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ABSTRACT

In this paper we discuss in detail an algorithm that addresses cylinder-to-cylinder imbalance issues. Maintaining even equivalence-ratio (ϕ) control across all the cylinders of an engine is confounded by imbalances which include fuel-injector flow variations, fresh-air intake maldistribution and uneven distribution of Exhaust Gas Re-circulation (EGR). Moreover, in markets that are growing increasingly cost conscious, with ever tightening emissions regulations, correcting for such mismatches must not only be done, but done at little or no additional cost. To address this challenge, we developed an Individual Cylinder Fuel Control (ICFC) algorithm that estimates each cylinder's individual ϕ and then compensates to correct for any imbalance using only existing production hardware.

Prior work in this area exists[1,2], yet all disclosed production-intent work was performed using wide-range oxygen sensors, representing cost increases. In our production-bound algorithm, modeling and control of the cylinders' dynamic ϕ was performed using a single switching oxygen sensor. Our ICFC algorithm was developed on a 1996 Pontiac Grand Am with a production LD9 2.4L four-cylinder DOHC engine. It met internally defined performance requirements and LEV emissions. Other important contributions in this work include an analysis of exhaust gas transport and mixing phenomenon, and an analysis of digitally acquiring and post processing oxygen sensor data.

RATIONALE FOR THE ALGORITHM'S DEVELOPMENT

Both automotive manufacturers and their suppliers are under increasing pressure to reduce costs while meeting ever-tightening emission standards. This objective is impeded by cylinder-to-cylinder imbalances in air, fuel and diluent. Figure 1 shows typical contributions to maldistribution. ICFC provides an algorithmic solution rather than a hardware solution, and is a tool to help achieve both emissions and cost-reduction objectives.

FUEL	AIR	EGR	PCV	PURGE	RESULT
± 3 % (±0.44 A/F)	± 3 % (±0.44 A/F)	± 5 % (±0.15 A/F)	± 10 % (±0.03 A/F)	± 10 % (±0.23 A/F)	**± 0.7** A/F ratios

ASSUMPTIONS: Max EGR Contribution is 20%
Max Purge Contribution is 2 %
Max PCV Contribution is 2%
Purge is 16 % of fuel, Max

Figure 1. Maldistribution Contributions

Presently, most automotive applications control the average ϕ of all the cylinders[3, 6]. With imbalances present, this method forces some of cylinders to run rich, and others to run lean. Many applications provide static calibration gains for each cylinder to correct for maldistribution, but provide only an average correction across a fleet of engines. They do not take into account differences from component to component or from engine to engine.

Our ICFC algorithm was designed to reduce engine and component costs while maintaining or reducing engine emissions and emission variability, using only existing production hardware. It was implemented using a model-based approach[4] with a focus on reducing manual and iterative calibration processes[5] associated with fuel and emissions control.

ICFC is a real-time online adaptive controller than learns each cylinder's maldistribution and stores the corrective terms into the Powertrain Control Module's (PCM) memory. It accomplishes this task by analyzing each cylinder's exhaust using a single oxygen sensor, and compensating for imbalances by individually modifying fuel-injector commands.

Our ICFC, using a switching oxygen sensor, has shown the following benefits:

1. Cost Benefits
    - No requirement for additional hardware beyond that typical to current US and European production.

- A relaxation in engine and component tolerances contributing to ϕ maldistribution.

2. Emissions Benefits
   - More repeatable emissions.
   - Simultaneous reduction in hydrocarbons (HC), carbon monoxide (CO), and nitrous oxides (NO_x) in steady-state emissions studies. See Figure 2.
   - A 27% reduction in NO_x emissions in vehicle emission testing with no statistically significant impact on HC emissions.
   - Possible reduction in NO_x emissions with increased EGR due to balancing.
3. Drive-ability Benefit
   - Improved idle quality and drive-ability by reducing the variance of indicated mean effective pressure (IMEP). See Figure 2.
4. Fuel Economy Benefits
   - Increased torque and improved engine efficiency and fuel economy. See Figure 2.
   - Extended lean-limit operation. The leanest running cylinder defines the lean drive-ability limit. With cylinder balancing, the engine can be run much closer to this limit.
5. Diagnostic Benefit
   - Bad-injector identification capability. The algorithm will first try to correct the error, but if it is too large, the diagnostic will flag the bad component.

