

Warm-up Strategy for a Diesel Oxidation Catalyst

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Abstract—This paper proposes a warm-up strategy for a Diesel Oxidation Catalyst (DOC) which is grounded on a simple distributed parameter model. This first principles model of the propagation of the temperature variations accounts for spatially distributed heat generation (due to chemical reactions). We show that heat generation can be regarded as inlet temperature variations. This fact is supported by experimental results. As a consequence, a simple warm-up strategy can be developed. It allows to decrease the DOC response time using pulse input signals. The parameters of the proposed warm-up strategy are exhaustively studied. We show that, to achieve good performance, the strategy need not include more than two pulses and that the pulse magnitude need not be greater than three times the desired final magnitude.

I. INTRODUCTION

A. Motivation

On most new Diesel vehicles, increasing requirements regarding particulate matter emissions [1] are satisfied using a Diesel Particulate Filter (DPF). This filter, located in the vehicle exhaust line, stores particulate matter until it is burnt in a regeneration process [2]. During this phase, DPFs behave like potentially unstable reactors [3], and their inlet temperature must be carefully controlled to prevent filter runaway.

In most aftertreatment architectures [4], 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.

From a dynamical system standpoint, the amount of reductant is a control variable, while the DOC inlet temperature can be regarded as a disturbance.

A DOC is a chemical system difficult to control. Classical models are usually composed of a dozen of coupled PDEs [5], 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 [6]. 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. We focus on the slowest responses, that are the

most difficult to control. Strategies that are commonly used to deal with this problem rely on look-up tables, which, in practice, are difficult (and tedious) to calibrate.

This paper comes as a follow up of our previous contribution [7]. In this last paper, it was shown that using pulse control signals could significantly reduce the DOC outlet temperature response time while preventing overshoot. The purpose of the current paper is twofold. First, we show how the model proposed in [7], 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 use this new control variable to experimentally validate the warm-up strategy presented in [7] on a DOC testbench.

After a presentation of a theoretical formulation of the problem in the second part of this introduction, recalling main results of [7], we show in Section II how to approximate a model with reductant flow as control variable by a model with inlet temperature as control variable. Then, in Section III we present results of the proposed warm-up strategy obtained on DOC testbench. Finally, in Section IV, we make an exhaustive study of the considered pulse input signals parameters and show how they can be chosen in view of real application.

B. Problem Formulation

It has been shown in [7] that, considering only inlet temperature variations and neglecting chemical reactions, a DOC thermal behavior can be accurately described by the following model

$$\begin{cases} \frac{\partial T}{\partial t}(z, t) + v \frac{\partial T}{\partial z}(z, t) &= -k_1(T(z, t) - T_s(z, t)) \\ \frac{\partial T_s}{\partial t}(z, t) &= k_2(T(z, t) - T_s(z, t)) \end{cases} \quad (1)$$

with boundary control

$$T(z = 0, t) = T^{in}(t) \quad (2)$$

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 [8] or identified from experimental data [7]. The output of the system is the outlet gas temperature

$$T^{out}(t) = T(z = L, t) \quad (3)$$

Considering steady-state initial conditions

$$\begin{cases} T(z, 0) = 0 \\ T_s(z, 0) = 0 \end{cases} \quad (4)$$

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system (1) yields the transfer function

$$\hat{T}(z, s) = \hat{T}^{in}(s) \exp\left(-\frac{z}{v}s - \frac{k_1 z}{v} + \frac{m}{s + k_2}\right) \quad (5)$$

where $m = k_1 k_2 z / v$, \hat{x} is the Laplace transform of x , and s is the Laplace variable. We note Υ the Heaviside function. The system step response is

$$T(z, t) = \Upsilon\left(t - \frac{z}{v}\right) \exp\left(-\frac{k_1 z}{v}\right) \times \left[1 + \int_0^{t-z/v} \exp(-k_2 \tau) \sqrt{\frac{m}{\tau}} I_1(2\sqrt{m\tau}) d\tau\right] \quad (6)$$

