, nonlinear control, flatness, feedforward, feedback.

1. INTRODUCTION

Due to the better fuel economy and higher power output compared with gasoline engines, diesel engines have been the dominant power sources of medium-duty and heavy-duty vehicles. However, diesel engine emission control, especially NO_x control, still faces challenges. Recently, advanced diesel engine technologies such as exhaust gas recirculation and low-temperature combustion mode have been demonstrated of being able to reduce engine-out NO_x emissions Wang (2008). However, it has also been studied that the near-future emission regulations cannot be satisfied by these means alone Johnson (2009).

Exhaust aftertreatment systems are indispensable to satisfy the vehicle emission regulations, and urea selective catalytic reduction (urea-SCR) technique as one of the most promising approaches can meet the increasingly stringent NO_x emission regulations worldwide Johnson (2009). This technique requires 32.5% aqueous urea solution(AdBlue) as the reductant. Since both tailpipe NO_x and ammonia emissions are undesirable, urea dosing control is quite a challenge, particularly for vehicle applications where transient operations are common. Some urea dosing control designs have been proposed in recent years, and most of them focus on feed-forward controller designs or utilize linearized urea-SCR models for feedback controller designs Willems et al. (2007), Devarakonda et al. (2009), Devarakonda et al. (2009). The study in Willems et al. (2007) points out that open-loop feed-forward control can not well handle engine transient exhaust gas conditions and feedback control is necessary to compensate the uncertainties during regular driving the mission test cycle.

Some feedback controllers utilize the values sensed through NO_x sensor and/or ammonia sensor directly as the feedback signals Devarakonda et al. (2009), Zhao et al. (2014). While, current onboard NO_x sensor has cross-sensitive to ammonia Devarakonda et al. (2009) and there have not been the ammonia sensors in production, practical applications are yet rarely seen. To increase the deNOx efficiency and avert the ammonia slip excessively, some nonlinear methods using the ammonia coverage ratio as the control target are proposed Hsieh and Wang (2009b), Hsieh and Wang (2009a), Hsieh and Wang (2011), Zhang et al. (2013). In the papers Hsieh and Wang (2009b), Hsieh and Wang (2011), the backstepping based nonlinear ammonia surface ratio controllers are designed for diesel engine selective catalytic reduction systems. And due to the capacity of the urea nozzle, MPC controller which can handle the hard constraint is designed to track the ammonia surface coverage rate.

In recent years, the differential flatness Fliess et al. (1995) is widely used for trajectory planning and tracking control Gao et al. (2010). For a differentially flat system, if a trajectory for the flat outputs is given, the desired states and inputs can be derived as functions of the outputs and their derivatives. The advantages of the flatness-based control include at least computational efficiency and avoidance of control saturation Gao et al. (2010). Moreover, flatness-based control can improve the performance of an

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existing linear feedback control system by introducing a feedforward compensator, which is suitable for a large amount of automotive control systems.

It must be noted that the chemical reactions of urea-SCR systems is very sensitive to exhaust gas temperature and engine-out NO_x, etc., moreover, these system parameters are all variable. This paper, therefore, will construct a nonlinear feedforward-feedback control where the feedforward control is designed based on differential flatness with the flat output being the ammonia coverage ratio. In order to accommodate the model errors and the disturbances, a linear feedback controller is added.

The rest of the paper is organized as follows. In Section 2, a control-oriented nonlinear simple model of SCR system is built. In Section 3, the nonlinear controller is designed. In Section 4, simulation results are given to verify the effectiveness of the proposed controller. Finally, some conclusions are given in Section 5.

