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# Identification of Cross-Sensitivity of Smart $NO_x$ Sensors to Ammonia in Urea-Selective Catalyst Reduction Systems via Fast Fourier Transform

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The smart $NO_x$ sensor (SNS) is prevailingly used in exhaust after-treatment systems such as urea-selective catalytic reduction (SCR) to monitor the concentration of $NO_x$ emission. Owing to the cross-sensitivity of SNS to ammonia concentration, however, the sensor signal suffers significant interference and leads to false reading if excessive ammonia is present. In this paper, an effective method that avoids the cross-sensitivity of SNS to ammonia is proposed on the basis of a periodic modulation of the urea dosage rate and Fast Fourier Transform (FFT) of the SNS signal. This method enables us to measure the true $NO_x$ concentration correctly even if the $NO_x$ is overkilled by excessive ammonia.

## 1. Introduction

For the purpose of exhaust gas after-treatment, various exhaust gas sensors that are sensitive, stable, and cost effective have been developed.(1,2) The selective catalyst reduction (SCR) system, being one of the most effective after-treatment systems, uses an inexpensive urea solution as a reductant to reduce the harmful $NO_x$ emission in engine exhaust. The SCR after-treatment system allows the engine to operate at high performance and under low-fuel-consumption conditions while satisfying the regulations of environmental protection.

In the SCR system, the Nichiyu Giken Kogyo/Continental Smart $NO_x$ Sensor (SNS) is widely used for exhaust $NO_x$ emission monitoring and control. Owing to the cross-

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*Corresponding author: e-mail: cjchiang@mail.ntust.edu.tw sensitivity of SNS to ammonia concentration, however, the sensor signal cannot be interpreted in a straightforward way as it is not clear whether excessive $NH_3$ is present.(3,4) In this paper, a method based on the periodic modulation of the urea dosage rate and fast Fourier transform (FFT) of the SNS signal, which identifies the cross-sensitivity of SNS to $NH_3$, is proposed. Specifically, the amplitude of the SNS signal at the dosage driving frequency provides a direct interpretation of the true $NO_x$ emission in applications where ammonia is involved. On the other hand, ammonia leakage can be identified when the peak amplitude occurs at a much lower frequency than the perturbed frequency.

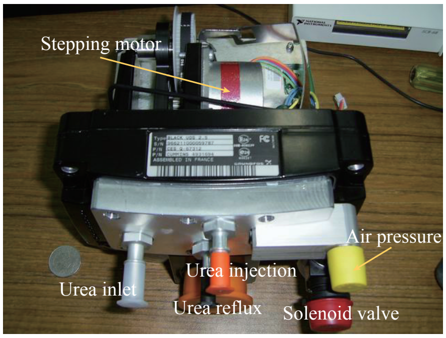
## 2. SCR Working Principle and Experimental Setup

The SCR systems reduce the engine-out $NO_x$ emission mainly via a series of reactions including evaporation of the urea solution, decomposition of the urea molecules, $NH_3$ adsorption and desorption on the catalyst surface, and reduction of $NO_x$.(3) For safety reason, the urea aqueous solution is stored in a urea tank. The urea aqueous solution is injected into an exhaust pipe located upstream of the SCR catalyst and decomposes to form ammonia and $CO_2$: $(NH_2)_2CO + H_2O \rightarrow 2NH_3 + CO_2$. Adsorption and desorption of ammonia then take place on the surface of the SCR catalyst: $NH_3 \leftrightarrow NH_3^*$. The adsorbed ammonia reduces $NO_x$ based on the Eley-Rideal mechanism: $4NH_3^* + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$. At higher temperature (above 450 °C), an increasing amount of ammonia is converted directly to nitrogen: $4NH_3^* + 3O_2 \rightarrow 2N_2 + 6H_2O$.

