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Fast estimation of diesel oxidation catalysts inlet gas temperature

C. Guardiola, V. Dolz, B. Pla, J. Mora*

CMT–Motores Térmicos, Universitat Politècnica de València, Valencia, Spain

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ABSTRACT

With the tightening of on-board diagnostics requirements, accuracy of sensors is essential to monitor the efficiency and ensure a proper control of the after-treatment systems. Temperature sensors are commonly used in the exhaust line at the diesel oxidation catalyst-inlet of turbocharged diesel engines for control and diagnosis of the after-treatment system. In particular, negative temperature constant sensors are used for this purpose. However, due to the necessary robustness that on-board sensors must fulfil, thermal inertia causes significant differences during engine transient operating conditions in temperature measurements. A Kalman filter is proposed in this paper for the on-line dynamic estimation of the catalyst-inlet temperature, which combines a slow but accurate measurement of the on-board temperature sensor with a fast but drifted temperature model. A fast research-grade thermocouple is used as reference of the actual exhaust gas temperature as well as a frequency analysis is performed in order to calibrate the model and analyse results of the signal reconstruction. Results of the algorithm are then successfully proved in experimental transient tests and typical European approval test cycles.

1. Introduction

Temperature plays a key role in the efficiency of after-treatment systems: Diesel Oxidation Catalysts (DOC) have an activation threshold, referred as Light-Off Temperature (LOT), which has to be overcome to oxidise HC, CO and NO species (Sutjiono, Tayal, Zhou, & Meckl, 2013); Selective Catalytic Reduction (SCR) has to operate in a temperature band to ensure high conversion efficiency (Nova & Tronconi, 2014); and Diesel Particulate Filters (DPF) regeneration needs an accurate closed loop control of the temperature (Frobert, Creff, Lepreux, Schmidt, & Raux, 2009; Kim, Nieuwstadt, Stewart, & Pekar, 2014). As DOCs efficiency affects the performance of the rest of after-treatment systems (Johnson, 2010), two temperature sensors have been traditionally used for control and On-Board Diagnostics (OBD) purposes (Guardiola, Pla, Mora, & Lefebvre, 2015; Nieuwstadt, Upadhyay, & Yuan, 2005; Riegel, Neumann, & Wiedenmann, 2002). One is placed at the DOC inlet and the other at the outlet.

Increasing emissions standards for Diesel engines (C. Regulation, 2007, 2012) makes manufacturers struggle to find an after-treatment system configuration which optimizes the trade-off between low cost, low emissions, low fuel consumption and robustness (Johnson, 2014). Temperature sensors must be robust enough to stand up to the vehicle's life (El-Awar, Geer, Krellner, Straub, &Eriksson,Erik). These robustness requirements are satisfied by increasing the sensor mass, whose thermal inertia implies filtering the exhaust gas temperature measurements. Negative Temperature Constant (NTC) sensors are the traditional sensors used in production vehicles for measuring exhaust gas temperature (Mollenhauer & Tschöke, 2010).

Fig. 1 represents the DOC-inlet temperature evolution during a temporal window of the New European Driving Cycle (NEDC). T_{TC} represents the signal provided by a thin thermocouple (TC), whilst T_{NTC} represents the signal of the NTC sensor. It can be observed how the NTC sensor is not able to properly capture the temperature dynamics. Peak errors between the NTC sensor measurement and the thermocouple are over ±50 °C, as shown in the bottom plot of Fig. 1. If these differences occur near the LOT of the DOC, which is around 200 °C (Schultz & Meckl, 2012), as it happens in Fig. 1, a DOC model using the NTC measurement as input would not estimate any oxidation, which would lead to undesired errors in the DOC efficiency monitoring and diagnosis. Authors like Kar, Roberts, Stone, Oldfield, and French (2004) and Kee et al. (2006) addressed solutions to improve temperature measurements during transient conditions by a reconstruction technique based on applying an energy balance to the heat transfer around two thermocouples at the same place. However, on-board limitations do not allow the use of two temperature sensors.

As it happens with temperature measurements, concentration

* Corresponding author.
E-mail addresses: carguaga@mot.upv.es (C. Guardiola), vidolrui@mot.upv.es (V. Dolz), benplamo@mot.upv.es (B. Pla), jamopre1@mot.upv.es (J. Mora).

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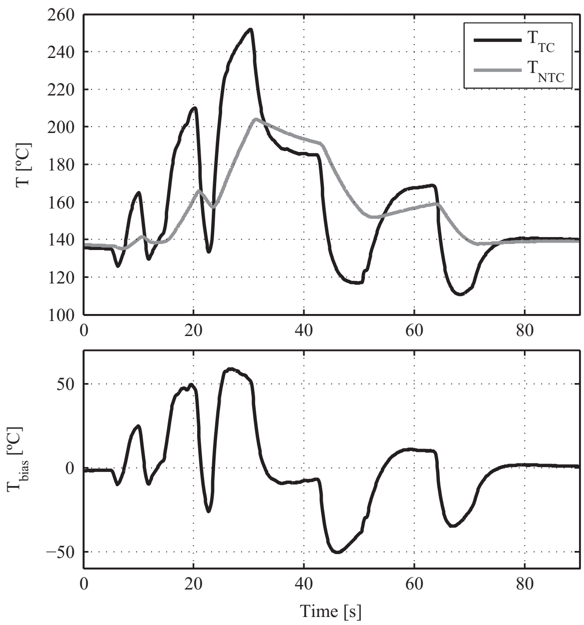

