DYNAMIC SURFACE CONTROL OF ENGINE EXHAUST HYDROCARBONS AND CATALYST TEMPERATURE FOR REDUCED COLDSTART EMISSIONS

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Abstract: Almost three quarters of the hydrocarbon (HC) emissions emitted by an automobile in a typical drive-cycle are produced during the first three minutes of its operation called the coldstart period. In this paper, we propose a way to decrease cold start emissions. A Model-Based paradigm is used to aid the generation of an efficient controller. The controller is built around a mean value engine model and a simplified catalyst model characterized by thermal dynamics, oxygen storage and static efficiency curves. It is shown that the control of engine-out exhaust gas temperature for faster catalyst light-off could be detrimental to the catalyst. A control scheme comprising engine-out hydrocarbon emissions control and catalyst temperature control through dynamic surface control is developed to reduce the tailpipe emissions. It is shown that reduced tailpipe emissions can be achieved without the risk of damaging the catalyst. *Copyright© 2005 IFAC.*

Keywords: Automotive control, coldstart, catalyst light-off, dynamic surface control

1. INTRODUCTION

New technologies are required to meet the strict regulations on the automotive emission levels. As much as 80 % of the hydrocarbon (HC) emissions in a typical engine drive cycle come from the initial 2-3 minutes commonly termed as the coldstart period. There are three main factors why a significant portion of the hydrocarbon emissions occur during the coldstart: the first one is that the cold engine walls make the flame unstable due to the heat transfer rate from the gas to the walls; the second one is that the catalyst is not active at low temperatures; and the third one is that the oxygen sensor has not reached its operating temperature. Dealing with the coldstart emissions is one of the biggest challenges for automotive engineers.

Alternative technologies have been proposed to improve the performance of catalytic converters during the coldstart period. In those attempts, the catalyst has been made to decrease the light-off time. One such instance is a catalyst that reacts to the environment to achieve faster light-off (Tanaka *et al.*, 2001). In most of the cases, improvements have been shown to the performance of the control of emissions. However, extra cost is added as new devices and materials are incorporated into the system. Many catalyst models have been developed for studying the coldstart emissions problem. (Shen *et al.*, 1999) deals with very detailed physical model involving 13-step kinetics and 9-step oxygen storage mechanisms,

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while (Ohsawa *et al.*, 1998) develops numerical algorithms to predict catalyst characteristics. Being complicated, these are not suitable for control purposes. (Jones *et al.*, 1999) and (Jones *et al.*, 2000) consider storage dominated models (simplified storage and conversion modeling) which are more suitable for real time control and on-board diagnostics. (Brandt *et al.*, 2000) develops a phenomenological model using least squares for identifying model parameters. Though not very detailed, these models have not been developed with an aim of designing controllers. (Fiengo *et al.*, 2002) suggests use of control oriented model in which genetic algorithm is applied for identifying the model parameters. (Shaw, 2002) develops simplified control oriented thermal models of the catalytic converter and the engine. Such models are the most suitable ones for designing controllers.

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. (Tunestal *et al.*, 1999) uses in-cylinder measurement to predict the engine AFR for engine cold-start control.(Lee *et al.*, 2001) uses lean-limit control to reduce the HC emissions. (Sun and Sivashankar, 1998) studies the trade-off between catalyst light-off and feed-gas HC, and the effect of different operating constraints on the catalyst light-off. (Chan and Hoang, 1999) follows a practical approach: maintains high idle speed with high value of ignition retard (HVIR) with excess air factor; both together give high engine exhaust temperature (T_{exh}). (Shaw, 2002) uses isolated engine and catalyst models to determine optimum engine-out parameter profiles that can reduce the overall tailpipe emissions. It further shows that reducing the engine-out HC does not necessarily mean reducing the tailpipe emissions. In most of the attempts to make a model-based controller, the main focus has been on faster catalyst light-off which is mainly achieved by increasing T_{exh} using ignition retard.

In this paper, a brief review of the engine and the catalyst models is presented. It is shown that controlling (T_{exh}) for faster catalyst light-off can raise the catalyst temperature (T_{cat}) to very high values and hence, damage the catalyst. A control scheme, where the focus is on the catalyst temperature control, instead of T_{exh}, is developed using robust dynamic surface control due to the highly nonlinear nature of the model. Controllers for engine exhaust HC and T_{cat} run in parallel. Results show that reduced tailpipe HC emissions can be achieved without the risk of the catalyst being damaged.