The main result of [7] consists of a warm-up strategy for a

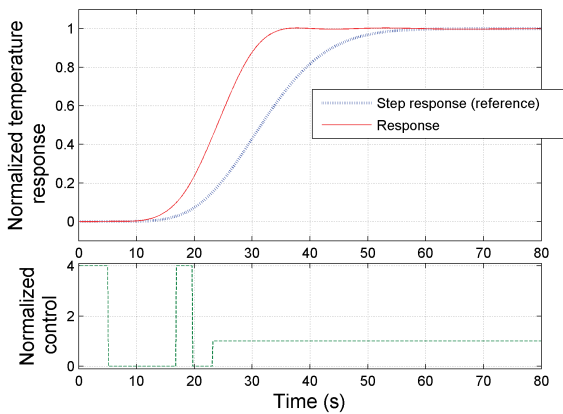


Fig. 1: Optimized control using pulse input signals and accelerated response of the DOC

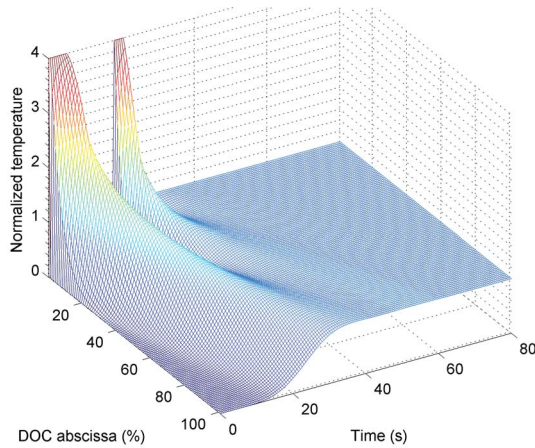


Fig. 2: Spatially-distributed temperature evolution

DOC. An example of result obtained in simulation is reported in Fig. 1 and in Fig. 2. The use of pulse control signals significantly accelerates the DOC response compared to its step response.

II. APPROXIMATING REDUCTANT RESPONSE BY INLET TEMPERATURE'S

It is shown in [7] that experimentally measured step responses of the system can be identified to model (1) with

excellent quality. However, inlet temperature variations are difficult to control and cannot be used directly as control variable. In practice, reductants (HC) are injected at the inlet of the DOC. They are oxidized on the catalyst and, consequently, increases the DOC temperature. In this section, we compute HC step response and compare it against T^{in} step response.

A. Reduction of Model with 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. For the experiments presented in Section III, gas flows through the DOC in approximately 1/10 s, the response times are about 100 s, and the DOC conversion rate is close to 100%. These transfers are very effective, and the time scales implying the thermal phenomena are much lower than the ones implying chemical reactions. 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

$$\begin{cases} \frac{\partial T}{\partial t}(z, t) + v \frac{\partial T}{\partial z}(z, t) = -k_1 (T(z, t) - T_s(z, t)) \\ \frac{\partial T_s}{\partial t}(z, t) = k_2 (T(z, t) - T_s(z, t)) + \Psi(z, t) \end{cases} \quad (7)$$

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 space interval. These assumptions are supported by experimental identification results. 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 combustion takes place (see Fig. 3). Formally, we consider

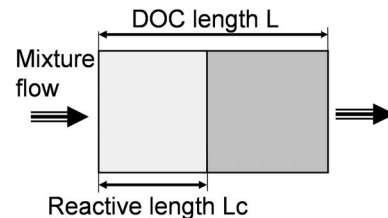


Fig. 3: HC reaction zone

the following discontinuous function

$$\begin{cases} \hat{\Psi}(z, s) = \alpha/s, & 0 \leq z \leq L_c \\ \hat{\Psi}(z, s) = 0, & L_c < z \leq L \end{cases} \quad (8)$$

Then, several steps of operational calculus on (7) lead to

$$\hat{T}(L_c, s) = \hat{T}^{in} \exp(-\hat{A}L_c) + \frac{\hat{B}}{\hat{A}} \left(1 - \exp(-\hat{A}L_c)\right) \quad (9)$$

with

$$\begin{cases} \hat{A}(s) = \frac{1}{v} \left(s + k_1 - \frac{k_1 k_2}{s + k_2}\right) \\ \hat{B}(s) = \frac{k_1}{v} \frac{\alpha}{s(s + k_2)} \end{cases} \quad (10)$$

