

Smart Sensing and Decomposition of NO_x and NH_3 Components from Production NO_x Sensor Signals

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ABSTRACT

Production NO_x sensors have a strong cross-sensitivity to ammonia which limits their use for closed-loop SCR control and diagnostics since increases in sensor output can be caused by either gas component. Recently, Ammonia / NO_x Ratio (ANR) perturbation methods have been proposed for determining the dominant component in the post-SCR exhaust as part of the overall SCR control strategy, but these methods or the issue of sensor cross-sensitivity have not been critically evaluated or studied in their own right. In this paper the dynamic sensor direct- and cross-sensitivities are estimated from experimental FTIR data (after compensating for the dynamics of the gas sampling system) and compared to nominal values provided by the manufacturer. The ANR perturbation method, and the use of different input excitations are then discussed within an analytical framework, and applied to experimental data from a large diesel engine. The method successfully discriminates between NO_x and NH_3 in the post-SCR exhaust, and is extended to provide an estimate of the composition in situations where simultaneous NO_x and NH_3 emissions occur. The results are validated against the previously processed and independent FTIR data.

1. INTRODUCTION

Production zirconia-based exhaust gas sensors have found widespread applicability in automotive emission reduction systems. Heated Exhaust Gas Oxygen (HEGO) sensors and wide-range 'Universal' Exhaust Gas Oxygen (UEGO) sensors, for example, have been used for many years for three-way catalyst control in stoichiometrically operated

gasoline engines. Production NO_x sensors are also now increasingly used in diesel aftertreatment systems, and are critical to the goal of realizing the benefits of diesel fuel economy without the high NO_x emissions traditionally associated with lean or diesel combustion, [1-2]. Such sensors, however, are not ideal and may have cross-sensitivities to exhaust gas components other than those they are intended to measure. HEGO and UEGO sensors, for example, have a strong cross-sensitivity to hydrogen which can bias the operation of a closed-loop catalyst control system [3]. Likewise, NO_x sensors are known to have a strong cross-sensitivity to ammonia, which can degrade the performance of closed-loop SCR catalyst control, and potentially cause it to become unstable, [4, 5, 6, 7, 8, 9]. This cross-sensitivity arises because ammonia is oxidized to NO_x in the first sensor detection cavity, and the NO_x thus produced adds to the indicated NO_x signal output.

A typical diesel aftertreatment system is shown in figure 1. A diesel particulate filter (DPF) and diesel oxidation catalyst (DOC) are situated upstream of a selective catalytic reduction (SCR) catalyst. The composition of the exhaust gas at the inlet to the SCR is relatively well known since there is no ammonia. Sensor cross-sensitivity to different gas components is therefore not an issue at this point. The gas composition downstream of the SCR, however, depends dynamically on the reactions taking place on the catalyst surface. These reactions decompose urea, injected at the SCR inlet, into ammonia which is stored on the catalyst surface where it combines to reduce the NO_x to N_2 , [10]. The urea dosing, or Ammonia / NO_x Ratio (ANR) is controlled by the engine management system in order to avoid both tailpipe

'ammonia slip' (over-dosing), and tailpipe NO_x emissions (under-dosing). Open loop dosing strategies using map-based feedforward control have proven sufficient to meet Euro-4 and Euro-5 emissions standards, but they require extensive calibration and cannot adapt to catalyst ageing, or environmental variations. Closed-loop SCR control is therefore receiving considerable attention [4, 5, 6, 7, 8], and is considered essential to meet future legislative requirements [1,8]. However, the cross-sensitivity of production NO_x sensors, results in ambiguous feedback to the controller since both ammonia slip and tailpipe NO_x result in an increase in the post-SCR sensor signal. If ammonia slip is misinterpreted as NO_x , the controller may increase the urea dosing when in fact the opposite action is required.