In this study, the tests are conducted with a Hino W06E diesel engine connected to a SCHENCK W230 eddy current dynamometer, which has a maximum absorption horsepower of 230 kW at 7500 rpm. The SCR after-treatment system contains an SCR catalyst device made of $V_2O_5$, $WO_3$, and $TiO_2$ from KJ Co., Ltd., a urea injection system from Cummins (including a urea injection pump, a nozzle, and a urea tank), a $NO_x$ sensor from NGK/Continental, and two thermocouples upstream and downstream of the SCR catalyst. The amount of urea aqueous solution injected upstream of the SCR catalyst is controlled with the air-assisted urea pump driven by a two-phase stepping motor. The data acquisition and control algorithm is implemented in the MOTOTRON ECU. Figure 1(a) shows the urea injector pump from Cummins. The urea injector pump contains a four-wire bipolar permanent magnet stepping motor driving a camshaft-link pump. The urea pump extracts the urea aqueous solution from the urea tank, and high-pressure air controlled by opening a solenoid valve is applied to spray the urea aqueous solution into the exhaust pipe through a nozzle. The atomization of the urea aqueous solution out of the nozzle facilitates the decomposition of urea to form ammonia and $CO_2$ in the hot exhaust gas.

## 3. Smart $NO_x$ Sensor

SNS is produced by NGK/Continental for exhaust gas after-treatment systems such as SCR and lean $NO_x$ trap (LNT). SNS consists of three main parts, namely, the sensor body, control module, and transmission harness. The sensor body is manufactured using zirconia ($ZrO_2$) with an integrated heater, two cavities, and three oxygen pumps. The



| | |
|---|---|
| Communication type | SAE J1939 |
| Drive voltage | 12–32 V |
| Measurement data range | 0–3012 ppm |
| Resolution (Baud rate) | 0.05 ppm/bit (250 kbps) |
| Measurement accuracy | ±10% @ 100–1500 ppm |
| Response time (33–66%) | 1.3–1.65 s |

(a) (b)

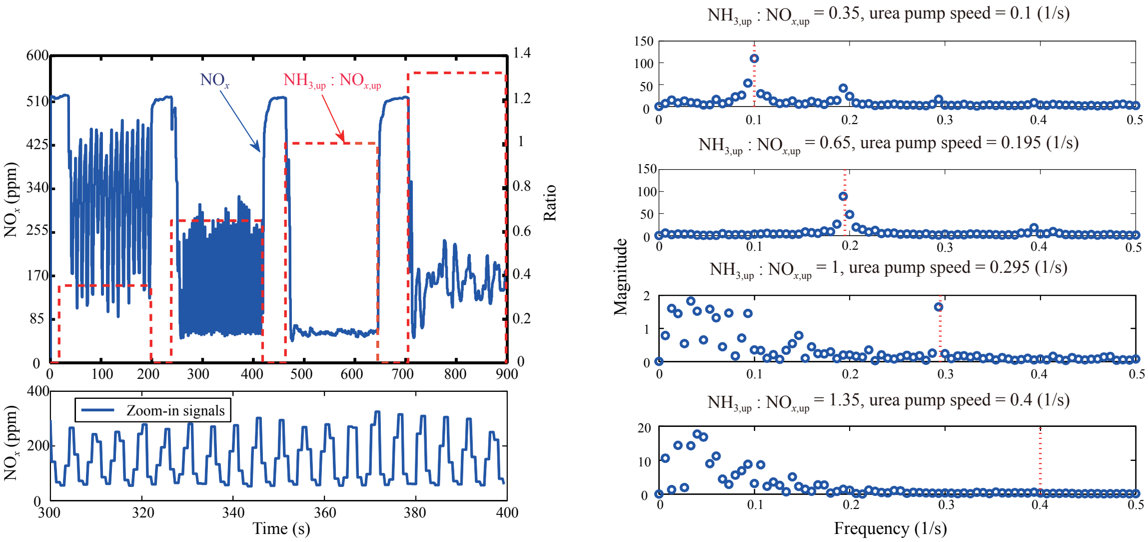
Fig. 1. (Color online) (a) Cummins urea pump and (b) smart $NO_x$ sensor specifications.(5)

heater is integrated in the sensor body to increase the temperature up to 800 °C. After the oxygen concentration is decreased to a predetermined level in the first cavity, $NO_x$ reduction catalytic activity takes place in the second cavity, and the oxygen generated is detected as an oxygen pumping current, which is proportional to the $NO_x$ concentration.(6) The SNS control module communicates with the engine control module (ECM) through the SAE J1939 (CAN1) data link.(7) Figure 1(b) shows the SNS communication and performance specifications.