Further, for $z > L_c$, equation (7) can be solved with $\Psi = 0$ and $T(L_c, s)$ as boundary condition. This leads to

$$\hat{T}(z, s) = \hat{T}(L_c, s) \exp(-\hat{A}(z - L_c)) \quad (11)$$

and, we get

$$\begin{aligned} \hat{T}(z, s) = & \hat{T}^{in} \exp(-\hat{A}z) - \frac{\hat{B}}{\hat{A}} \exp(-\hat{A}z) \\ & + \frac{\hat{B}}{\hat{A}} \exp(-\hat{A}(z - L_c)) \end{aligned} \quad (12)$$

Eventually, by an inverse Laplace transform of (12) [9] [10] [11], one obtains the reductant step response (13), including T^{in} effects

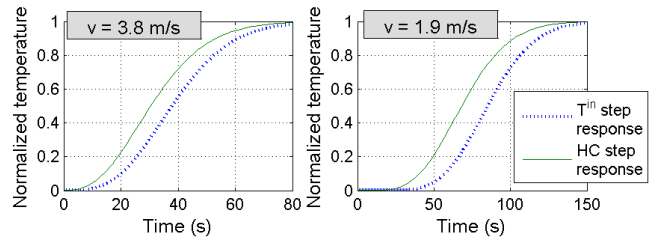
$$\begin{cases} T(z, t) = \Upsilon(t - z/v) \exp\left(-\frac{k_1 z}{v}\right) Y(z, t - z/v) \\ \quad - \Upsilon(t - z/v) \exp\left(-\frac{k_1 z}{v}\right) F(z, t - z/v) \\ \quad + \Upsilon(t - z/v) \exp\left(-\frac{k_1 z}{v}\right) F(z - L_c, t - z/v) \\ Y(t) = T^{in}(t) \\ \quad + \int_0^t \exp(-k_2 \tau) \sqrt{\frac{m(z)}{\tau}} I_1(2\sqrt{m(z)\tau}) T^{in}(t - \tau) d\tau \\ F(t) = g(t) \\ \quad + \int_0^t \exp(-k_2 \tau) \sqrt{\frac{m(z)}{\tau}} I_1(2\sqrt{m(z)\tau}) g(t - \tau) d\tau \\ g(t) = \frac{k_1 \alpha}{k_1 + k_2} t - \frac{k_1 \alpha}{(k_1 + k_2)^2} (1 - \exp(-(k_1 + k_2)t)) \end{cases} \quad (13)$$

Considering $T^{in}(t) = \Upsilon(t)$, the static gain G can be computed using (12)

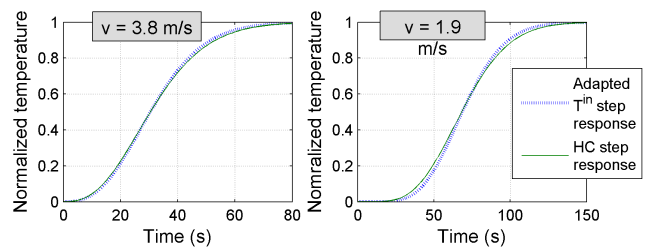
$$\begin{aligned} G &= \lim_{t \rightarrow \infty} T(t) = \lim_{s \rightarrow 0} s \hat{T}(s) \\ &= \lim_{s \rightarrow 0} \left[\hat{T}^{in} + s \frac{\hat{B}}{\hat{A}} \left(1 - \hat{A}(z - L_c)\right) - s \frac{\hat{B}}{\hat{A}} \left(1 - \hat{A}z\right) \right] \\ &= T^{in} + \frac{k_1 \alpha L_c}{k_2 v} \end{aligned} \quad (14)$$

This last formula is useful during the identification and normalization process in the rest of this paper. In practice, it is possible to link α , L_c , the current HC conversion efficiency and the amount of injected reductants (itself linked to the injector energizing time): at given (identified) L_c , α can be seen as the control variable.

In Fig. 4a, it is shown that the overall shape of the reductant step response, computed with (13), is very similar to the T^{in} step response (6). This similarity suggests that



(a) Comparison between HC step response and T^{in} step response. Analytic results obtained respectively from (13) and (6).



