Improved Cylinder Air Charge Estimation for Transient Air Fuel Ratio Control

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Abstract

Modern automobile engines require precise regulation of air-fuel ratio (A/F) to attain high catalytic converter efficiency and minimize tailpipe emissions. During engine transients, good A/F control requires, in turn, accurate estimation of the air charge entering the cylinders during each induction event. This paper describes the development and validation of a nonlinear, open-loop air charge estimator. A key feature is the inclusion of the dynamics of the mass air flow meter. The estimator was implemented on a V8 engine in a dynamometer test cell. Experimental results confirm the improved A/F control predicted by simulation. The prototype implementation was accomplished using an automatically generated high-level language control code executing in a dedicated PC and communicating via a shared memory board with the production microprocessor-based controller.

1 Introduction

Precise control of air-fuel ratio (A/F) to the stoichiometric value is necessary to minimize exhaust emissions in vehicles employing a three-way catalytic converter (TWC). A/F control has two principal components: a closed-loop portion in which a signal related to A/F from an exhaust gas oxygen (EGO) sensor located in the exhaust stream of the engine is fed back through a digital PI controller to regulate the fuel injection pulse width, and an open-loop, or feedforward portion in which injector fuel flow is controlled in response to a signal from an air flow meter. Due to the relatively long delay inherent in the induction-compression-power-exhaust cycle of the engine, plus the transport delay in the exhaust manifold, the feedback, or closed-loop portion of the A/F control system is fully effective only under steady-state operating conditions. Equally important, a reliable EGO sensor signal is available only after the sensor has attained a stabilized operating temperature, and thus closed-loop A/F control is not possible immediately upon starting the engine. Hence, under transient and cold start conditions, the feedforward portion of the A/F controller is particularly important.

In this paper, we describe the development and implementation of an air charge estimator for an eight cylinder engine. The estimator is required to predict the air charge entering the cylinders downstream of the intake manifold plenum from available measurements of air mass flow rate upstream of the throttle. A schematic diagram of the system is shown in Figure 1.

One of the main motivations for this study was the practical problem posed by the fact that the hot-wire anemometer used to measure mass air flow rate has fairly slow dynamics. Indeed, the time constant of this sensor is on the order of an induction event for an engine speed of 1500 revolutions per minute, and is only about four to five times faster than the dynamcis of the intake manifold. We will show that taking these dynamics into account in the air charge estimation algorithm can significantly improve the accuracy of the algorithm; it will also be seen to have substantial benefits for reducing emissions.

In the following sections, a phenomenological model incorporating the dynamics for the air meter and intake manifold is assembled, and an on-line estimator for cylinder air charge is developed. Simulation evidence is first presented showing the importance of including the dynamic characteristics of the air meter in the estimator. An experimental implementation is discussed and corroborating engine data are presented.

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2 Manifold Filling and Cylinder Air Charge Model

Mathematical models of the air path in an n-cylinder combustion engine have been studied for many years. The models can be roughly categorized as two types: PDE models for engine component design or off-line simulation [1, 3, 9] and lumped models for control law design and real-time simulations [5, 7, 6]. In the following, we will assemble a lumped model suitable for developing an on-line cylinder air charge estimator[1].

Let P, V, T and m be the pressure in the intake manifold (psi), volume of the intake manifold and runners (liters), temperature (°R) and mass ($\mathrm{lb_m}$) of the air in the intake manifold, respectively. By the ideal gas law,

$$P = mRT/V \ , \tag{2.1}$$

where R is a gas constant. Differentiating (2.1) with the assumption that the manifold air temperature is constant[2] gives

$$\frac{d}{dt}P = (RT/V)\frac{d}{dt}m \ . \tag{2.2}$$

The last term in (2.2) represents the net mass flow rate of air into the intake manifold, and thus is the difference of the mass air flow metered in by the throttle, MAF_a, and the air pumped out of the intake manifold by the cylinders; the latter can be represented by a function of engine speed, N, and manifold pressure designated $Cyl(N,P)$; it is assumed that both MAF_a and $Cyl(N,P)$ have units of lbm/sec. Equation (2.2) can thus be expressed as

$$\frac{d}{dt}P = (RT/V)[MAF_a - \mathrm{Cyl}(N,P)] \tag{2.3}$$

which is a nonlinear differential equation for manifold pressure in terms of engine speed and mass air flow rate metered by the throttle.

