MIMO CONTROL FOR AUTOMOTIVE COLDSTART

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Abstract: The problem of controlling combustion engine emissions during the coldstart period is addressed by designing a MIMO sliding mode controller. The task of the controller is to track a given set of desired profiles of engine-out hydrocarbon emissions and catalyst temperature using spark timing and fuel injection rate as the inputs. This is an important step in solving the coldstart problem. The throttle is not used as a control input. Different profiles of desired engine-out hydrocarbons and catalyst temperatures are used to analyze the coldstart problem. Simulation results indicate that the controller tracks the desired profiles as long as the inputs are not saturated. The controller presented here could be used as a tool to investigate the optimal input profiles. Experiments are being carried out to validate the simulations. Submitted to Fifth IFAC Symposium on Advances in Automotive Control

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1. INTRODUCTION

It is well known that during the coldstart period of a combustion engine, a large percentage of total cumulative hydrocarbon emissions are produced. Previous approaches to the problem can be broadly classified into two categories. One of them consists of changing the physical capabilities of the subsystems to reduce the emissions. For instance in (Nishizawa et al. 2000), new technologies are presented to achieve the SULEV (Super Ultra Low Emissions Vehicle) standards for an automotive engine: high velocity air and high swirl combustion, super low-heat mass substrate catalyst, two-stage high efficiency HC trap catalyst system and triple sensor highly accurate air-fuel ratio control system. In (Tanaka et al. 2001), a catalyst that reacts to the environment is presented. The second category considers the features of the plant as fixed and seeks strategies in which the control system can improve the emissions reduction performance of the engine. For instance, in (Fischer and Brereton 1997), the different strategies investigated to minimize HC emissions consist of finding optimal settings in the fuel injection pattern (single versus dual fuel injection pulse), the use of air-assisted fuel injection, and changes in the fuel injection mode (open intake valve injection versus closed intake valve injection). In (Arsie et al. 1998), models are developed to reduce the uncertainty in the prediction of emissions and improve the controller performance. Other efforts focus in reducing emissions by improving both aspects of the engine performance: changes in hardware and changes in control algorithms. In (Kaiser et al. 1998) and (Alkidas and Drews 1996),
hydrocarbon emissions are compared with different setups for fuel preparation.

Coldstart controllers with various control inputs have been developed, though exhaust gas temperature, ignition timing and air-fuel ratio (AFR) continue to be used the most. Many of these try to optimize the trade-off between reducing the raw emissions and achieving a faster catalyst light-off. Refer to the following for related information (Aquino 1981), (Souder and Hedrick 2004), (Tseng and Cheng 1999), (Shaw and Hedrick 2003) (Sanketi et al. 2005), (Baotic et al. 2003). (Tunestal et al. 1999) and (Lee et al. 2001) have used incylinder pressure measurement for control and estimation purposes. Hybrid automata have also been used in modeling and control, for example in (Sanketi et al. 2006) and (Giorgetti et al. 2005).

In this paper, it is assumed that the physical features of the engine components are fixed. We focus in designing controllers that track engine-out hydrocarbon emissions ($HC_{raw}$) and catalyst temperature ($T_{cat}$). The models for $HC_{raw}$, exhaust temperature ($T_{exh}$) and $T_{cat}$ are presented in another paper submitted to this symposium.

The controller has a three-tier architecture: (i) Topmost is a $T_{cat}$ dynamic surface controller that uses $T_{exh}$ as the control input. (ii) At next level is a MIMO (2 output, 2 input) sliding mode controller that achieves desired profiles of $T_{exh}$ and $HC_{raw}$ using AFR and spark timing ($\Delta$) as inputs. (iii) finally an AFR dynamic surface controller that uses the fuel injection rate ($\dot{m}_{inj}$) as the control input. See Fig. 1. First, different profiles of desired catalyst temperature and engine-out HC emissions based upon typical coldstart experimental data are tracked. Furthermore, the total tailpipe HC emissions in different cases and the feasibility of the control inputs are used as parameters to investigate the minimization of coldstart emissions.