(b) Comparison between HC step response (model with source) and adapted T^{in} step response (model with no source)

Fig. 4: HC step response approximation in various operating conditions

it is possible to approximate HC step response by T^{in} step response at the expense of an additional identification procedure. We show in Fig. 4b that it suffices to adapt the DOC length, using the model with no source (1), to get results very close to the ones obtained with the model with source (7). In other words, generating enthalpy by HC is quite equivalent to generating enthalpy by T^{in} with a DOC having a shorter length.

B. Experimental model validation

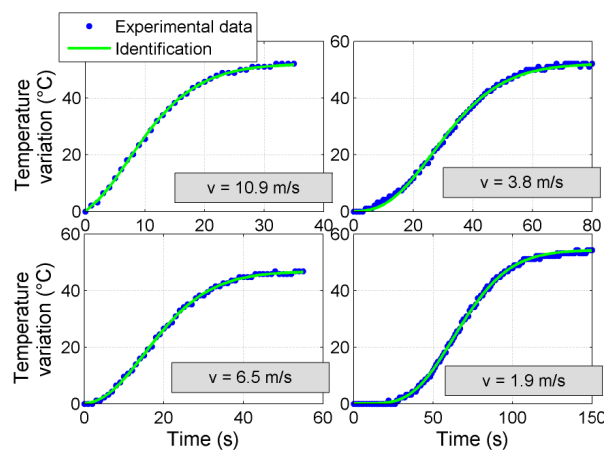


Fig. 5: Experimental HC step response identified to T^{in} model (1) in various operating conditions

As we stressed it in the previous discussion, considering an additional model adaptation of parameters, model (1) and model (7) yield pretty similar results. In Fig. 5, we present experimental HC step responses in various operating conditions. These responses are fitted by the T^{in} step

response (6) corresponding to the model with no source (1). The steady state value depends on the injected amount of HC and has no consequence on the identification results of the dynamics. It is shown that the model with no source kindly fits experimental data, usually described using a source term.

III. EXPERIMENTAL VALIDATION OF WARM-UP STRATEGY

Once the parameter identification mentioned in Section II has been performed, the model can be used to determine an optimal control law. Following [7], we restrict ourselves to a limited number of pulse input signals and formulate a constrained optimization problem. The degrees of freedom are the number of pulses n and the choice of the pulse magnitude. Two experimental cases are studied. Both consider $n = 2$, because it is found in Section IV that it provides good performance. Also, very low gas speed is used for experiments, so that responses are slow and the performance of the proposed method appears unambiguously. In the first case studied here, the pulse magnitude is set twice as high as the final step value ($M = 2$); whereas in the second case, it is set three times as high as the final step value ($M = 3$). These restrictive choices are consistent with experimental constraints. After a brief presentation of the experimental setup in Subsection III-A, we present experimental results obtained for outlet temperature in Subsection III-B. Then, in Subsection III-C, we investigate the behavior of the intra-catalyst temperature.

A. Experimental Setup

Our experimental setup is as follows. The DOC is located in a 2.2-L 4-cylinder Diesel engine exhaust line. The OEM ECU is fully bypassed. The engine is used to control the air flow and the DOC inlet temperature. They are roughly constant during the tests. Reductant flow is controlled by an additional injector located right upstream the turbine. Temperature is measured at three different locations (as presented in Fig. 6).

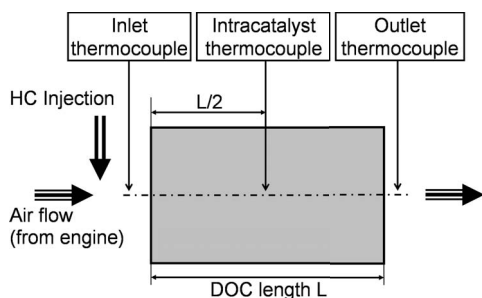


Fig. 6: Experimental setup

B. Outlet Temperature

Fig. 7 shows several optimized control laws and the corresponding system responses with $M = 2$. The first pulse occurs at $t = 0$. Step response is plotted for comparisons. It clearly appears that the proposed strategies significantly shorten the rise time while keeping oscillations about final

values very small. It is shown how oscillations appear when pulses get more spaced. This stresses that the choice of pulse switch times allows to cancel any potential oscillations. Fig. 8 show similar results with $M = 3$. In this last case,

