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Fuel-Injection Control of S.I. Engines

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Abstract

It is known that about 50 % of air pollutants comes from automotive engine exhaust, and mostly in a transient state operation. However, the wide operating range, the inherent nonlinearities of the induction process and the large modeling uncertainties make the design of the fuel-injection controller very difficult. Also, the unavoidable large time-delay between control action and measurement causes the problem of chattering.

In this paper, an observer-based control algorithm based on sliding mode control technique is suggested for fast response and small amplitude chattering of the air-to-fuel ratio. A direct adaptive control using Gaussian networks is applied to the compensation of transient fueling dynamics.

The proposed controller is simple enough for on-line computation and is implemented on an automotive engine using a PC-386. The simulation and the experimental results show that this algorithm reduces the chattering magnitude considerably and is robust to modeling errors.

1 Introduction

The method selected to meet the new exhaust emissions standards has been to use a catalytic converter that simultaneously oxydizes excess levels of the tail pipe pollutants. Unfortunately, the efficiency of the catalyst is very sensitive to the variation of the air-to-fuel(A/F) ratio. As shown in figure 1, the conversion efficiency of the catalyst is very sensitive to the variation of the ratio, and even 1 % deviation from the stoichiometric ratio results in up to 50 % degradation in the conversion of one or more pollutants. Therefore, it is apparent that the main issue of the control of the S.I. engine is to control the fuel-injector(s) to keep the A/F ratio to stoichiometry(14.7) to maximize the efficiency of the three-way catalyst both in steady-state and transient operations.

The A/F ratio control in steady-state operation is easy compared to the transient control, since all the air-induction dynamics and the fueling dynamics disappear at steady-state. However, in the urban traffic mode, the engine is operated mostly in a transient. A crucial fact that makes the problem difficult is that the oxygen sensor which detects the A/F ratio only tells leanness or richness of the air-fuel mixture, and there is considerable measurement time delay.

Many of the current production fuel-injection controllers rely on open-loop feed-forward control based on a look-up table with PI(proportional plus integral) feedback control [3]. However, building the table is a laborious process of calibration and tuning. Other linear control techniques, such as LQG, pole placement and LQG/LTR have little advantage, since they need the output magnitude information while the control system is nonlinear and the sensor output is nearly binary [4][13].

As a solution to this problem, a sliding mode fuel-injection control method was proposed [6][7]. This is an analytic design method and in good agreement with the binary nature of the oxygen sensor signal. However, in spite of many merits, this method has the problem of large amplitude chattering which is due to an unavoidable measurement time-delay. The chattering problem limits the magnitude of the feedback gain while an appropriate amount of gain is required to guarantee the surface attraction condition under the existence of modeling errors. Both the 'speed-density' method and the 'mass-air-flow-meter' method have sufficient errors which force the gain to be increased.

There has been a great deal of research on transient air/fuel characteristics, and it is concluded that three characteristic delays are responsible for unwanted air/fuel ratio excursions during the transient operations [1][12][15][16][17]. These are the time-delay of the com-

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puter control system, a physical delay in the intake manifold and a physical delay of the fuel flow which results from the finite rate of evaporation of the fuel film on the intake manifold and port walls.

Recently, Baruah suggested a simulation model for the transient operation of spark-ignition four cylinder engines [2]. Matthews et. al. suggested an intake and ECM(Engine Control Module) submodel and examined tip-in/tip-out behavior [17]. Hendricks et. al. suggested a Mean Value engine model and observation air/fuel control techniques using their Mean Value model [15]. Chang et. al. suggested a similar event-based observation control technique [5].

In this paper, an observer-based fuel-injection control algorithm is derived to calculate the necessary fueling rate into the cylinders. Numerical simulation shows the algorithm results in much less chatterings than those of the sliding mode control. To compensate the transient fuel delivery dynamics, a direct adaptive control algorithm using Gaussian neural network[18] is applied.

The performance of the controller combining both the algorithms are compared with those of a production engine controller. The suggested controller is implemented on an 3.8 liter V-6 engine using a PC-386.