The cylinder pumping or induction function $Cyl(N,P)$ is usually determined by regressing the coefficients of a polynomial against engine dynamometer data [7]. For the V8 engine used in Section 5, this was determined to be

$$\begin{aligned}\mathrm{Cyl}(N,P) = 30 \times \Bigg[&-6.56 + 6.69\frac{P}{15} + 3.94\left(\frac{P}{15}\right)^2 - 1.96\left(\frac{P}{15}\right)^3 + 11.1\frac{N}{1000} + 2.3\frac{N}{1000}\frac{P}{15} \\ &+3.02\frac{N}{1000}\left(\frac{P}{15}\right)^2 - 5.57\left(\frac{N}{1000}\right)^2 \\ &+4.42\left(\frac{N}{1000}\right)^2\frac{P}{15} + 0.809\left(\frac{N}{1000}\right)^3\Bigg] \text{ lbm/sec.}\end{aligned} \tag{2.4}$$

where N is engine speed in revolutions per minute (RPM) and P is manifold pressure in psi. The mass air flow rate through the throttle is modeled as a function of the throttle position, α (degrees), throttle body inlet pressure, P_{TB} (psi), and manifold pressure [8, 6].

Cylinder air charge per induction event, CAC, is the critical quantity required for the feedforward computation of the fuel injector pulse width. It can be determined directly from (2.3). In steady state, the integral of the mass flow rate of air pumped out of the intake manifold over two engine revolutions, divided by the number of cylinders, is the air charge per cylinder. Assuming that engine speed (RPM) is constant over a single induction event leads to a dynamic approximation of the inducted air charge on a per cylinder basis:

$$CAC = \frac{120}{nN}\mathrm{Cyl}(N,P) \text{ lbm.} \tag{2.5}$$

Remark: Assuming dry air, the gas constant R is 53.36 ft-lb_f / lbm_m °R. Further assuming that the manifold volume is approximately 7 liters and manifold air temperature is 560 °R (100 °F) gives that R T / V is equal to 1.125 $10^3\mathrm{lb}_f$ / lbm-in^2.

3 Cylinder Air Charge Estimator

For simulation studies, it is usual to include the throttle in the air path model. However, air flow through the throttle is a sensitive function of P_{TB}, the throttle body inlet pressure, and in most vehicles, this is not measured. Ambient air pressure is normally not measured, and in any event, is not easily related to P_{TB} due to the pressure drop across the air filter and also due to air ram charging effects associated with vehicle motion. Secondly, in production vehicles, the throttle position sensor is typically not very accurate. For these reasons, the estimator will be based on the measurement of mass air flow rate provided by the mass air flow meter.

The dynamics of the mass air flow meter can be approximately modeled as a first order lag with a time constant on the order of 20 msec. That is,

$$\tau\frac{d}{dt}MAF_m + MAF_m = MAF_a \ , \tag{3.1}$$

where MAF_m is the measured mass air flow, MAF_a is the actual mass air flow through the throttle and τ,

[1] The model will not capture the individual cylinder maldistribution effects which are the focus of [5].

[2] Admittedly, this is not a totally accurate assumption; however, manifold temperature is slowly varying enough relative to the duration of an induction event that substituting the current estimated value (based on inlet air temperature and water coolant temperature) or an actual measured value for the manifold temperature into (2.3) is adequate to represent variations in manifold pressure due to temperature fluctuations.

the time constant of the air meter, is approximately 20 msec. Substituting the left hand side of (3.1) for MAF_a in (2.3) yields

$$\frac{d}{dt}P = (RT/V)\left[\tau\frac{d}{dt}MAF_m + MAF_m - \mathrm{C}yl(N,P)\right] \tag{3.2}$$

To eliminate the derivative of MAF_m in the above equation, let $x = P - (RT/V)\tau MAF_m$. This yields

$$\frac{d}{dt}x = (RT/V)\left[MAF_m - \mathrm{C}yl(N, x + (RT/V)\tau MAF_m)\right]. \tag{3.3}$$

Cylinder air charge is then computed from (2.5) as

$$CAC = \frac{120}{nN}\mathrm{C}yl(N, x + (RT/V)\tau MAF_m)\ . \tag{3.4}$$

Note that the effect of including the mass air flow meter's dynamics is to add a feedforward term involving the mass air flow rate to the cylinder air charge computation. When $\tau = 0$, (3.3) and (3.4) reduce to an estimator which ignores the air meter's dynamics, or equivalently, treats the sensor as being infinitely fast.

