

Model Predictive Functional Control for an Automotive Three-way Catalyst

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ABSTRACT

In this work, a model predictive functional control approach for automotive three-way catalyst oxygen storage state control is demonstrated on a Ford 2.0 liter I4 Duratec SI engine. The control system uses a UEGO sensor for the pre-catalyst air fuel ratio (AFR) measurement and a switching-type HEGO sensor for the post-catalyst measurement. The model predictive controller is the primary control loop within a multi-rate cascade control configuration that adapts the parameters of a post-catalyst HEGO relay controller in an optimal manner using a predictive functional control approach. This relay controller adjusts the target of a delay-compensated feedback controller for the pre-catalyst AFR in order to maintain the post-catalyst HEGO sensor signal within a specified range of the desired target voltage. The use of a multi-rate cascade control structure allows the relay controller to execute within a short control interval in order to ensure that the post-catalyst HEGO sensor does not saturate and allows the model predictive controller to execute within a longer control interval in order to provide sufficient computation time to perform the on-line optimization necessary for predictive control. This cascade structure can also tolerate failure of the catalyst controller to solve the on-line optimization problem because the post-catalyst relay controller will continue to stabilize the catalyst system without the predictive controller operating.

INTRODUCTION

The improvements made in modern automotive catalytic exhaust after-treatment systems have been driven by

the continuing legislative demands for reduced tailpipe emissions and consumer demands for increased vehicle performance, fuel economy, and refinement. Automotive three-way catalysts have been the primary component of systems designed to meet these demands. Although improvements in catalyst formulation and substrate design are on-going, there is also still considerable potential for improved emissions reduction and vehicle performance from advanced control of the catalytic exhaust after-treatment system operation. Additional benefits of advanced catalyst system control also include a potential reduction in precious metal content and catalyst size. These factors are becoming increasingly important in today's volatile precious metal markets.

In this work, a model-based predictive functional controller for three-way catalyst system control is described and implemented on an experimental engine. Model-based control techniques offer an attractive advanced control methodology for automotive three-way catalyst systems. The predictive properties of model-based control, which has led to its widespread adoption in industrial applications [1], are ideal for preventing emissions breakthrough before they occur. Because model predictive controllers are based on the dynamic optimization of a specified cost function [2], they offer the ability to consider competing control objectives, such as emission reduction, performance, and fuel economy, in a systematic manner. The same dynamic catalyst model used in model-based control can also be used for model-based on-board diagnostic (OBD) techniques [3] as part of an integrated catalyst control and diagnostic system.

MODEL PREDICTIVE CATALYST CONTROL

A common operating practice for automotive catalyst systems is to cycle the pre-catalyst air fuel ratio (AFR) across stoichiometry at a frequency determined during engine calibration or obtained through relay feedback from a post-catalyst HEGO sensor [4]. A more sophisticated control strategy is to maintain the estimated catalyst oxygen storage level near the stoichiometric equilibrium state in order to maximize the time required to reach either rich or lean tailpipe emission breakthrough when subject to a disturbance. Linear control strategies of this type have been proposed based on Linear Quadratic Regulator [5], H -infinity [6], and Internal Model Control [7] design methods. Nonlinear model-based control formulations following this strategy include [8] and [9]. A multi-objective nonlinear model-based strategy that uses the oxygen storage capacity of the catalyst to optimize engine performance and fuel economy while preventing emission breakthrough is described in [10].

The model predictive catalyst controllers that are mentioned above are based on a pre- and post-catalyst Universal (UEGO) sensor configuration. In this work, a UEGO sensor is employed for the pre-catalyst measurement where larger variations in air fuel ratio are necessary, and a HEGO sensor is employed for the post-catalyst measurement where the detection of small air fuel ratio deviations is desired to prevent emission breakthrough. Application of model-based catalyst control using a similar post-catalyst HEGO sensor configuration is presented in [11]. With this sensor configuration, the control system must ensure that the post-catalyst AFR remains within a window that does not cause the post-catalyst HEGO sensor to saturate and result in a loss of feedback information on the state of the catalyst.

All of the model predictive catalyst controllers mentioned above also directly manipulate the pre-catalyst AFR controller target which is the decision variable for the on-line optimization of the performance objective. Since the direct on-line solution of these optimization problems is limited by the computational capability of the engine control module, it is unlikely that these controllers can execute quickly enough to avoid saturation when a post-catalyst switching-type HEGO sensor is used. Spurious targets are also possible with these controllers due to

numerical optimization failures because the pre-catalyst controller target is determined directly by the predictive control algorithm. The cascade control structure proposed in this work avoids these issues.

CATALYST CASCADE CONTROL STRUCTURE

There are a number of requirements for the on-line implementation of model-based catalyst control that must be considered in automotive applications. The most critical of these requirements is a model-based catalyst control algorithm that is computationally efficient in order to execute within the limitations of a standard Powertrain control module computer. The key aspect to meeting this requirement is an efficient dynamic on-line optimization methodology for the specified catalyst performance objective. Related requirements are a catalyst model that can adequately predict the dynamic behavior of the three-way catalyst system and the ability to estimate the current state of the model from available measurements with modest computational effort. Finally, a base control system that provides acceptable regulatory and servo response for the commands issued by the model predictive controller is also required. These requirements are addressed in this work through the implementation of predictive functional control in the multi-rate cascade control configuration shown in Fig. 1.