2 Engine model for control

A dynamic engine model for designing a fuel-injection controller can be composed of the air flow dynamics through the intake manifold and the fuel delivery dynamics. The air flow dynamics through the intake manifold can be expressed as :

$$\dot{m}_a = \dot{m}_{ai} - \dot{m}_{ao}(\omega_e, m_a) \tag{1}$$

where m_a is the mass of air in the intake manifold, ω_e the engine speed, $\dot{m}_{ai}$ the air-mass-flow rate into the manifold and $\dot{m}_{ao}$ the air-mass-flow rate out of the manifold given as a function of ω_e and m_a. The air flow dynamics(1) is a part of the two-state continuous-time engine model developed by D. Cho and K. Hedrick[10][11]. The air mass flow rate into the manifold, $\dot{m}_{ai}$ is measured by a hot-wire sensor. The air mass flow rate out of the manifold , $\dot{m}_{ao}$ can not be measured, but during steady state operation, can be calculated by measuring other engine variables such as engine speed and manifold pressure. By noting the steady state air flow rate out of the manifold as $\dot{\bar{m}}_{ao}(m_a, \omega_e)$, the true air flow rate during transient operations can be expressed as :

$$\dot{m}_{ao} = (1 + e)\, \dot{\bar{m}}_{ao}(m_a, \omega_e) \tag{2}$$

where e is the multiplicative error fraction. The steady state air flow rate is a nonlinear engine map as a function of engine speed and manifold air mass. For S.I. engines, the slope of the map in the direction of m_a, is always positive. This characteristics is exploited in the controller design.

The fuel delivery dynamics can be approximated as a combination of pure time delay and a first order lag, i.e.

$$\dot{m}_{fo}(t) = \frac{1}{s/\tau_f + 1}\, \dot{m}_{fc}(t - t_{fd}) \tag{3}$$

where $\dot{m}_{fc}$ is the fuel command, $\dot{m}_{fo}$ the delivered fuel, τ_f the fueling time constant, and t_{fd} the pure time delay. The pure time delay is caused by computation time delay and the delays in opening the intake valves. The lag is accounted for fuel evaporation on the intake wall. The $\tau - X$ fueling model[15] is well known, but does not include the pure time delay.

3 Observer-based sliding mode control

The sliding mode control method has been developed as a systematic way to design a controller for a nonlinear plant [19][21]. Moreover, the binary nature of the measurement signal is in good agreement with that of the sliding mode control method. The oxygen sensor at the exhaust only tells richness or leanness of the air to fuel mixture, and has considerable time delay(t_d) which can be approximated by

$$t_d = 0.02 + \frac{4\pi}{\omega_e} \qquad \text{(sec.)} \tag{4}$$

where ω_e is the engine speed in rad/sec. The objective of the fuel injection control is maintaining the air to fuel ratio close to 14.7(stoichiometry ratio), i.e.

$$\frac{\dot{m}_{ao}}{\dot{m}_{fo}} = 14.7 = \beta \tag{5}$$

To decide the rate of fuel to be injected is not trivial because the mass air flow rate into the cylinder, $\dot{m}_{ao}$, can not be measured. In this section, $\dot{m}_{fo}$ will be calculated, and the compensation of fuel delivery dynamics is dealt in next section using Gaussian neural network. Following the sliding mode control technique, we define the sliding surface as :

$$s = \dot{m}_{ao} - \beta \dot{m}_{fo} \tag{6}$$

Then the control objective is to maintain s close to zero. The measurement output, y by the oxygen sensor is expressed as :

$$y(t) = sign(s(t - t_d)) \tag{7}$$

The sliding surface is rewritten as :

$$s = (1 + e)\dot{\bar{m}}_{ao} - \beta \dot{m}_{fo} \tag{8}$$

Differentiation of the sliding surface yields :

$$\begin{aligned} \dot{s} &= \ddot{\dot{m}}_{ao} + e\ddot{\dot{m}}_{ao} + \dot{e}\ddot{m}_{ao} - \beta\ddot{m}_{fo} \\ &= \frac{\partial \dot{m}_{ao}}{\partial m_a}\,\dot{m}_a + \frac{\partial \dot{m}_{ao}}{\partial \omega_e}\,\dot{\omega}_e + e\ddot{m}_{ao} + \dot{e}\dot{m}_{ao} - \beta\ddot{m}_{fo} \end{aligned}$$