2. SYSTEM MODELING AND PROBLEM STATEMENT

2.1 Problem Statement

A schematic diagram of urea-SCR operations is shown in Fig. 1. As can be seen from the schematic diagram, Part

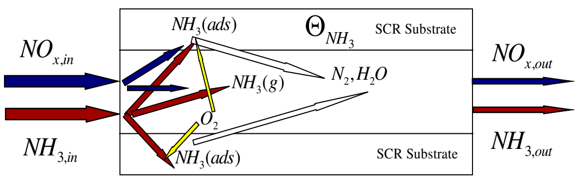

Fig. 1. Schematic presentation of the urea-SCR reactions

of the NH_3converted from the AdBlue is firstly adsorbed on the catalytic substrate as the NH_3(ads)and than the ammonia (NH_3(ads)) applied to reduce the $NO_{x,in}$ generated by the engine. The amount of the NH_3(ads) is represented as the ammonia coverage ratio (Θ_{NH_3}). The function of urea-SCR systems is to decrease the output NO_x. So the control task of urea-SCR systems is to simultaneously achieve high deNOx efficiency and low ammonia slip. It seems to be feasible to find a trade-off parameter values (Θ_{NH_3}) for feedback control. In this paper, a novel nonlinear feedforward-feedback controller will be designed to track the desired ammonia coverage ratio. The optimal value of ammonia coverage ratio may be obtained from analysis and experiments with respect to a specific engine urea-SCR systems, and it can be another interesting research topic.

A series of investigations about more detailed models reveals that a simple model structure is able to represent the relevant dynamics in the catalytic converter Schär (2003). The simple model presented here refers to the assumptions and simplifications in Schär et al. (2006). All nomenclature of parameters and variables used for modeling are shown in Table 1 and Table 2.

Table 1. Parameters nomenclature

symbol	description	value/unit
S_c	the area of active surface atoms per molar	581[m^2/mol]
α_{Prob}	sticking probability	1.11e-3[-]
c_s	concentration of active surface atoms with respect to gas volume in converter	7.30[mol/m^3]
$c_{\mathrm{p,EG}}$	specific heat at constant pressure of exhaust gas	1060 [J/kgK]
$c_{\mathrm{p,c}}$	specific heat of the catalysts	1054[J/kgK]
$M_{\mathrm{NH_3}}$	Molar mass of NH_3	17 [g/mol]
R	universal gas constant	8.3145 [J/molK]
$R_{\mathrm{S,EG}}$	gas constant of engine	288 [J/kgK]
k_{Des}	desorption pre-exponential factor	0.514 [1/s]
k_{SCR}	SCR pre-exponential factor	2.6776[m^2/s]
k_{Ox}	NH_3 oxidation pre-exponential	3.34e6[1/s]
$E_{\mathrm{a,Des}}$	activation energy of desorption	15.2 [J/mol]
$E_{\mathrm{a,SCR}}$	activation energy of SCR	28471[J/mol]
$E_{\mathrm{a,Ox}}$	NH_3 oxidation activation energy	1.16e5[J/mol]
P_{amb}	ambient pressure	101325[Pa]
V_c	volume of the SCR cell	0.0199 [m^3]
m_c	mass of catalytic converter	19[kg]
n_{cell}	numbers of the SCR cell	1[-]
ε	ratio of gas to total converter volume	0.81[-]
$\varepsilon_{\mathrm{rad,scr}}$	radiation coefficient of silencer	0.507[-]
σ_{sb}	radiation constant	5.67e-8[-]
$A_{\mathrm{rad,scr}}$	the silencer radiating surface area	0.9044[m^2]

Table 2. Variables nomenclature

symbol	description/unit
C_x	Mole concentration of species x[mol/m^3]
$n^*_{\mathrm{NH_3,in}}$	NH_3 molar mass flow [mol/s]
$n^*_{\mathrm{NO_x,in}}$	NO_x molar mass flow [mol/s]
m_{EG}	exhaust gas mass flow [kg/s]
$T, T_{\mathrm{in}}, T_{\mathrm{amb}}$	Temp, exhaust gas Temp, ambient Temp [K]
$\Theta_{\mathrm{NH_3}}$	surface coverage with NH_3 in an SCR cell [-]

