2008 American Control Conference
Westin Seattle Hotel, Seattle, Washington, USA
June 11-13, 2008

Adaptive Air Fuel Ratio Control for Internal Combustion Engines

Y. Yildiz, *Student Member, IEEE*, A. Annaswamy, *Fellow, IEEE,* D. Yanakiev, *Member, IEEE,* I. Kolmanovsky, *Fellow, IEEE* [1]

Abstract— **This paper treats the control of engine air-to-fuel ratio from the perspective of adaptive control of time-delay systems. High accuracy of engine air-to-fuel ratio control is required to meet stringent emissions regulations. Two adaptive controller designs are considered. The first design is based on feed-forward adaptation while the second design is based on both feedback and feedforward adaptation incorporating the recently developed Adaptive Posicast Controller. The two adaptive designs are compared with the baseline controller using simulations and vehicle experiments.**

I. Introduction

THE air-to-fuel ratio control is one of the most important control problems for conventional gasoline engines. Air-to-fuel ratio control performance can strongly impact key vehicle attributes such as emissions, fuel economy and drivability. For instance, the air-to-fuel ratio 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 operates efficiently when the fuel is matched to air charge in stoichiometric proportion. The TWC can also compensate for the air-to-fuel ratio deviation from stoichiometry, by either storing excess oxygen or releasing oxygen to compensate for its deficit. 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 [1]. The oxygen storage level in the TWC may be inferred on the basis of the TWC model and a signal from a switching Heated Exhaust Gas Oxygen (HEGO) sensor located downstream of the TWC.

A conventional air-to-fuel ratio control system includes two nested controllers. The outer-loop controller generates a reference air-fuel-ratio (set-point) for the inner-loop controller based, for instance, on the deviation of the estimated TWC stored oxygen state. The inner-loop controller maintains the air-to-fuel ratio upstream of the TWC at this set-point by using the measurements of the feedgas air-to-fuel ratio with a linear Universal Exhaust Gas Oxygen (UEGO) sensor to appropriately correct engine fueling rate. Small amplitude slow periodic modulation may also be superimposed over the set-point to further improve catalyst efficiency. The HEGO sensor downstream of the TWC is also used to improve robustness to UEGO sensor drifts, changes to fuel type, and for diagnostics.

The design of the inner loop consists of a feed-forward component which is fast but may not be always accurate and a feedback component that is slower but eliminates steady-state error [1]. The feed-forward component consists of estimation of the air and fuel path dynamics combined with appropriate compensations. These air and fuel dynamics correspond, mainly, to the intake manifold lag that affects the air charge, and the wall-wetting that determines the amount of fuel inducted into the cylinder for each fuel injection event during transient operation.

The air-fuel ratio control problem has been extensively investigated over many years. In terms of advanced approaches, here we mention the use of adaptive controllers [2], observer based controllers [3], H_∞ controllers [4] and Model Predictive Controllers [5]. The use of an electronic throttle as an additional control actuator [6] or secondary/port throttles [7] has been also explored. Apart from stoichiometric air-to-fuel ratio controllers, reference [8] considers control of air-to-fuel ratio in a lean burn engine using linear parameter-varying controllers. The motivation for these and related studies has been to achieve improved performance and robustness of the air-to-fuel ratio control thereby enabling emission, fuel economy and drivability improvements.

In this paper we consider two adaptive approaches to the design of the inner loop controller, which we refer to as "the controller" from now on. Our approach is different from [2] in that we use direct adaptive control whereas [2] presents an application of indirect adaptive control using nonlinear parameter estimation to realize the control law.

Main challenges in the design of the air-to-fuel ratio controller include variable time delay, uncertain plant behavior and disturbances introduced by purging the fuel vapor from the carbon canister or due to air charge estimation errors. The time delay in the system comprises two basic components [8]: the time it takes from the fuel injection calculation to exhaust gas generation and the time it takes for the exhaust gases to reach the UEGO sensor. The time delay in the system is a key factor limiting the bandwidth of the air-to-fuel ratio feedback loop. The plant uncertainty is the result of inaccuracies in air-charge estimation and wall-wetting 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.

[1] This work was supported through the Ford-MIT Alliance.

Yildiray Yildiz and Anuradha Annaswamy are with Massachusetts Institute of Technology, MA 02139 USA (e-mail: yildiray@mit.edu, aanna@mit.edu).