Putting the manifold dynamics equation(1), and by setting,

$$\beta\ddot{m}_{fo} = -\beta\frac{\partial \dot{m}_{ao}}{\partial m_a}\,\dot{m}_{fo} + (\frac{\partial \dot{m}_{ao}}{\partial m_a}\,\dot{m}_a + \frac{\partial \dot{m}_{ao}}{\partial \omega_e}\,\dot{\omega}_e) + l\,y(9)$$

the closed loop dynamics of the sliding surface becomes

$$\dot{s} = -\frac{\partial \dot{m}_{ao}}{\partial m_a}\,s + e\ddot{m}_{ao} + \dot{e}\dot{m}_{ao} - l\,y \tag{10}$$

where l is a positive constant. Since the slope $\partial\dot{m}_{ao}/\partial m_a$ is in between 15 - 20, the resulting closed loop dynamics is much faster than that of the conventional sliding mode control, which is

$$\dot{s} = e\ddot{m}_{ao} + \dot{e}\dot{m}_{ao} - l\,y \tag{11}$$

It can be shown that the chattering magnitude of the control is only 20 % of that of the sliding mode control[8,9]. The first order dynamic equation(9) of $\dot{m}_{fo}$ has the form of Luenberger observer with observer gain l.

The rate of fuel injection is calculated by integrating (9) :

$$\begin{aligned} \dot{m}_{fo}(t) &= \dot{m}_{fo}(0) \\ &+ \frac{1}{\beta}\int_0^t [\frac{\partial \dot{m}_{ao}}{\partial m_a}(\dot{m}_{ai} - \beta\dot{m}_{fc}(\tau)) + \frac{\partial \dot{m}_{ao}}{\partial \omega_e}\,\dot{\omega}_e]\,d\tau \\ &+ \frac{1}{\beta}\int_0^t l\,y(\tau)\,d\tau \end{aligned}$$

This control law suggests a good way to combine the speed-density method which uses $\dot{m}_{ai}$ and the air-mass-flow-meter method which uses $\dot{m}_{ao}$.

4 Gaussian network for transient fuel compensation

During transient operation, i.e. when the throttle position changes quickly, the amount of steady state fueling rate($\dot{m}_{fo}$) should be compensated because of the fueling dynamics(3). In this section, the amount of transient fueling rate is estimated using a direct adaptive control. In subsection 4.1, an introduction of the direct adaptive control using Gaussian network[18] is given.

4.1 Direct adaptive control using Gaussian network

Given a nonlinear dynamic system in a Canonical form

$$x^{(n)}(t) = f(x(t), \dot{x}(t), \cdots, x^{(n-1)}(t)) + bu(t) \tag{12}$$

where f is an unknown function, $u(t)$ the input, and b a non-zero known constant. We try to approximate the unknown function f with $\hat{f}(x)$ which is expanded by Gaussian functions.

$$\hat{f}(x) = \sum_{i=1}^{n} \hat{c}_i \cdot exp\left(-\frac{r_i^2}{\sigma^2}\right) \tag{13}$$

where n is the number of the sampling points in the state space, σ a positive constant, $\hat{c}_i$ are the estimations of true values of the coefficients c_i, and r_i the distances from the state x to the fixed sampling points in the state space. The construction of $\hat{f}(x)$ can be represented as a network with one hidden layer. For a smooth function $f(x)$, it is shown that $\hat{f}(x)$ can uniformly approximate $f(x)$ within chosen degree of accuracy using finite number of Gaussian function, i.e.

$$f(x) = \hat{f}(x) + e(x) \tag{14}$$

where the error $e(x)$ satisfying $|e(x)| < c$ for a given constant c [18].