2.2 SCR System Modeling

The simple model of the SCR catalytic converter includes four reactions. The adsorption (Ads) and desorption (Des) of NH_3 on the catalyst are described as:

$$\mathrm{NH_3(g)} \underset{r_{\mathrm{Des}}}{\overset{r_{\mathrm{Ads}}}{\longleftrightarrow}} \mathrm{NH_3(ads)}, \tag{1}$$

where NH_3(ads) represents the ammonia adsorbed on the SCR substrate, r_{Des} and r_{Ads} are rate constants of ammonia adsorption reaction, ammonia desorption reaction. The rate of the NH_3 adsorption/desorption can be expressed as:

$$\begin{aligned} R_{\mathrm{Ads}} &= r_{\mathrm{Ads}} C_{\mathrm{NH_3}}(1-\Theta_{\mathrm{NH_3}}), \\ R_{\mathrm{Des}} &= r_{\mathrm{Des}}\Theta_{\mathrm{NH_3}}. \end{aligned} \tag{2}$$

The reduction reaction is governed by an Eley-Rideal mechanism consuming adsorbed NH_3(ads) and gaseous NO_x

$$\mathrm{4NH_3(ads) + 4NO_x + zO_2} \xrightarrow{r_{\mathrm{SCR}}} \mathrm{4N_2 + 6H_2O}, \tag{3}$$

where r_{SCR} is rate constant of NO_x reduction reaction, the NO_x reduction reaction rate is described as:

$$R_{\mathrm{SCR}} = r_{\mathrm{SCR}} C_{\mathrm{NO_x}} \Theta_{\mathrm{NH_3}}. \tag{4}$$

The oxidation reaction of adsorbed NH_3(Ox) is described as:

$$\mathrm{4NH_3(ads) + 3O_2} \xrightarrow{r_{\mathrm{Ox}}} \mathrm{2N_2 + 6H_2O}, \tag{5}$$

where r_{Ox} is rate constant of oxidation reaction of adsorbed $\mathrm{NH_3}$ and the oxidation rate of $\mathrm{NH_3}$(ads) is described as:

$$R_{\mathrm{Ox}} = r_{\mathrm{Ox}}\Theta_{\mathrm{NH_3}}, \tag{6}$$

where

$$r_{\mathrm{Ads}} = c_s S_c \alpha_{\mathrm{Prob}}\sqrt{\frac{RT}{2\pi M_{\mathrm{NH_3}}}}, r_{\mathrm{Des}} = c_s k_{\mathrm{Des}} e^{(\frac{-E_{\mathrm{a,Des}}}{RT})},$$

$$r_{\mathrm{SCR}} = c_s RT k_{\mathrm{SCR}} e^{(\frac{-E_{\mathrm{a,Red}}}{RT})}, r_{\mathrm{Ox}} = c_c k_{\mathrm{Ox}} e^{(\frac{-E_{\mathrm{a,Ox}}}{RT})}.$$

In this paper, a Continuous Stirred Tank Reactor (CSTR) is used to represent the SCR system, which is suitable for the light- and medium-duty diesel engine applications. Based on the molar balance and energy conservation,and considering the reactions rate shown in (2),(4) and (6), the ordinary differential equations (ODEs) of the one-cell SCR catalyst dynamic model can be presented below:

$$\dot{C}_{\mathrm{NO_x}} = a_1 n^*_{\mathrm{NO_x,in}} - C_{\mathrm{NO_x}}(a_0 a_1 m^*_{\mathrm{EG}} T + r_{\mathrm{SCR}}\Theta_{\mathrm{NH_3}}), \tag{7a}$$

$$\dot{C}_{\mathrm{NH_3}} = a_1 n^*_{\mathrm{NH_3,in}} - C_{\mathrm{NH_3}}[a_0 a_1 m^*_{\mathrm{EG}} T + r_{Ads}(1-\Theta_{\mathrm{NH_3}})] + r_{\mathrm{Des}}\Theta_{\mathrm{NH_3}}, \tag{7b}$$