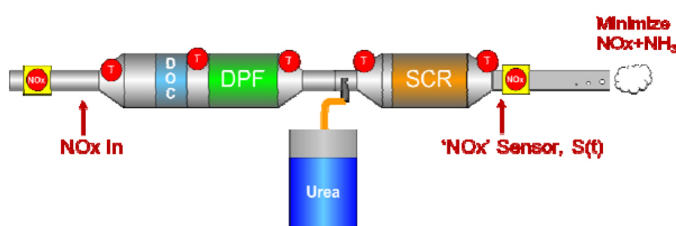


Fig. 1. Diesel Aftertreatment System

To address this issue, it is necessary to decompose / disambiguate the NO_x and NH_3 components of the sensor signal in some way. One approach is to model the behavior of the SCR to predict the outlet composition and to use an extended Kalman filter to estimate the true gas composition and sensor cross-sensitivities online, [9]. However, this approach depends on the availability of an accurate real-time dynamic model for the SCR, and as yet the method has only been applied in simulation. An alternative approach, which is investigated more fully in this paper, is to perturb the ANR and observe the resultant perturbations in the catalyst response [1,4,5]. If NO_x is the predominant output component, then a small increase in ANR will improve conversion and lead to a *decrease* in the NO_x sensor signal. However, if NH_3 is the predominant component, then a small increase in ANR will exacerbate the degree of overdosing and lead to an *increase* in NO_x sensor signal (due to ammonia cross-sensitivity). The sign of the correlation between sensed input and output perturbations is therefore indicative of the true gas composition of the post-SCR exhaust.

Though promising in concept, there is still relatively little literature on the perturbed ANR method, and the focus of the few existing papers has been on overall SCR control rather than the cross-sensitivity issue alone. Nevertheless some difference in the application of the approach can be seen. References [1,4], for example, apply step perturbations about the operating condition and observe the direction of the resulting step change in the response. Although successful results are reported, step perturbations are not persistently

exciting from a system identification perspective and may not result in consistent estimates, [11]. Furthermore, the delay as the step increment propagates through the SCR leads to an undesirable measurement delay, and the method may fail under transient conditions, [5]. By contrast, the method outlined in reference [5], employs a sinusoidal perturbation. Such inputs are persistently exciting and concentrate the excitation energy at a single frequency, resulting in an improved signal to noise ratio at that frequency. In common with the other reported applications, however, the algorithm attributes either all, or none, of the NO_x sensor output to ammonia. (In some situations, both components may be emitted simultaneously by the catalyst). The method was clearly effective as part of the overall SCR catalyst control system, but the signal decomposition was not directly validated against independent NO_x and ammonia measurement instrumentation during the experimental engine tests.

In this paper FTIR (Fourier Transform Infrared Spectrophotometer) data is used to estimate the actual sensor cross-sensitivities present in real engine data and the results are also used to provide an independent prediction of the gas composition at the SCR outlet (Section 3). A more detailed and critical evaluation of the ANR perturbation method is presented in Section 4, including an extension aimed at providing improved signal decomposition under simultaneous NO_x and NH_3 emission. The method is applied to experimental data from a large diesel engine (experimental details are found in Section 2), and the results assessed using the independent FTIR data analysis of Section 2. Finally, brief conclusions are presented in Section 5.

2. EXPERIMENTAL DETAILS

Data was recorded from a 6 cylinder 8.9 liter turbocharged Cummins engine which was coupled to the exhaust aftertreatment system depicted in [figure 1](#). The SCR catalyst was a copper / zeolite type. Production NO_x sensors were mounted at the SCR inlet and outlet points. Sample lines were also inserted at these points and connected to an FTIR analyzer situated approximately 10 meters from the engine. The flow rate was 40L/min and the temperature of the sample line was kept at 190C to avoid condensation of NH_3 . At these temperatures, soot oxidation is theoretically possible, but the practical effects are negligible due to the very low soot concentration downstream of the DPF. Prior tests also showed urea decomposition in the sample line to be negligible. A third NO_x sensor was mounted at the inlet to the FTIR and used to assess sample line delay times as discussed in section 3. The engine was loaded with an eddy-current dynamometer and exercised across a range of different operating conditions. Throughout the tests, urea dosing was controlled by the engine management system which was also used to apply the ANR perturbations required by the

decomposition algorithm where applicable. Data was recorded both through the engine management system, and a separate data acquisition system. The SCR system has relatively slow dynamics, so a sample rate of 1Hz was adequate for the current investigation.