Diana Yanakiev and Ilya Kolmanovsky are with Ford Motor Company, MI 48121 USA (email: dyanakie@ ford.com, email: ikolmano@ ford.com)

978-1-4244-2079-7/08/$25.00 ©2008 AACC.

We, therefore, are interested in a control approach which can handle both uncertainties and large time-delays, and that can achieve excellent performance. The Adaptive Posicast Control (APC) is a recently developed control design approach that is especially suited for plants with large time-delays [9]. It can effectively combine adaptation to deal with uncertainties and ability to handle time delays, and it can be viewed as the adaptive counterpart to the classical Smith predictor. Previously, we have demonstrated a successful application of this approach to the engine Idle Speed Control (ISC) [10]. In this paper we will demonstrate an application of the APC to the air-to-fuel ratio control problem which, in comparison with ISC, has a larger delay that varies with the engine operating conditions. Thus, in comparison to ISC, the air-to-fuel ratio control problem represents a more formidable challenge to our approach.

For comparison with the APC, we will also develop in this paper a simple feed-forward adaptive controller that attempts to minimize the impact of the purge fuel disturbance. We will compare the adaptive feedforward and adaptive Posicast control designs with the baseline controller using simulations and in-vehicle experiments.

The content of this paper is as follows: In section II, the plant model is introduced with descriptions of the challenges for the controller design. In section III, three different controllers are presented: the baseline controller used in the experimental vehicle, the adaptive feed-forward controller developed under certain assumptions on the plant dynamics, and the APC. Simulation and experimental results are given in section IV. Finally, a summary is given and conclusions are discussed in section V.

II. SYSTEM MODEL

A block diagram representation of the plant, from fuel injection to the UEGO sensor measurement, is shown in Fig. 1, where "A" stands for the air charge. The fuel inducted into the engine cylinders is viewed as the output of the wall-wetting dynamics block, while the fuel injected by the injectors is an input to that block. The multiplication by the gain in the "1/A" block gives the Fuel-Air-Ratio (FAR) of the mixture in the engine cylinders (we will consider the control of FAR as opposed to AFR form now on as it scales linearly with fuel) and the delay block represents the combined effect of time delays in the system. The largest contributors to that delay are the time from the fuel injection to exhaust gas formation and the time needed for the exhaust gases to reach the UEGO sensor location.

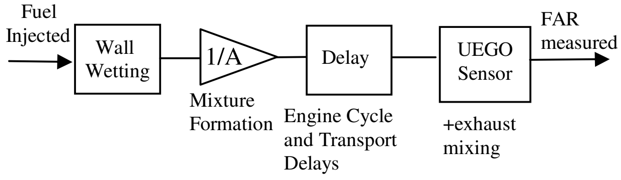


Figure 1: Plant block diagram representation.

Finally, the exhaust gases undergo mixing and the fuel-to-air ratio (FAR) is measured by the UEGO sensor.

Transfer functions used to model these dynamics are given below:

A. Wall wetting:

$$WW(s) = \frac{1+(1-X)\tau s}{\tau s+1} \tag{1}$$

where X is the fraction of the injected fuel that enters the liquid fuel puddle and τ is the time constant for fuel evaporation from the puddle.

B. Delay and UEGO sensor dynamics:

The total time delay and UEGO sensor dynamics are modeled as a first order transfer function in series with a pure time delay:

$$S(s) = \frac{K}{\tau_u s+1} e^{-\delta s} \tag{2}$$

III. CONTROLLER DESIGN

A. Baseline Controller

The baseline controller, which we now describe, is similar to the one operating in our test vehicle. The structure of the closed-loop system for the baseline controller case is described in Fig. 2, where $\hat{A}$ denotes the air charge estimate and $(F/A)_d$ designates the desired fuel-to-air ratio.

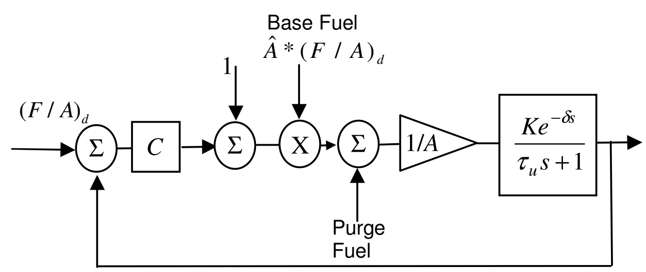


Figure 2: System structure with baseline controller.

