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Spark ignition engine fuel-to-air ratio control: An adaptive control approach

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ABSTRACT

This paper presents the control of spark ignition (SI) internal combustion (IC) engine fuel-to-air ratio (FAR) using an adaptive control method of time-delay systems. The objective is to maintain the in-cylinder FAR at a prescribed set point, determined primarily by the state of the three-way catalyst (TWC), so that the pollutants in the exhaust are removed with the highest efficiency. The FAR controller must also reject disturbances due to canister vapor purge and inaccuracies in air charge estimation and wall-wetting (WW) compensation. Two adaptive controller designs are considered. The first design is based on feedforward adaptation while the second design is based on both feedback and feedforward adaptation incorporating the recently developed adaptive posicast controller (APC). Both simulation and experimental results are presented demonstrating the performance improvement by employing the APC. Modifications and improvements to the APC structure, which were developed during the course of experimentation to solve specific implementation problems, are also presented.

1. Introduction

The fuel-to-air ratio (FAR) control performance can strongly impact key vehicle attributes such as emissions, fuel economy and drivability. For instance, the FAR in engine cylinders must be controlled in such a way that the resulting exhaust gases can be efficiently converted by the three-way catalyst (TWC). The TWC efficiency is about 98% when the fuel is matched to air charge in stoichiometric proportion and drops abruptly outside a narrow region. The TWC can also compensate for the temporary FAR deviation from stoichiometry, by either storing excess oxygen or releasing oxygen to convert excess hydro-carbons (HC) and carbon monoxide (CO). Thus, for the TWC to operate efficiently, the stored oxygen level must be regulated so that a range to accommodate further release or storage during transient conditions is available (Guzzella & Onder, 2004). In addition, the oxygen storage capacity of the TWC depends on the size and precious metal loading of the TWC. Therefore, if the FAR excursions and their durations are reduced with a well-performing controller, the storage capacity of TWC and its cost may be reduced as well.

The FAR control problem has been extensively investigated over many years. See for instance (Onder & Geering, 1993; Powell, Fekete, & Chang, 1998; Rupp, Onder, & Guzzella, 2008; Zhang, Grigoriadis, Franchek, & Makki, 2007) and references therein.

Main challenges in the design of the FAR controller include variable time delay, which is a key factor limiting the bandwidth of the feedback loop, uncertain plant behavior and disturbances. The plant uncertainties are the result of inaccuracies in the air charge estimation and in the wall-wetting (WW) compensation, as well as changes in the UEGO sensor due to aging. When the carbon canister, which stores the fuel vapor generated in the fuel tank, is purged, the fuel content in the purge flow into the intake manifold is also uncertain and creates disturbance to the FAR control loop.

Therefore, a control approach which can handle both uncertainties and large time-delays, and that can achieve a high performance is of interest. This work builds upon earlier literature by eliminating the need of a precise engine model for classical or optimization based algorithms and by eliminating the conservatism introduced by the robust control approaches. This is achieved by using the adaptive posicast controller (APC) (Yildiz, Annaswamy, Kolmanovsky, & Yanakiev, 2010), which is an adaptive controller for time delay systems. Successful adaptive control approaches are presented also in Ault, Jones, Powell, and Franklin (1994), Turin and Geering (1995), Jones, Ault, Franklin, and Powell (1995), Rupp et al. (2008), and Rupp (2009), but the approach presented in this paper is different from them: APC is based on direct adaptation where an online parameter identification scheme is not used and uncertainties are not confined to oxygen sensor parameters only but are allowed to appear elsewhere in the overall plant dynamics. In addition, APC is applied to a Lincoln Navigator test vehicle with eight cylinders, provided by Ford Motor Company, Dearborn, USA, which makes the control task much harder due to cylinder to cylinder