The set of equations (3.3) and (3.4) provides an estimate of cylinder air charge based upon measured mass air flow through the throttle. This is not a standard "observer" where one assumes that the inputs to a system are direclty measurable *with no sensor dynamics*; it is more an inverse of the air meter propagated through the manifold and cylinder induction dynamics. However, if a manifold pressure sensor were available, then a better estimator could still be derived by applying the extended Kalman filter or recent results in nonlinear observer theory. This would allow one to essentially apply an "error correction term" (that is, output injection) to the estimator (3.3)-(3.4). If a model of the throttle body could be used, then a "true" asymptotic observer could be designed, but this would require an accurate throttle position sensor and a throttle inlet pressure sensor (unless only correction during sonic flow is desired).

The estimator (3.3) and (3.4) must be discretized for implementation. As is often done in engine models [2], an event based sampling scheme will be used. Let k be the recursion index and let Δt_k be the current time in seconds per 45 crankangle degrees or $\frac{1}{8}$ revolution; that is, $\Delta t_k = \frac{7.5}{N_k}$ sec., where N_k is the current engine speed in RPM. Then (3.3) can be Euler integrated as

$$\begin{aligned} x_k &= x_{k+1} + \Delta t_k (RT_k/V)\left[MAF_{m,k}\right. \\ &\left.-Cyl(N_k, x_{k-1} + (RT_k/V)\tau MAF_{m,k})\right]\ . \end{aligned} \tag{3.5}$$

The cylinder air charge is calculated by

$$CAC_k = \frac{16\Delta t_k}{n}Cyl(N_k, x + (RT_k/V)\tau MAF_{m,k})\ . \tag{3.6}$$

Remark: An (analog) anti-aliasing filter is used on the mass air flow meter signal. It was determined that, with the above sampling scheme, a filter time constant of 33 Hz appears to be a good value for noise rejection and anti-aliasing purposes over a wide range of engine speeds.

4 Simulation Evidence for the Effectiveness of the Estimator

A Matrix$_X$-based simulation model of a V8 engine was constructed to investigate the effectiveness of the proposed method of estimating cylinder air charge on the basis of measured mass air flow rate. Equation (2.3) was used to represent the "true" engine, with Cyl(N,P) given by (2.4); the model contains (3.1) plus a 33 Hz analog filter to represent the relation between the measured mass air flow and the actual air flow; noise was added to assess its deleterious effects as well. Equations (3.5) and (3.6) with $\tau = 0$ were used in the case that the air meter's dynamics were ignored; this is termed the "uncompensated method"; the same set of equations with $\tau = 0.02$ is termed the "compensated method". The uncompensated method is actually a good representation of the air charge algorithm used in the on-board controller of the V8 engine of Section 5.

A throttle square wave of twenty degrees amplitude and 0.5 Hz was applied to the engine model and the engine speed was set at 1500 RPM. The resulting manifold pressure varied between 5 and 13 psi. A zero mean uniform white noise signal (20/1 SNR) was added to the measured mass air flow rate before sending it through the two estimators: neglecting air meter dynamics and including the dynamics. This was done to assess the sensitivity of the inversion process. Figure 2 shows the relative errors in the estimated cylinder air charge for the compensated and uncompensated methods. It can be seen that neglecting the air meter dynamics results in maximum relative errors exceeding 20% during transient operation. Incorporating the air meter dynamics reduces the peak error to less than 7%. Even more importantly, the integrated error of the compensated method is also greatly reduced, which should correlate with reduced emissions.