The output of the baseline controller is calculated as:

$$u = (1+C)F_b , \tag{3}$$

where the base fuel is calculated as $F_b = \hat{A} * (F / A)_d$ and C is basically a Proportional-plus-Integral controller. In the actual vehicle implementation, a first-order filter in series with the PI controller and relay logic are used. The baseline controller uses the air charge estimate to calculate the necessary amount of fuel to feed-forward (this fuel quantity is referred to as the base fuel), and it uses the feedback controller C in a multiplicative manner to compensate for the uncertainties and unmeasured disturbances. The advantage of the multiplicative feedback over additive feedback (the latter is more typical in controls literature) is that the feedback fuel quantity scales proportionally to the value of the base fuel thereby providing better ability to compensate in transients when changes in vehicle operating point occur.

The wall-wetting dynamics (WW(s)) are not shown explicitly in Figure 2 because in the design of the baseline controller an assumption is made that wall-wetting dynamics are accurately compensated by the wall-wetting compensation function. In other words, the output of (3) is passed through an accurate inverse model of (1) to determine the fuel quantity to be injected.

Note that, to maintain stability in the presence of delay, the gains of the PI controller cannot be made very aggressive. Moreover, since the feed-forward path reacts to changing operating conditions immediately while the feedback path can react only after a delay, the overshoot in the response is difficult to avoid.

B. Adaptive Feed-Forward Controller (AFFC)

The system diagram with the Adaptive Feed-Forward Controller (AFFC) is shown in Fig. 3. Instead of the feedback path in Figure 2, a gain multiplier on the $(F/A)_d$ is adapted. The motivation for AFFC is to avoid overshoot in the air-to-fuel ratio response and to compensate for errors in the base fuel calculation due to, for example, injector uncertainties (modeled by the value of K different from 1) or "lost-fuel" effects present at cold engine conditions.

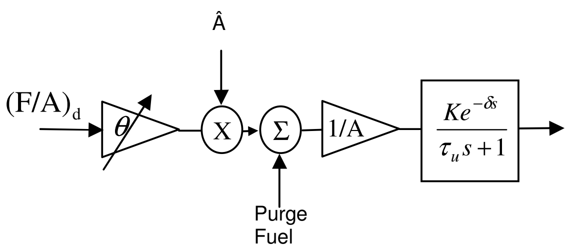


Figure 3: Overall system structure with AFFC.

The adaptive parameter θ is updated according to the following law:

$$\dot{\theta} = -\gamma e (F/A)_d (t-\delta), \tag{4}$$

where γ is the adaptation rate and the error e is defined as

$$e = (F/A)_{fb} - (F/A)_{\mathrm{m}}\,. \tag{5}$$

Here, $(F/A)_{fb}$ denotes the measured fuel-to-air ratio and $(F/A)_m$ is the output of a reference model. The reference model is given by a first order transfer function with a DC gain of 1 and a time constant equal to the time constant of the UEGO sensor's nominal time constant τ_u.

C. Adaptive Posicast Controller (APC)

When a non-perfect wall-wetting dynamics compensation is considered, the plant dynamics can be represented as in Fig. 4.

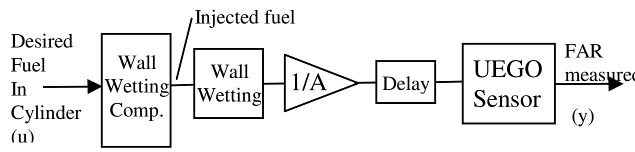


Figure 4: Plant representation for APC design.

Wall-wetting compensation is determined as the estimated inverse dynamics of the wall wetting model:

$$\mathrm{WWC(s)} = \frac{\hat{\tau} s + 1}{1 + (1-\hat{X})\hat{\tau} s} \tag{5}$$

The inclusion of wall-wetting model and non-perfect wall wetting compensation makes the problem harder, since now the system is 3rd order and includes more uncertainties. A simple adaptive feed-forward controller may not be able to make this system behave like the reference model due to a shortage of degrees of freedom. The plant model is given by

$$\mathrm{G(s)} = \frac{\hat{\tau} s + 1}{1 + (1-\hat{X})\hat{\tau} s} \frac{1 + (1-X)\tau s}{\tau s + 1} \frac{K e^{-\delta s}}{\tau_u s + 1} \tag{6}$$

The input-output description corresponding to the transfer function given in (6) can be written as

$$y(t) = G_0(s) u(t-\delta), \qquad G_0(s) = \frac{k_p Z_p(s)}{R_p(s)} \tag{7}$$

where 'y' is the deviation of the measured fuel-to-air ratio, 'u' is the deviation of the control input and $G_0(s)$ is the delay free part of the system transfer function $G(s)$. $G_0(s)$ is an n^{th} order transfer function model with relative degree n^* less than or equal to two ($n=3$ and $n^*=1$ in our case) and has minimum phase zeros. Moreover, all the poles of $G_0(s)$ have multiplicity one. Note that only input-output measurements are available.

