Model-based Control Design of a Diesel Oxidation Catalyst

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Abstract:
This paper proposes a control strategy for a Diesel Oxidation Catalyst (DOC) which is grounded on a one-dimensional distributed parameter model. This first principles model for the propagation of the temperature variations accounts for spatially distributed heat generation (due to oxidation of reductants). As is discussed, heat generation can be regarded as equivalent inlet temperature variations. This fact is supported by experimental results. By nature, DOC outlet temperature response includes long and time-varying delays. An approximation of the proposed model allows to derive delays analytically, and can be used to schedule control parameters. As a consequence, it is easy to design several standard controllers for the DOC outlet temperature which account for the effects of the inlet temperature (disturbance) and the reductant (control). In this paper, simulation results are presented for a PI, a PID, and a Smith predictor. Interestingly, the three controllers use solely parameters determined from the previous analysis and do not need any extra tuning parameter. The strategies are tested on a standard NEDC driving cycle in simulation. It appears that, among these standard strategies, the DOC partial derivative equations can be efficiently controlled using the presented Smith predictor.

Keywords: Automotive exhaust aftertreatment systems, Diesel oxidation catalyst, Distributed-parameter systems, Boundary control, Control applications

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1. INTRODUCTION

1.1 Motivation

On most new Diesel vehicles, increasing requirements regarding particulate matter emissions (Ecopoint Inc., 2008) are satisfied using a Diesel Particulate Filter (DPF). This filter, located in the vehicle exhaust line, stores particulate matter until it is burnt in an active regeneration process (Bisset, 1984). During this phase, DPFs behave like potentially unstable reactors (Achour, 2001), and their inlet temperature must be carefully controlled to prevent filter runaway.

In most current aftertreatment architectures (Koltsakis and Stamatelos, 1997), a Diesel Oxidation Catalyst (DOC) is placed upstream the DPF in the vehicle exhaust line. To increase the DPF inlet temperature, reductant is oxidized in the DOC, which, in turn, increases its outlet temperature. The DOC also conveys, up to some heat losses, its inlet enthalpy flow: in other words, inlet temperature variations propagate through the DOC.

A DOC is a chemical system difficult to control. Classical models are usually composed of a dozen of coupled partial differential equations (PDEs) (Depcik and Assanis, 2005), which complexify the development of model-based control laws. Experimentally, it can be observed that a step change on the inlet temperature propagates to the output of the system with long response times (Oh and Cavendish, 1982). Depending on the engine outlet gas flow rate, these response times significantly vary: they roughly decrease by a factor of 10 from idle speed to full load. Strategies that are commonly used to deal with this problem rely on look-up tables, which, in practice, are difficult and time-consuming to calibrate.

The purpose of this paper is to propose implementable control laws tuned according to a simple control-oriented model. This approach allows faster calibration. To achieve this goal, simplification of the above-mentioned classical models is needed.

After a presentation of a mathematical formulation of the control problem in the second part of this introduction, we show in section 2 how the model proposed in Lepreux et al. (2008), initially using inlet temperature as control variable, can be used to accurately describe actual cases of engineering interest, i.e. cases where the reductant flow is the control variable. Then, we show in section 3 how to approximate the model. Finally, in section 4, this approximation is used to tune several classic controllers. Simulation results serve as comparisons and stress that a Smith predictor tuned using the proposed methodology represents an efficient controller for the DOC.

1.2 Problem Formulation

It has been shown in Lepreux et al. (2008) that, considering only inlet temperature variations and neglecting chemical reactions, a DOC thermal behavior can be accurately described by the following model

$$\begin{cases} \dfrac{\partial T}{\partial t}(z,t) + v\dfrac{\partial T}{\partial z}(z,t) \;=\; -k_1(T(z,t) - T_s(z,t)) \\[2ex] \qquad\qquad\quad \dfrac{\partial T_s}{\partial t}(z,t) \;=\; k_2(T(z,t) - T_s(z,t)) \end{cases} \tag{1}$$

with boundary control

$$T(z=0,t) = T^{in}(t)$$

where T and T_s are respectively gas and solid temperature variations about steady state, v is the channel gas speed which can be derived from mass flow, parameters (k_1,k_2) can be either derived from usual correlation (Osizik, 1977) or identified from experimental data (Lepreux et al., 2008). The output of the system is the outlet gas temperature

$$T^{out}(t) = T(z=L,t)$$

Considering steady-state initial conditions

$$\begin{cases} T(z,0) = 0 \\ T_s(z,0) = 0 \end{cases}$$

system (1) yields the transfer function

$$\hat{T}(z,s) = \hat{T}^{in}(s)\exp\left(-\frac{z}{v}s - \frac{k_1 z}{v} + \frac{m(z)}{s+k_2}\right) \tag{2}$$

where $m(z) = k_1 k_2 z/v$, $\hat{x}$ is the Laplace transform of x, and s is the Laplace variable. We denote Υ the Heaviside function and I_i the modified Bessel functions of the first kind. The system step response is

$$\begin{gathered} T(z,t) = \Upsilon(t - \frac{z}{v})\exp\left(-\frac{k_1 z}{v}\right)\times \\ \left[1 + \int_0^{t-z/v} \exp\left(-k_2\tau\right)\sqrt{\frac{m(z)}{\tau}}\mathrm{I}_1(2\sqrt{m(z)\tau})d\tau\right] \end{gathered} \tag{3}$$

For an easy evaluation of (3), a formulation using power series expansion is given in Lepreux et al. (2008).