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Nomenclature

F_c	fuel entering the cylinders
F_i	injected fuel
X	fraction of fuel contributing to the fuel puddle
τ_v	puddle evaporation time constant
Φ_{bm}	equivalence ratio right before measurement
Φ_{eng}	equivalence ratio right after the engine exit
τ_{gm}	gas mixing time constant
τ_{tr}	transport delay
τ	total delay
Φ_m	measured equivalence ratio
τ_s	sensor time constant
τ_m	reduced order model time constant
u_c	total control signal without WW compensation
u	feedback control input
F_b	base fuel
$(\frac{F}{A})$	desired fuel-to-air ratio
$\hat{A}$	estimated air mass flow rate
γ	adaptation gain
W_p	delay-free part of the plant transfer function
R_p	denominator polynomial of the plant transfer function
Z_p	numerator polynomial of the plant transfer function
k_p	high frequency gain of the plant transfer function
R_m	denominator polynomial of the reference model transfer function
k_m	high frequency gain of the reference model transfer function
A_p	plant state matrix
A_m	reference model state matrix
b_p	plant input vector
b_m	reference model input matrix
h_p	plant output vector
h_m	reference model output vector
Λ	signal generator state matrix
l	signal generator input vector
$(\cdot)^*$	ideal controller parameter
$\tilde{(\cdot)}$	deviation from the ideal controller parameter
e	state error
e_1	output error
ω_1,ω_2	signal generator states
Ω	vector consisting of signal generator states and reference signal
α_1,α_2,k	finite dimensional controller parameters
λ	infinite dimensional controller parameter
θ	vector/scalar of finite dimensional controller parameters/parameter
Φ	equivalence ratio
Γ	adaptive gain matrix for finite dimensional parameters
γ_λ	adaptive gain for infinite dimensional parameters

variations. Finally, in this work, not only the APC results are presented but also a comparison with the existing control design in the test vehicle and with a gain scheduled Smith predictor (GSSP) are provided. It is noted that the GSSP used for comparison consists of a PI controller in series with a Smith block which predicts one delay interval ahead future output (FAR) of the engine. This future prediction is used as the feedback signal, which eliminates the effect of the time-delay to stability. In addition, the PI gains are scheduled according to the operating point of the engine. This combination of prediction and gain scheduling makes GSSP perform like a perfect "adaptive" controller. Therefore, the comparison of the APC with the GSSP presents how closely the APC is performing versus a high-performance controller.

The APC can be described as an adaptive controller that combines explicit delay compensation, using the classical Smith predictor (Smith, 1959) and finite spectrum assignment (Manitius & Olbrot, 1979), and adaptation (Ichikawa, 1985; Ortega & Lozano, 1988). As explained above, the Smith Predictor is simply a predictor that calculates one-delay-interval ahead future output of the plant by using the plant dynamics, to be used as the feedback signal. The Smith Predictor, however, has some disadvantages, one of which is unstable pole zero cancellations. Finite spectrum assignment controller solves this problem by using finite integrals in the future prediction. More details of the APC, Smith Predictor and finite spectrum assignment controller can be found in Yildiz et al. (2010). Due to such a unique combination, the APC effectively deals with both uncertainties and large time-delays both of which are dominant features of the FAR control problem. Previously, the authors explained preliminary implementation results of this controller to idle speed control and FAR control problems in conference papers (Yildiz, Annaswamy, Yanakiev, & Kolmanovsky, 2007; Yildiz, Annaswamy, Yanakiev, & Kolmanovsky, 2008a; Yildiz, Annaswamy, Yanakiev, & Kolmanovsky, 2008b). This paper expands on those results with further theoretical improvements, new experimental results and more detailed explanations of the experimental issues.

To fit the specific needs of the FAR application, APC design has been extended with additional features: First, an adaptive feedforward term is added which is crucial for disturbance rejection. Second, procedures are developed for the controller parameter initialization and the adaptation rate selection to reduce the calibration time and effort. Third, an algorithm to take care of the variable delay is introduced. Fourth, an anti-windup logic is used to prevent the winding up of the integrators used for parameter adaptation. Finally, a robustifying scheme is used to prevent the drift of the adaptive parameters. The main contribution of this work is the demonstration of the potential of this adaptive controller to improve the performance and to reduce the time and effort required for the controller calibration.

For comparison with the APC, in this paper a feedforward adaptive controller is also developed that attempts to minimize the impact of the purge fuel disturbance. This controller is also compared with the baseline controller using simulations and in-vehicle experiments.

While the control approach is adaptive, its development both benefits from and depends on the structural properties of the plant model. This model is briefly discussed next. The reader is referred to Guzzella and Onder (2004) for a more extended treatment of the underlying modeling techniques.

2. Plant model

The fuel–air ratio process dynamics are illustrated in Fig. 1 for which the reduced order model from the deviation in the commanded in-cylinder equivalence ratio to the measured equivalence ratio has the form (Yildiz et al., 2008b)

$$G(s) = \frac{1}{\tau_m s+1} e^{-\tau s}. \tag{1}$$