$$c_s\dot{\Theta}_{\mathrm{NH_3}} = r_{\mathrm{Ads}}(1-\Theta_{\mathrm{NH_3}})C_{\mathrm{NH_3}} - [r_{\mathrm{Des}} + r_{\mathrm{SCR}}C_{\mathrm{NO_x}} + r_{\mathrm{Ox}}]\Theta_{\mathrm{NH_3}}, \tag{7c}$$

$$\dot{T} = a_2 m^*_{\mathrm{EG}}(T_{\mathrm{in}} - T) - a_3(T^4 - T^4_{\mathrm{amb}}), \tag{7d}$$

where

$$a_0 = \frac{R_{\mathrm{S,EG}}}{P_{\mathrm{amb}}}, a_1 = \frac{n_{\mathrm{cell}}}{\varepsilon V_c},$$

$$a_2 = \frac{n_{\mathrm{cell}} c_{\mathrm{p,EG}}}{c_{p,c} m_c}, a_3 = \frac{\varepsilon_{\mathrm{rad,scr}}\sigma_{sb} A_{\mathrm{rad,scr}}}{c_{\mathrm{p,c}} m_c}.$$

2.3 State Space Model

In this section, a model for controller design is obtained. Since the dynamics considered are only ammonia concentration (7c) and ammonia coverage ratio (7d), regarding temperature T and $\mathrm{NO_x}$ as measurable variations Hsieh (2010), then the control-oriented model is simplified as the following state space equation:

$$\begin{cases} \dot{x}_1 = f_{11}(x_1,p) + f_{12}(x_1,p)x_2, \\ \dot{x}_2 = r_{Des}x_1 + f_{21}(x_1,p)x_2 + a_1 u, \end{cases} \tag{8}$$

where $x = [\Theta_{\mathrm{NH_3}}, C_{\mathrm{NH_3}}]^T$ is the state variable, $u = n^*_{\mathrm{NH_3},in}$ is the control input, $\Theta_{\mathrm{NH_3}}$ is the controlled output, $p = [T_{\mathrm{in}}, T_{\mathrm{amb}}, C_{\mathrm{NO_x}}, m^*_{\mathrm{EG}}, r_x]^T$ is the varying parameter, and

$$f_{11}(x_1,p) = -\frac{1}{c_s}[r_{\mathrm{Des}} + r_{\mathrm{SCR}}C_{\mathrm{NO_x}} + r_{\mathrm{Ox}}]x_1,$$

$$f_{12}(x_1,p) = \frac{1}{c_s}r_{\mathrm{Ads}}(1-x_1),$$

$$f_{21}(x_1,p) = -[a_0 a_1 m^*_{\mathrm{EG}} T + r_{\mathrm{Ads}}(1-x_1)].$$

3. CONTROLLER DESIGN

3.1 Nonlinear Feedforward Controller

The target of the controller is to track the desired coverage rate, denoted as x_{1d}. For derivation of the nonlinear feedforward controller,

$$y = x_1 \tag{9}$$

is chosen as the control output. Differentiating (9) and inserting it to the state equations(8), it becomes:

$$\dot{y} = f_{11}(x_1,p) + f_{12}(x_1,p)x_2, \tag{10a}$$

$$\ddot{y} = \dot{f}_{11} + \dot{f}_{12}x_2 + r_{\mathrm{Des}}f_{12}x_1 + f_{12}f_{21}x_2 + a_1 f_{12}u. \tag{10b}$$

On the contrary, the state variables and the system input can be expressed as the following functions of the system output y and a second order of its time derivatives

$$x_1 = y, \tag{11a}$$

$$x_2 = \frac{\dot{y} - f_{11}(y,p)}{f_{12}(y,p)}, \tag{11b}$$

$$u = \frac{(\frac{\dot{y}-f_{11}}{f_{12}})' - f_{12}f_{21}(\frac{\dot{y}-f_{11}}{f_{12}}) - r_{\mathrm{Des}}f_{12}y}{a_1}. \tag{11c}$$