2. MODEL BACKGROUND

The system under consideration consists of a mean value engine model and a simplified lumped thermal catalyst model; and includes the rotational, manifold and thermal dynamics of the engine and the catalyst. Since the main focus of this paper is not on modeling, the details are omitted here. For details of the model, please refer to (Shaw, 2002).

The engine model consists of four states:

$$x = \left[\, \omega_e \ \dot{m}_{fo} \ T_{exh} \ m_a \,\right]^T$$

where, ω_e = engine speed in rad/s, $\dot{m}_{fo}$ = fuel flow rate being injected into the engine in kg/s, T_{exh} = engine exhaust gas temperature in $\deg C$, m_a = mass air contained in the intake manifold in kg.

Only the state equations of $\dot{m}_{fo}$ and T_{exh} are discussed here since these would be used in our controllers.

The fuelling dynamics of the injector are modeled as a simple first order system given by

$$\ddot{m}_{fo} = \frac{1}{\tau_f}[-\dot{m}_{fo} + \dot{m}_{fc}] \qquad (1)$$

where, $\dot{m}_{fc}$ is the commanded fuel flow rate by the controller.

The exhaust gas temperature is strongly dependent on the ignition timing with a weaker dependency on the overall AFR of the engine. The temperature measurement is delayed by 2π radians to account for the transport delay of one revolution between ignition and exhaust valve opening. The AFI (air fuel influence factor) is based on the adiabatic temperature of a premixed gasoline-air flame.

$$\dot{T}_{exh} = \frac{1}{\tau_e}[-T_{exh} + ST * AFI] \qquad (2)$$

where, $ST = 7.5\Delta + 600$, Δ being the spark timing in degrees after Top Dead Center (TDC), $AFI = \cos[0.13(AFR - 13.5)]$ and $\tau_e = \frac{2\pi}{\omega_e}$ is the time constant to account for the measurement delay.

The effect of retarded spark timing on increasing the exhaust gas temperature is widely reported in literature. The catalyst gets more heat input as a result of which, the light-off is rapid, subsequently reducing the tailpipe HC emissions. However, the retard in spark timing is limited by the driveability of the engine and the maximum temperature so as not to damage the catalyst.

The warmup of the catalyst during the coldstart period is an important factor in the overall production of HC emissions. The efficiency of the catalyst depends on the T_{cat} and the AFR. The catalyst is generally not active at low temperatures and therefore necessary for the catalyst to achieve light-off temperature as soon as possible. The catalyst model consists of thermal dynamics, oxygen storage and static efficiency curves (Shaw, 2002). We deal with the lumped thermal submodel here which comprises the catalyst monolith temperature as its state. The catalyst temperature depends on the heat obtained from the engine exhaust gas ($\dot{Q}_{in}$), the amount of heat generated due to oxidation of pollutants from the feed-gas ($\dot{Q}_{gen}$) and the heat transfer to the surroundings ($\dot{Q}_{out}$).

$$\dot{T}_{cat} = \frac{1}{mC_p}[\dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out}] \quad (3)$$

where, m is the mass of the catalyst and C_p is the specific heat capacity at constant pressure of the catalyst material.

The next section outlines the controller development.

3. CONTROL ALGORITHM

The main idea in the control algorithm presented here is the combined use of the catalyst and the engine models. Desired input profiles to the engine that minimize the tailpipe emissions are determined using the emissions reduction performance of the system.

Sliding mode control laws are used to to track the desired profiles based on input requirements. Independent Sliding mode control laws are developed for T_{cat}, engine exhaust hydrocarbons HC_{out} and the engine speed ω_e. Control laws are also developed for T_{exh}, intake manifold air m_a and the AFR. Here we would concentrate on the control laws for T_{cat} and HC_{out}.

3.1 Catalyst Temperature Control

Catalyst temperature is mainly dependent on the engine exhaust temperature, which is strongly dependent on the ignition timing. 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 the catalyst temperature.

$$S_1 = T_{cat} - T_{cat,d} \quad (4)$$

$$\dot{S}_1 = \dot{T}_{cat} - \dot{T}_{cat,d}$$

Substitute for the dynamics of the catalyst temperature from (3). We get,

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

Denoting the catalyst internal surface area and heat transfer coefficient as A_{in} and h_{in} respectively, we have

$$\dot{Q}_{in} = h_{in}A_{in}(T_{exh} - T_{cat})$$

Similarly,

$$\dot{Q}_{out} = h_{out}A_{out}(T_{cat} - T_{atm})$$

where T_{atm} is the ambient temperature.