	HC	*CO*	*NOx*	*Torque* *(N-m)*	*IMEP*
Cylinder Imbalances max +/-8% tolerances	6.0	49	70	60	5.6%
Balanced Cylinders	5.5	29	14	61.21 (+2.0%)	2.5%
	Emissions Emissions in (ppm)			Fuel Economy	Driveability

Figure 2. Individual Cylinder Fuel Control Opportunities

MODELING

Modeling the relevant physical effects and dynamics involved is key to the ICFC algorithm (see Figure 3). While the control law used is rather simple (proportional-integral (PI) feedback with adaptive feed-forward), pre-processing sensor information for the controllers is non-trivial. Knowledge and understanding of how these dynamic effects behave are used to properly enable the PI controllers and preprocess information upon which control depends. We address each major dynamic separately: fuel wall-wetting dynamics, exhaust gas mixing, engine cycling, gas transport, and sensor delay.

FUEL WALL-WETTING DYNAMICS – For engines without direct fuel injection, one should consider the existence of dynamics of fuel films in the intake runner and on the intake valve. Commanded changes to the fuel injector are filtered by fuel wall-wetting dynamics resulting in what is often referred to as “transient fuel”. In our case, ICFC was only enabled during warm, steady-state engine conditions. Both conditions act to minimize transient fuel effects. First, fuel-film lags decrease with increasing engine temperatures. Secondly, under steady-state conditions, the dominant changes to the fueling ordered by closed-loop fuel and ICFC, are relatively small. For these reasons, fuel film dynamics were assumed insignificant in this context.

EXHAUST GAS MIXING – There are two types of blurring or smearing effects that accompany measuring ϕ using one sensor for multiple cylinders. The first effect comes from the physical mixing of exhaust packets, both between different cylinders, and also from packets from the *same* cylinder from subsequent exhaust cycles. The second blurring effect is due to the sensor being non-ideal, in that, its response to step inputs is not instantaneous. One must be careful not to confuse the two. Also, the dynamics involved must be understood physically and not just mathematically. We first address physical gas mixing.

Concerning physical gas mixing, unlike in other documented approaches[1], we found no need to consider gas mixing between cylinders in our exhaust manifold. First, our engine’s exhaust manifold has virtually no plenum to accommodate mixing. It is a set of four cast pipes dovetailing to meet the oxygen sensor. See Figure 4.

The second reason is that each runner is sealed back at its cylinder when its exhaust valve is closed. This inhibits mixing of one cylinder exhaust up into another’s runner. Virtually all the gas moving across the sensor during any given cycle is from the exhausting cylinder. For these two reasons we neglected cylinder-to-cylinder mixing of gas in the exhaust manifold.

In contrast, mixing that was found to be significant was not between cylinders but rather between a cylinder’s previous and current exhaust cycles. When a cylinder exhausts, the gas leaving that cylinder must first push a runner full of gas from its own previous cycle out and across the oxygen sensor (see Figure 5). There are two possible cases. Upon the exhaust valve opening, the runner will already be filled with gas from either one *or* two previous events. If a runner is long and the engine is running at a light loads, the volume of the gas exhausted V_g may be less than the volume of the runner V_r. In this case the runner would have gas from the previous two exhaust cycles. However, in our testing we did not see this happen. This effect acts as a varying FIR filter (EQ. 1), that averages $\phi_{incident}$, the ϕ of the gas contacting the oxygen sensor, over one or more exhaust events for a given cylinder.