3. DYNAMIC MEASUREMENT OF SENSOR GAS COMPONENT SENSITIVITIES

As discussed in the introduction, a production NO_x sensor responds to both NO and NO_2 , and has a strong cross-sensitivity to NH_3 . The sensor output $S(t)$ can therefore be expressed as,

$$S(t) = b_0 + b_1[NO(t)] + b_2[NO_2(t)] + b_3[NH_3(t)] \quad (1)$$

where the parameters b_i represent sensitivities to the various gas component concentrations, and where b_0 represents a possible dc offset term. The nominal values of the sensitivities b_i are provided by the manufacturer and given in the first column of [table 1](#), but the actual sensitivities may depend on operating condition, sensor location, and manufacturing tolerance. In this section, independent measurements of NO , NO_2 and NH_3 obtained from the FTIR analyzer are used to estimate the actual sensitivities evidenced by the sensor during the RMCSET cycle. Once these sensitivities are known, it is also then possible to predict the ‘true’ NO_x and NH_3 component contributions to the sensor output, and to use these results to validate any sensor signal decomposition algorithm.

It is important to note, however, that the FTIR analyzer is situated approximately 10m from the SCR and other sensors, and the long sample lines introduce a delay in the FTIR response. In the case of the FTIR NH_3 measurement, the sample lines also introduce a significant dynamic in the response due to the propensity of ammonia to ‘stick’ to the surface of the sampling system. If these effects are neglected, and nominal (rather than actual) sensitivities used to predict the sensor output, then significant errors can result (see [figure 2](#)). It is therefore necessary to model these effects in order to obtain an estimate for the ‘true’ gas composition at the SCR outlet from which the actual sensitivities can be computed.

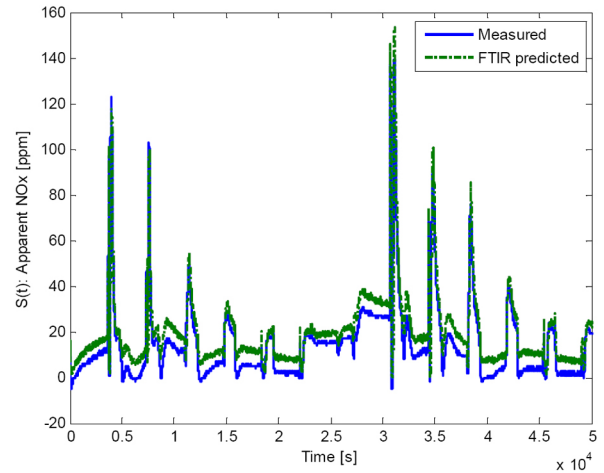


Fig. 2. Measured and FTIR-predicted sensor output $S(t)$, using nominal sensitivities and neglecting sample line dynamics

The FTIR measurements are therefore modeled according to,

$$\begin{aligned} [NO(t)]_{FTIR} &= [NO(t-d)] + c_1 \\ [NO_2(t)]_{FTIR} &= [NO_2(t-d)] + c_2 \\ b_4[NH_3(t)]_{FTIR} &= b_5[NH_3(t-k)]_{FTIR} + b_3[NH_3(t-d)] + c_3 \end{aligned} \quad (2)$$

where d represents a pure transport time delay, and constants c_i represent measurement offsets. The dynamics of the ammonia sampling system are represented as a simple first order system with coefficients b_4 , b_5 , and lag k . Inverting these relationships and substituting in (1) enables the sensor output to be predicted from the FTIR measurements according to

$$\hat{S}(t) = b_0 + [S(t)/\hat{NO}_x]_{FTIR} + [S(t)/\hat{NH}_3]_{FTIR} \quad (3)$$

where the effects of the individual dc offsets c_i are subsumed into the constant term b_0 , and where $[S(t)/\hat{NO}_x]_{FTIR}$, and $[S(t)/\hat{NH}_3]_{FTIR}$, define the predicted NO_x and NH_3 components of the sensor output according to,

$$[S(t)/\hat{NO}_x]_{FTIR} = b_1[NO(t+d)]_{FTIR} + b_2[NO_2(t+d)]_{FTIR} \quad (4)$$

$$[S(t)/\hat{NH}_3]_{FTIR} = b_4[NH_3(t+d)]_{FTIR} - b_5[NH_3(t+d-k)]_{FTIR} \quad (5)$$

Note that the steady state gain of the ammonia model (5) represents the steady state ammonia sensitivity b_3 which can therefore be computed according to,