On an engine, it is difficult to measure directly the actual cylinder air charge[3], so it is important to find another way of experimentally assessing the effectiveness of including the air meter's dynamics in the cylindr air charge estimator. It turns out that the manifold pressure response presents another way to

[3] The experimental set-up used in Section 5 was not equipped with in-cylinder pressure sensors.

judge the performance of the estimators. The key observation is that the cylinder air charge and manifold pressure responses are dynamically similar[4]. This is illustrated in Figure 3 where cylinder air charge is scaled to manifold pressure, and the compensated and uncompensated methods are compared. It is evident that the true air charge follows manifold pressure very closely, the uncompensated air charge lags the manifold pressure substantially, and the compensated air charge is quite close to the true value. This comparison of estimated CAC to measured manifold pressure will be used to experimentally evaluate the performance of the estimator in Section 5.

5 Experimental Verification on a Dynamometer

In actual operation on the engine, the air charge estimator must take into account computation and scheduling delays between air measurement and fuel injection. Typically, a delay equal to 180 degrees of crankshaft rotation occurs between the computation of cylinder air charge and the time this value is used to generate a fuel pulse width. To account for this computation delay, a simple prediction algorithm was incorporated. The anticipation feature does a least squares fit of a line through the current and past two values of the air charge computation to predict forward two engine events (180 degrees).

For the purpose of identifying the function Cyl(N,P) from steady state engine mapping data, a SenSym^{TM} absolute pressure transducer was installed in the intake manifold. The mass air flow was recorded as a function of speed and manifold pressure on a warmed up engine (190 °F engine coolant temperature) over a range of speed from 800 to 2500 RPM and pressure from 4 to 14 psi. Exhaust gas recirculation was disabled. The expression used for Cyl(N,P) was given in (2.4).

The cylinder air charge calculations described by equations (3.5) and (3.6) plus the anticipation algorithm based on a simple linear extrapolation of the previous three air charge calculations were implemented in block diagram form using the Matrix$_X$ System Build simulation language and converted to real-time language control code using the Autocode facility. This code was executed in an INTEL 80486 based PC, synchronous with the embedded controller. A dual port shared memory interface between the embedded system and the PC allowed rapid implementation of the estimator without the necessity of modifying the production microprocessor control algorithms. For purposes of comparison, the final value of cylinder air charge was selectable: either the value calculated by the production embedded microprocessor, which is uncompensated for the dynamics of the air meter, or the air meter compensated value (3.5) and (3.6), could be used for fuel pulse width calculation [4].

The engine was equipped with an electronically controlled, stepper motor driven throttle with a closed-to-WOT (wide open throttle) time response of about 0.1 sec. The estimation algorithm was exercised over a range of engine operating conditions from 800 to 3000 rpm. Since all of the results are quite similar, only the data from 1500 RPM are reported here.

Figure 4 shows the dynamic engine conditions at the nominal 1500 rpm operating point. The throttle was stepped as rapidly as possible from closed to nearly wide open throttle, resulting in a manifold pressure excursion from about 5 psi to 13 psi. This is illustrated in Figure 5, where the manifold pressure computed from (3.5) is compared to the actual manifold pressure using the high bandwidth absolute pressure sensor referred to above. It can be seen that this excursion is accomplished in fewer than five 90-degree engine events (where four engine events comprise the complete engine cycle consisting of intake, compression, power and exhaust strokes. Engine events occur at intervals of 90 degrees of crankshaft rotation in an 8 cylinder engine). Figures 6 and 7 compare the cylinder air charge neglecting air meter dynamics (but including a prediction algorithm) and the compensated air charge calculation with the manifold pressure dynamics. It is clear that the uncompensated value, even with anticipation, barely keeps up with the manifold pressure. The compensated value, on the other hand, leads the manifold pressure by the required two engine events. Note that the compensated signal is "noisier" than the uncompensated air charge signal. Part of this is associated with the feedforward nature of the compensation as described previously. Some of it, however, is due to the fact that sampling is engine event based using a signal derived from a Hall-effect sensor located on the camshaft. Errors in the computation of Δt_k are due in large part to camshaft inertial effects. Since the predicted value of the compensated air charge for fueling purposes is calculated based on the past three values, and then predicted forward, the sample time variations are fed through to the anticipated value causing "noise".

The above dynamometer results provide indirect evidence that the estimator (3.5)-(3.6) yields a significantly improved estimate of cylinder air charge in comparison to the existing on-board algorithm used

[4] This is because $\frac{Cyl(N,P)}{N}$ is fairly affine in manifold pressure.

in the engine under study. This should translate into improved transient A/F control, which in turn, should lead to reduced emissions.