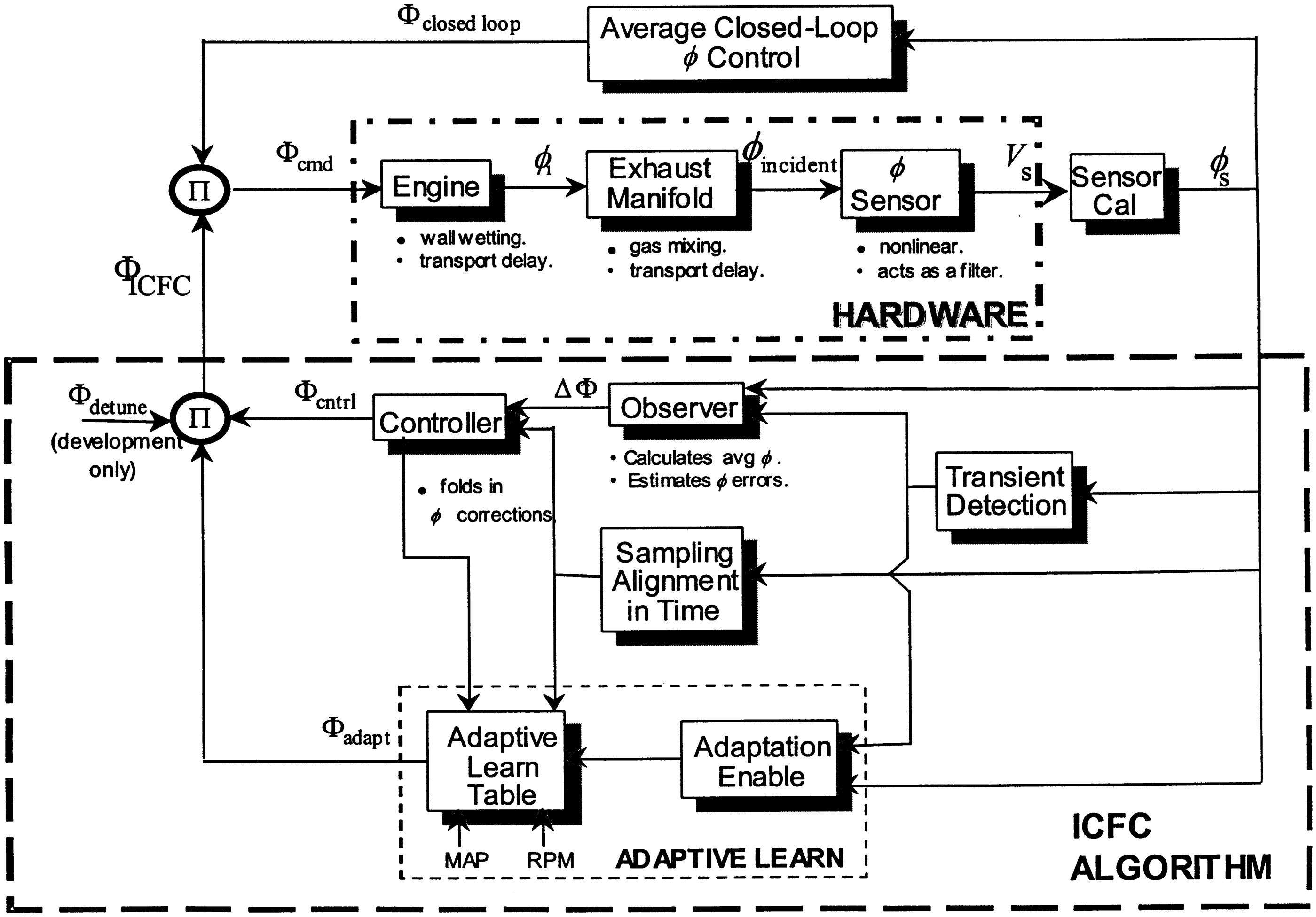

Figure 3. Model Diagram

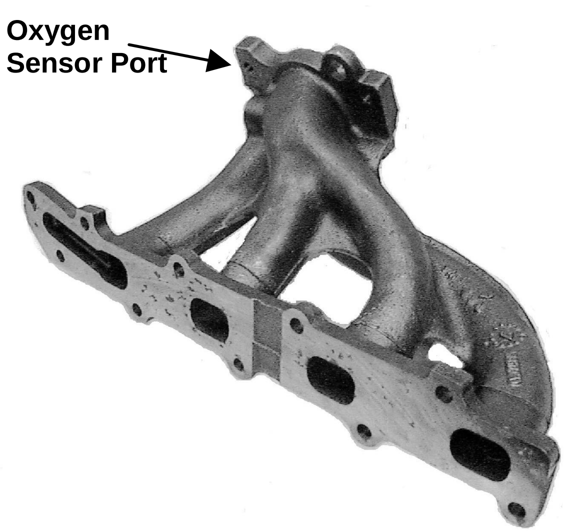

Figure 4. Exhaust Manifold Configuration

$$\phi_{incident} = \frac{V_r \phi_{k-1} + (V_g - V_r)\phi_k}{V_g}, \text{ for } V_g \ge V_r \qquad (1)$$

As V_g grows large with respect to V_r, $\phi_{incident}$ grows close to ϕ_k. Conversely, the filtering or mixing grows heavier as V_g diminishes to or below V_r. If V_g becomes smaller than V_r (again a condition we have not seen), we get:

$$\phi_{incident} = \frac{(V_r - V_g)\phi_{k-2} + (2V_g - V_r)\phi_{k-1}}{V_g} \qquad (2)$$

While this effect limits the speed at which ICFC can operate and remain stable, the change in ϕ should be slow enough such that $\phi_k \cong \phi_{k-1}$, and we can make the simplifying assumption that $\phi_{incident} = \phi_k$. This assumed equality is only valid when $\phi_{incident}$ is measured at the proper time.