Choose the sliding surface s as

$$s = x^{(n-1)}(t) + \lambda_{n-2}x^{(n-2)}(t) + \cdots + \lambda_1\dot{x}(t) + \lambda_0 x(t) \tag{15}$$

and choose a Lyapunov function V as

$$V = \frac{1}{2}\left(s^2 + \frac{1}{g}\sum_{i=1}^{n}\tilde{c}_i^2\right) \tag{16}$$

where $\tilde{c}_i = c_i - \hat{c}_i$, and g is a positive constant. The differentiation of V yields

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{g}\sum_{i=1}^{n}\tilde{c}_i\dot{\tilde{c}}_i \\ &= s\left(f + bu + \lambda_{n-2}x^{(n-1)}(t) + \cdots + \lambda_0\dot{x}(t)\right) - \frac{1}{g}\sum_{i=1}^{n}\tilde{c}_i\dot{\hat{c}}_i \end{aligned}$$

where $\dot{\tilde{c}}_i = -\dot{\hat{c}}_i$ is used. By choosing the control input u satisfying

$$bu = -\tilde{f} - \lambda_{n-2}x^{(n-1)}(t) - \cdots - \lambda_0\dot{x}(t) - Ks \tag{17}$$

where K is a feedback gain, we have

$$\dot{V} = -Ks^2 + e(x) + \sum_{i=1}^{n}\left(s \cdot exp\left(-\frac{r_i^2}{\sigma^2}\right) - \frac{1}{g}\dot{\hat{c}}_i\right) \tag{18}$$

By choosing the adaptation law for the coefficients c_i as

$$\dot{\hat{c}}_i = g \cdot s \cdot exp\left(-\frac{r_i^2}{\sigma^2}\right) \tag{19}$$

we have

$$\dot{V} = -Ks^2 + e(x) \tag{20}$$

Therefore, the Lyapunov function is bounded for a bounded approximation error $e(x)$.

4.2 Transient fuel dynamics compensation using Gaussian network

Since the transient fuel delivery dynamics includes pure time delay, feedforward control using the engine variables faster than the mass air flow rate out of the manifold($\dot{m}_{ao}$) is required. The positive or negative amount of transient fueling rate($\dot{m}_{ftr}$) is considered as a function of the rate of throttle change($\dot{\alpha}$) and the mass air flow rate into the manifold($\dot{m}_{ai}$). The total fuel command to the injector($\dot{m}_{fc}$) is expressed as

$$\dot{m}_{fc} = \dot{m}_{fo} + \dot{m}_{ftr}(\dot{\alpha}, \dot{m}_{ai}) \tag{21}$$

The reason for choosing $\dot{\alpha}$ as an independent variable is that the rate of throttle change is faster than the mass air flow rate out of the manifold, $\dot{m}_{ao}$, and decides the sign of the transient fueling rate, $\dot{m}_{ftr}$. The mass air flow rate into the manifold($\dot{m}_{ai}$) is selected because $\dot{m}_{ai}$ is faster than $\dot{m}_{ao}$, and is similar in form with the steady state fueling rate, $\dot{m}_{fo}$.

Following the procedure in section 4.1, and using a Lyapunov function

$$V = |s| + \frac{1}{2g}\sum_{i=1}^{n}\tilde{c}_i^2 \tag{22}$$

the transient fueling is decided by

$$\dot{m}_{ftr} = \sum_{i=1}^{n}\hat{c}_i exp\left(-\frac{r_i^2}{\sigma^2}\right) \tag{23}$$

with the adaptation law for the coefficients

$$\dot{\hat{c}}_i = sign(s)\cdot g\cdot exp\left(-\frac{r_i^2}{\sigma^2}\right) \tag{24}$$

Since at time t only $sign(s(t-t_d))$ is available, the adaptation is delayed by t_d in the actual implementation.

5 Simulation results

Simulation has been done assuming no fuel delivery dynamics. The model error in the mass air flow rate into the cylinder($\dot{m}_{ao}$) is assumed as :

$$e(t) = 0.1\sin(\pi t) \tag{25}$$

This represent ± 10 % error with 0.5 Hz frequency which is 5 times faster than the error model used in [6].