It is clear that all the state variables and the control input can be expressed by the selected output and the relative degree of the system equals to the system order, which implies that the simplified urea-SCR system is flat and $y = x_1$ is the flatness output. Inserting the desired system output $y_d = x_{1d}$ and its time derivatives, the nonlinear feedforward control can be obtained as:

$$x_{2d} = \frac{\dot{x}_{1d} - f_{11}(x_{1d},p)}{f_{12}(x_{1d},p)}, \tag{12a}$$

$$u_f = \frac{\dot{x}_{2d} - f_{12}f_{21}x_{2d} - r_{Des}f_{12}x_{1d}}{a_1}. \tag{12b}$$

For feedback requirement, differential signal of the state error should be obtained. In order to obtain $y(\Theta_{\mathrm{NH_3}})$ and $\dot{y}(\dot{\Theta}_{\mathrm{NH_3}})$ from the measurement value of ammonia coverage ratio $\tilde{\Theta}_{\mathrm{NH_3}}$, let $\tilde{\Theta}_{\mathrm{NH_3}}$ pass through a first order filter. The filter is usually used to suppress the influence of measurement noise, the block diagram of the first order filter is shown in Fig. 2, and it can be described by

$$\frac{\Theta_{\mathrm{NH_3}}}{\tilde{\Theta}_{\mathrm{NH_3}}} = \frac{1}{Ts+1}. \tag{13}$$

The output of the filter is $\Theta_{\mathrm{NH_3}}$, which is actually used in the controller. It is worth noting that we can also obtain $\dot{\Theta}_{\mathrm{NH_3}}$ from the filter. In this paper, the time constant for the first order filter is chosen as 0.03s.

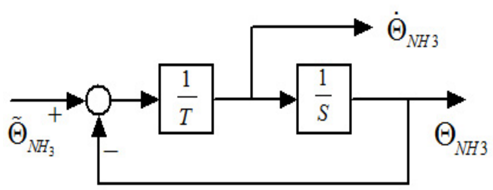

Fig. 2. First order filter for input shaping

3.2 PI Feedback Controller Design

Flatness-based control allows to use simple linear feedback part in a two-degree-of-freedom control structure. Here, a P controller is adopted, where Δu is the feedback controller expressed as:

$$\Delta u = K_{p1}e_1 + K_{p2}e_2, \tag{14}$$

with $e_1 = x_1 - x_{1d}$ and $e_2 = x_2 - x_{2d}$. K_{p1} and K_{p2} are the feedback control coefficients. The structure of the complete controller is shown in Fig. 3 and the control value u is the combination of the nonlinear feedforward control and the linear feedback control, so the system control input can be obtained as:

$$u = \Delta u + u_f, \tag{15}$$

Thus, the urea-SCR controller is constructed, assuming that the measurement of ammonia coverage ratio $\Theta_{\mathrm{NH_3}}$ is available. However, for production vehicles, the ammonia coverage ratio is seldom measured. Fortunately, a ammonia coverage ratio observer can be constructed using observer Ong et al. (2010); Hu et al. (2011), which is another research topic.