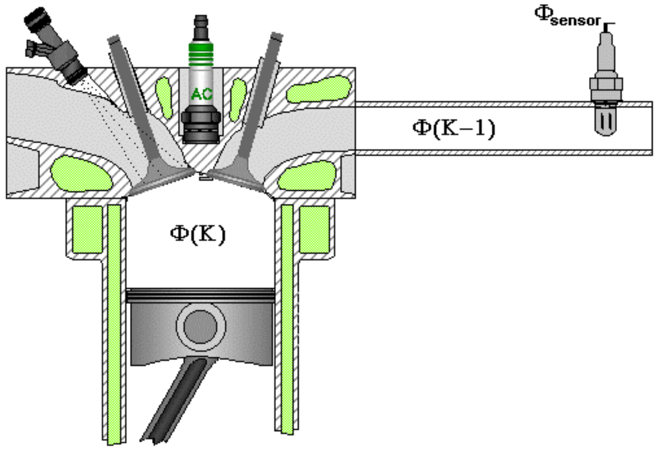

Figure 5. Same-Cylinder Gas Mixing

MEASUREMENT DELAY

A key factor in successfully implementing ICFC is reading the oxygen sensor at a time when it best represents the relative ϕ for each cylinder. In other words, to successfully trim a cylinder's ϕ imbalance, the algorithm must align sensor data with the corresponding control action. For our processor, the low-level output drivers are loaded with new fuel injector pulse-width commands on what we refer to as "cylinder fuel events", triggered by certain teeth on the crankshaft angle sensor. The event-based portion of ICFC runs synchronously with these fueling events. So, to align exhaust sensor readings with the proper cylinder, we must find the time from the cylinder-event fuel interrupts to the time the sensor reports the resulting ϕ. This measurement delay time varies with engine operating conditions. This overall delay t_{align} is composed of:

1. $t_{fuel\,2evo}$, the time from when the fuel command is issued to the injector to the time the exhaust valve opens,
2. $t_{transport}$, the time for the gas to move from the exhaust port to the oxygen sensor, and
3. t_{sensor}, the oxygen sensor's reaction time, EQ. 3.

$$t_{align} = t_{fuel\,2evo} + t_{transport} + t_{sensor} \tag{3}$$

Knowing the individual components of t_{align} allows for a compact physical representation in the algorithm. t_{sensor} is the only component that can vary significantly for the same set of engine operating conditions due to sensor temperature and component aging and variability.

ENGINE CYCLING AND PCM TIMING – Fuel-control command updates are made to the fuel injectors at very precise times in the PCM, and are triggered by hardware interrupts from specific angles along the engine cycle's 720° of rotation of the crankshaft. In our development, the angle-based event marking the instant to write to the register controlling the fuel injector, was roughly 7.4 cylinder events ahead of the time when that cylinder's exhaust valve opened, expelling the first slug of gas reflecting the new fuel command. This can be left in units of events, or converted to seconds in EQ. 4, where t_{event} is one fourth of an engine's cycle time.

$$t_{fuel\,2evo} = 7.4 \cdot t_{event} = 7.4 \cdot \left(30 / RPM \right) \tag{4}$$

GAS TRANSPORT – The gas transport delay $t_{transport}$ is the time taken for the exhausting gas to travel from the cylinder's exhaust port to the oxygen sensor. With the exhaust manifold having a small effective plenum, this time may be modeled as gas travelling down a pipe.

$$t_{transport} = \begin{cases} \left(\dfrac{\bar{v}_g}{l_r} \right), & \text{if } V_g > V_r \\ \left(\dfrac{\bar{v}_g}{l_r} \right) + t_{\text{engcycle}}, & \text{otherwise.} \end{cases} \tag{5}$$

where:

$$\bar{v}_g = \frac{\rho_g A_r}{\dot{m}_g} \tag{6}$$

$$\rho_g = \frac{P_g MW_g}{\tilde{R} T_g} \tag{7}$$

We set out to validate EQ. 5 using an exhaust manifold with five wide-range oxygen sensors—one in each runner very near the exhaust ports, and one in the production location. Each cylinder, in turn, was fired extremely rich for one event (see Figure 6). However, this yielded ambiguous results requiring further deliberation.