The goal of the controller is to make the output (deviation of the measured fuel-to-air ratio in our case) to follow a reference model with a transfer function

$$y_m(t) = G_{0ref}(s) u(t-\delta), \qquad G_{0ref} = \frac{k_m}{R_m(s)}, \tag{8}$$

where R_m is a monic Hurwitz Polynomial of degree n^*.

It is shown in [9] that the following controller

$$u = \theta_1^T \omega_1 + \theta_2^T \omega_2 + \int_{-\delta}^{0} \lambda(t,\sigma) u(t+\sigma) d\sigma + \theta_4 r \tag{9}$$

$$\frac{\partial \theta}{\partial t} = -\Gamma e_1(t) \omega(t-\delta),$$

$$\dot{\omega}_1 = \Lambda \omega_1 + l u(t-\delta), \tag{10}$$

$$\dot{\omega}_2 = \Lambda \omega_2 + l y(t), \tag{11}$$

where,

$$\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \lambda \\ \theta_4 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} \gamma_{11} & 0 & 0 & 0 \\ 0 & \gamma_{12} & 0 & 0 \\ 0 & 0 & \gamma_{13} & 0 \\ 0 & 0 & 0 & \gamma_{14} \end{bmatrix} \tag{12}$$

$$\omega = \begin{bmatrix} \omega_1 \\ \omega_2 \\ u \\ r \end{bmatrix}, \quad e_1 = y - y_m$$

$\theta_1, \theta_2, \omega_1, \omega_2 \in R^n$, $\lambda, \theta_4, u, r, \gamma_{13}, \gamma_{14} \in R$, and $\gamma_{11}, \gamma_{12} \in R^{nxn}$, Λ is an nxn stable matrix and (Λ, l) is a controllable pair, makes the plant output y follow the reference model output y_m, asymptotically. The APC structure is shown in Fig. 5.

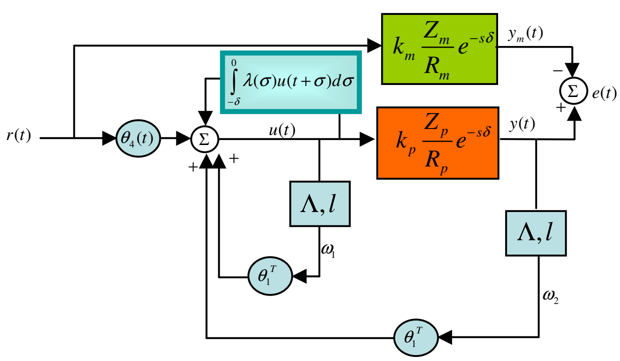


Figure 5: Block diagram of the Adaptive Posicast Controller (APC).

IV. Simulations and Experimental Results

Fig. 6 compares the tracking and purge disturbance rejection performance of the baseline controller and of the AFFC when wall-wetting dynamics are assumed to be perfectly compensated. In Fig. 6, Φ denotes the normalized fuel-to-air ratio or the equivalence ratio (ER) (so that stoichiometric fuel-to-air ratio of 0.0685 corresponds to Φ =1). The upper plot shows the simulated response to a pulse train reference and the lower plot shows the response to a step purge disturbance introduced at time t=20 sec and removed at time t=40 sec. It is assumed that the wall-wetting compensation is perfect and the time delay is known to be 0.4 sec. While designing the AFFC, the UEGO dynamics are assumed to have nominal values but then the plant dynamics were chosen to have 20% deviations in K and τ_u. The baseline controller is tuned to perform well for both tracking and disturbance rejection. As discussed before, the baseline controller cannot avoid overshoots due to the delay in the system, while the AFFC can track the reference comparatively better. On the other hand, the disturbance rejection capabilities are similar, since when the reference is constant, the AFFC is essentially an integral controller.