## 4. $NO_x$ Sensor Signal Characteristics

The supply dosage of urea is controlled by adjusting the rotation speed of the pump motor. Figure 2(a) shows step responses of the SCR after-treatment system with various urea dosages when the engine is operating at ESC mode 6 (1650 rpm, 75% load). During the test shown in Fig. 2(a), increasingly higher urea pump speeds are applied, resulting in increasing amounts of urea dosage. Note that Fig. 2(a) only shows the average ratios of $NH_3$ to $NO_x$ molar concentrations (dashed lines), while the urea dosage rate is expected to be perturbed by the reciprocating motion of the camshaft-link pump. The SNS signal is less noisy at the stoichiometric point (the ratio of $NH_3$ to $NO_x$ equals 1, around 500 to 600 s) when the lowest $NO_x$ emission without perceptible ammonia leakage is achieved. More oscillatory sensor signals are observed when less urea is injected (the ratio of $NH_3$ to $NO_x$ is less than 1, before 400 s). The cross-sensitivity of SNS to ammonia concentration for higher-than-stoichiometric ammonia dosage is also shown in Fig. 2(a) (the ratio of $NH_3$ to $NO_x$ is greater than 1, after 700 s). The sensor signal level cannot be interpreted in a straightforward way, as it is not clear whether excess $NO_x$ or $NH_3$ is present.(3)

In an effort to identify the cross-sensitivity of SNS, spectral analysis of the SNS signals is conducted using FFT, which computes the discrete Fourier transform (DFT) in an efficient manner.(8) In DFT, the sequence of $N$ data points $x(0), x(1),\ldots, x(N-1)$ is



(a) (b)

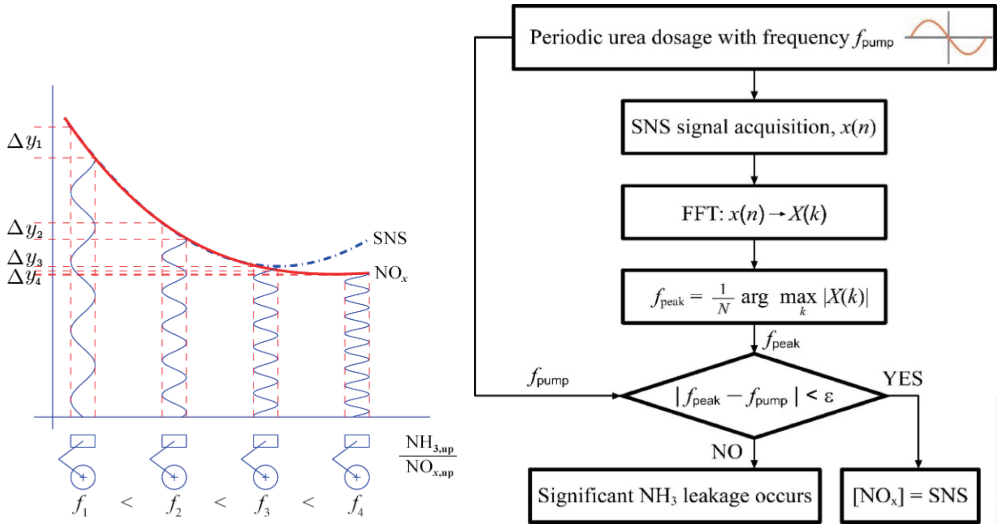
Fig. 2. (Color online) (a) Step responses of SCR at ESC mode 6 and (b) spectral analysis of NO$_x$ sensor signals.

transformed into the list of coefficients of a finite combination of complex sinusoids, ordered by their frequencies.

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j\left(\frac{2\pi}{N}\right)kn} \tag{1}$$