Recall that the exhaust runners are at all times full of exhaust gas either from the previous cycle or the current. Now, for $V_g > 2V_r$ along with the previously justified assumption of $\phi_k \cong \phi_{k-1}$, we found $t_{transport}$ to effectively be zero! This explains why we could use the same t_{align} for all four cylinders at any given operating point, in spite of having a very asymmetric manifold[8].

SENSOR DYNAMICS – Switching oxygen sensors are nonlinear dynamic devices. For instance, the time response for rich-to-lean shifts is faster than for lean-to-rich shifts. Thus finding t_{sensor} directly is difficult, and fortunately is not necessary. A dependable, efficient way to determine the delay is to enable ICFC and monitor its control action. We began by selecting the minimum $t_{align} = t_{fuel\,2evo}$, which assumes instantaneous sensor response and no transport delay. If the control is unstable, increase t_{align} by one event (or one minimum unit of sampling time) until the control is stable. Next, to ensure sufficient accuracy, we purposely imbalanced the cylinders by multiplying their commanded ϕ's with detuning gains. We then again enabled ICFC using the t_{align} found before looking for both stable convergence and accurate performance. We validated performance by comparing the difference between the first ICFC ϕ steady-state results and the ones found with the artificial imbalances. Those differences should equal the artificial imbalances. This approach provides important information. First it reveals if the minimum unit of sampling time is too large (i.e. the sample-time resolution is too coarse) to allow for acceptable control performance. Second, it will report the optimum t_{align} for the given sample-time resolution.

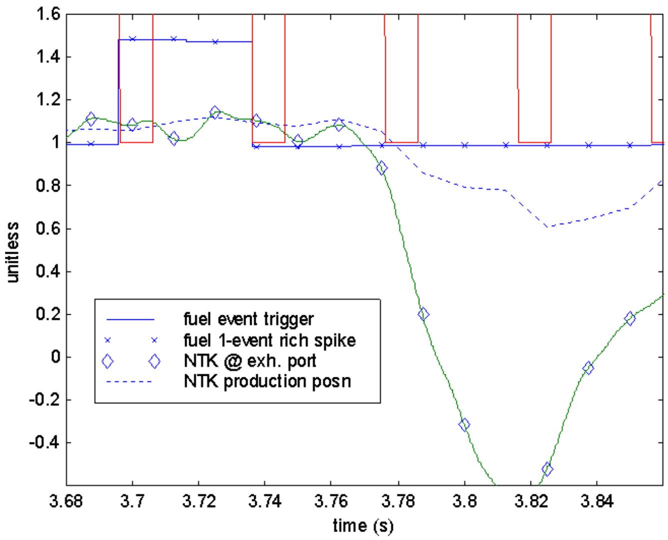

Figure 6. Determine Transport Delay

OXYGEN SENSOR SAMPLING

To properly read the oxygen sensor, the rules of digital data sampling must be followed. As stated, the sensor used to implement the algorithm is a switching sensor, however, to better facilitate this discussion we will use data from a wide-range ϕ sensor. As previously mentioned, the response of the sensor is not solely a function of $\phi_{incident}$, although ideally it would be, but is also a strong function of tip temperature and mass rate. But for discussion, assume now a linear sensor exists. The Bode plot for an NTK wide-range lambda sensor, available from the manufacturer, showed roughly a 25dB drop from 1 to 10Hz. It crosses the relative –3dB point well below 2 Hz. For our engine, by alternating cylinder firings of rich, lean, rich, and lean, the maximum ϕ imbalance frequency (EQ. 8) is created. To accurately capture this information, the ϕ sensor must have a bandwidth of 50 Hz or greater to operate out to 3000 RPM. But for ICFC, detecting *relative* differences in ϕ is all that matters, making such a requirement overly stringent. Still, the signal-to-noise ratio in the sampled data must be large enough to facilitate control. In looking at data taken in a neutral condition at 3000 RPM, we see the spectral information at the perturbation frequency (50Hz) has basically the same magnitude as closely adjacent noise components (see Figure 7). Conventional time-based sampling methods would require a great deal of post-sampling processing to extract the signal from the noise.