An attempt was made to evaluate the transient A/F improvement associated with the the estimator (3.5)-(3.6). To this end, an NTK UEGO sensor was installed in the engine very close to the production location and the 1500 rpm step response tests were repeated. This is a linear-type, exhaust gas oxygen sensor with a time constant of about 250 msec. No attempt was made to adjust the fuel portion of the transient A/F strategy. The A/F trace for the two estimation schemes is shown in Figure 8. Bearing in mind that the time constant of the A/F sensor is much larger than the time constant of the mass airflow meter which is being compensated, it is nonetheless gratifying to note that the measured A/F exhibits improved performance on both tip in and tip out. More importantly, engine dynamometer data indicate an improvement of greater than 10% in HC mass emissions over the Federal Test Procedure (FTP) driving cycle; recent vehicle data have confirmed the estimate.

6 Acknowledgement

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7 Figures

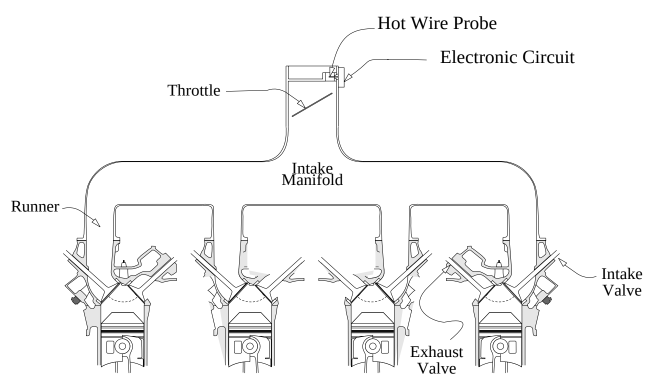

Figure 1: Schematic of air path in engine.

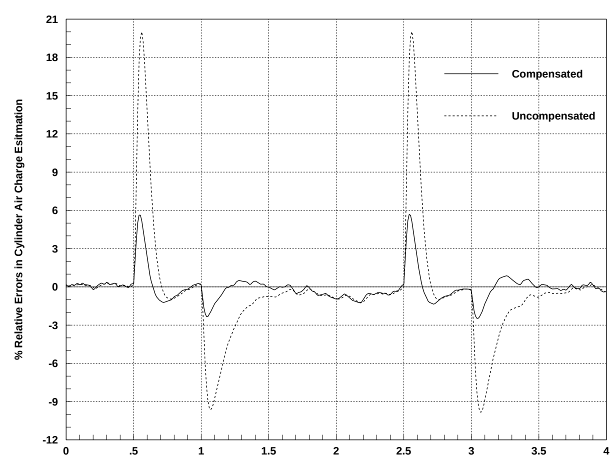

Figure 2: Percent relative errors in air charge estimation.

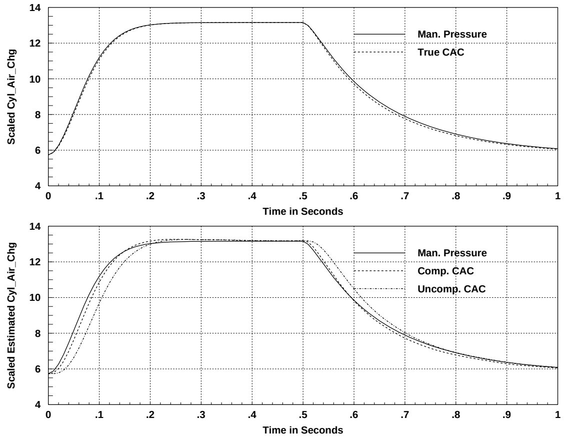

Figure 3: Indirect method to assess fidelity of air charge estimation.