Figure 2(b) shows the spectra of the SNS signals at various supplied urea dosages (or motor speeds). The NO$_x$ readings at various urea dosages are all sampled at a uniform time step of 0.25 s for a sampling time of 150 s. This leads to a spectrum with a maximum frequency $f_{\max}$ of 4 Hz and a frequency resolution of 0.0067 Hz. Only the frequency range from 0 to 2 Hz of the spectra is meaningful because the Nyquist frequency of the sampled data is 2 Hz. For clarity, only the spectra from 0 to 0.5 Hz are shown in Fig. 2(b). The higher peaks of magnitude can be clearly identified in the first three subplots while the urea supply pump speeds are set to about 0.1, 0.2, and 0.3 rev/s, respectively. Obviously, the intermittent phenomena at those specific frequencies result from the periodic urea supply associated with the reciprocating motions of the motor pump. The bottom of Fig. 2(a) shows the close-up view of the NO$_x$ response when the pump speed is about 0.2 rev/s. The main frequency (about 0.2 Hz) and its corresponding magnitude can be clearly observed in Fig. 2(a). Moreover, discretization distortions (small amplitude steps) that resulted from digitization of the continuous data during data acquisition can be clearly observed. They are responsible for the higher harmonics existing in the spectra shown in Fig. 2(b). In this urea SCR system, the faster pump speeds result in higher urea dosages and thus lower $NO_x$ emissions. This monotonic trend, however, is misrepresented by the cross-sensitivity of SNS to the excess ammonia as the magnitude close to DC (lower frequency) in the last subplot in Fig. 2(b) increases significantly. The spectra in Fig. 2(b) indicate that this monotonic trend can be revealed by the magnitudes at the corresponding motor speeds.

Figure 3(a) shows the monotonic (but nonlinear) curve of $NO_x$ downstream SCR and the nonmonotonic SNS signal with respect to the dosage ratio, which is defined as the ratio of ammonia dosage $NH_{3,up}$ to the engine-out $NO_x$ concentration $NO_{x,up}$.(3) The periodic fluctuations of the ammonia dosage input and the changes in slope on the nonlinear curve for $NO_x$ concentration in Fig. 3(a) result in different oscillation magnitudes at corresponding pump speeds as shown in Fig. 2(b). In other words, the faster pump speeds ($f_1 < f_2 < f_3 < f_4$) result in lower magnitudes at the corresponding speeds ($\Delta y_1 > \Delta y_2 > \Delta y_3 > \Delta y_4$). These monotonic magnitude changes at various ammonia dosage rates have a significant implication on the application of SNS. Specifically, the amplitude of the SNS signal at a perturbed dosage frequency can be used for the direct interpretation of the true $NO_x$ emission in applications where excessive ammonia is involved.



(a) (b)

Fig. 3. (Color online) (a) Nonlinear curve of $NO_x$ downstream SCR with respect to perturbed ammonia dosage ratios and (b) flow chart for identification of cross-sensitivity of SNS to $NH_3$.

## 5. Method for Identification of Cross-Sensitivity

On the basis of the above synthesis, an algorithm is proposed to identify the cross-sensitivity of SNS to $NH_3$, as shown in the flow chart in Fig. 3(b). In this specific case, the urea dosage rate is inherently perturbed by the reciprocating motion of the crankshaft-link pump. For different types of urea pump, a periodic modulation of the urea dosage signal can be used for perturbation. The spectrum of the SNS signal is then obtained by applying FFT, and the frequency with the peak amplitude $f_{\mathrm{peak}}$ can be calculated. By comparing the frequency $f_{\mathrm{peak}}$ and the modulated pump frequency $f_{\mathrm{pump}}$, the cross-sensitivity is identified. Specifically, if the frequency $f_{\mathrm{peak}}$ is close to the modulated pump frequency $f_{\mathrm{pump}}$, the SNS measurement reveals the true $NO_x$ emission. On the other hand, if the frequency $f_{\mathrm{peak}}$ is much lower than the modulated pump frequency $f_{\mathrm{pump}}$, significant ammonia leakage is expected.

## 6. Conclusions

In an effort to identify the cross-sensitivity of the SNS to ammonia, spectral analysis of the SNS signals from an SCR system with perturbed urea dosage rate is conducted using FFT. The spectral analysis reveals that the amplitude of the SNS signal at the perturbed dosage frequency can be used for the direct interpretation of the true $NO_x$ emission in applications where ammonia is involved. In this specific case, the urea dosage is inherently perturbed by the reciprocating motion of a crankshaft-link pump. For different types of urea pump, a periodic modulation of the urea dosage signal can be used for perturbation. A comparison between the frequency with peak amplitude and the pump frequency tells when the SNS signal represents the true $NO_x$ concentration and when significant $NH_3$ leakage occurs.

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