$$f_{imbalance\,\max} = \frac{1}{2}\cdot\frac{1}{t_{event}} = \frac{1}{2}\cdot f_{event} = \frac{1}{2}\cdot\frac{RPM}{30} \qquad (8)$$

The sensor must either be sampled rapidly enough to capture the waveform, or it must be sampled at the right moment to extract the required information. Due to processing throughput limitations of the PCM, only the second option is feasible. This is accomplished by correlating sampling with the information in the signal, by sampling at the frequency (or a harmonic) of the information. This is commonly referred to as “event-based” sampling. The advantage to this type of sampling is it removes non-correlated noise. This scheme requires that there be enough resolution in the sampling frequency to get sufficiently close to the optimum t_{align} to align the measurement with the control action. Experimentally we determined that for this application, the once-per-cylinder-event loop provided adequate speed and time resolution for control out to 3000 RPM. Sampling once per event to represent information varying at that same rate is risky, with one of the main risks being that natural phasing may place the peaks that best represent the individual ϕ‘s, in between sampling points. Sampling a minimum of twice per event is strongly recommended.

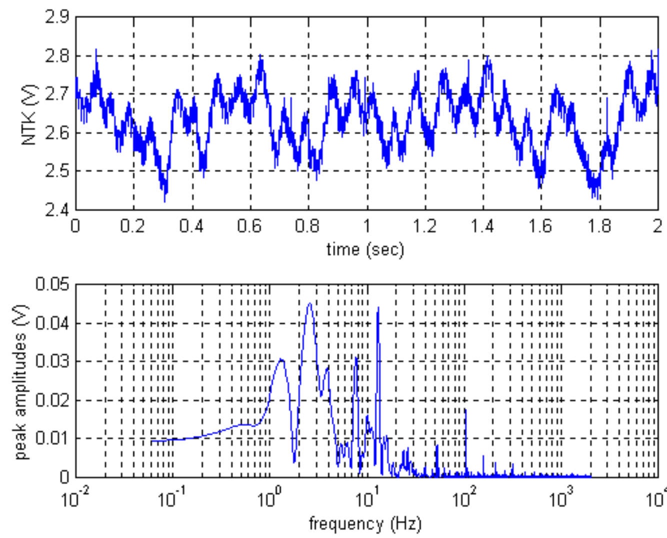

Figure 7. NTK Data in the Time and Frequency Domains

INFORMATION EXTRACTION

One of the engineering challenges included extracting the magnitude of the errors. Due to the switching oxygen sensor’s characteristics and its lack of bandwidth, it is not capable of accurately reporting error magnitudes. The switching oxygen sensor is only capable of providing directional (rich or lean) information relative to the stoichiometric point. The directional information provides the basis for driving out the maldistribution errors. Figure 8 illustrates how we obtained maldistribution information from the oxygen sensor to make ICFC possible. The top graph in Figure 8 is the output of a switching oxygen sensor measuring induced cylinder imbalances. The boxed-in area in the top graph was expanded and plotted in the second graph, and overlaid with the real-time computed four-point linear regression. In this second graph, imbalance is clearly visible. The third graph marks fueling events with vertical transitions, giving a sense of relative timing.