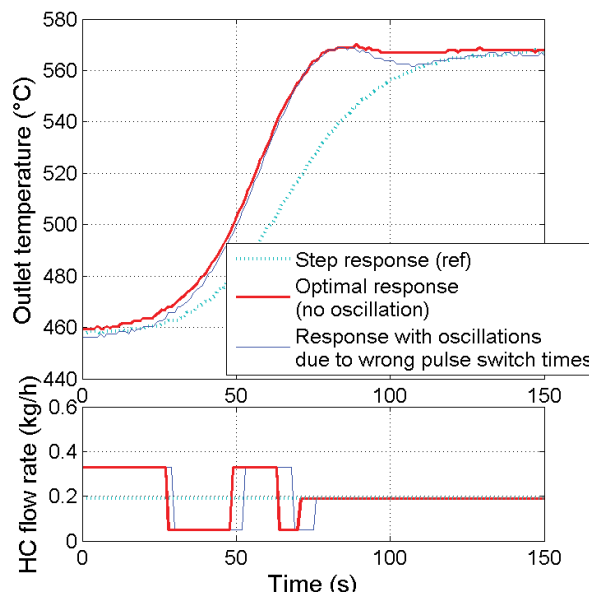


Fig. 7: Outlet temperatures and controls $M=2$ (experimental data)

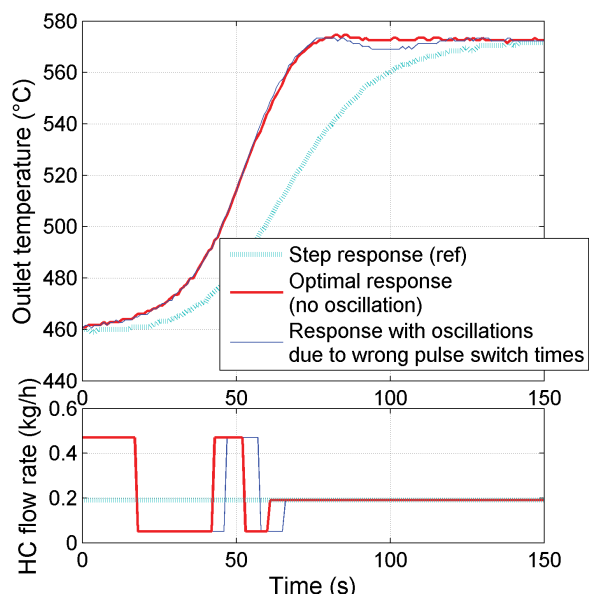


Fig. 8: Outlet temperatures and controls $M=3$ (experimental data)

the 95%-rise time (time from 0% of the step size to 95% of the step size) is reduced by a factor of 37%.

C. Intra-catalyst Temperature

As detailed in Subsection III-A, the intra-catalyst temperature has also been measured. It is not a control objective, but it is instructive to examine how its variations are captured

by the model. This shows how sounded is the simplifying assumption about the oxidation kinetics. An example of experimental results is presented in Fig. 9 for both the cases $M = 2$ and $M = 3$. Oscillations are clearly visible and

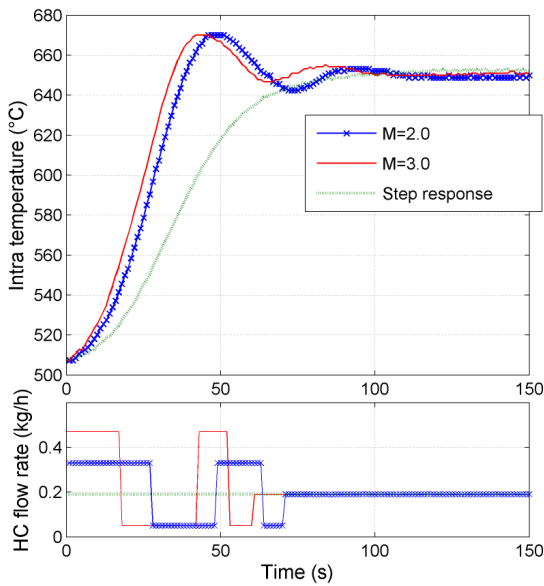


Fig. 9: Intra-catalyst temperature (experimental data)

give a representation of spatial evolution of boundary pulses: they produce large oscillations near the inlet that gradually fade out at the outlet, as described in simulation in Fig. 2. This phenomenon is well captured by our models. We select an experimental result that has no outlet oscillations and we apply the corresponding boundary control to model (7). In Fig. 10 we present results of simulation and experimental