2. CONTROLLER

2.1 Control Algorithm

The main idea in the control algorithm presented here is the combined use of the catalyst and the engine models. The inputs to the engine to reduce tailpipe emissions are determined using dynamic surface and MIMO sliding controllers. MIMO Sliding mode control laws are developed for $T_{exh}$ and engine exhaust hydrocarbons $HC_{raw}$. Control laws are also developed for $T_{cat}$ and the AFR. The control architecture is shown in the Figure 1.

![Fig. 1. The controller architecture](image)

Overall strategy is driven by the $T_{exh}$ and $HC_{raw}$ models. Each of these, as described in (2), depends on both $\Delta$ and AFR. Together, these form a good platform for a MIMO control design. To start with, profiles of $T_{cat}$ and $HC_{raw}$ as given by typical coldstart experimental data are chosen as the desired profiles to be tracked. From the catalyst model, we know that $T_{cat}$ depends mainly on $T_{exh}$. So we use the principle of dynamic surface controller, where $T_{exh}$ is set such that the desired $T_{cat}$ is achieved. Next in the hierarchy is a MIMO (2 inputs and 2 outputs) controller which uses the spark timing and the AFR to control the raw HC and $T_{exh}$. Then, the desired AFR is obtained through dynamic surface controller by using fuel injection rate as the input.

2.2 Catalyst Temperature Control

Catalyst temperature is mainly dependent on $T_{exh}$. Using dynamic surface control, we control $T_{cat}$ treating $T_{exh}$ as a synthetic input. We define a sliding surface equal to the difference between the actual and desired value of $T_{cat}$.

$$S_1 = T_{cat} - T_{cat,d}$$

Substitute for the dynamics of $T_{cat}$ from (2). We get,

$$\dot{S}_1 = \frac{\dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{evap} - \dot{Q}_{cav}}{mC_v + MC} - \dot{T}_{cat,d}$$

Treating $T_{exh}$ as the input, design the control law to obtain

$$\dot{S}_1 = -\lambda_1 S_1$$

where $\lambda_1$ is a positive gain. This leads to

$$\dot{T}_{exh} = \frac{(\dot{T}_{cat,d} - \dot{S}_1)(mC_v + MC)}{\dot{m}_{exh}C_p} + \frac{-\dot{Q}_{gen} + \dot{Q}_{out} + \dot{Q}_{evap} + \dot{m}_{exh}C_pT_{ip}}{\dot{m}_{exh}C_p}$$

$$+ m_{exh}C_p$$
where $\dot{T}_{exh}$ is the synthetic input. To track the desired value of the synthetic input, we need to find its derivative, which can lead to too many terms called the "explosion of terms" problem. Also, the term $T_{exh}$ may include uncertainties which can lead to problems on differentiation. Hence, the desired value of $T_{exh}$ to be tracked is found by passing the synthetic input through a low-pass filter so that explosion of terms and taking unknown derivatives is avoided. That is the basic principle of dynamic surface control.

$$\tau T_{exh,d} + T_{exh,d} = \dot{T}_{exh}$$

(3)

Then, we use a MIMO sliding control design to achieve the desired profiles of exhaust gas temperature and raw $HC$ using spark timing $\Delta$ and AFR as inputs.

2.3 MIMO control

We define a vector of sliding surfaces as follows:

$$S = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} T_{exh} - T_{exh,d} \\ HC_{raw} - HC_{raw,d} \end{bmatrix}$$

(4)

The $T_{exh,d}$ profile is obtained from the $T_{cat,d}$ as described in the previous subsection. Differentiating, and using the dynamics of $T_{exh}$ and $HC_{raw}$, we set AFR and $\Delta$ to obtain

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = -KS$$

(5)

where, $K \in \mathbb{R}^{2x2}$, the gain on the MIMO control, is strictly a positive definite matrix. This will yield the desired profiles of AFR and $\Delta$.

The outputs $HC_{raw}$ and $T_{exh}$ are coupled. These are two competing objectives playing an important role in the reduction of tailpipe emissions. It is important to choose a non-diagonal gain so that the coupling between the two outputs is not overlooked. If a diagonal matrix is chosen, it will be equivalent to two SISO sliding controllers.