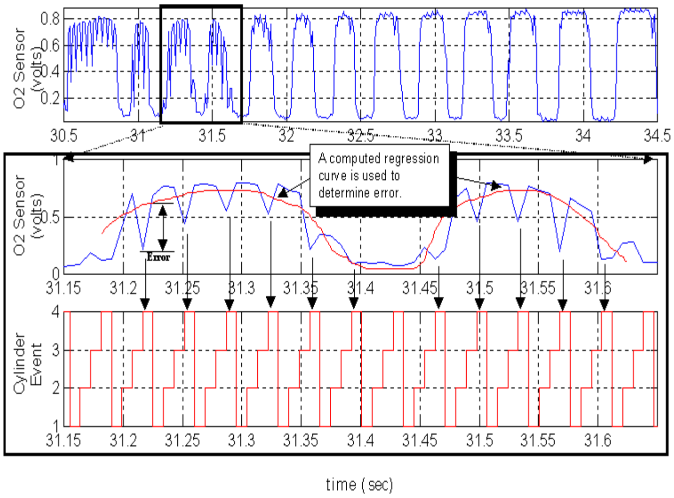

Figure 8. Determining the Errors

Figure 9 illustrates how the oxygen sensor signal was analyzed to obtain a quantifiable metric of maldistribution. First, the raw oxygen sensor signal was sent through a 10Hz second-order, high-pass Butterworth filter to help isolate the firing-frequency information by stripping out the large oscillations from the closed-loop average fuel controller. Next, the signal was rectified to retain only magnitude information as shown in the second plot of Figure 9. Finally, the rectified signal was passed through a first-order filter to quantify the maldistribution activity as shown in the third plot. Once the cylinder errors rose above a certain threshold, ICFC was activated. The cylinder maldistribution errors were then driven toward zero (visible in the oxygen sensor plot).

CONTROL OVERVIEW

The control portion of ICFC for this engine is partly basic and partly novel. It is basic in that a rather ordinary PI controller modifies each cylinder's ϕ. It is novel in all the information processing required to enable and feed rational data into the four PI controllers.

OBSERVER – EQS. 9 and 10 provide a useful model for an ICFC observer[1]. It is only valid under steady-state conditions with constant imbalances, and for exhaust manifolds having runners all the same length. In contrast to Ref. [1], our output matrix is simplified by assuming there is no gas mixing. The states $\mathbf{x}$ are the ϕ imbalances.

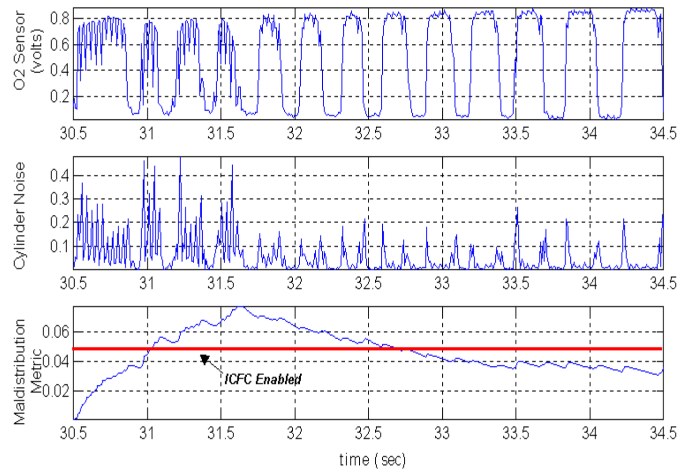

Figure 9. Quantifying the Maldistribution

$$\mathbf{x}(k+1)=\begin{bmatrix}0&0&0&1\\1&0&0&0\\0&1&0&0\\0&0&1&0\end{bmatrix}\mathbf{x}(k) \tag{9}$$

$$y(k)=\begin{bmatrix}1&0&0&0\end{bmatrix}\mathbf{x}(k) \tag{10}$$

Note that since $\mathbf{x}$ is a numerical carousel, the positions in the vector have no meaning, except for recency. The first position $\mathbf{x}(1)$ in the vector corresponds to the cylinder currently exhausting. The second position $\mathbf{x}(2)$, to the one previously measured, et cetera.

Ref. [1] used a Kalman filter approach since the output matrix had coupling. Our model has shown little or no such coupling, allowing us to create an extremely simple observer that is a first-order low-pass filter. The input u is defined as the instantaneous ϕ minus a linear regression (ϕ_{fitted}) of the last four ϕ values.

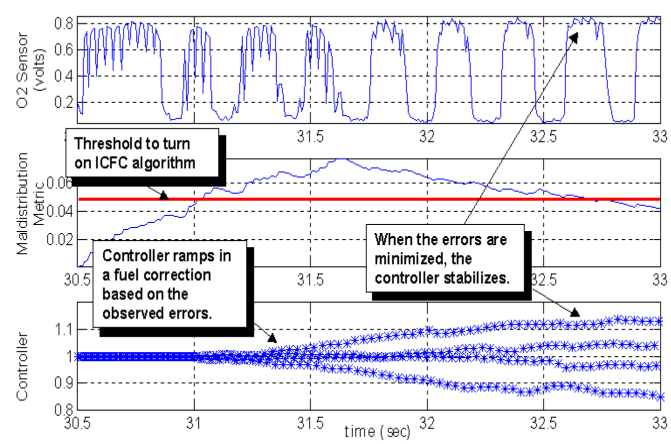

Figure 10. Individual Cylinder Fuel Controller in Action

$$u \equiv \phi_s - \phi_{fitted} \tag{11}$$

$$\hat{\mathbf{x}}(k+1)=\begin{bmatrix}0 & 0 & 0 & (1-k)\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\hat{\mathbf{x}}(k)+\begin{bmatrix}k\\0\\0\\0\end{bmatrix}\cdot u \qquad (12)$$

The filter coefficient *k* may be found using Kalman filter methods, or by other means. The form of the observer illustrates the de-coupling in the model.