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

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

where λ_1 is a positive gain. This is called the sliding condition. This leads to

$$\bar{T}_{exh} = \frac{(\dot{T}_{cat} - \lambda_1 S_1)mC_p - \dot{Q}_{gen} + \dot{Q}_{out}}{h_{in}A_{in}} + T_{cat} \quad (5)$$

where $\bar{T}_{exh}$ 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 $\bar{T}_{exh}$ 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 idea of dynamic surface control.

$$\tau_T\dot{T}_{exh,d} + T_{exh,d} = \bar{T}_{exh} \quad (6)$$

Then, we define a sliding surface based on the difference between the actual and the desired exhaust gas temperature as

$$S_2 = T_{exh} - T_{exh,d} \quad (7)$$

$$\dot{S}_2 = \dot{T}_{exh} - \dot{T}_{exh,d}$$

Design to the control law using Δ, which is the spark timing in degrees after TDC, as the control input to obtain

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

$$\implies S_2\dot{S}_2 < 0$$

where λ_2 is a positive gain.

Using the plant dynamics given by (2), we get the control law as,

$$\Delta = \frac{1}{7.5}(\frac{\tau_e}{AFI}[\frac{T_{exh}}{\tau_e} + \dot{T}_{exh,d} - \lambda_2 S_2] - 600) \quad (8)$$

3.2 Engine Exhaust HC control

The engine-out HC emissions denoted by HC_{out} are strongly dependent on the AFR. Therefore, AFR is treated as a pseudo input to control HC_{out}. The inversion of the following expression in terms of AFR is used to devise the controller

$$\dot{HC}_{out} = \dot{m}_f \frac{(r_c - 1)}{r_c} exp\{-a(\frac{\theta_{EVO} - \theta_0}{\Delta\theta}^m)\} \quad (9)$$

where, r_c is the compression ratio, θ_{EVO} is the exhaust valve opening angle and

$$\theta_0 = k1(\Delta) + k2$$
$$\Delta\theta = k3(AFR - 14.7)^2 + k4$$

k2, k3, k4, a and m being the model parameters.

Define a sliding surface as the difference between the engine out HC emissions rate and the desired rate.

$$S_3 = \dot{HC}_{out} - \dot{HC}_{out,d} \tag{10}$$

For our purposes, the $\dot{HC}_{out,d}$ is assumed to be zero. Differentiating,

$$\dot{S}_3 = \ddot{HC}_{out} - 0 \tag{11}$$

But since the equation $\ddot{HC}_{out}$ is complex, it will be difficult to invert that equation in terms of AFR. Hence, we pass $\dot{HC}_{out}$ through a first order filter to obtain $\dot{HC}_{f,out}$ as follows.

$$\tau_p \ddot{HC}_{f,out} + \dot{HC}_{f,out} = \dot{HC}_{out}$$
$$\implies \ddot{HC}_{f,out} = \frac{1}{\tau_p}(\dot{HC}_{out} - \dot{HC}_{f,out}) \tag{12}$$

Substituting this in (11), and using AFR as a synthetic input, we can design the controller to get

$$\dot{S}_3 = \frac{1}{\tau_p}(\dot{HC}_{out} - \dot{HC}_{f,out}) = -\lambda_3 S_3 \tag{13}$$

λ_3 being a positive gain.

After some algebra, we get the synthetic input as

$$A\bar{F}R = \left\{ \left(X^{-1/m} \frac{1}{\theta_{EVO} - \theta_0} - k4 \right) \frac{1}{k3} \right\}^{1/2} + 14.7 \tag{14}$$

where,

$$X = \frac{1}{a} log\left[\frac{\dot{m}_f (r_c - 1)}{(\dot{HC}_{f,out} - \tau_p \lambda_3 S_3) r_c}\right]$$

Again, this is passed through a filter to get the desired AFR and $A\dot{F}R_d$. As mentioned before, taking unknown derivatives is avoided using this method.

$$\tau_A A\dot{F}R_d + AFR_d = A\bar{F}R \tag{15}$$

To track the desired AFR, we define a sliding surface as follows.

$$S_4 = \dot{m}_{fo} - \gamma \tag{16}$$
$$\gamma = \frac{\dot{m}_{ao}}{AFR_d}$$
$$\implies \dot{S}_4 = \ddot{m}_{fo} - \dot{\gamma}$$