2.4 AFR Control

To track the desired AFR, instead of defining a sliding surface on the AFR signal, it is more convenient to define a sliding surface on the fuel flow rate, as follows

$$S_2 = \dot{m}_{fo} - \dot{m}_{fo,d}$$

(6)

with

$$\dot{m}_{fo,d} = \frac{\dot{m}_{ao}}{AFR_d}$$

(7)

where $AFR_d$ is the desired AFR and $\dot{m}_{ao}$ is the manifold out air flow rate. The commanded fuel flow is used as the input to obtain

$$\dot{S}_2 = -\lambda_2 S_2$$

where $\lambda_1$ is a positive gain. Using (6) and (8) together with the description of the fuel dynamics as given in (Sanketi et al. 2006), we get,

$$\epsilon \dot{m}_{fc} + \frac{1}{\tau_f} \dot{m}_{fc} = \frac{1}{\tau_f} \dot{m}_{fo} - \dot{m}_{fo,d} = -\lambda_2 S_2$$

(8)

and expanding the term $\dot{m}_{fo,d}$ gives the equation for the control input

$$\dot{m}_{fc} + \frac{1}{\epsilon \tau_f} \dot{m}_{fc} = \frac{1}{\epsilon \tau_f} \dot{m}_{fo} + \frac{1}{\epsilon (AFR_d)} + \frac{\dot{m}_{ao}}{AFR_d} A\dot{FR}_d - \lambda_2 S_2$$

As in the case of $T_{cat}$ control, $AFR_d$ is obtained by passing the synthetic input $AFR$ through a low-pass filter so that explosion of terms and taking unknown derivatives is avoided.

$$\tau_{AFR} A\dot{FR}_d + AFR_d = A\dot{FR}_d$$

(10)

2.5 Notes on the controller

A nominal throttle profile during the coldstart is treated as an exogenous input to the system. Also, for the case of our analysis, the control input space was considered constant, whereas in practice it is dependent on the operating point.

The main sensors required for the controller implementation are the HC analyzer, a linear AFR sensor, exhaust and catalyst temperature sensors. Although, all the results presented in Section 3 are simulations, the inputs to the controller are based on experimental data.

Also, it is assumed that a full state feedback is available. Given $HC$ and $T_{exh}$ sensors, it is easy to implement the observers for the states. Currently, the possibility of estimating $HC$, $AFR$ and $T_{exh}$ using in-cylinder pressure measurements is being investigated.

Regarding the desired profiles, it should be noted that it is not verified if the profiles of $HC_{raw,d}$ and $T_{cat,d}$ used in this paper are the optimal ones for coldstart purposes. However, they provide a basis for analysis of optimality.

3. RESULTS AND DISCUSSION

Various sets of desired profiles of catalyst temperature ($T_{cat,d}$) and raw HC ($HC_{raw,d}$) are proposed to be tracked by the controller. The desired profiles cannot be chosen arbitrarily since there are physical constraints on the system. For example, $T_{cat}$ will always have a plateau, because of the evaporation effect inside the catalyst. Similarly, the initial peak in the $HC_{raw}$ cannot be completely wiped out because that will risk stalling...
the engine. Initially, those profiles were taken from experimental results of a typical coldstart run. The profiles were then modified to achieve a wider set of desired values. In this section, all the figures contain plots of a set of cases, which are grouped into runs. Where the plots show a single line, it means all the cases of the same run resulted in the same curve for that variable.

Figures 2 and 3 show the first set of desired profiles, $HC_{raw,d}$ and $T_{cat,d}$. $HC_{raw,d}$ was taken from a typical $HC_{raw}$ coldstart profile. The corresponding $T_{cat,d}$ profile was offset by constants between -40°C and 100°C to obtain different $T_{cat,d}$ profiles. It should be noted that since the throttle position was treated as an exogenous input, the range of viable $T_{cat}$ profiles was such that some of the $T_{cat,d}$ profiles could not be tracked. The reason can be explained by the $AFR$ profile in Fig. 11. The corresponding $AFR_d$ reached the value of 16, which is the saturation level of $AFR$ that we have used for the simulations.