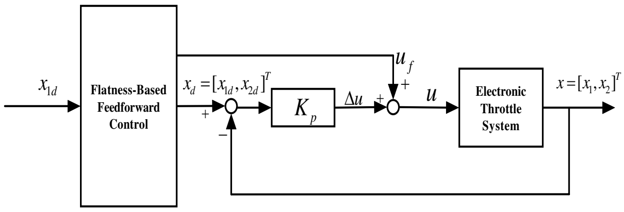

Fig. 3. Designed Feedforward-feedback Controller

4. SIMULATION RESULTS

Simulations are conducted using the enDYNA developed by TESIS company Philipp and Huber (2004). Based on a certain type of light-duty diesel engine, the enDYNA model is established. The engine has four cylinders, a total displacement volume of 1.9L, turbocharged and incorporates an intercooler and the maximum engine speed is 4500 rpm. For considering the capacity of the nozzle, 0.003 mol/s is chosen as ammonia molar flow constraint. Simulations are performed in a transient driving cycle FTP75, which is used for the purpose of evaluating the control system performance. Variation processes of the engine speed and torque during the FTP75 transient test cycle are shown in Fig.4, and the variation of engine $\mathrm{NO_x}$ emission is shown in Fig.5, which is one of the major interference for the ammonia coverage tracking controller. The main purpose of the simulations is to demonstrate the effectiveness and robustness of the proposed ammonia coverage tracking controller.

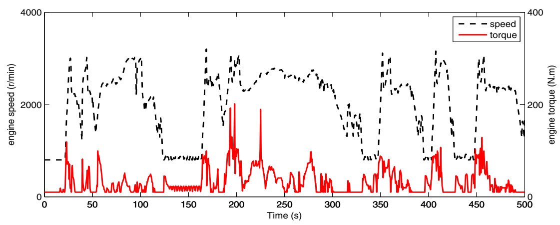

Fig. 4. Engine operating condition

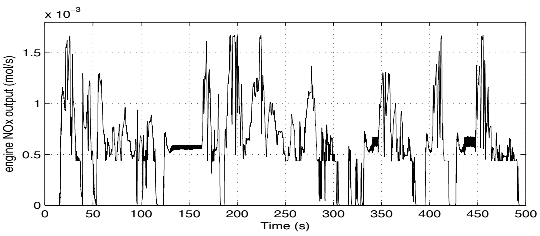

Fig. 5. Engine NO_x emission

First of all, the Monte Carlo methods is used to tune the coefficients of the controller Wang et al. (2012). The important issue in the method is how to choose good random number generators. In the following, the linear congruential generators is employed to generate uniform distribution samples for $K_{p1} \in [0, 1]$ and $K_{p2} \in [0, 1000]$, recursively Tempo et al. (2005). The parameters of K_{p1} and K_{p2} for feedback gain are differentiated for "good" set and "bad" set by the ammonia coverage tracking results. We choose the absolute average and standard deviation of tracking error as the criterion, shown as (16). If the controller parameters produced by the linear congruential generator make the controller meet the requirement, they are deemed as the good set, vice versa. The result is shown in Fig.6.

$$\bar{e}_1 = \frac{\sum_{i=1}^{400} |e_{1i}|}{400}, \tag{16a}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{400} (e_{1i} - \bar{e}_1)^2}{400}}. \tag{16b}$$

In Fig.6, the original 400 sampling points can be seen clearly. The symbol of "◦" represents the elements in "good" set, and the symbol of "∗" represents the elements in "bad" set, respectively. According to the above analysis

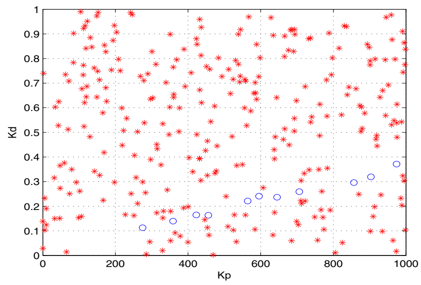

Fig. 6. Distribution and division of random samples

results of parameter selection, the controller coefficients are selected as $K_{p1} = 0.12$, $K_{p2} = 280$, which are relatively small.

In order to validate the control effectiveness of the proposed controller, the transient simulations are constructed under different kinds of reference signals. The tracking performance of sine input signal is depicted in Fig.7 and Fig.8, where the amplitude of the signals are same and the frequency are different. The implementation situation of ammonia injector are shown respectively.