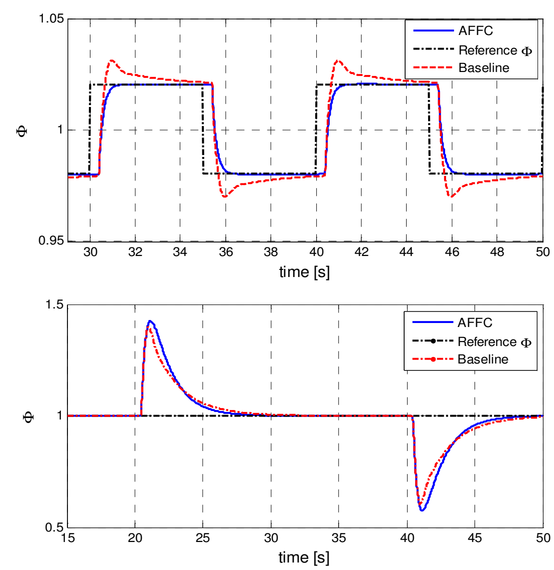
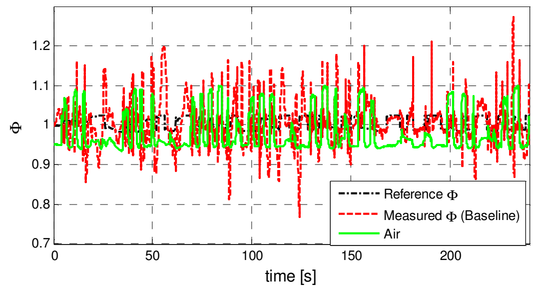


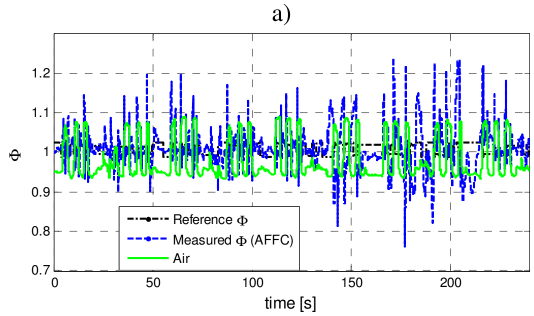
Figure 6: Comparison of baseline controller and Adaptive Feed-forward Controller (AFFC). Response to a set-point change (upper plot) and response to purge disturbance (lower plot).

We have also tested AFFC experimentally and compared it with the existing baseline controller. The development vehicle used for the experiments was equipped with a 5.4-liter V8 engine. At the test time, the calibration of transient fuel compensation was not fully completed, which allowed to subject both controllers to challenging scenarios. Also, the time delay varies in the experiments as opposed to the cases simulated above. Fig. 7 shows the results from a 4-minute drive test. Note that the air charge values have been scaled to show them in the same plot with Φ. The test was conducted in a relatively uncontrolled environment, e.g., without controlling the speed or load, as can be observed in Figs. 7a-c. The vehicle was accelerated and decelerated rather sharply and the purge flow was also not controlled, as shown in

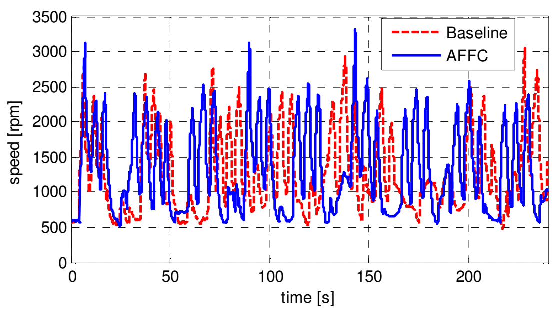
Fig. 7-d. The RMS error value of the deviations from the reference is calculated as 0.0052 and 0.0051 for the baseline controller and for the AFFC, respectively. Their performances are similar, consistently with our simulation results, as the dominant factors affecting the response are the purge and air disturbances, and not the reference tracking.