The measurement time-delay of the oxygen sensor is the transportation time for an amount of air to enter the cylinders, go through combustion, and travel down to the sensor plus sensor response time. In this paper, $t_d = 20ms + 4\pi/\omega_e(t)$ was chosen for simulation[6]. The throttle is varied as shown in figure 2 to simulate fast acceleration and deceleration which allows the engine to be operated between $1000rpm$ and $4000rpm$.

The performance of the observer-based controller was demonstrated for the case with modeling error but without measurement time-delay. The simulation result is as shown in figure 3. Next, the observer-based control was simulated for the plant with the time-delay . Figure 4 shows that this controller is very robust to the time-delay and the A/F ratio is in the desired boundary of $\pm$ 1.4 % error for most of the time.

6 Experimental results

Most of the experimental results reported in the literature are obtained for tip-in tip-out throttle modes but for a fixed engine speed. However, in many cases, the engine speed changes dramatically during the throttle modes, since such throttle modes generally accompany gear shifting. Other results are obtained when the tip-in tip-out modes are in the large throttle opening zone. Since the intake manifold air pressure(or air mass) reaches more than 80 % of the atmospheric(or full-open throttle) pressure before the throttle is half-opened, the wild throttle modes in the large throttle opening zone give only mild variations of the manifold pressure.

In this study, all the experimental results are obtained under more severe and more realistic conditions: the dynamometer load is fixed, dynamometer inertia is the only external inertia, the throttle varies in a small throttle opening zone.

The suggested controller was evaluated at the University of California Berkeley engine dynamometer test rig, and compared with a production ECM and a sliding mode controller. The engine used for the test is a 3.8 liter V-6 sequential port-injection S.I. engine. The air-mass-flow rate through the throttle body, the manifold air mass, pressure and temperature and the oxygen in the exhaust gas were measured using typical production engine sensors.

The throttle variation in the experiment is shown in figure 5. With the external load fixed to 67.7 N-m, the variation induces large variation of the manifold pressure. During transient operation, the air to fuel ratio of the observer based sliding control with transient fuel compensation(figure 6) shows smaller amplitudes of excursions than those of the production ECM(figure 7). Comparing the duration times of the air to fuel ratio outside the 14.5 - 14.7 band, the observer based controller is better than the production ECM. Figure 8 shows the compensated transient fueling rate. Sufficient learning process(on line adaptation of the constants, $\hat{c}_i$) has been done in obtaining the transient fueling rate map, $\dot{m}_{ftr}(\dot{\alpha}, \dot{m}_{ai})$. Large peaks of the air to ratio are observed when the transient fuel compensation is not accompanied with the observer based control (figure 9).

7 Conclusion

The air to fuel ratio control of S.I. engine has been conducted using an observer based sliding mode control and a Gaussian neural network. The simulation and experimental results shows that the closed loop dynamics is much faster than that of the conventional sliding mode control. Also the transient air to fuel ratio excursion is considerably smaller than those of the production ECM. With the new control method, the time consuming gain tuning process can be avoided. The transient fueling compensation algorithm can be used to different types of engines and is insensitive to the aging of engines, because on-line adaptation is carried out.

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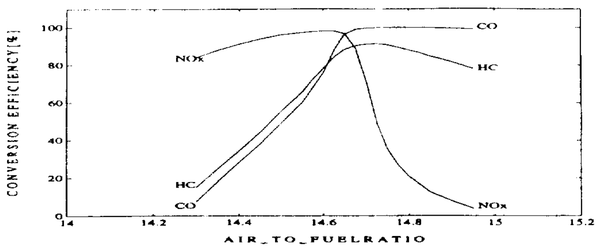