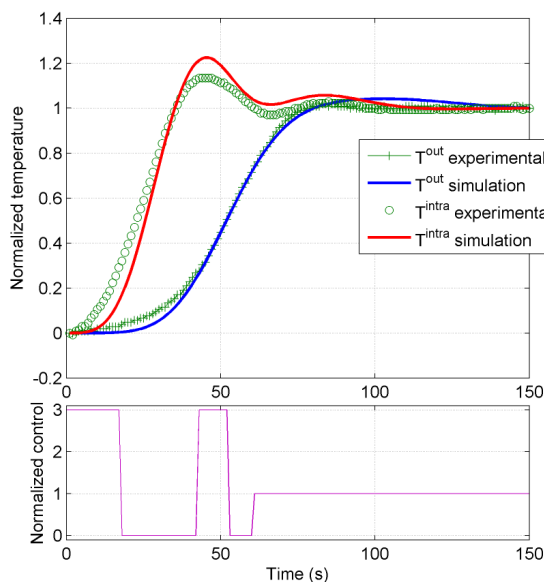


Fig. 10: Pulse control signals responses (intra-catalyst and outlet temperatures) applied to a model with source (simulation and experimental data)

data for both intra-catalyst temperature (at $z = L/2$) and

outlet temperature (at $z = L$). Temperatures are normalized for easier comparison. We notice that simulated intra-catalyst temperature oscillations match closely the experimental data, although simulated temperature is slightly higher. Globally, dynamics are captured for the intra-catalyst temperature and for the outlet temperature as well. Although all phenomena are not included in this model (diffusion, thermal losses, ...), the essential features of the DOC thermal dynamics appears to be well captured. This point stresses the relevance of the proposed model (7).

IV. CHOICE OF STEP INPUTS PARAMETERS

A. Choice of Pulse Magnitude M

It is found in [7] that two different control strategies can lead to very similar responses. In [7], control laws were obtained using different methods. On the contrary, temperature responses corresponding to these controls are quite similar. In Section III, the two control laws are obtained by the same method but with different control magnitudes M . Once again, the obtained temperature responses are very similar whereas control laws are largely different. This effect is clearly shown in Fig. 11 where experimental cases for $M = 2$ and $M = 3$ are reported. Temperatures are normalized for direct comparison. Temperature response in the case $M = 3$ is a bit faster than in the case $M = 2$. In simulations presented in Fig. 12, we validate this fact for

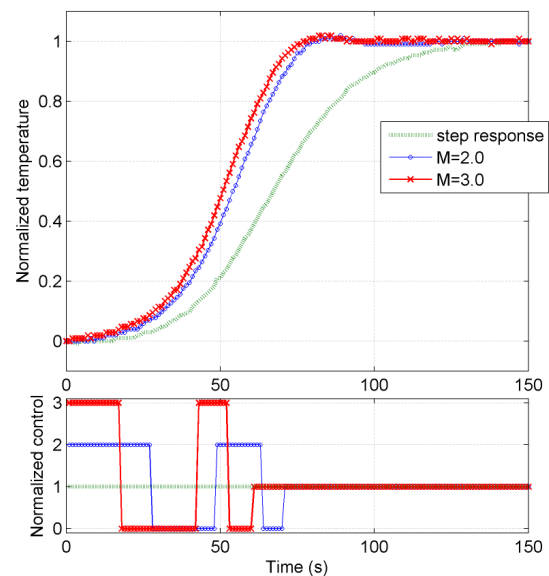


Fig. 11: Influence of pulse magnitude (experimental data)

higher pulse magnitudes. Using $M = 3, 4, 5, 6...$ instead of $M = 2$ does not increase performance much. This fact is explained because a DOC is a very low-pass system. Using a constantly varying high frequency control yields almost no performance improvement. Indeed, the system is mainly sensible to the low-pass content of the control. Choosing a high pulse magnitude allows the next pulse to take place sooner. Nevertheless, consequences on the response are only