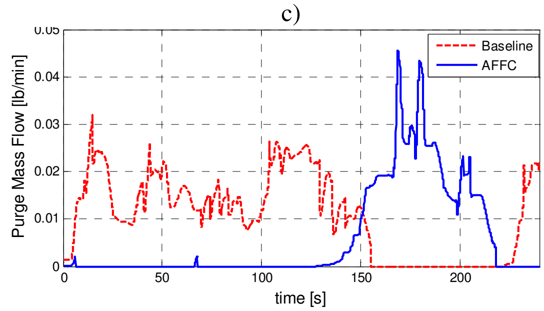
a)



b)



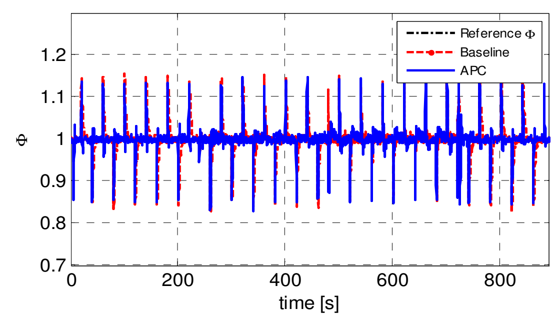
c)



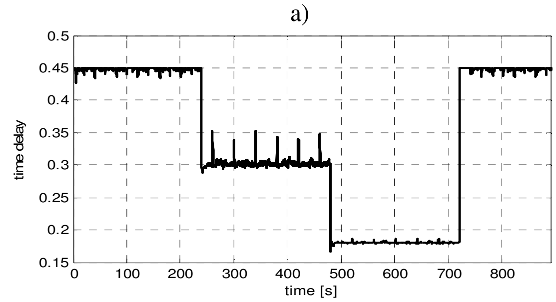
d)

Figure 7: Experimental performance of baseline controller and AFFC during actual driving tests. a) Fuel air ratio when baseline controller is active b) Fuel air ratio when AFFC is active, c) Engine speeds during the tests, d) Purge fuel disturbances during the tests.

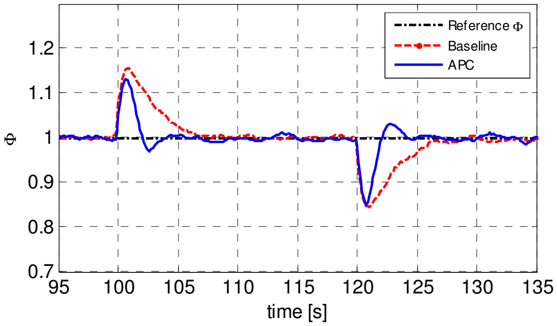
The results of experimental testing of the APC over a fifteen-minute period are presented in Fig. 8. To simplify the development and implementation of the APC, the system dynamics from fuel injection to ER measurement have been approximated by a first-order lag with a pure delay in series. A similar approximation has been adopted in [1] for the purpose of designing the fuel-to-air ratio feedback controller. Our experiment was conducted while the vehicle was idling at different speeds. From t=0 sec to t=240 sec, the idling speed was 700 rpm. The speed increased to 1000 rpm at t=240 sec and increased again to 2000 rpm at t=480 sec. It then decreased back to 700 rpm at t=720 sec. Figs. 8a and 8b show the ER change and the delay variation during this experiment. As expected, the delay decreases as the engine speed and load increase. Figs. 8c-8e show the ER change at different time windows of the experiment. Notice that at engine speeds 700 rpm and 1000 rpm, the APC performs much better than the baseline controller. At 2000 rpm, the difference between the two controllers becomes less noticeable. The main reason for this is that as the engine speed increases to 2000 rpm, the delay in the system becomes less prominent, thus the delay compensation does not provide as much of a benefit as when the delay is large. Another reason is that our APC was designed for the worst-case delay value, which is 0.45 sec at 700 rpm. When the speed increases to 2000 rpm, the delay becomes equal to 0.18 sec. Although the controller maintains robustness, its performance may not be as good as it can be given the reduced value of the delay. An approach where we incorporate a time-varying delay estimate in the implementation of the APC is under on-going investigation, with promising preliminary results.



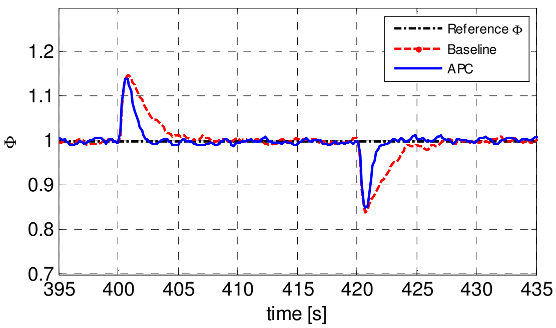
a)