Figure 1. A typical catalytic converter efficiency

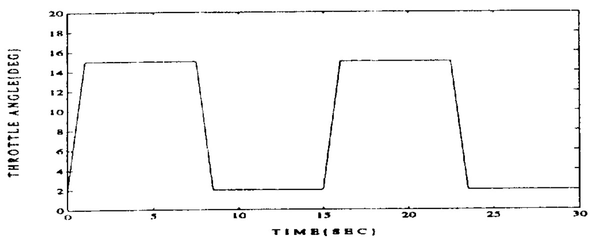

Figure 2. Throttle changes for simulation

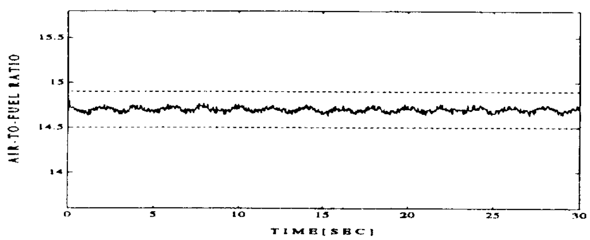

Figure 3. A/F ratio of the observer-based control without measurement time-delay(Simulation)

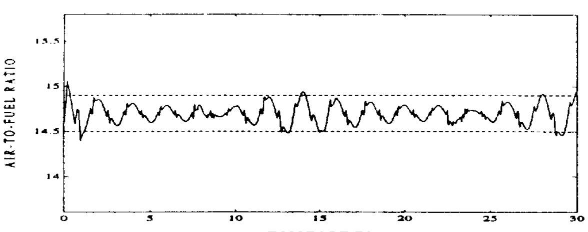

Figure 4. A/F ratio of the observer-based control with measurement time-delay(Simulation)

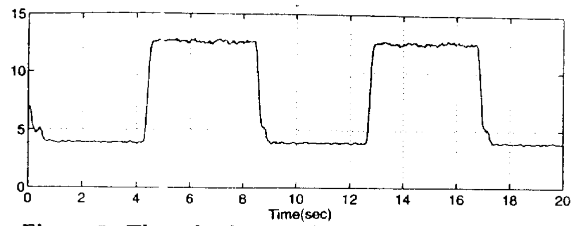

Figure 5. Throttle changes for experiment

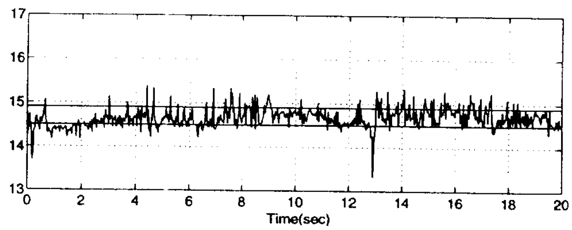

Figure 6. A/F ratio of the observer-based control with transient fuel compensation(Experiment)

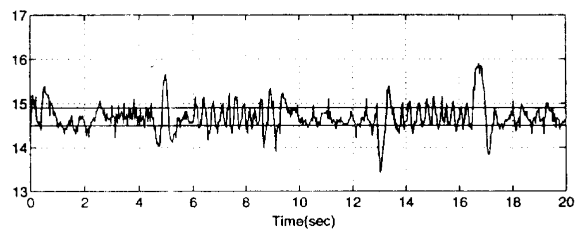

Figure 7. A/F ratio of production ECM

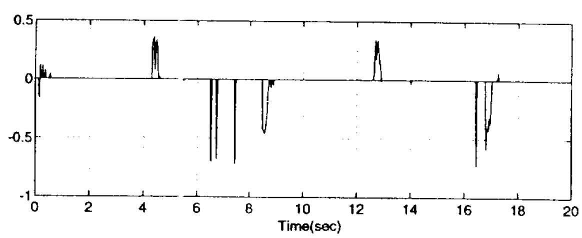

Figure 8. Transient fueling compensation(Experiment)

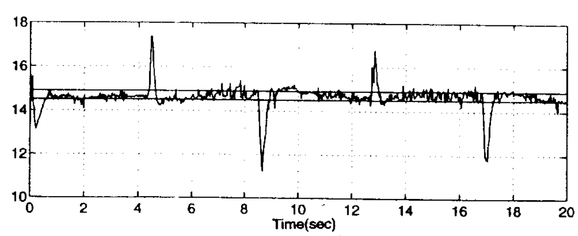

Figure 9. A/F ratio of the observer-based control without transient fuel compensation(Experiment)