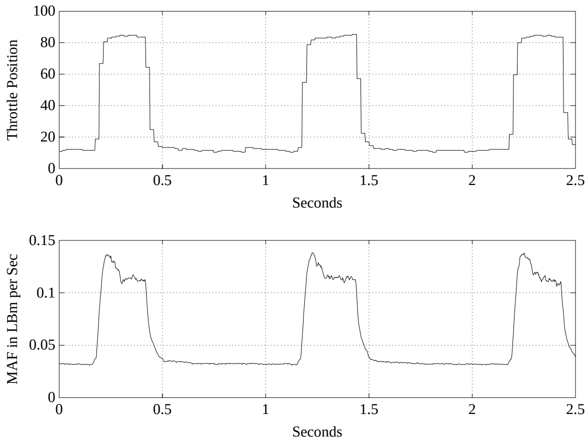

Figure 4: Engine operating conditions at nominal 1500 RPM.

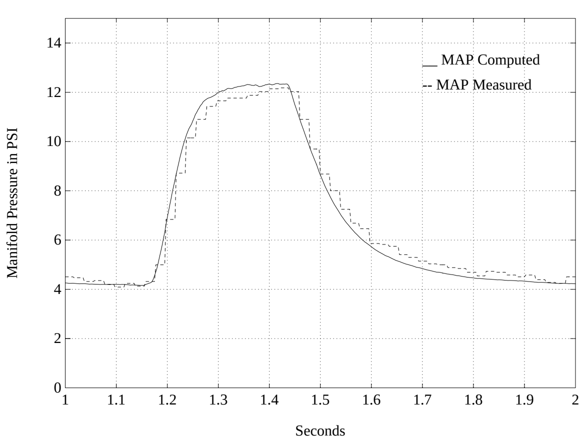

Figure 5: Comparison of measured and computed manifold pressure.

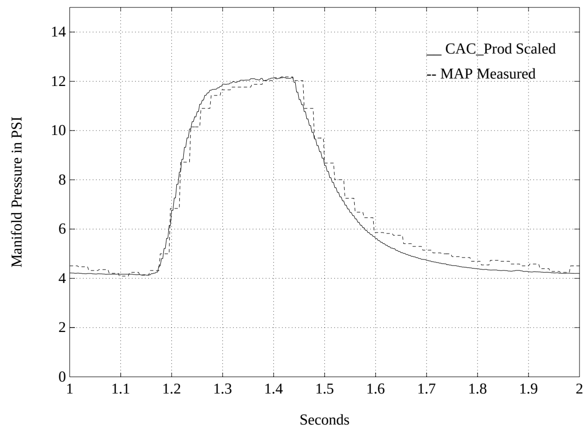

Figure 6: Cylinder air charge which ignores air meter dynamics.

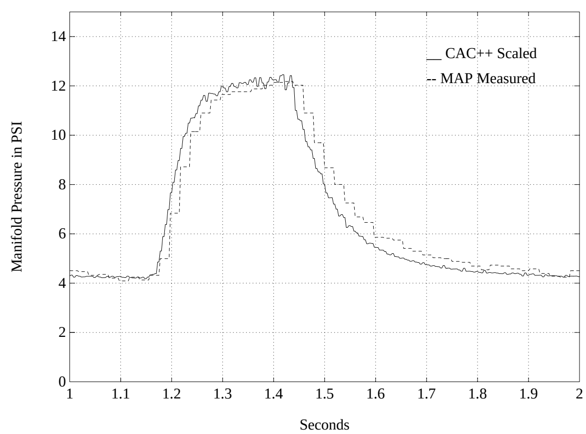

Figure 7: Cylinder air charge which accounts for air meter dynamics.

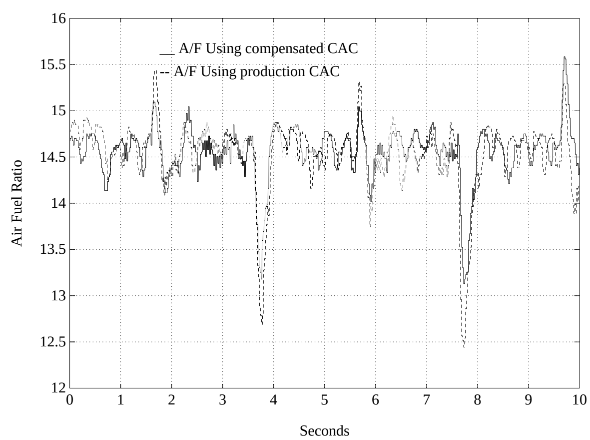

Figure 8: Air fuel ratio traces.