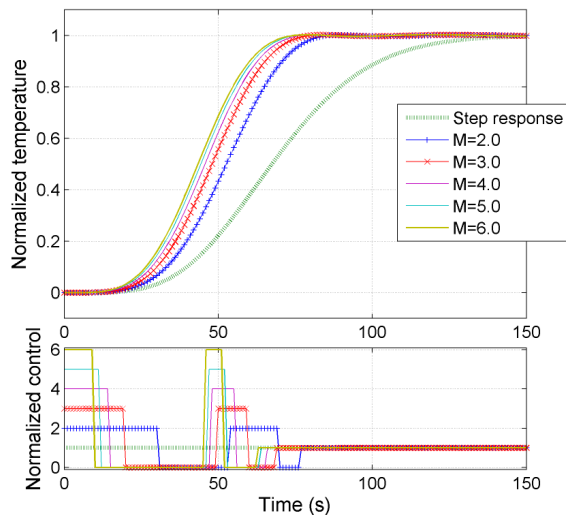


Fig. 12: Influence of pulse magnitude (simulation)

minor. To obtain good results, the critical point is, for a given maximum magnitude, to compute switch times accurately.

So, increasing pulse magnitude does not increase performance much. In real application, choice of M is limited by the decrease of the DOC efficiency when a very large amount of reductant is injected during pulses. Moreover, increasing pulse magnitude - that is enthalpy flow - obviously implies shortening pulse durations and, consequently, requires to determine very accurately the pulse switch times. The model may also fail to provide such accuracy. For all of these reasons, it is judicious to limit pulse magnitude to about $M = 2$ to $M = 3$, depending on application case.

B. Choice of the Number of Pulses

The other parameter to tune is the pulse number n . Using a small number of pulses reduces computational efforts [7]. It is shown in Fig. 13 that, compared with step response,

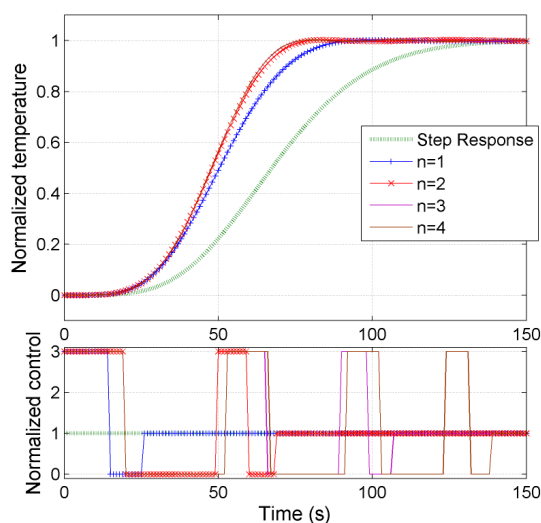


Fig. 13: Influence of pulse number (simulation)

performance is much improved when using 1 pulse, slightly more when using 2 pulses, and that it is almost useless to consider more than 2 pulses. Results are identical for other pulse magnitudes. Hence, we choose to use 2 pulses in our applications.

V. CONCLUSIONS AND FUTURE WORKS

A first approach in Diesel Oxidation Catalyst (DOC) control-oriented modeling was proposed in a former contribution [7]. A warm-up strategy using pulse control signals was developed. In the present paper, it is first shown how the previous results can be transposed to real applications, i.e. using reductant flow as control variable. Reductant step response is analytically computed and validated by experimental data. Secondly, the proposed warm-up strategy, which decreases DOC response time while preventing oscillations, is validated by experimental results obtained on a DOC testbench. Finally, the numerical strategy is exhaustively studied. It is shown how to choose pulse magnitudes and pulse number.

Results found in this study, validate those sketched in [7] based on simulations. Speeding up the DOC warm-up process is effective and straightforward to realize, and provides good results as long as DOC natural dynamics are accounted for. This is the purpose of the model and the derivation of its step response (13). On the other hand, being a very low-pass system, the DOC cannot be warmed up as fast as desired. Beyond “natural trend”, every little gain on performance is expensive in terms of energy, risk of overshoot and computational effort.

On one hand, a future work will be to investigate how reductant model can be approximated by inlet temperature model under varying air flow conditions. On the other hand, a forthcoming contribution will be to show how it is possible to do tracking on these equations and integrate the full warm-up strategy in a feedback controller.

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