The case of step reference input is shown in Fig.9. The set value of ammonia coverage ratio is 0.2 at the beginning and then is increased to 0.4 at the 50th second, it is stepped down 0.3 at the 150th second, and it also experiences a series of step process subsequently. The variations of the set values intend to show the tracking capability of the controller. As can be seen, the ammonia coverage ratio well tracks the desired value and the tracking adjust time is less than 10s even without overshoot. the longer tracking adjust time at the 150th second is because that at the stepped down moment the ammonia injection actuator failures and the engine-out $\mathrm{NO_x}$ emission is not enough

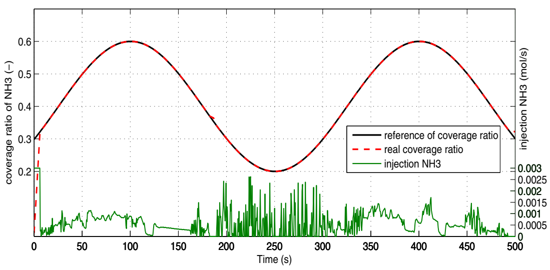

Fig. 7. Tracking response of sine input signal with high frequency

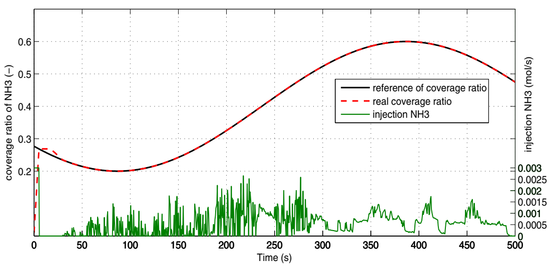

Fig. 8. Tracking response of sine input signal with low frequency

in the FTP75 test cycle. Therefore, the proposed flatness-based controller has the ability to make a good tracking performance for the nominal system.

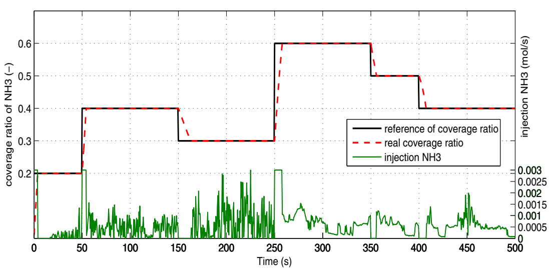

Fig. 9. Tracking response of step input signal

Comparison results in terms of step tracking capability is shown in Fig.10-Fig.12 between the proposed controller and the well-tuning PID controller. The Urea-SCR catalyst volume/length is same between the two cases entirely. Obviously, the PID controller has some heavy vibration and the proposed method has better tracking capability. Therefore, the proposed method has more robust to the interferences of transient operating conditions compared with the PID controller.

Due to the system calibration error and variety of the external situation such as exhaust temperature, the parameters of the urea-SCR will be changed in a certain range. Here, the robustness is verified by changing the parameter c_s as the half of the initial value. As showed in Fig.13-Fig.16, the influence comparison of parameter variation between the proposed controller and the PID controller can demonstrate the food robustness of the Feedforward-Feedback Nonlinear method. Apparently, the parameters uncertainties both will lead to a slower adjust time for the two controllers, but the proposed controller

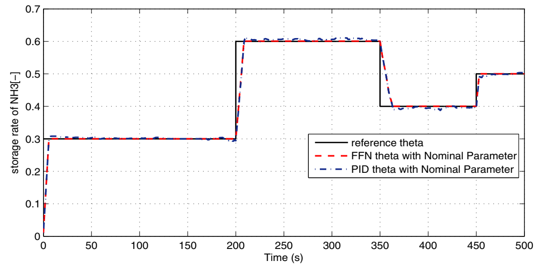

Fig. 10. Tracking response comparison: step input

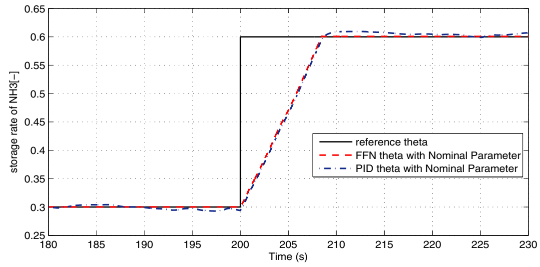

Fig. 11. Zoom-in of Figs.10 (180-230s)