The indexing in EQS. 13 and 14 was used to align $\hat{\mathbf{x}}$ with the feedback controllers so that the sensor readings align with the correct cylinder. t_{align} is defined in EQ. 3. N_{align} is t_{align} expressed in whole event periods. The index term, which is used in $\hat{\mathbf{x}}(index)$ is calculated as EQ. 14. For instance, if N_{align} is three events, for a four cylinder ($N_{cyl} = 4$) engine, we use $\hat{\mathbf{x}}(4-3+1)$ or $\hat{\mathbf{x}}(2)$ to feedback on the current fueling event.

$$N_{align} = \text{round}\left(t_{align} / t_{event}\right) \qquad (13)$$

$$index = N_{cyl} - N_{align} + 1 \qquad (14)$$

CONTROLLER – The feedback portion of the controller is a set of four PI controllers, one for each cylinder, along with a feed-forward table of learned values for each cylinder. The PI loops operate to drive $\hat{\mathbf{x}}$ toward **0**. When the imbalances are sufficiently small, the values contained in the four integrators are moved into the feed-forward tables stored in PCM non-volatile memory, as shown in Figure 10.

IMPLEMENTATION ISSUES

Since the algorithm works on event-to-event differences, at least some portion must be event synchronous. These portions include the routines to sample the sensor and run the observer. The remaining subroutines were placed in relatively slow fixed-rate loops to minimize computational burden[7]. Another option to further reduce this burden is to disable ICFC above a certain engine speed.

A second implementation issue involves sample-time alignment. If, due to large variations in the sensor delay time t_{sensor}, the offset delay times cannot be known a priori, then they must be determined on-line. This involves assuming an offset, monitoring for stable convergence of the four controllers, and modifying the offset when required. This was our original approach, and was implemented in form ready for production.

CONCLUSION

This paper provides a blend of theoretical contributions tempered by engineering savvy, yielding a practical solution to Individual Cylinder Fuel Control using only existing production hardware. This algorithm has been implemented in a production package, and is now an “off-the-shelf” software module. We have provided an economical software-only solution, which if one so desires, allows for a relaxation and cost-reduction in component design compared to non-ICFC applications.

The technical contributions include the algorithms to extract cylinder-imbalance information from the switching oxygen sensor useful for compensating for the imbalances and for knowing when to “learn” such compensation values. Other valuable contributions are the expanded physical understanding of gas dynamics and transport delays, allowing us to simplify our approach. Future work may seek to further simplify the algorithm in both of these areas.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A_r **:** = manifold runner inner cross-sectional area
l_r **:** = manifold runner length
$\dot{m}_g$ **:** = gas mass rate
MW_g **:** = gas molecular weight
N_{align} **:** = t_{align} expressed in whole multiples of T_{event}
N_{cyl} **:** = number of cylinders in the engine
P_g **:** = gas pressure

$\tilde{R}$ **:** = universal gas constant
t_{align} **:** = time between a cylinder's fueling event and corresponding sensor response
$t_{engcycle}$**:** = time period for one engine cycle
t_{event}**:** = time between cylinder events
$t_{fuel2evo}$ **:** = time between a cylinder's fueling event and subsequent exhaust valve opening
t_{sensor} **:** = oxygen sensor reaction time
$t_{transport}$ **:** = gas transport time from the exhaust valve to the oxygen sensor
T_g **:** = gas temperature
$\bar{v}_g$ **:** = mean exhaust gas velocity
V_g **:** = gas packet volume
V_r **:** = runner volume
$\phi_{incident}$ **:** = fuel-air ratio at the oxygen sensor
ϕ_{fitted} **:** = linear fit of the last N_{cyl} points of ϕ_s
ϕ_s **:** = fuel-air ratio reported by the oxygen sensor
ρ_g **:** = gas density

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