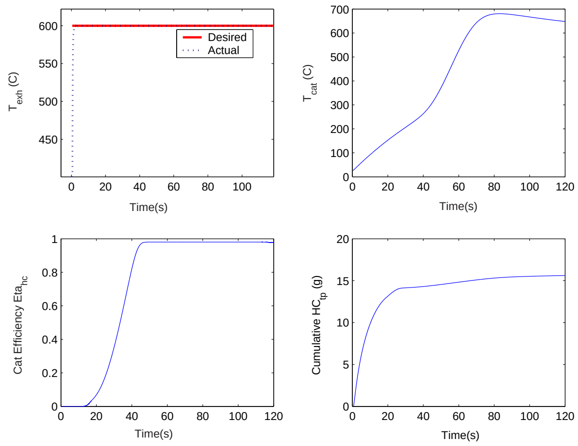

Fig. 1. Isolated engine and catalyst models: T_{exh} control

where, $\dot{m}_{ao}$ is the manifold out air flow rate. Using the fueling dynamics (1),

$$\dot{S}_4 = \frac{1}{\tau_f}[-\dot{m}_{fo} + \dot{m}_{fc}] - \dot{\gamma}$$

The commanded fuel flow is used as the input to achieve the sliding condition given by

$$\dot{S}_4 = -\lambda_4 S_4$$
$$\implies S_4 \dot{S}_4 < 0$$

where λ_4 is a positive gain. After a bit of algebra, we get the following control law:

$$\dot{m}_{fc} = \dot{m}_{fo} + \tau_f \left[\frac{\ddot{m}_{ao}}{AFR_d} - \frac{\dot{m}_{ao} A\dot{F}R_d}{AFR_d{}^2} - \lambda_4 S_4\right] \tag{17}$$

4. SIMULATION RESULTS AND DISCUSSION

The controllers designed were applied to the engine and the catalyst models and the performances were compared against each other. Initially, the performance results using isolated engine and catalyst models are discussed. It is followed by the results of T_{cat} control and then by those of the combined use of $\dot{HC}_{out}$ control and T_{cat} control.

4.1 Closed Loop Performance using Isolated Engine and Catalyst Models

The desired engine out profiles of T_{exh}, ω_e and the AFR which minimize the tailpipe emissions are calculated using a separate catalyst model (Shaw, 2002). Figure (1) shows the overall performance of the controller. Here, the profile of only T_{exh} is shown, which is used to induce faster catalyst light-off, hence decreasing the tailpipe emissions. The controller results in 16g of cumulative HC, the catalyst light-off being achieved at

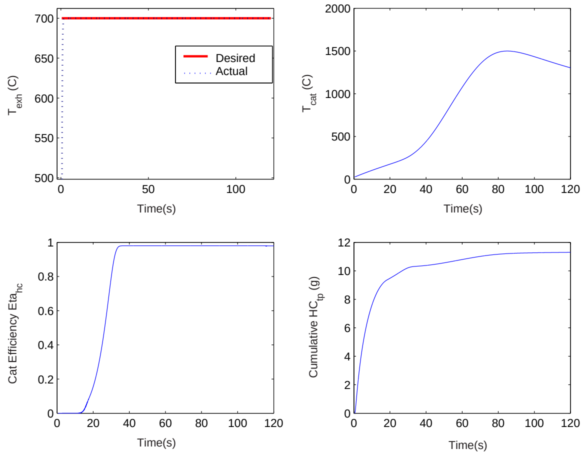

Fig. 2. T_{exh} control can lead to catalyst damage

around 45s. But the catalyst temperature rises almost up to 700C. Due to longevity concerns, the catalyst temperature should not go beyond 900C. If a faster catalyst light-off is required, the desired T_{exh} must be raised so that T_{cat} increases rapidly. Though the tailpipe emissions are decreased, the faster catalyst light-off comes at the expense of very high temperature rise in catalyst as seen in Figure (2) which may damage the catalyst. To avoid this, an algorithm for controlling the catalyst temperature instead of the exhaust temperature is developed. The performance of this controller is discussed next.

4.2 Closed Loop Performance using Catalyst Temperature Control

This algorithm uses both the catalyst and the engine model in real time. The catalyst temperature is fed back to the controller along with the engine parameters. The aim is to control the catalyst temperature rather than the exhaust temperature so as to make sure that there is never a surge in the catalyst temperature even while trying to get a faster catalyst light-off. This is used along with an independently developed AFR controller based upon (Shaw, 2002).