Simulations were also performed using different $HC_{raw,d}$ profiles. In this case, the profiles were obtained by multiplying a typical actual $HC_{raw}$ coldstart profile by constants between 0.3 and 2.0. Fig. 8 shows $HC_{raw,d}$ together with the values of $HC_{raw}$ given by the model. One of the desired profiles could not be tracked. The reason can be explained by the $AFR$ profile in Fig. 11. The corresponding $AFR_d$ reached the value of 16, which is the saturation level of $AFR$ that we have used for the simulations.
Note in Fig. 11 the different levels of cumulative $HC_{raw}$ reached by different simulations. Three of them are almost constant after 30s, however one of them still increases till about 60s. The catalyst efficiency shown in Fig. 12 explains this behavior, where one of the curves of efficiency drops below 50% between 30s and 60s. Further, a combination of different profiles of $T_{cat,d}$ and $HC_{raw,d}$ was simulated. The results for $T_{cat}$ and $HC_{raw}$ are shown in Fig. 13. The fuel injection rate, spark timing, cumulative tailpipe $HC$ and $AFR$ are shown in Figures 14 and 15. Observe that the $HC_{raw,d}$ profiles can be tracked well, however one of the $T_{cat}$ profiles cannot be tracked properly. This is due to the nature of the desired profiles and the value of the exogenous input. A higher $HC_{raw}$ needs the $AFR$ to be maintained rich and a retarded spark. Under such a scenario, $T_{cat}$ cannot be maintained as low as you want. This basically illustrates the trade-off during coldstart. Also note
that even though the catalyst conversion efficiency $\eta_c$ (shown in Fig. 16) for case 1 reaches 1 at around 30s, the total cumulative $HC$ are less than for that case 3, where $\eta_c$ reaches 1 in about 15s. The reason is the difference in $HC_{raw}$ emissions level.

Simulations were also performed with different throttle angle profiles, as shown in Fig. 17. The profiles were obtained by multiplying three different factors (0.7, 1.0 and 1.3) to a typical cold-start throttle angle profile given by the ECU. The desired $T_{cat}$ was chosen to be the same for the different throttle angles. As seen in Figures 18 and See Fig. 20, the system could not track the desired profile for one of the cases, viz. case 1. At low engine speed, the engine pressure is low due to which the combustion quality is low. Hence, $HC_{raw}$ cannot be maintained as low as desired and $T_{cat}$ cannot be increased as fast as desired. The low $T_{cat}$ affects adversely $\eta_c$, as seen in Fig. 19.

In another set of experiments (Run 5), different constant profiles for the accessory torque were used as disturbances during the system simulations. The values of the accessory torque were between 10 and 70 N-m The throttle and engine speeds are shown in Fig. 21. The desired $T_{cat}$ and $T_{exh}$ were the same for all different cases of the simulation. However in one of them the desired profiles could not be achieved, mainly due to the low values of crankshaft speed for that case. See Fig. 22 The degradation in the $HC_{tp}$ emissions can be observed in Fig. 23 and Fig. 24. The performance in case 3 is related to the low values of $\eta_c$. This case has the largest accessory torque (70 N-m).
4. CONCLUSIONS

A coldstart controller with three components was designed. The first component is a DSC (dynamic surface control) controller which tracks a desired $T_{cat}$ profile. The second is a MIMO (multiple input-multiple output) sliding mode controller that tracks $HC_{raw}$ and $T_{exh}$. The third one is a DSC AFR controller. Simulations are performed using typical coldstart $HC_{raw}$ and $T_{cat}$ profiles as initial tracking references for the controller. The desired $HC_{raw}$ and $T_{cat}$ were modified from their respective initial profiles and the changes in tailpipe emissions ($HC_{tp}$) were analyzed. The tradeoff of fast light-off vs. low $HC_{tp}$ was evident when several combinations of desired $HC_{raw}$ were used.
profiles with desired $T_{cat}$ were used. Simulations with external disturbances in the throttle angle and accessory torque showed some degradation in the performance of the controller. In all the cases, changes in the desired $HC_{raw}$ seemed to have a larger effect on tailpipe emissions than the changes in the desired $T_{cat}$.

At this time, experiments are being carried out to validate the results of simulations. Also, methods are being analyzed to approach the problem of the optimization of the system. The use of the actual allowed ranges of control inputs represents an aspect of the optimization problem, too. In practice, the control input space is dependent on the operating point. For the case of our simulations, for ease of analysis, it was considered constant. The controller was designed based on the engine model presented in another paper submitted to this symposium.

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