2. REDUCTANT FLOW AS CONTROL VARIABLE

It is shown in Lepreux et al. (2008) that experimentally measured step responses of the system can be identified to model (1) with good quality. However, this representation might seem a bit simplistic in view of real applications since inlet temperature variations are difficult to control and cannot be used directly as control variable. In practice, reductants (hydrocarbons HC) are injected at the inlet of the DOC. They are oxidized on the catalyst and, consequently, increase the DOC temperature. In this section, we compute HC step response and compare it against T^{in} step response.

2.1 Model with Heat Source

During the regeneration process, the DOC is working at high temperatures, which ensures that the rate of conversion of reductants is high. Moreover, large quantity of HC is injected to generate exothermicity. Consequently, the inlet fraction of this reductant is very important, and its effect is dominating over other species'. By construction, a DOC is designed to yield large heat and mass transfer. These transfers are very effective, and the time scales implying the thermal phenomena are much lower than the ones implying chemical reactions. For the experiments presented in § 2.3 gas flows through the DOC approximatively 1000 times faster than the outlet temperature response time. For these reasons, to model the DOC thermal behavior, we propose to encompass all the chemical reactions in a "source term Ψ", leading to the following model

$$\begin{cases} \dfrac{\partial T}{\partial t}(z,t) \;+\; v\dfrac{\partial T}{\partial z}(z,t) = -k_1\left(T(z,t) - T_s(z,t)\right) \\[2ex] \dfrac{\partial T_s}{\partial t}(z,t) \;=\; k_2\left(T(z,t) - T_s(z,t)\right) + \Psi(z,t) \end{cases} \tag{4}$$

where $\Psi(z,t)$ is the control variable and $T^{in}(t)$ is regarded as a disturbance. Ψ includes the sum of the enthalpies of the various reactions taking place inside the DOC. We formulate a strong simplifying assumption. Namely, we assume that the rate of reaction is independent of the species concentration. Further, we also assume that it is independent of the temperature. In other words, Ψ is constant over some spatial interval. These assumptions are supported by experimental identification results of § 2.3. Over the whole range of considered operating conditions, the obtained results are quite accurate. We note L_c the length of the portion of the DOC where the enthalpy of reaction is released (see Fig. 1). Formally, we consider the following discontinuous function

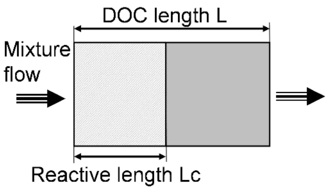

Fig. 1. HC reaction zone

$$\begin{cases} \hat{\Psi}(z,s) = \alpha/s, & 0 \le z \le L_c \\ \hat{\Psi}(z,s) = 0, & L_c < z \le L \end{cases} \tag{5}$$

Then, several steps of operational calculus on (4) lead to

$$\hat{T}(L_c,s) = \hat{T}^{in}\exp\left(-\hat{A}(s)L_c\right) + \frac{\hat{B}(s)}{\hat{A}(s)}\left(1 - \exp\left(-\hat{A}(s)L_c\right)\right) \tag{6}$$

with $\hat{A}(s) = \dfrac{1}{v}\left(s + k_1 - \dfrac{k_1 k_2}{s+k_2}\right)$ and $\hat{B}(s) = \dfrac{k_1}{v}\dfrac{\alpha}{s(s+k_2)}$. In (6), the first term corresponds to the transfer from the inlet temperature $T^{in}(t)$ to the output $T(L_c,t)$, while the second term corresponds to the transfer from the input signal $\hat{\Psi}$ defined in (5) to the output $T(L_c,t)$. The linearity of the two effects will be used to study these phenomena separately in our control strategy. Further, for $z > L_c$, equation (4) gives $\hat{T}(z,s) = \hat{T}(L_c,s)\exp\left(-\hat{A}(z-L_c)\right)$ and, we get

$$\begin{aligned} \hat{T}(z,s) &= \hat{T}^{in}\exp\left(-\hat{A}z\right) - \frac{\hat{B}}{\hat{A}}\exp\left(-\hat{A}z\right) \\ &\quad + \frac{\hat{B}}{\hat{A}}\exp\left(-\hat{A}(z-L_c)\right) \end{aligned} \tag{7}$$

Eventually, by an inverse Laplace transform of (7) (Abramowitz and Stegun, 1965), one obtains the reductant step response

$$\begin{aligned} T(z,t) &= \Upsilon\left(t - z/v\right)\exp\left(-\frac{k_1 z}{v}\right)M(z,t-z/v) \\ &\quad - \Upsilon\left(t - z/v\right)\exp\left(-\frac{k_1 z}{v}\right)F(z,t-z/v) \\ &\quad + \Upsilon\left(t - z/v\right)\exp\left(-\frac{k_1 z}{v}\right)F(z-L_c,t-z/v) \end{aligned} \tag{8}$$

where