Figure (3) shows very good tracking of the desired T_{cat} profile. The catalyst temperature stabilizes and the $\dot{HC}_{out}$ behaves smoothly. The T_{cat} is always less than 450C even though catalyst light-off is achieved faster than the previous case. The T_{exh} rises initially till the catalyst temperature equals its desired value. During this interval, the HC rate is really high due to high ignition retard. The controller keeps T_{exh} below 1000C which is acceptable. The controller is deficient in the fact that it only focusses on the catalyst light-off, which leads to negligence of the HC_{out} and

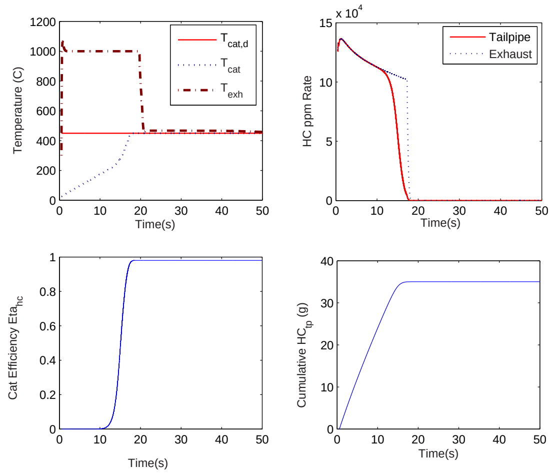

Fig. 3. Dynamic Surface T_{cat} control

hence, increased tailpipe emissions, even though the light-off is achieved much faster.

4.3 Closed Loop Performance using T_{cat} and $\dot{HC}_{out}$ Controllers Simultaneously

One way to deal with the problem of T_{cat} control can be to set an optimum time for the catalyst light-off by choosing an appropriate gain for the controller. A better solution, as we found out, is to use T_{cat} controller in combination with the $\dot{HC}_{out}$ controller outlined in Section (4.2). The gains of both the controllers are tuned such that the tailpipe emissions are minimized. The results are shown in Figure (4).

The cumulative emissions are less than the previous controllers. The feedgas HC rate is very low initially, but increases once T_{exh} rises. It is essential to tune the gains to achieve catalyst light-off at an optimal time, since HC controller acting for a long time will saturate the input. It should be noted that even though this does not necessarily achieve a very fast light-off, it ensures that the catalyst temperature is not very high at any point of time.

5. CONCLUSION

A mean value combustion automotive engine model and a lumped thermal three-way catalyst model were used to develop control algorithms for reducing coldstart hydrocarbon (HC) emissions. It is shown that using isolated engine and catalyst models for control where the engine exhaust temperature is used for faster catalyst light-off can damage the catalyst.

Dynamic surface control algorithms for catalyst temperature and engine out HC are developed. Catalyst temperature is controlled using engine

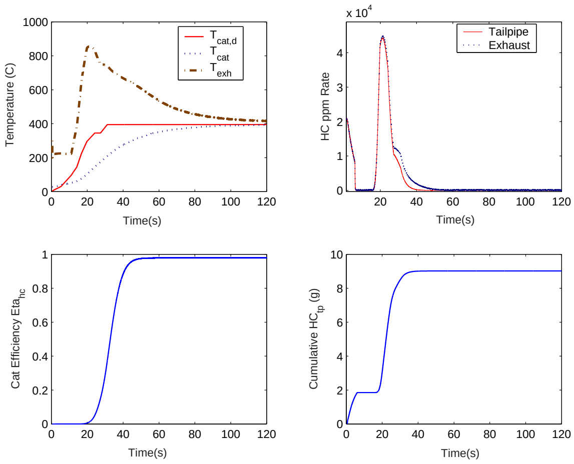

Fig. 4. Combined dynamic surface T_{cat} and $\dot{HC}_{out}$ control

exhaust temperature as the synthetic input and HC is controlled using AFR as the synthetic input. It is shown that faster catalyst light-off can be achieved using catalyst temperature control without damaging the catalyst. However, the emissions reduction performance of this controller was not found to be good. The emissions reduction performance is shown to improve when both the HC and catalyst temperature controllers are used together. Even though the catalyst light-off is not very fast in this case, the catalyst temperature is always under control and hence there is no risk of damaging the catalyst.

Further work is necessary to develop and integrate model-based controllers for various automotive engine parameters to find an optimized set of inputs that would minimize the coldstart emissions. Currently, a modification of the integrated HC and catalyst temperature controller is being pursued so that the controller gains can be varied online to achieve a better performance.

ACKNOWLEDGEMENTS

Authors acknowledge the financial support provided by the National Science foundation (under by NSF Cooperative Agreement No. CCR-0225610) and by Toyota Motor Corporation.

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