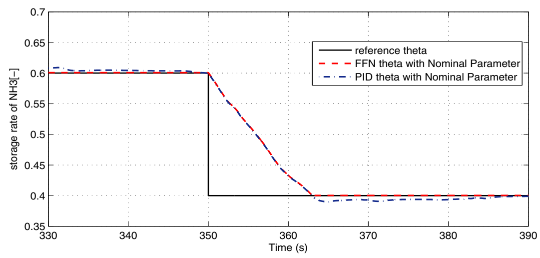

Fig. 12. Zoom-in of Figs.10 (330-390s)

is less affected. Moreover, the parameters uncertainties lead to a larger static error for the PID controller. So the designed flatness-based controller has strong robustness to parameter uncertainties compared with the PID controller.

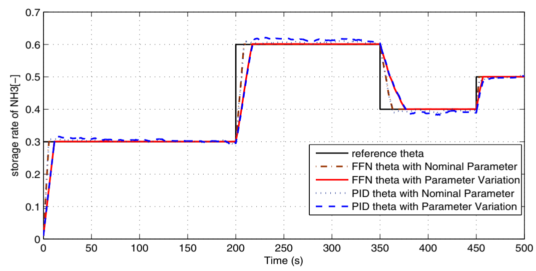

Fig. 13. Tracking response comparison with parameter variation

5. CONCLUSION

In this paper, to track the desired ammonia coverage ratio a feedforward-feedback nonlinear controller is designed, which contains a nonlinear feedforward controller based on flatness and a PI feedback controller. A tuning method of controller parameters is presented based on randomized

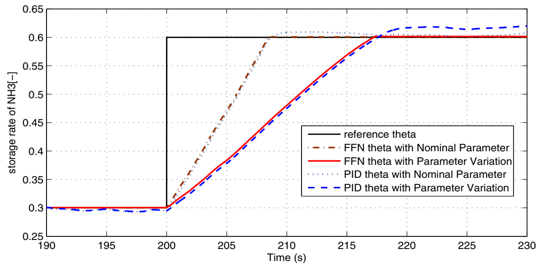

Fig. 14. Zoom-in of Figs.13 (190-230s)

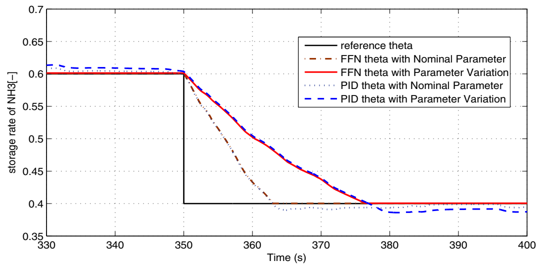

Fig. 15. Zoom-in of Figs.13 (330-400s)

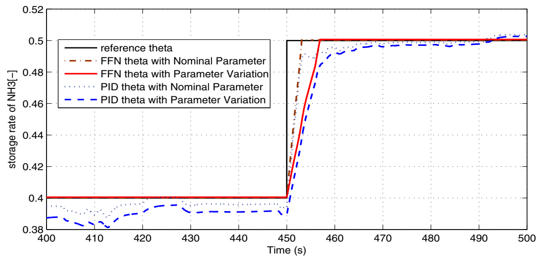

Fig. 16. Zoom-in of Figs.13 (400-500s)

algorithms. Based on the enDYNA diesel model, FTP75 transient driving cycle simulation has demonstrated the good tracking effectiveness of the proposed controller. Comparison results verify that the proposed controller has more robustness to the interferences of transient operating conditions and the parameter uncertainties compared with the PID controller. The randomized algorithms is just applied to the off-line simulation and will be used in the real implementation in the future.

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