Fig. 1. *Top plot*: temperature measurements during a time window of a NEDC. *Bottom plot*: $T_{TC}-T_{NTC}$ during the time window.

sensors are not fast enough to measure exhaust gas composition in transient conditions. The contribution of the transient emission peaks during the standardized test cycles becomes in an important fraction of the cumulative total emissions (Alberer & Re, 2009). Therefore, the problem of the dynamic response of concentration sensors has been addressed during last years. For instance, techniques like the combination of sensors and models in order to rebuild a signal are being commonly used in recent years in automotive industry (Del Re, Allgöwer, Glielmo, Guardiola, & Kolmanovsky, 2010). Authors like Alberer (2012) and Guardiola, Climent, Pla, and Blanco-Rodriguez (2015) have researched diesel engine exhaust O_2 and NO_x concentrations with special focus in transient conditions through the use of oxygen (UEGO) and NO_x sensors, which are widespread in the state of the art vehicles. These authors have determined a wide methodology of data fusion from sensors and models by using filtering techniques in order to have fast estimations of exhaust gas concentrations.

This work addresses the trade-off between robustness and dynamic response of on-board temperature sensors. In particular, the goal is to have a good transient response using a robust NTC sensor. To this aim, the NTC sensor provides a reliable but slow measurement, while a non-necessarily precise but fast model, based on real-time ECU engine variables, provides dynamic information. The NTC sensor is located upstream the after-treatment systems while the fast model is based on a look-up table depending on injected fuel quantity and engine speed.

While this paper is focused on the DOC for being the first after-treatment system placed in the exhaust line, this methodology could be also applicable to other exhaust line configurations with different after-treatment platforms. In fact, the fast temperature estimation provides a better measurement of the thermal energy entering in the system at the location of the NTC sensor.

The paper is structured as follows. Section 2 describes the experimental set-up. Section 3 explores engine dynamics in order to select suitable signals for the fast temperature model. Section 4 identifies the coefficients of the modelled systems. Section 5 contains the description of the used filtering technique and its calibration procedures. Section 6 contains results of the temperature estimation. Finally, Section 7 contains the conclusions.

2. Experimental set-up

Experimental tests were carried out in a Euro IV direct injection diesel engine, installed on an engine test bench. Characteristics of the engine, mainly composed of a high pressure common-rail fuel injection system, an Exhaust Gas Recirculation (EGR) system and a Variable Geometry Turbine (VGT), are described in Table 1. The DOC was the only after-treatment system placed in the exhaust line. The pressure drop originated by a DPF and an SCR was generated by a back pressure valve. Experiments shown in this article consist of dynamic cycles and load steps that allow characterising the system dynamics.

As shown in Fig. 2, the main sensors used in this work were a thin thermocouple, an NTC sensor placed at the DOC-inlet and other signals available from the ECU. The thermocouple is a *K* type sensor with naked wires of 0.5 mm width and 3 m long (model *TC 1WC-K-3m*), able to measure in a range of temperatures from 0 °C to 1100 °C. The fast response was obtained at the cost of having to replace the sensor several times during experimentation due to its low robustness. Additionally, a thermocouple of 1.5 mm width, placed between the turbine and the engine block, was also used. Both thermocouples were connected to a PUMA measuring system with an acquisition frequency of 10 Hz.

The NTC sensor is a Denso unit, able to measure in a range of temperatures from −30 °C to 1000 °C with standard responsiveness, which error is ±7 °C at mid temperatures and ±10 °C at low and very high temperatures, according to the sensor manufacturer. Manufacturers of both sensors do not give information about response time. It was connected to a real time National Instruments PXI with an acquisition frequency of 1000 Hz. Note that the NTC sensor was placed in the DOC canning itself, in front of the catalyst monolith, where it would be placed in on-board applications, while the fast thermocouple was connected in the exhaust line, as close as possible to the DOC-inlet.

An engine speed sensor and a hot film flow-meter were also used and connected to the engine ECU, which also provided the estimated injected fuel. The ECU signals had an acquisition frequency of 100 Hz. A summary of the signals and variables used throughout the article can be found in Table 2.

Table 1
Engine characteristics.

Stroke (*S*)	88 mm
Bore (*D*)	85 mm
S/*D*	1.036
Number of cylinders (*z*)	4
Displacement	1997 cm^3
Turbocharging system	VGT
Valves by cylinder	4
Maximum power	120 kW @3750 rpm
Compression ratio	16:1

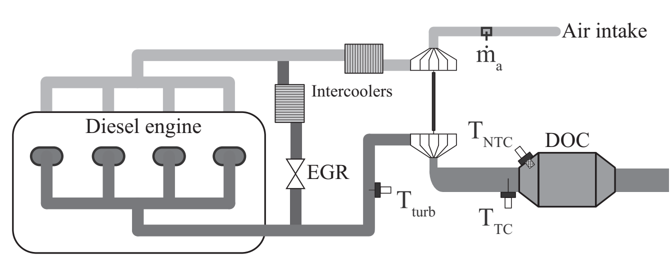

Fig. 2. Engine air path and on-purpose sensors layout at the test bench.