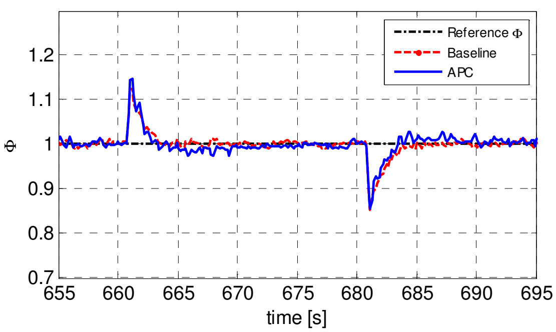
b)



c)



d)



e)

Figure 8. Experimental performance of baseline controller and APC during actual driving tests. a) FAR change during 15 min. of experiment b) Delay variation c),d),e) FAR change at certain time windows during the experiment.

V. Summary

In this paper, we have considered the air-to-fuel ratio control problem in port-fuel-injection (PFI) spark-ignition (SI) engine. Two controllers, an Adaptive Feed-Forward Controller (AFFC) and an Adaptive Posicast Controller (APC), have been developed and implemented in a vehicle. The AFFC is a simple controller based on feedforward adaptation while the APC is a more elaborate controller that uses adaptation in both feed-forward and feedback paths and is based on a recently developed adaptive control method for time-delay systems. The AFFC has been shown in simulations and experiments to have better reference tracking and similar disturbance rejection capabilities when compared to the existing baseline controller. The APC, a more complex adaptive controller, has been shown in experiments to achieve faster recovery from disturbances. It has also been observed in our vehicle experiments that implementing APC using an upper bound on the delay as a delay estimate assures robustness against delay variations.

In terms of applications of the APC, the air-to-fuel ratio control problem is more challenging than the Idle Speed Control problem which the authors of this paper have treated in [10], due to a larger delay and different character of disturbances and uncertainties. The experimental results reported here are promising and demonstrate that the APC can be effective for the air-fuel ratio problem as well. Further optimizations of the APC in presence of fast engine speed and load changes are currently under investigation.

Acknowledgments

We would like to gratefully acknowledge Steve Magner, Mrdjan Jankovic and Bruce Anderson at Ford Research and Advanced Engineering for several valuable discussions and suggestions.

References

[1] Guzzella, L. and Onder C. H., *Introduction to Modeling and Control of Internal Combustion Engine Systems.* Springer, 2004.

[2] Turin, R. and Geering H., "Model-Reference Adaptive A/F Ratio Control in an SI Engine Based on Kalman-Filtering Techniques," *American Control Conference*, 1995, pp. 4082 – 4090

[3] Powell, J. D., Fekete, N. P., Chang C. F., "Observer-Based Air-Fuel Ratio Control," *IEEE Control Systems Magazine*, vol. 18, issue 5, pp. 72-83, Oct 1998.

[4] Mianzo, L., Peng, H., Haskara I., "Transient Air-Fuel ratio H_∞ Preview Control of a Drive-by-Wire Internal Combustion Engine," *American Control Conference,* 2001, pp. 2867 – 2871.

[5] Muske, K. R., Jones, C. P. J., "A Model-based SI Engine Air Fuel Ratio Controller," *American Control Conference,* 2006, pp. 3284 – 3289

[6] Chang, C. F., Fekete N. P., Powell J. D., " Engine Air-Fuel Ratio Control Using an Event-Based Observer," *SAE* Paper No. 930766, 1993

[7] Stefanopoulou, A. G., Grizzle, J. W., Freudenberg, J. S., "Engine Air-Fuel Ratio and Torque Control using Secondary Throttles," *Conference on Decision and Control,* 1994, pp. 2748 – 2753.

[8] Zhang F., Grigoriadis, K., Franchek, M., and Makki, I., "Linear Parameter Varying Lean Burn Air-Fuel Ratio Control for a Spark Ignition Engine," *Journal of Dynamic Systems, Measurement and Control*, Vol. 129, pp. 404-414, 2007.

[9] Niculescu, S.I., and Annaswamy, A., "An Adaptive Smith-Controller for Time-Delay Systems with Relative Degree $n^* \leq 2$," *Systems & Control Letters*, vol. 49, issue 5, pp. 347-358, Aug 2003.

[10] Yildiz, Y.; Annaswamy, A.; Yanakiev, D.; Kolmanovsky, I., "Adaptive Idle Speed Control for Internal Combustion Engines," *American Control Conference,* 2007, pp. 3700 – 3705.