The post-catalyst relay controller ensures that the post-catalyst HEGO sensor does not saturate. Because the pre-catalyst AFR controller target is not directly manipulated, the multi-rate nature of the cascade controller allows the predictive catalyst controller to execute within a control interval that provides sufficient computation time to perform on-line optimization. This cascade structure can also tolerate failure of the catalyst controller to solve the on-line optimization problem at every control interval because the post-catalyst HEGO relay controller will continue to stabilize the catalyst system. The disadvantage of this approach is a loss of performance due to manipulation of the post-catalyst HEGO relay controller parameters to control the state of the catalyst as opposed to manipulating the pre-catalyst AFR target directly which has a more direct influence on the state of the catalyst system. The resulting loss of performance, however, is easily justified by the advantages of this approach.

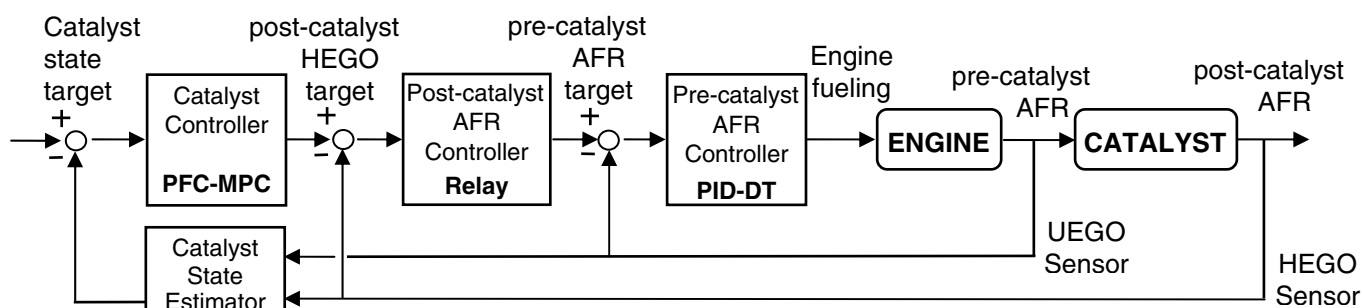


Fig. 1: Multi-rate cascade control configuration.

PRE-CATALYST AIR FUEL RATIO CONTROLLER

A key requirement for any catalyst control strategy is good servo and regulatory control of the engine-out or pre-catalyst air fuel ratio. Any deficiencies in the pre-catalyst AFR control loop performance will propagate to the post-catalyst air fuel ratio and affect the entire aftertreatment control system resulting in increased tailpipe emissions. The difficulty in achieving good pre-catalyst AFR control is the rather long and time-varying delay in the pre-catalyst EGO sensor response to changes in the engine fueling. As engine speed and load change, the time required for the exhaust gas to travel through the engine and exhaust manifold to the EGO sensor changes significantly. The magnitude of this varying time delay in the pre-catalyst EGO sensor response is on the order of the dominant time constant.

In order to address this difficulty, the adaptive delay-compensated PI controller for pre-catalyst air fuel ratio control described in [12] is used in this work. The controller operates using feedback from the pre-catalyst UEGO sensor. Time delay compensation is used to address the difficulties traditionally associated with the relatively long and time-varying time delay in the UEGO sensor response due to the exhaust gas transport process. The delay compensation is performed by computing a correction to each control move based on the current delay and the corresponding values of the past control moves. The current delay is determined from the measured engine speed and load using a two dimensional map. The tuning for this controller is based on the tuning rules developed in [13].

POST-CATALYST AIR FUEL RATIO CONTROLLER

The post-catalyst air fuel ratio controller is a relay feedback controller that manipulates the pre-catalyst air fuel ratio controller target. Relay control has been used for many years as a robust way of controlling post catalyst AFR [4]. The advantages of relay feedback control in this application are that it is a simple controller that executes quickly and it can very effectively prevent HEGO sensor saturation. Relay control will result in

limitcycle behavior, but catalyst conversion efficiency remains high as the catalyst fills and empties, providing saturation of the catalyst state or HEGO sensor signal can be avoided.

The relay amplitude and hysteresis parameters were tuned manually such that its performance was similar to a switch and ramp type catalyst relay control algorithm. In this application, however, the model-based controller adapts the relay controller target which is the center of HEGO voltage switching values. The actual upper and lower switching voltages are determined using manually entered delta values that are added and subtracted from the relay controller target as shown in Fig. 2.

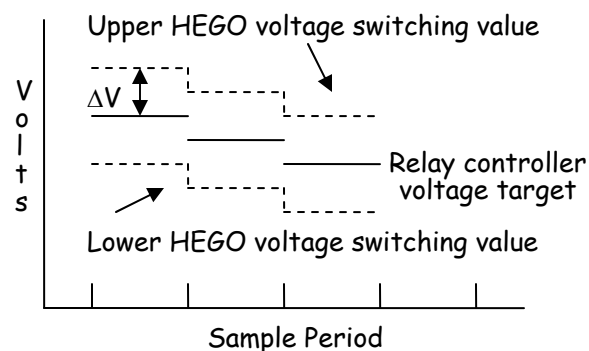


Fig. 2: Relay controller switching voltages.

CATALYST CONTROLLER

The catalyst controller is a nonlinear model predictive controller (MPC) that incorporates a dynamic catalyst model to determine the post-catalyst HEGO sensor relay controller parameters required to minimize the desired catalyst operating objective. The simulated performance objective presented in [14] that tracks a desired catalyst stored oxygen value is considered in the experimental application in this work

$$\min_{V_H^i(k)} \sum_{j=1}^{N_1+N_2} (\theta(k+j) - \theta^d)^2 \quad (1)$$



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